Design Decisions and Analysis for Automated Fencing Dummy

Technical Report

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ME 450
Sponsors: Wenda Tan, Professor, University of Michigan, Department of Engineering;
Ian Rozich, Coach, Plymouth/Ann Arbor Fencing Club.
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ABSTRACT

This report outlines development of an automated fencing dummy that simulates fencing drills for Plymouth Fencing Academy. Sponsored by Coach Ian Rozich and Professor Wenda Tan, the project navigates challenges like time constraints, interdisciplinary demands, and budget limitations. Strategies such as role assignment, and modular development were employed. From 200 diverse design ideas, the team chose a humanoid robotic arm with two degrees of freedom. Detailed force analysis guided material and motor selections, resulting in an arm with a motorized elbow and manual forearm angle adjustment. A prototype target and arm was created that allows for actuation of the four most common parries seen in fencing.

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FOREWORD

Our team has been asked by our sponsors Coach Ian Rozich and Professor Wenda Tan to design an engineering solution capable of simulating fencing exercises. The robot must be able to wield a sword, be safe for children and inexperienced people to use, automated, and execute the most common parries 4, 6, 7, and 8. The purpose of this report is to provide the reader with information regarding the design choices and data related to the fencing dummy arm.

EXECUTIVE SUMMARY

Pre-existing technology that are similar to our stakeholder's requirements such as a spring loaded drill stand or an opposable dummy (the only commercially available options), don't offer an automated motion of the parry movements [1, 5]. Alternatively, there are student and independently designed options that do offer this range of motion, but are not commercially available such as the German Nationals Fencing team custom made fencing robot [10, 43, 48, 49].

Our design process consists of a need statement, problem definition, concept exploration, prototyping, and verification, with iteration to a previous step available at any point. Coach Ian Rozich and Professor Wenda Tan, and Fencers at Plymouth Fencing Academy are important stakeholders in this project.

A successful project would ideally cover all five of the Tier I Requirements and Specifications: has to follow US Fencing Safety Standards, simulates most commonly used fencing drilling exercises, accommodates a wide range of users from age 13+, which accounts for size and skill, elbow rotation, and forearm angle adjustment.

Anticipated challenges include time constraints, coordination of multiple disciplines, durability of elbow joint and safety of pinch points. To tackle these challenges, a structured project plan, modular development, good communication and documentation, completing strength calculations with a safety factor and enclosing moving components with a protective housing are essential.

From nearly 200 ideas, the concept was narrowed to a humanoid robotic arm with two degrees of freedom with 'independent actuators' being the driving system. For the second degree of freedom, a Pugh Chart was made which showed that the best mechanism for flexion and extension would be a pin in a hole. A design was created including a wood target stand and aluminum fencing arm with a stacked 1:80 planetary gearbox and pin and hole elbow joint. A detailed CAD shows the features selected throughout this report.

Our engineering analysis consists of free body diagrams, force analysis, material selection, and motor selection. The diagrams and subsequent equations will allow us to make crucial design decisions such as choosing materials, motors, and gearboxes. We also modeled the motion of a fencer executing parries by utilizing long exposure photography and a bright light attached to the foil sword. This was compared to the trace in CAD to ensure our design met the motion requirements of each parry.

Lasty, we need to verify and validate our solution. We outline several key tests to ensure the requirements are met. We also plan to conduct in depth testing with real fencers and coaches at the Plymouth Fencing Academy. This will provide us with valuable feedback to confirm the functionality of our dummy.

Upon completion of our build, we critically evaluated the functionality of components, and determined it met our modified requirements in speed and torque. Critiques of our build design include the need for a stronger motor if it is desired to accommodate a human fencer, as our model proved the range of motion with a weaker, under budget motor. Additionally, a second method of actuation could prove to be a task for another semester, as the time constraints forced us to reduce the scope. The incorporation of the lamè into the Arduino circuit would also make the dummy completely functional in a fencing drilling setting. Overall, our solution proved a dummy could be constructed to conduct parries 4, 6, 7, and 8 for a wide range of users of different heights, skill levels, speed, and right/left handedness.

INTRODUCTION

During the summers, the Plymouth Fencing Academy welcomes many new students that would like to learn fencing. In order to meet the demand for an increase in students, Fencing Coach Ian Rozich, our primary sponsor and coach at Plymouth Fencing Academy, has asked our ME 450 team to design a drilling robot for fencing students to practice on whilst coaches divide their attention. Coach Rozich specializes in foil fencing, which is a discipline of fencing in which the foil style sword is used during sparring and points are scored by making contact with the tip of the foil to your opponent's torso. He intends for this product to be used by his fencing students, so the robot must be able to accommodate a wide variety of users.

Our main objective as a team is to first design a product that is capable of simulating flexion/extension of the forearm, rotation of the forearm, as well as replicating the average fencer strength for these movements. This product must be stable and durable as it will undergo various stresses during use. Moving forward, we need to implement an electronic control system that is capable of guiding the movements of the system, and allowing us to program in autonomous motion. Lastly, using the electronic control system, we'll have to program in precise maneuvers that replicate foil fencing drills specified by Coach Rozich (I. Rozich, personal communication, September 14, 2023). Our team believes that if we can achieve these objectives whilst maintaining US Fencing Safety Standards, that our project will be a success.

Design Context and Stakeholder Analysis

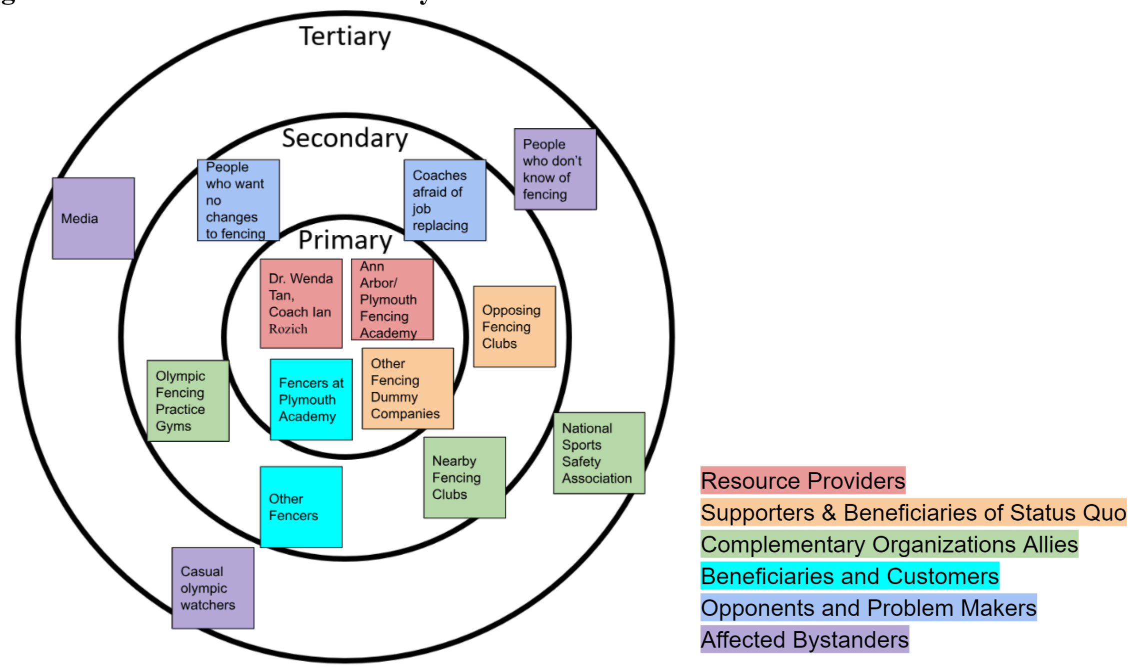


Figure 1: Stakeholder map with all stakeholders involved in the project listed and categorized into primary, secondary and tertiary stakeholders.

As seen in Figure 1 above, the main stakeholders that the team has contact with are Professor Tan, Coach Ian, Plymouth Fencing Academy, the fencers at the academy, and other fencing dummy companies. However, there are a lot more, such as opposing clubs, general fencers in their club and in other clubs, other coaches, the USA Fencing organization and of course the media. The stakeholders who would be affected positively are Plymouth Fencing Academy/their fencers and Coach Ian. He wants to have a way for people to practice when he or other coaches aren't able to assist (I. Rozich, personal communication,

September 14, 2023). A wanted design goal is that the dummy can switch its skill level. This way, it can train beginners all the way to advanced members. Some negatively affected stakeholders would be coaches who might be replaced by this dummy and possibly some users who are too accustomed to the dummy's timing. This project will be made out of mostly steel/machined parts and disposal should be related to scrapping, which might be environmentally unfriendly.
For the social impact of this training dummy, Coach Ian wishes to expand his consumer base while keeping his personal touch when teaching fencing (I. Rozich, personal communication, September 14, 2023). A dummy that is able to help teach will be able to increase the teaching time per student. Hopefully, this allows his club to compete more and increase its standing in the Detroit Metro Area.

The intellectual property rights are assigned to the University of Michigan. The team are to be co-inventors with the university.

With respect to sustainability, this will be using machined parts. The scrapping should be done in environmentally friendly ways, but the use of power will be a bit harder as there are many natural-gas power plants that are being run by DTE [8]. One could persuade Coach Ian and Plymouth Fencing to go all renewable power, but that would not be in the scope of this project.

There are no ethical dilemmas as long as the safety requirements set down by the US Fencing Safety Standards are followed. This dummy is a one-off device that will help supplement coaches in Plymouth Fencing Academy. This means that it won't have as much impact with automation of jobs.

Finally, the stakeholder has a lot of power over the team and will be influencing how the end users interact with this device. The stakeholder has influenced nearly 50% of the requirements.

Background
The most common solution for fencing dummies used in most home and training gym applications is a stationary target attached to the wall or a stand, seen in Fig. 2 [14]. They are commonly homemade and made out of recycled materials like plywood, carpet and old fencing equipment. Some targets are a 2D surface for students to practice their lunging distance, speed or blade precision on. Other targets look more like a humanoid opponent in an en garde stance with a weapon attached to an arm [5].

Figure 2: Stationary fencing targets to allow users to practice weapon aim and footwork spacing [14, 5].

The en garde stance, seen in Fig. 2, is a defensive position where both legs are bent with the front foot facing forward and the back foot 90 degrees angle from the front foot, the arm is holding the blade with the elbow bent.

Figure 3: En garde position: this position allows fencers to react quickly and provides balance and stability [24].

What is currently being used by Coach Rozich is a spring loaded drill stand, seen in Fig. 3, that allows the user to parry with the “arm” in different configurations [1]. Once released from the parry, the arm springs back to the original set position as the user lunges to hit the foam target attached to a wall behind the “arm”.

Figure 4: Spring loaded fencing drill stand. [1]

Some robotic solutions have been designed and built by high school students, Seen in Fig. 4, which model the parry and repost movements using pneumatics and motors. These are remote controlled where a separate user must work with the primary user practicing. One of these systems is for sale, but none are tested for safety or durability [49, 10].

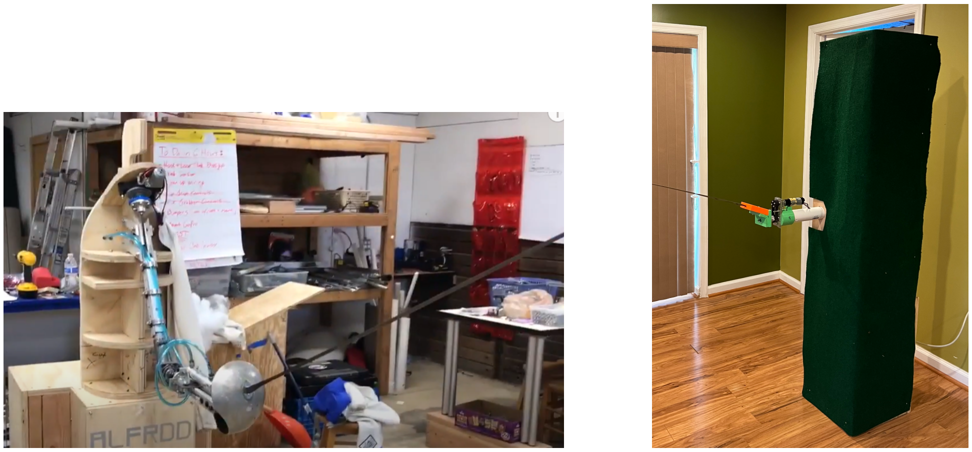


Figure 5: High school student created fencing arms and targets, the left picture is run by pneumatic [49] and motor joints while the right uses motors to actuate the parry movements [10].

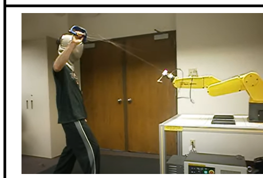
There are also autonomous industrial robotic arms programmed to fence, seen in Fig. 5. There is no target for the users to hit and there are currently none on the market [43, 48].

Figure 6: Student coded autonomous fencing robotic arm [48].

Seen in Fig 7, the moving fencing dummy created for the German Nationals Team most closely resembles the requirements for our project. This solution was created as a complex performance test to analyze speed, endurance, tactics and technique in elite fencers. This dummy moves along the floor, has safety features like ultrasonic range finders are integrated to avoid obstacles and the arm is able to parry [43].

Figure 7: Moving fencing dummy used by the German National Fencing Team [43].

Table 1: A comparison of existing fencing practice technology

Picture	Product	Pros	Cons
	**Static, Opposable Dummy**	- Allows fencers to practice with a static, human sized dummy. - For some commercial products, the body positioning can be adjusted.	- Incapable of any motion.
	**Spring Loaded Drill Stand**	- Resets sword position - Allows for sword clashing during practice.	- Sword only resets position and is completely static otherwise; ie no complex movements.
	**Light-Up Target**	- Allows fencers to practice sword striking accuracy.	- Doesn't account for any actual swordplay, only strikes.
	**DIY/Student Designed Robotic Arm**	- Some are remote controlled, some are autonomous - Either provide complex ranges of motion with a sword.	- Currently no such devices exist commercially for sale.
	**German Nationals Team Fencing Dummy**	- Same Pros as DIY/student designed robotic arms, but can also move laterally across the floor using motorized wheels	- Not commercially available and can only simulate parry 1

Looking at Table 1 above, we can see that many of these pre-existing technologies don't meet the requirements specified by Coach Rozich. Even the devices that do meet most of our requirements, such as the German Nationals Team Fencing dummy, are not commercially available. This leaves our sponsor with very limited options, meaning our team will have to come up with a novel and affordable solution.

PROBLEM DESCRIPTION

Some initial problems that arose include complex applications of mechatronics, control systems, and a limited knowledge of certain topics. This project will likely incorporate multiple systems, including dynamic systems, electronics, pneumatics, and multiple disciplines of mechanical engineering. This covers a wide range of knowledge, some of which we don't know much about strictly from courses. Many guides exist to help with these topics, including detailed documentation of systems such as pneumatics, electronics, or programming.

We will need to understand safety standards outlined by the International Federation of Fencing, as well as USA Fencing. This will include limits on how hard of a hit is allowed, travel speed of the foil, and information on acceptable protective gear. Reading through these technical documents will take time and could be challenging. Properly allocating our time to adequately understand these will be the key to successfully addressing this requirement. Additionally, to ensure our dummy will simulate parries 4, 6, 7, and 8, we will need to review videos, discuss with Coach Ian, and record the complexities of these motions. This is discussed further in the Requirements and Specifications section.

Another important topic that will require more information are mechatronics systems. This includes a wide range of topics such as pneumatics [13], power supply [32], computer programming, control systems, and dynamic modeling. We will have to coordinate the rotation of the elbow with the expected speed of a human fencer. This will require a full understanding of the motor controls, and the programming of the system likely using an Arduino. Additionally, we expect an encoder to be necessary to accurately position the motor. Using prior knowledge from mechanical engineering courses such as control systems and design and manufacturing will prove useful in tackling these problems.

Problems that we may encounter during the build and test phase will rely on accurate machining of the parts. A manufacturing plan and engineering drawing will prove crucial in ensuring that each component is manufactured accurately and in a timely manner. As the design expo approaches, we have limited time to ensure our dummy is complete in time. It will be important to not rush and sacrifice accuracy. Another concern we have is ensuring the Arduino will provide adequate control in the short time we have to finalize the code. The starter code from ME 350 will prove useful and give us a good head start.

Intellectual Property

There are very few intellectual property protections that would apply to our project, except for patent rights. Patent rights are a form of governmental protection granted for technical invention. Since our project is highly technical rather than artistic, symbolic, or a trade secret, a government patent is likely the only form of intellectual property protection applicable to our project. The 450 Project rights have been assigned to the Regents of the University of Michigan. The team has to inform the University of any inventions that have been created. The team will be treated as employee-inventors under the official University Policy. Lastly, as this design was conceived of by the entire team, this makes us all the inventors of the design solution.

Design Process

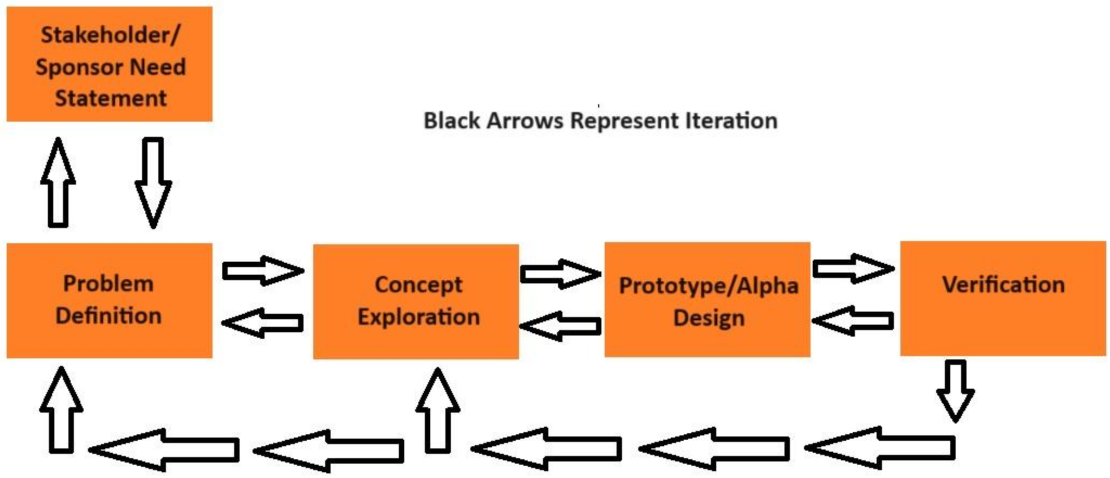


Figure 8: Our own custom design process flow chart with iteration.

As depicted in Figure 8 above, our design process consists of a need statement, problem definition, concept exploration, prototyping, and verification. We also account for extensive iteration in our design process. Our initial need statement was given to us by our sponsor Coach Ian Rozich, and is to construct a device that can simulate parries 4, 6, 7, and 8, as well as execute the three part sequence. Along with our need statement from Coach Rozich, we have subsequently considered all stakeholders impacted by our design, as well as any social, ethical, or environmental ramifications of our design.

Moving into the problem definition stage, we listed out all requirements and specifications that our design must achieve in order to satisfy the need statement. After considering all requirements and specifications, we can then move into the concept exploration stage. It was during this stage that we realized our problem definition needed some iteration in order to keep the scope of this project reasonable for one semester. After returning to our sponsor and discussing the scope of the project, we decided to iterate on our requirements and specifications and removed the requirement of executing the three part sequence.

Next, as we moved into the concept exploration portion of the design process, the team generated dozens of ideas that one can implement. There was a 'wide variety of solution concepts that represent divergent thinking and full exploration of the solution space' [4]. From this, these ideas were iterated on using design heuristics, function decomposition and morphological analysis to create different ideas and modifications of those original ideas. Furthermore, with stakeholder engagement, a general solution was picked, and we could now move forward with engineering analysis. Our engineering analysis will justify the necessary motor and transmission for correct rotational speeds and torques, as well as material choice and angle of adjustment. Lastly, we designed our concept solution out in CAD with our engineering analysis and bill of materials in mind.

With the CAD design and the finishing of all engineering analysis, the Bill of Materials was created and the team was able to move into the prototyping/final design phase. In the prototype/final design phase, the team has created detailed CAD drawings using their engineering analysis. With this, our team was able to order materials and start manufacturing these materials to finish the prototype. For any design components that had to be manufactured by our team, we created engineering diagrams from CAD as well as a build plan for each manufactured component. Once all components were ordered, received, and manufactured, we were able to assemble the drilling dummy and begin testing various code for the control system.

Verification can also be done with the final design. With verification, the team has created a plan to cover each one of the requirements and specifications. This will be done with virtual analysis, stakeholder input/engagement and user engagement to see whether the solution is a good proof of concept for the idea. While the figure says that there are possibilities of going back to previous steps in the design process, the team thankfully has the foresight to avoid these types of situations.

Information Sources

One of our main sources of information on fencing in general was our primary sponsor Coach Ian Rozich. He proved to be an exceptional information resource on foil fencing as well as a guiding hand in our design process. Our team minimally engaged with the librarian and librarian tools on canvas, and opted to find sources using search engines instead. This proved useful for the majority of our sources such as material parameters, specific equations, design concepts, and pre-existing technologies. Information gathering became a greater challenge when trying to find specific information on the physics of a fencer for comparison with our design. In order to create useful technical benchmarks for our design, we opted to use medical research papers on the human body and its average torque and rotational speed outputs at the wrist. Using medical research papers, we were able to give ourselves specific technical benchmarks to use in our requirements and specifications, and in turn in our engineering analysis.

REQUIREMENTS AND SPECIFICATIONS

As Coach Ian and Professor Tan are the two stakeholders where there is a communications line, all of these design requirements, with the exception of standards that have to be followed for safety, are coming from them. The relative importance of requirements were determined by the stakeholder himself and then expounded upon. As an example, he wanted the dummy to ‘Accommodate a wide range of users from 13+, accounting for skills.’ This means that the dummy needs to be able to ‘switch’ its speeds, which is something that has been addressed with the arm articulation and the wrist articulation. The accomplishment of all Tier I Requirements and Specifications would classify a successful device. Tier II and other requirements were deprioritized based on consultation with Coach Ian, however, those requirements would still be great to have when delivering the final product to him.

Table 2: A list and ranking of all project requirements

Requirement Tier	Table of Contents for Requirements
1	Has to Follow US Fencing Safety Standards
1	Simulates fencing drilling exercises
1	Accommodate a wide range of users from 13+
1	Elbow Rotation
1	Forearm Angle Adjustment
2	Stability
2	System Controls
3	Power

4	System must be durable
5	Setup
6	Portability
6	Easy to Service

Tier I Requirements

1. Has to follow US Fencing Safety Standards
    a. Ripostes must create a force from $800 \leq x \leq 5000$ N [21]
    b. Ripostes or ‘lunges’ must go from $2.7 \leq x \leq 6$ m/s [21]
    c. Rationale:
        i. The US Fencing Safety Standards legislate safety with fencing gear. Anything faster or more forceful than these numbers can perforate the safety equipment and harm the end-user. One of the other requirements is that this can be used with kids, so this device must be safe
        ii. This also sets the range of values that the arm and wrist should be able to reach

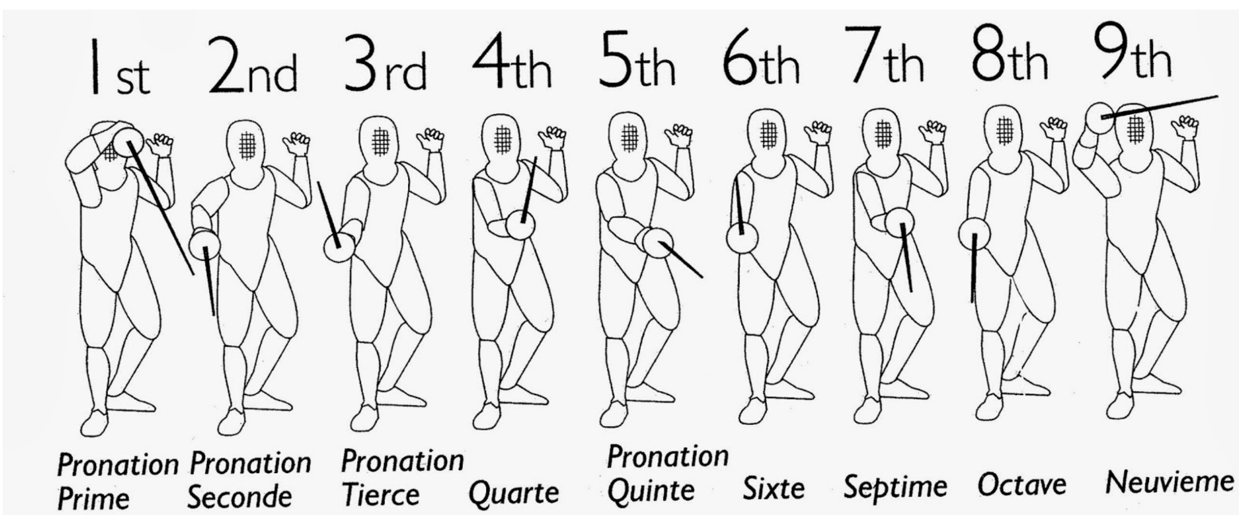


Figure 9: This shows the nine fencing hand positions and where the parries should be placed. [21]

2. Simulates most commonly used fencing drilling exercises in [21]
    a. Can parry 4, 6, 7 and 8
        i. Parry 4 is moving the hand position from en garde and slightly to the left, blocking an attack in that direction such as in Figure 9
        ii. Parry 6 is moving the hand from en garde and slightly to the right, blocking an attack from that direction such as in Figure 9
        iii. Parry 7 is moving the hand from en grade and down to the right, blocking any attacks from that direction such as in Figure 9

        iv. Parry 8 is moving the hand from en grade and down to the left, blocking any attacks from that direction such as in Figure 9
    b. Can simulate 3 part sequence: parry, riposte, recover
        i. Parry is moving the hand position sideways/down and blocking an existing attack.
        ii. Riposte is extending the arm to simulate someone attacking the body.
        iii. Recover is retracting the arm to simulate someone moving back after a successful attack
    c. **Rationale:**
        i. Parries 4, 6, 7 and 8 are the most used parries of the entire sport and keep with the requirement that beginners-advanced fencers are going to be able to use this
        ii. Coach Ian additionally wants the dummy to be able to simulate these parries specifically (I. Rozich, personal communication, September 14, 2023)
        iii. The 'arm and wrist' are the two parts of the dummy that should be accomplishing this
3. Accommodates a wide range of users from age 13+, which accounts for size and skill
    a. Adjustable height is 5'3" ≤ 6'3" [3]
    b. Left and right handed individuals
    c. **Rationale:**
        i. Coach Ian wants this to be accessible to all fencers from beginning to advanced. This means that there needs to be an adjustable height as it exemplifies the different heights of fencers. This was going to be accomplished by the actual 'backboard'/spine of the dummy that is going to be able to be extendable.

The scope of the project was reduced by simplifying the joint motions needed by the robotics arm. Instead of shoulder, elbow and wrist joints, the parry movements will be achieved from rotation and angle adjustment joints on the elbow. This change was authorized by Coach Ian.

Addendums to Tier I Reqs and Specs:
The recent changes to the design scope means that 'Arm Articulation' won't be as important as it used to be in the first revision of this report. That requirement has been removed as there won't be horizontal movement.

Additionally, the wrist articulation has been modified to include a 'cone of movement' that is represented in this picture:

In order to execute the four most common parry movements effectively, it is necessary for the wrist and forearm to attain specific positions within a defined range of motion, the pink cone seen in Fig. 10. This approach is rooted in the principles of effective fencing instruction. According to insights from Coach Ian Rozich, it is crucial for the wrist and forearm to maintain alignment (I. Rozich, personal communication, October 7, 2023). Instead of actuating the shoulder, elbow and wrist of the humanoid arm, we deduced that a mechanical system to provide rotation about the elbow and an angle adjustment perpendicular to the elbow rotation would only be needed to achieve the necessary parry motions. The two elbow joint requirements, elbow rotation and forearm angle adjustment, serve as substitutes for the concepts of 'Arm Articulation' and 'Wrist Articulation'.

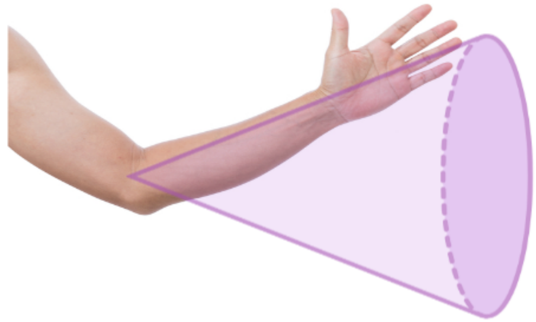


Figure 10: The fencers cone of movement required to complete the four most common parries. [6, 11]

1. **Elbow Rotation**
    a. Rotate -83 degrees ≤ x ≤ 100 degrees [19]
    b. Has to be able to create pronation and supination motions
    c. **Rationale:** this cone of movement has to be able to cover the four important parries that are laid out. To do two of these parries, the elbow has to be able to 'turn', so pronate and supinate.
2. **Forearm Angle Adjustment**
    a. Rotate -90 degrees ≤ x ≤ 80 degrees [19]
    b. Has to be able to create flexion (moving up) and extension (pushing back)
    c. This movement will be perpendicular to elbow rotation
    d. Adjustment of forearm angle relative to upper arm
    e. **Rationale:** The cone of movement also relates to positions that are 'down'. This means there needs to be flexion and extension.

Tier II Requirements

1. Stability
    a. Must not tip when hit by a force from 350 ≤ x ≤ 1500 N [21]
    b. **Rationale:**
        i. Coach Ian wants the dummy to not tip over. This is so that he can easily set it up for multiple practises. (I. Rozich, personal communication, September 14, 2023)
        ii. A possible design solution will be done by lowering the center of gravity by creating a larger and heavier baseplate for the dummy to 'stand' on.
2. System Controls
    a. Autonomous parry movements
    b. Dummy will sense when the user hits target area
    c. Sensing of hit was put into System Controls as both are using Arduino to sense how the motor moves and how the user will interact with the dummy.
    d. **Rationale:**
        i. Coach Ian wants this to be autonomous so that this can help beginners simulate how it is to fence against a real opponent (I. Rozich, personal communication, September 14, 2023)
        ii. This would take electronic controls engineering such as PID controllers for regulating the speed and torque of the arm/wrist.
        iii. This would also take sensors to see where an opponent is going to hit

3. Power Source
    a. 12 V Corded
    b. Rationale
        i. Coach Ian dislikes battery operated systems. He wishes this to be stationary so he can ‘plug and play’. This means that this device will be mounted near a wall-socket. (I. Rozich, personal communication, September 14, 2023)

Other Requirements

1. System must be durable
    a. Needs minimal maintenance up to 5 years
    b. Rationale
        i. Coach Ian wants something that can last for five years. (I. Rozich, personal communication, September 14, 2023)
2. Setup
    a. ≤ 20 minute setup time
    b. Rationale:
        i. To provide a way for coaches to help drill even more students, the setup time must be short. (I. Rozich, personal communication, September 14, 2023)
3. Budget
    a. ≤ $400
    b. Rationale:
        i. This is the maximum budget for this project. This means that the team needs to be able to reuse metal and wiring for prototyping. Additionally, there needs to be cognizance of this limit so that less extraneous additions are made to the device. Finally, if this were to be a marketable device, then costs are absolutely necessary to keep the vending of this device profitable
4. Portability
    a. 40 kg ≤ x ≤ 60 kg
    b. Rationale:
        i. Coach Ian doesn’t need this to be moved, so mobility doesn’t need to be a requirement. (I. Rozich, personal communication, September 14, 2023). However, this still needs to be moved via his car or a UHaul truck. (I. Rozich, personal communication, September 14, 2023)
5. Easy to Service
    a. Needs only hex keys, screwdrivers, lubricant to be serviced
    b. Wires can be soldered
    c. Good wire management
    d. Rationale:
        i. Coach Ian is experienced with using these tools and he doesn’t want to bring the dummy back to the University for service (I. Rozich, personal communication, September 14, 2023). This way, he can keep the time that it takes to service this device low.

General Narrowing of Scope

Due to budget constraints, the arm was reduced to being a proof of concept on November 7, 2023. This means that both the angular velocity/rotation speed of the arm, and the torque generated by the motors that will drive the arm have been decreased. The only available motors within the price range would reduce the torque output to about 8 Nm, and the RPM to 75. Unfortunately, no motor in budget allowed us to keep torque at 8 Nm, and RPM near 362.

1. General angular velocity/rotational speed
    a. Decreased from 362 RPM to 75 RPM
2. General torque created by the motor
    a. Decreased from 15.237 Nm to 8 Nm

CONCEPT GENERATION

Initially, the team started out with a basis of design. The basis of design were the Tier I requirements of, '[Simulating] fencing drilling exercises', 'Accomodating a wide variety of users', 'Arm articulation' and 'Wrist articulation'. The team needed to create divergent designs to avoid groupthink and cover ideas throughout the solution space.

To accomplish this, the first ideas that were listed would be able to accomplish the requirements that were set down initially. Divergent ideas are ideas that span the solution set without setting boundaries with respect to practicality. Some examples of these divergent ideas covered thoughts like a 'VR simulation of fencing' or an 'exoskeleton that fits around the user's hand to guide their motions through a parry'. After the divergent ideas were created, the ideas that took into account practicality were then enumerated. This is where the robotic arm that would be using Arduino for the controls was first introduced. In fact, all members of the team listed this as one of their ideas. Other ideas were a pneumatic, robotic arm that would be able to accomplish each one of the requirements.

Morphological analysis is important as it allows each function to be delved into. Each key function would be expanded and elaborated upon with more ideas. The general operating procedure was that the amount of ideas rather than the quality of ideas was focused upon when first doing concept generation.

For example, when creating the 'robotic arm', the general arm was decomposed into parry movements, motors and gears. The ways that these would be propelled were then created, such as the parry movements being propelled via pneumatics, springs or two motors. There were also ways for hit feedback, whether it be an alarm sound along with light activation. From the stakeholder, the team was able to narrow the design scope and solidify more motions and actions. Through this, the team was able to focus on a humanoid robotic arm.

Next, there was a general convention with each group member coming and discussing each of these ideas. The ideas were then binned into realistic and unrealistic based on what the team thought. An unrealistic solution meant that it was not within the timeline that is required for a fully developed solution. Finally, after narrowing the solutions down, the team was able to present to Coach Ian to see which solution he presented. He wanted to know whether each solution was able to fit his needs.

In total, over 160 ideas were explored. By the details enumerated above, along with stakeholder input, the team then picked the most realistic solutions, which were all going to be related to something physical rather than virtual, such as robotic arms. The team then ideated more using morphological analysis and function decomposition.

After generating ideas for the robotic arm, the team went through the process of concept generation for the user interface of using the robotic arm. The basis of design was in line with the 'System Controls' requirement and wanted an autonomous system that would activate when triggered. The team first created ideas that pushed the definitions of realistic to cover the entire problem space.

Some of the ideas, such as a way for a sensor to sense parries, were unrealistic as none of the group had the skills to program a sensor in that way. Some of the other ones were using mechatronics and electronics knowledge to change how a fencing scoring machine to update the direction that the arm would be going.

Next, a general convention was called where each group member voiced their opinions on the various concepts that were created. As this was nearly out of scope, the stakeholder was not consulted on this, and the system controls would be falling to the next group who choose to take on this project.

CONCEPT SELECTION

Narrowing The Solutions

Initially, there were about 160 ideas that were trialed with each person creating 40 ideas each individually. This meant that the group needed to decrease the number of solutions. Each member of the team went back to their 40 generated ideas and screened the concepts. Initially, there was the ‘Gut Check’, where each member of the team thought about their abilities and whether the team could do each one of these ideas. Naturally, all of the virtual ideas could not be done using the skill sets of the team, so much of those ideas were put away. Some of the ideas were also seen as too time consuming, so those ideas were next removed off of the list. From 40 generated ideas per person, the ideas went down to 10.

Next, from those 10 ideas per person, the team called a concept generation meeting where each of their 10 ideas were critiqued. In this idea generation meeting, the concepts were screened and discussed against their requirements and specifications. Each requirement and specification was screened to see whether or not the ideas that were generated would be able to accomplish them. With this, the 10 ideas were narrowed to a humanoid robotic arm as that idea was able to accomplish the requirements and specifications.

Finally, for stakeholder engagement and evaluation, the team went to the stakeholder and asked his opinion on the idea. Coach Ian thought that he would like to have a humanoid robotic arm as it was confirming what he would like (I. Rozich, personal communication, October 7, 2023). This meant that the stakeholder and the team were on board and going forward with the Humanoid Robotic Arm.

Through working with the stakeholder and concept generation, the team focused on a humanoid robotic arm. The Humanoid Robotic Arm is important according to Coach Ian as fencers need to feel the timing of when their blades get hit to understand the parry and repost movement. This is mainly because fencing actions are quick, so beginners need to have a feel for the movement of a parry so that they can counter or move out of their position.

This humanoid robotic arm would be able to have two degrees of freedom as there needs to be elbow rotation and forearm angle adjustment. Additionally, Coach Ian said that the emphasis on wrist rotation isn’t as necessary as the team thought it was. A quote that he said was that, ‘Less point direction, but not the worst simulation’ (I. Rozich, personal communication, October 7, 2023).

This way, this humanoid robotic arm could be focusing on two degrees of freedom. The first degree of freedom would be the forearm angling up or down (flexion and extension, seen in Fig. 11). The second degree of freedom would come from the ‘wrist’ as there would be a motor which is able to rotate the elbow and forearm (pronation and supination seen in Fig. 11).

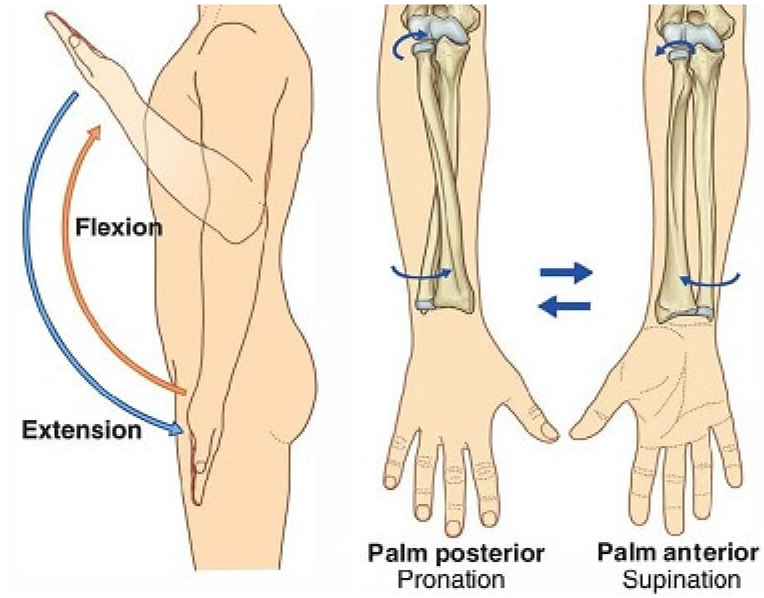


Figure 11: Human arm movements. [7]

Elbow Rotational Joint Analysis
Five main elbow joint actuators and mechanisms were analyzed.

1. **Independent Actuators Joint**
    a. This was the baseline of the Pugh Chart scoring
    b. 2 degrees of freedom
    c. Torque can be controlled via choice of motor and gear ratios
    d. Simpler to create controls
    e. Has two separate points of control which could be more complicated
    f. Could require bulky pneumatics
    g. Heavier system

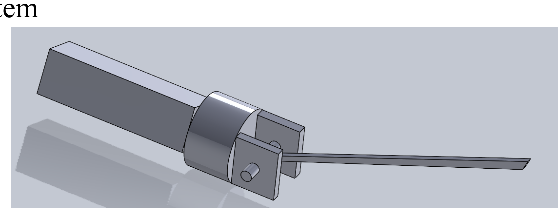


Figure 12: CAD model of 2 degrees of freedom and independent actuator

2. **Cable Ball Joint**
    a. Motor to control cable could be located more towards the torso and not weigh down the arm
    b. Large range of motion
    c. Quick maneuverability
    d. Not very durable (teeth will wear down with the users strike of blade and through general movement use)
    e. Would need 2-4 motors to accurately control
    f. Less precise motion control

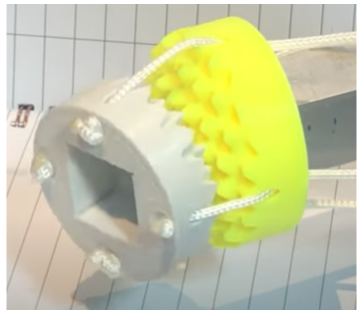


Figure 13: Cable ball joint. [50]

3. **Rolling Contact Joint**
    a. Wide range of motion
    b. Durable
    c. Complex controls for multiple DoF
    d. Complex to engineer and build

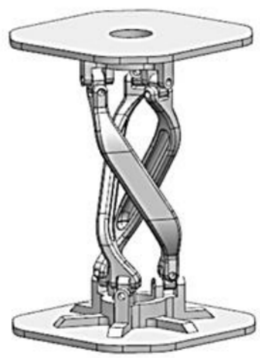


Figure 14: Rolling contact joint from prosthetic wrist.[28]

4. **Differential Joint**
    a. 2 degrees of freedom
    b. Variable torque depending on motor and gear choice
    c. Gear teeth strength concerns with arm weight
    d. Would require two motors
    e. Complicated motor control

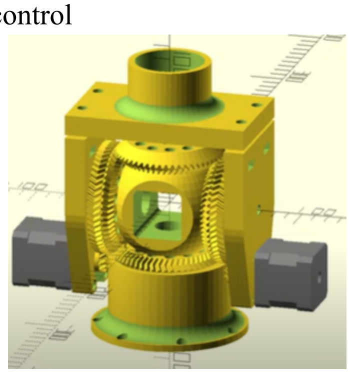


Figure 15: CAD of differential joint. [46]

5. **Cable and Pulley Joint**
    a. Mimics human elbow joint motion

b. Motors do not add weight to the arm as cables would be able to be spooled from torso
c. Expensive
d. 1 degree of freedom
e. Concerns over cable spooling predictability

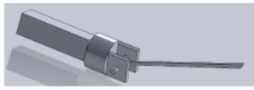
Figure 16: Cable and pulley joint from robotic arm. [45]

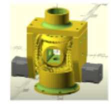
Summary of Pugh Chart

After considering the advantages and disadvantages mentioned above, a Pugh chart, seen in Table 3, was developed to systematize the trade-offs among various elbow joint mechanisms. The criteria on the left side of the chart were derived from the system's requirements and were assigned weights based on their importance to the stakeholders. The independent actuator mechanism served as the reference point, and all other mechanisms were ranked on a scale of 0.5, 1, and 2 in comparison to the baseline. Ultimately, the independent actuators received the highest ranking, and we will proceed with this design for the elbow joint.

The differential and rolling contact joints closely followed the independent actuator's overall score, and they will be further evaluated if the independent actuators do not fully meet the elbow joint requirements. Following discussions with our primary stakeholder, Coach Ian, it was determined that the angle joint adjustment did not require automation, and only the elbow rotation needed to be automated (I. Rozich, personal communication, October 7, 2023).

Table 3: Pugh chart to determine the mechanism to provide two degrees of freedom joint motion for the humanoid arm elbow.




	Weight	Independent Actuators (1)	Cable Ball (2)	Rolling Contact (3)	Differential (4)	Cable and Pulley (5)
RoM	10	0	1	1	0	-2
Stability	9	0	-1	0	-0.5	-1
Torque	9	0	-1	0.5	0	-0.5
Durability	8	0	-1	0	1	-1
Weight on Arm	7	0	1	0	-1	1
Speed	7	0	-0.5	-0.5	-0.5	-1
Controls Complexity	5	0	-2	-1	1	0
Mechanical Complexity	3	0	0	-2	0.5	-1
Cost	1	0	-1	-1	0	1
Totals		0	-23.5	-1	-0.5	-43.5

Forearm Angle Joint Analysis
There were 10 different joints that were analyzed for setting and securing the forearm angle.

1. **Pin and Hole**
    a. This was the baseline of the Pugh Chart scoring
    b. Has resolution for rotational degrees of freedom as it depends on how many holes that the team decides to put in it
    c. Easy to machine
    d. No big costs

Figure 17: A pin and hole joint [36]

2. **Bevel Gears**
    a. As much rotational freedom as the pin in hole
    b. No ways to lock
    c. No obstructive geometry/other places for foil to get stuck on

Figure 18: Bevel gears [22]

3. **Wheelchair Leg Lifts**
    a. Doesn't seem to have a locking mechanism
    b. Doesn't seem to have that much rotation freedom
        i. Can only go to two positions, which is a concession that our stakeholder can live with but doesn't really want (I. Rozich, personal communication, October 7, 2023).
    c. Not as easy to machine, but can be acquired through buying
    d. Durable due to the locking

Figure 19: Wheelchair leg lifts [12]

4. **Laptop Stand**
    a. No way to lock
    b. Has as much rotational freedom as the pin and hole
    c. Easy to machine

Figure 20: Laptop stand [36.3]

5. **Lamp Linkage**
    a. Locking mechanism
    b. Can rotate through and has resolution
    c. Hard to machine
    d. Can be durable

Figure 21: Light linkage [35]

6. **Tripod Mechanism**
    a. Lots of rotation freedom as one can position the angle from 0 to 90 degrees
    b. No locking mechanism
    c. A lot worse on the durability because of the lack of a locking mechanism.
    d. Not that durable as a result of the rotation freedom

Figure 22: Tripod angle adjustment mechanism [0.2].

7. **Hinge**
    a. Lots of rotation degree of freedom

b. Locks as well as the pin in hole
c. No advantages over the pin and hole, although could be harder to adjust
d. As easy as the pin in hole to machine

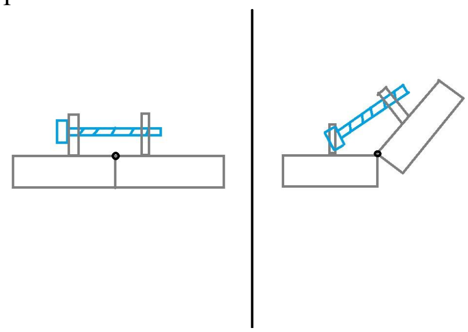


Figure 23: A hinge joint with angle adjustment by bolt.

8. **Teeth Clamp**
    a. Lots of rotational degree of freedom
    b. Lots of ways to lock
    c. Very hard to machine
    d. Will be expensive to get parts for
    e. Durable because of locking mechanism

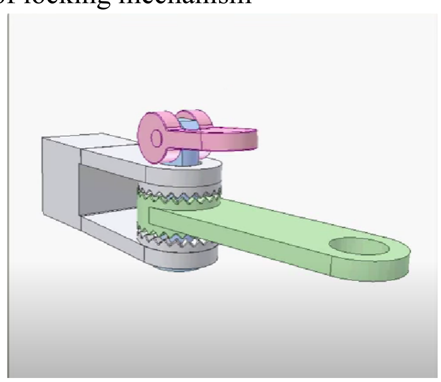


Figure 24: A lever actuated clamp with teeth [46].

9. **Car Seat Adjuster**
    a. Incredible amount of rotational degrees of freedom
    b. Incredible amount of locking positions
    c. Very hard to machine or buy
    d. Nearly impossible to find

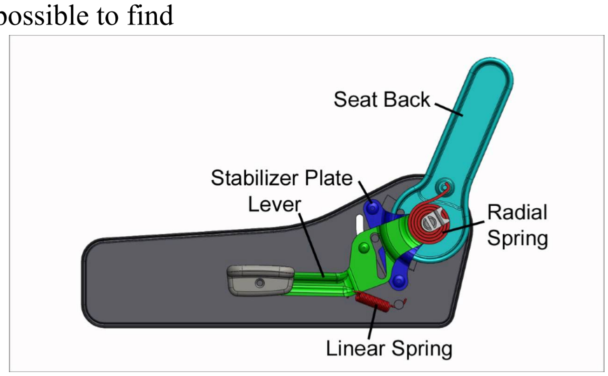


Figure 25: Lever-actuated, car seat adjuster that locks gear teeth in place [44].

10. **Crank and Ratchet**
    a. Not easy to acquire or machine as there are specific aspects the team wants, such as finding a crank that could easily lock.
    b. Has rotational degree of freedom, especially with angular resolution.
    c. Can be durable because we could find a locking mechanism, but the team needs to find one and those are quite hard to find.

Figure 26: A winch that utilizes a crank and ratchet [17].

11. **Worm Gear**
    a. Has slightly more rotational resolution than the pin in the hole. However, because of that resolution, there's less durability.
    b. Seems to have easier adjustment as the pin in hole also depends on the pin, so if one loses that, it can be difficult to find another pin.
    c. No locking
    d. Easy to buy
    e. However, hard to pin in one place

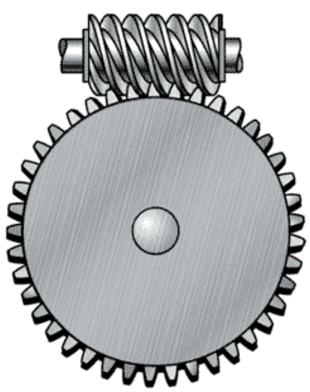


Figure 27: A regular gear and worm gear interacting [41].

Summary of Pugh Chart
The Pugh Chart, seen in Table 4, was a way that we could summarize the advantages and disadvantages of the ten different types of joints. The criteria on the left explain how the different joints on the top row are judged. The base point was the pin and hole and each criterion was judged from -10 to 10 on whether it would be more or less effective than the base.

By the definitions that we put on the Pugh Chart, the team thought that the pin in hole was the best due to the fact that it had the best rotational degree of freedom and locking positions, without any of the manufacturing issues that plagued the mechanisms with high rotation degree of freedom. Additionally, it would be easy to buy online or to manufacture ourselves, is easy to use, and will last a long time compared to our other joint options.

	Weight	Pin in Hole (1)	Bevel Gears (2)	Wheelchair Leg Lifts (3)	Lap Stand (4)	Lamp Linkage (5)	Tripod (6)	Hinge (7)	Teeth Clamp (8)	Car Seat Adjuster (9)	Crank and Ratchet (10)	Worm Gear (11)
Rotation Degree of Freedom	10	0	1	-1	0	0	2	0	2	2	0	0
Locking Position	10	0	-1	0	0	0	-1	0	3	3	0	0
Machining or Buying	7	0	0	0	0	-0.5	-2	0	-10	-10	0	0
Cost	6	0	0	0	0	0	0	0	-1.5	-1.5	0	0
Durability	5	0	-2	0	-0.5	0.5	-1	0	1	1	-1	-0.5
Ease of Adjustment	4	0	0	0	0	0	0	-0.5	0	0	-0.5	0
Obstructive Geometry	4	0	0	0	0	-0.5	-1	0	0	0	0	0
Totals		0	-10	-10	-2.5	-3	-13	-2	-24	-24	-7	-2.5

Table 4: Pugh chart to determine the mechanism for the angle forearm joint.

Servo vs Motor - Rotational Elbow Joint
In looking to choose whether a server or motor is better for a rotational elbow joint, three factors were evaluated: torque capabilities, effectiveness of choosing angles, ease of coding and cost, seen in Table 5. While our team initially thought that servos were able to be more effective than motors at rotating and finding angles, our team looked at their Arduino and programming experience needed and realized that more experience is needed to work with servos. While motors are less precise, it is much easier to use them with Arduino. Next, the motors can have a bit more range of motion, especially as servos are used to precisely go to a degree. Finally, the nail in the coffin of this debate is the cost of a servo, which can go for nearly half the budget [2]. The servo in 2 would be ~$400 for ~10.7 Nm of torque. From reference [25], one can see that the motor is $200 for 10 Nm of torque. This allows our team to focus our budget on lighter, more expensive, materials. As seen in the Pugh Chart below, while the motor might be harder to get to an angle, it has better cost for the same amount of torque.

Table 5: Pugh chart to showcase the pros and cons of a servo and a motor.

	Weight	**Servo**	**Motor**
Cost	20	0	1
Torque	10	0	0
Goes to set angle	9	0	-0.5
Ease of coding	6	0	1
Totals		0	17

Target Stand

A target was designed to facilitate the attachment of the arm portion to a base and serve as a target for fencers to execute reposts or parry's. Priority was given to ensuring the stability of the target so that when fencers engaged in parries or reposts on the torso, the stand would remain steady, mimicking the resistance of a human opponent. Figure 28 displays the results of benchmarking efforts that influenced design decisions.

Figure 28: Benchmark design of homemade standing fencing target [34]

The design incorporated a base consisting of four primary beams to provide a substantial surface area for enhanced stability. Additionally, a network of interconnected beams at the center was devised to add weight to the base.

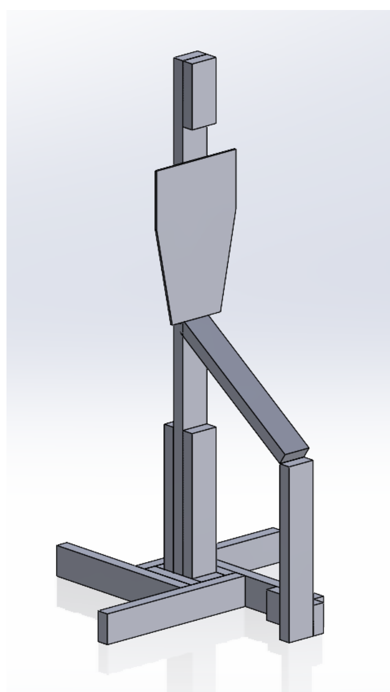


Figure 29: CAD of final target stand design

Figure 30 illustrates the utilization of average male human dimensions to determine the height and lengths of the target limbs, emphasizing the humanoid nature of the target. The plywood torso was shaped to replicate the en garde target area of an average male torso, turned to the side, with a bent leg and the forearm extending from the torso.

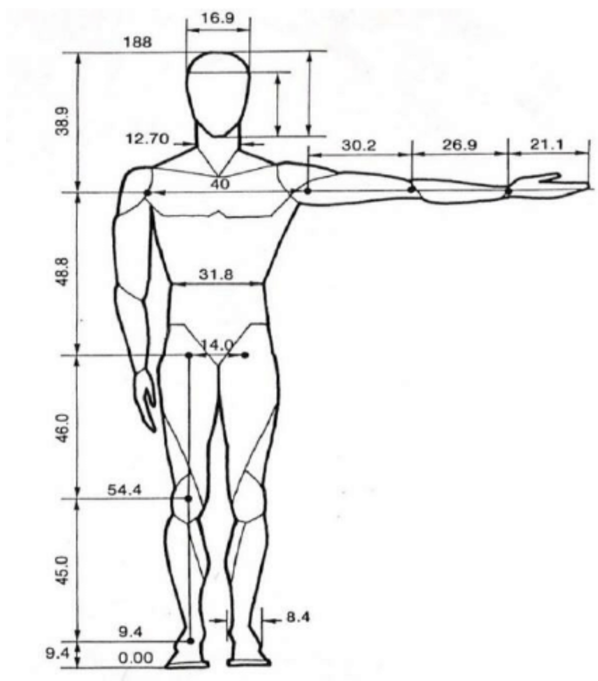


Figure 30: General dimensions for the dummy target stand [5]

To construct the majority of the components, two by four wood was selected, and care was taken to use the same lengths of wood many times in the design. For example, the four long base pieces match the lengths of the leg and supporting vertical beam pieces, while the shorter center base pieces correspond to the face. To enhance safety and simulate realistic fencing conditions, the plan included draping the torso with multiple layers of sweatshirts or t-shirts to provide padding for the blade's point, as recommended by Coach Ian.

Finally, old fencing gear provided by Coach Ian, such as a face mask, lame, and foil sword, will be draped on the fencing target to enhance its humanoid appearance, creating a more authentic fencing experience for the user.

Lamé User Interface - Electrical Scoring Method
The user is required to communicate their desired parry type (clockwise or counterclockwise rotation) to the Arduino.

In a collaborative group meeting, the team engaged in ideation to conceptualize various sensor types. Considering the expansive scope of the project within the constraints of a single semester, simplicity of the designs were prioritized. Among the concepts, two were subject to intensive discussion – concept one involving buttons on the floor for user-initiated parries and concept four, which proposed initiating the parry motion by touching the foil to the Lamé. Following deliberations and consultation with Coach Ian, coupled with additional research into Arduino capabilities, the team reached a consensus to advance with concept four in Table 6:

Table 6: Concept generation for user interface options

Number	Concept Description
1	• Button(s) on floor ○ force pad on floor
2	• Distance Sensor (user position to front facing dummy)
3	• Button/switch on arm
4	• Sword contact (ground out) ○ Contact with sword is “when” and separate metal fabric on lame into two isolated sections to hit with sword to determine direction of rotation
5	• Verbal/audio (voice command, clapping, snapping)
6	• Retina sensor (death stare)
7	• Distance sensor (On dummy shoulders for fencer to motion towards)
8	• Gyroscope on shoe to kick back
9	• Remote control with preset buttons
10	• Integrate it into a fencing scoring machine

The objective is for the specific location on the Lamé touched by the fencer to indicate their preference for a particular drilling parry. The Lamé serves as an electrically conductive jacket worn by foil and sabre fencers, primarily tasked with defining the scoring area and detecting contact within it. In the Electrical Scoring system, the current flows from line B to the foil tip and then returns through line C to the ground. The Lamé is connected to the A line, featuring a switch on the foil tip. In its inactive state, the switch is closed, completing the circuit, and pressing the button breaks the circuit. Upon the foil's tip making contact with the opponent's Lamé, current flows from line B (the weapon) into the opponent's Lamé and through their A line, establishing a new circuit to the scoring box, as shown in Figure 32.

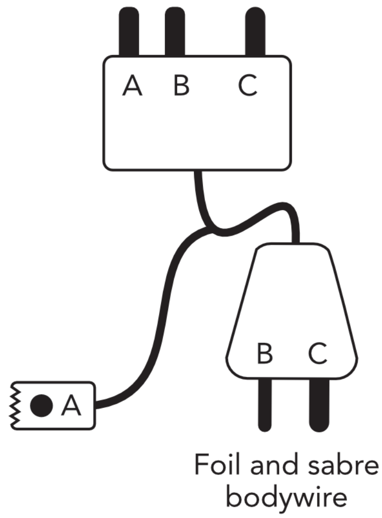


Figure 31: A Lamé scoring interface, utilizing the ability to close circuits with low voltage contact [18]

In terms of user interaction, this electrical scoring system is applied similarly to signal the dummy for parrying and specify the type of parry. This is facilitated through a segmented Lamé that electrically isolates the metal fabric into two independent sections, shown in Figure 32. The forearm angle is manually adjusted in advance to express a preference for a shallower angle (parry 7 and 8) or a steeper angle (parry 4 and 6). When the fencer contacts the right side of the Lamé with their weapon's tip, the dummy executes a clockwise parry (4 or 7). Conversely, touching the left side of the Lamé prompts the dummy to perform a counterclockwise parry (6 or 8). This portion has not been executed as of DR3 and may need to be addressed by a future 450 group.

Figure 32: A Lamé jacket that allows contact between the foil and the dummy. Split in half to allow for two communication "buttons" for direction of elbow joint rotation. [4]

SELECTED CONCEPT DESCRIPTION

Our chosen design will use a motor at the "elbow" for rotation. The forearm angle will be manually adjustable using a pin-in-hole mechanism. We chose this preliminary design to be lightweight, strong, and incorporate all design decisions so far. The foil will be fixed in line with the 'forearm', which has the pin-holes incorporated near the elbow. These pin-holes will set the angle between the rotating part of the elbow joint and the forearm, and lock it in place so it can rotate freely without worry of coming loose. This entire arm assembly will be attached to the motor and gearbox with the elbow shaft, and will be supported by a bracket that will be fastened to the target stand. The target stand will have Lamé material covering the chest portion, with it being divided into left and right portions. The user will indicate the rotational direction of the arm by making contact with the Lamé material on its respective side for the desired rotational direction. When the user uses their foil to make contact with the Lamé material, it grounds out a circuit, which we can use to communicate with the arduino control system to dictate motor direction. Below in Figure 33 are early drawings and basic CAD of our selected concept.

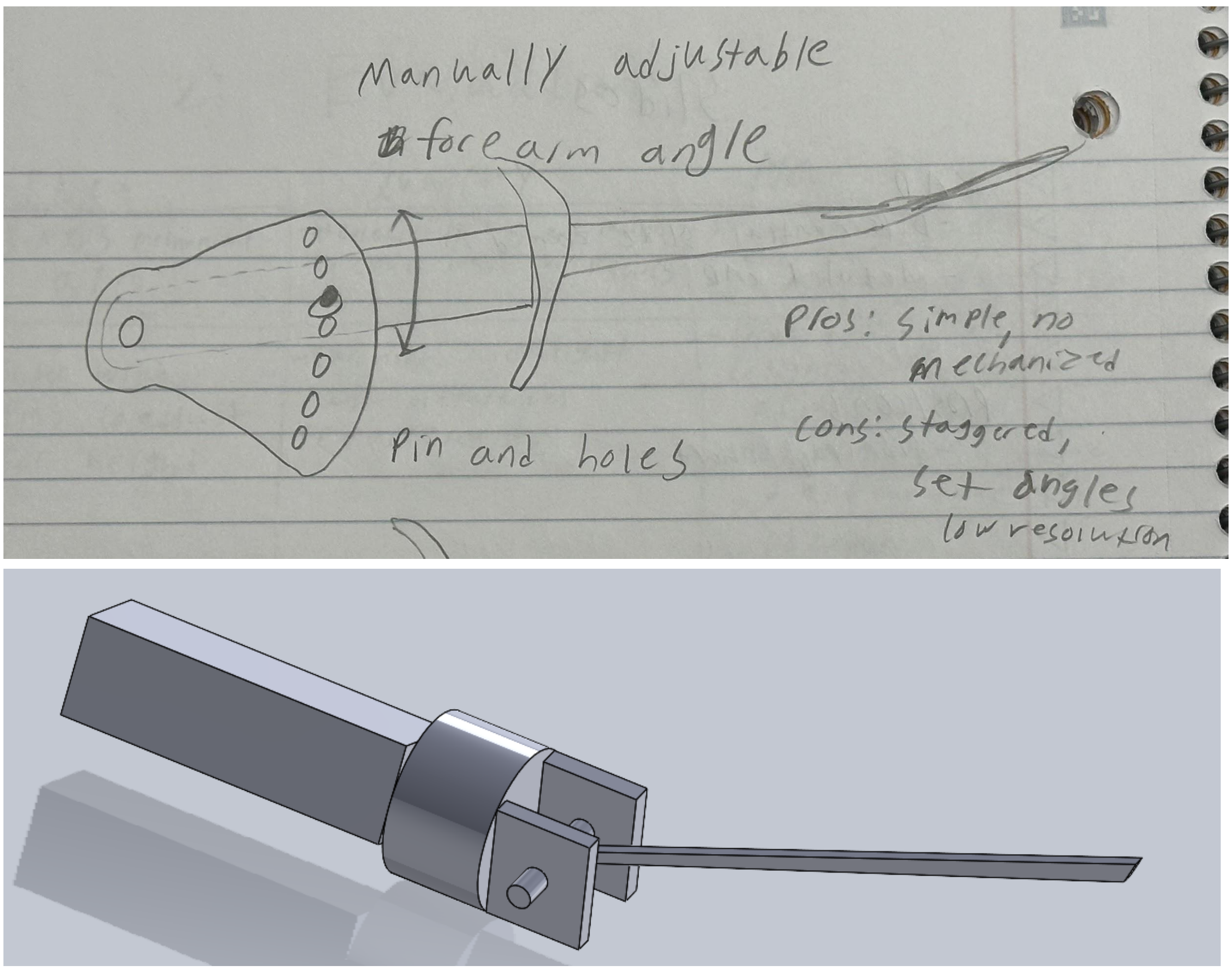


Figure 33: Early drawings of our selected pin and hole mechanism (top), and basic CAD for a proof of concept of our selected design concept (bottom).

ENGINEERING ANALYSIS

For our engineering analysis, we decided to start by drawing up some free body diagrams so that we can consider all the forces and torques that our design may undergo. Our analysis of the forces and torques will further help guide our design decisions such as material, specific motor, specific gears/gear ratios, as well as shaft diameter. Additionally, by utilizing light exposure photography, we can model the movements of a foil fencer and compare those movements to those of our design.

Free Body Diagram 1: Force Analysis

The first free body diagram makes the assumption that the system is completely static, and only accounts for the horizontal and vertical forces due to gravity as seen in Figure 34 below.

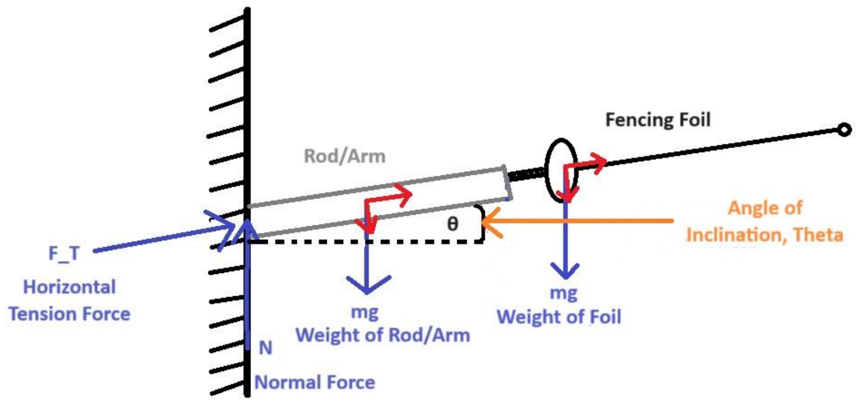


Figure 34: A drawn free body diagram depicting the weights of the arm and sword, as well as the resulting vertical normal force and horizontal tension force.

Now that the components, masses, the angle of inclination, and all of the horizontal and vertical forces were drawn out and considered, we can utilize Newton's second law (1), to balance all of the forces, as seen in Figure 34.

$$F = mg \qquad (1)[25.1]$$

Where F is the resultant force, m is the mass of the object, and g is the gravitational acceleration.

- $N = F_{Rod\ mass\ vertical} + F_{Foil\ mass\ vertical} \Rightarrow N - F_{Foil\ mass\ vertical} - F_{Rod\ mass} = 0$
    - $F_{Rod\ mass\ vertical} = m_{rod} * g * cos(\theta)$
    - $F_{Foil\ mass\ vertical} = m_{foil} * g * cos(\theta)$
        - $N - (m_{foil} * g * cos(\theta)) - (m_{rod} * g * cos(\theta)) = 0$
- $F_T = F_{Rod\ mass\ Horizontal} + F_{foil\ mass\ Horizontal} \Rightarrow F_T - F_{Rod\ mass\ Horizontal} - F_{foil\ mass\ Horizontal} = 0$
    - $F_{Rod\ mass\ Horizontal} = m_{rod} * g * sin(\theta)$
    - $F_{Foil\ mass\ Horizontal} = m_{foil} * g * sin(\theta)$
        - $F_T - (m_{rod} * g * sin(\theta)) - (m_{foil} * g * sin(\theta)) = 0$

Figure 35: List of equations that balance the static forces of our design

As seen in Figure 35 above, the vertical forces consist of the resultant normal force as well as the vertical forces due to the weight of the foil and rod/arm. Additionally, the horizontal forces consist of the resultant tension force as well as the horizontal forces due to the weight of the foil and rod/arm. These equations account for the fact that our design allows for a change in angle, which will change our vertical and horizontal forces.

Stress Analysis

Next, to help us determine which material will be sufficient to withstand the static forces of our design, we can use equation 2 to compare the tensile stress that the material will undergo, to the tensile strength of the material itself.

$$\sigma = F/A \quad (2)[9.1]$$

Where σ is stress, F is a force, and A is the area the force is acting on. In our analysis, F will be the tension force of our design depending on which material we choose, A will be the cross-sectional area of the elbow of our design, and σ will be the tensile stress of the design and material, which we will compare to the tensile strength of the material. Firstly, we must determine how the tension force varies for different materials used to construct the "forearm" as seen in Table 7 below. If we assume the mass of the foil to be 5 grams, the volume of the forearm to be 0.000336 m^3 (from CAD), and we multiply the density of the various materials by the volume of our design to determine the mass of the "forearm" or rod, we can use the equations from Figure 35 to determine the tension force.

Table 7: Comparison of tension forces of our design for different materials [4.2][24.3][32.1].

Material	Wood (oak)	ABS	PLA	Aluminum	Steel
Density (kg/m^3)	650	1050	1240	2710	775
m_{rod} **(kg)**	0.2184	0.3528	0.4166	0.9106	2.604
Tension Force (N)	7.021	8.334	8.958	13.785	30.334

Now that we have the various forces for different materials, we can use equation 2 to divide these tension forces by the cross sectional area of our design (A = 1270.965 mm^2), to determine the tensile stresses, which will be compared to the tensile strengths, as seen in Table 8 below.

Table 8: A comparison of the tensile stress of various materials to the tensile strength of the material [25.2][34.1][42].

Material	Wood (oak)	ABS	PLA	Aluminum	Steel
Tensile Stress (MPa)	0.00552	0.00656	0.00705	0.01805	0.02387
Tensile Strength (MPa)	5.5	13	32.938	276	250-1500

By viewing Table 8, we can determine that any material we choose should be more than sufficient to overcome the tensile stresses due to static forces. Final material selection will come later, as we still need to analyze the torques, but all factors considered in this analysis will help us in our final material selection.

Free Body Diagram 2: Torque Analysis
Furthermore, we drew out a second free body diagram as seen in Figure 36 below, that accounts for movement as well as all the torques our design will undergo. By analyzing the torques that will impact our design, we are able to use this analysis to guide decisions such as what motor to use, how much torque it needs to output, as well as what gear ratio may be necessary to match the torque and angular velocity requirements of our design.

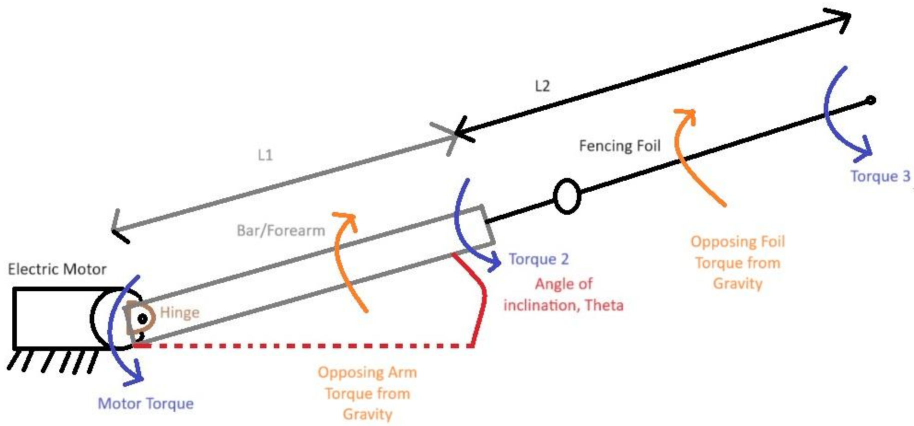


Figure 36: a free body diagram depicting the lengths of the components, angle of inclination, torques, and resulting torques.

The figure above depicts our overall design and the torques that will be acting upon it. It includes the torques required to overcome the weight of the design, the torque of the motor/elbow shaft, as well as the additional torque outputs of a fencer taken at the wrist as well as the tip of the foil. Next, we must outline the equations used to determine these torque values.

$$\tau = F * L = m * g * L \qquad (3)[36.2]$$

Where τ is a resultant torque, F is a force, and L is the length that force is acting over. Alternatively, we can break it down further and say that the torque is equal to the mass m times the gravitational acceleration g, times the length L.

With all components and parameters drawn out, and all torques being considered, we can use equation 3 to balance the torque equations as seen in Figure 37 below.

- $\tau_{elbow\ shaft} = \tau_{foil} + \tau_{arm} + \tau_{resultant\ 2}$
- $\tau_{foil} = m_{foil} * g * L_2 * sin(\theta)$
- $\tau_{arm} = m_{arm} * g * L_1 * sin(\theta)$
- $\tau_{resultant\ 2} = 3.313\ Nm$

Figure 37: A list of balanced torque equations of our design

The equations in Figure 37 above demonstrate that the torque required at the elbow shaft by the motor/transmission are due to the torques required to overcome the weight of the arm and foil, as well as the additional torque output of a human fencer. Ultimately, we had to reduce the scope of our design in order to meet budgetary restrictions, so we opted to reduce the additional torque output of a human fencer, $\tau_{resultant\ 2}$, from 10.55 Nm to 3.313Nm.

Our lengths, L_1 and L_2, of the subsequent forearm and foil, were pulled from the CAD model and determined to be; $L_1 = 0.254m$ and $L_2 = 0.889m$. Assuming that our foil mass remains the same at 0.5 kg, we were then able to generate a table of ranging elbow shaft torque requirements based on the angle of inclination θ, as well as the mass of the arm as seen in Table 9 below.

Table 9: A table of torque ranges for various angles and masses of materials

Angle, θ	**Wood (oak)**	**ABS**	**PLA**	**Aluminum**	**Steel**
5	3.740 Nm	3.770 Nm	3.783 Nm	3.891 Nm	4.258 Nm
10	4.165 Nm	4.223 Nm	4.250 Nm	4.464 Nm	5.197 Nm
15	4.582 Nm	4.669 Nm	4.710 Nm	5.029 Nm	6.618 Nm
20	4.990 Nm	5.105 Nm	5.159 Nm	5.580 Nm	7.023 Nm
25	5.386 Nm	5.527 Nm	5.594 Nm	6.115 Nm	7.898 Nm
30	5.765 Nm	5.933 Nm	6.012 Nm	6.628 Nm	8.737 Nm
35	6.126 Nm	6.318 Nm	6.409 Nm	7.115 Nm	9.535 Nm
40	6.465 Nm	6.681 Nm	6.783 Nm	7.574 Nm	10.286 Nm
45	6.781 Nm	7.018 Nm	7.130 Nm	8.000 Nm	10.984 Nm

After viewing the range of torques for various materials as well as considering the material stresses, strengths, and masses, we elected to use aluminum as our material for its moderate mass and torque as well as high strength and durability. This table allows us to consider the minimum and maximum torque that our elbow shaft will undergo. With this in mind, we can begin our search for a motor that will meet our torque requirements.

Gear Ratios and Motor Selection

Now that we have a torque range of 3.891 Nm < x < 8.000 Nm, as well as a required angular velocity of 38 rads/s or 362 RPM, we can begin to select a motor for our purposes. Considering that the torque requirement of 8 Nm is quite high, we will have to use a transmission to reduce the torque load on our motor. We utilized equation 4 below to see how different gear ratios impacted the torque and velocity requirements from the motor.

$$\frac{\omega_i}{\omega_o} = \frac{d_o}{d_i} = \frac{T_o}{T_i} = \frac{\tau_o}{\tau_i} \qquad (4)[0.1]$$

Where the subscript "i" stands for input gear and "o" stands for output gear. Additionally, ω is the angular velocity, d is the gear diameter, T is the number of teeth, and τ is the torque load.

Now, we can either generate a list of ranging torque and angular velocity values based on different gear ratios, then select our motor, or we can select our motor first, then see which gear ratio is necessary to achieve the torque and velocity requirements of 8 Nm and 362 RPM. We opted to choose our motor first, which happens to be the REV Robotics HD Hex motor. This motor was chosen as it has a built-in encoder, and is meant to integrate with premanufactured planetary gearboxes supplied by REV Robotics. The HD Hex motor has a torque output of 0.105 Nm as well as an angular velocity output of 6000 RPM. Using equation 4 above, we were able to determine the necessary gear ratio to be 80:1, as seen in Figure 38 below.

$$\frac{\tau_{output}}{\tau_{input}} = \frac{8}{0.105} = \frac{76.19}{1} \text{ or roughly } \frac{80}{1}$$

Alternatively

$$\frac{\tau_{output}}{0.105} = \frac{80}{1},\ \tau_{output} = 8.4\ Nm$$

Additionally

$$\frac{6000}{\omega_{output}} = \frac{80}{1},\ \omega_{output} = 75\ RPM$$

Figure 38: Determining gear ratio based on motor specifications and design requirements.

As shown in Figure 38 above, an 80:1 gear ratio allows us to exceed our torque requirement slightly, but undershoots our desired angular velocity of 362 RPM. We opted to continue on with our motor selection despite this, as our prototype design is a proof of concept, and we need to stay within budget.

Now that we know the necessary gear ratio for our design, and seeing that REV Robotics doesn't supply an 80:1 gearbox, we'll need to determine which combination of compounding gear trains will get us an 80:1 gear ratio.

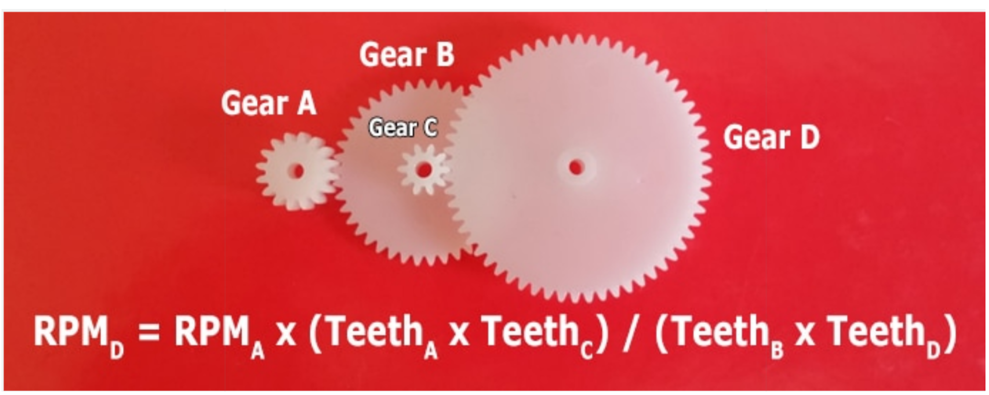


Figure 39: Compound Gear train example and equation [24.2].

By utilizing a similar method to Figure 39 above, we can determine which combination of gearboxes will give us the 80:1 gear ratio required. Figure 40 below shows exactly which gearboxes we plan to use considering that REV Robotics only offers 3:1, 4:1, and 5:1 gearboxes.

$$\frac{4}{1} * \frac{4}{1} * \frac{5}{1} = \frac{80}{1}$$

Figure 40: Compound gear train calculations

As shown in Figure 40 above, we will have to use two 4:1 gearboxes and one 5:1 gearbox in order to achieve the 80:1 gear ratio required.

Gear Ratio and REV Gearboxes

HD Hex Motor			
Stage 1 & Stage 2	Stage 3		
	3:1	4:1	5:1
3:1 & 3:1	24.3	30.4	43.9
3:1 & 4:1	30.4	37.9	54.8
3:1 & 5:1	43.9	54.8	79.3
4:1 & 4:1	37.9	47.4	68.5
4:1 & 5:1	54.8	68.5	99.0
5:1 & 5:1	79.3	99.0	143.1

Figure 41: The safe torques are detailed in the REV Robotics table.

Thankfully, REV Robotics have done torque analysis in the selection of the gearbox [31.1]. This chart details the highest torques that can damage the motor. As an example, for the first row, if one creates a 3:1 Gear Ratio, and then a 3:1 and then a 3:1 gear ratio, which creates a 27:1 gear ratio in general, this can create 24.3 Nm of torque. There is the highest amount of torque that can be output from the motor with this gear ratio.

In Figure 41, the 80:1 gear ratio with 4:1, 4:1, 5:1 gearboxes will be safe up to 68.5 Nm. Considering that the motor and gearing will be outputting 8.4 Nm, it means that the design is safe to use. Therefore, the motor and the gear ratio are rated to be safe.

Shaft Diameter Analysis

Now that our design material has been chosen, including our shaft material, we can determine the necessary diameter of the shaft to support the static forces of our dummy's arm. If we are to consider the maximum shear strength and normal strength of the aluminum shaft, we can determine the necessary area and subsequent diameter of the shaft so that we do not exceed the shear and normal strengths. By using equation 2 and equation 5 below, we can determine the necessary diameter.

$$\tau_{max} = (4 * F_T)/(\pi * D^2) \quad (5)[9.1]$$

Where τ_{max} is the max shear stress, but for our purposes we'll plug in the max shear strength, F_T is the tension force, and D is the diameter. Now if we are to assume that the tension force and normal force are at a maximum for our design, we can determine the necessary diameter, as seen in Figure 42 below.

Assuming Aluminum Shaft

$F_T = 13.838\ N$

$F_N = 13.838\ N$

Diameter required to withstand normal force

$\sigma_{max} = F_N/(\pi * (D/2)^2)$

We will plug in the max normal strength of the material for comparison

$\sigma_{max} = 90\ MPa$

$90\ MPa = 13.838/(\pi * (D/2)^2)$

D = 0.000442 m or 0.442 mm

Diameter required to withstand tension force

$\tau_{max} = (4 * F_T)/(\pi * D^2)$

We will plug in the max shear strength of the material for comparison

$\tau_{max} = 207MPa$

$207MPa = (4 * 13.838)/(\pi * D^2)$

D = 0.000292 m or 0.292 mm

Figure 42: Calculations for determining the necessary shaft diameter to support the maximum forces without exceeding material strength [34.1].

Modeling Range of Motion

In order to model the range of motion of a fencer, we planned to utilize long exposure photography in order to capture an image of the trace left behind from a bright light source. To get a sense of the exact trace the foil follows, we found a dark room, increased the exposure time of a phone camera, and taped an LED to the tip of the foil. We then set up the camera on a tripod, and photographed parries 4, 6, 7, and 8 in the same position. We then took photos from the front, side, and bottom views. These are documented in Figure 43:

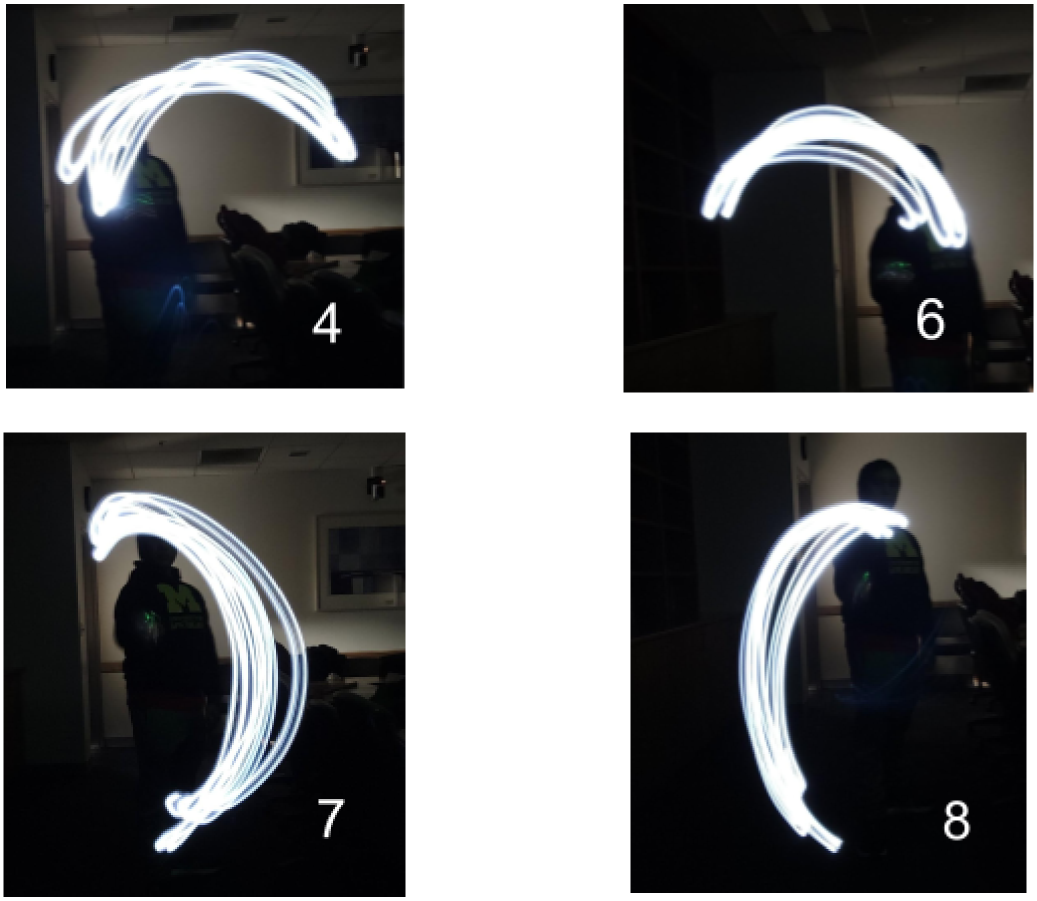


Figure 43: Front view traces of parries 4, 6, 7, and 8, respectively.

We then compared the traces to the path of the CAD motion profile to ensure an accurate simulation of the parry motion. A sample of this is shown in Figure 44:

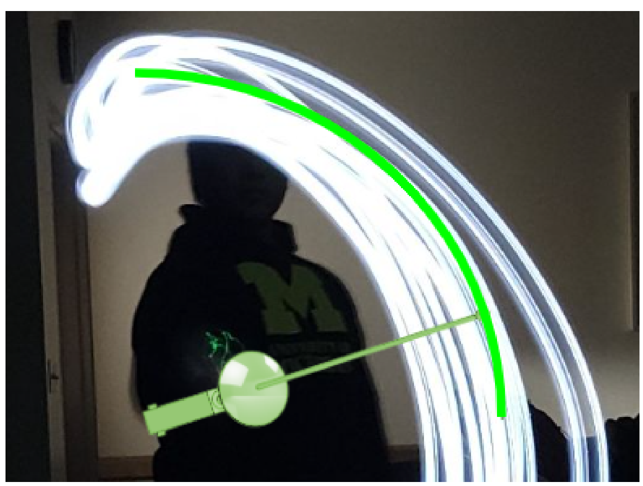


Figure 44: The CAD trace shown in green is compared to that of a real fencer for parry 7. This confirms our dummy will replicate the range of motion of a real fencer.

Motor Damping

In addressing the issue of vibrations resulting from the abrupt cessation of the system upon the completion of the motor's rotation of the parry, we propose the integration of a Proportional–Integral–Derivative (PID) controller within the Arduino framework. The primary objective of incorporating this control mechanism is to finely regulate the system's output, thereby minimizing deviations between the specified setpoint and the actual process variable. The PID controller operates by continuously computing an "error" value, representing the disparity between the desired setpoint and the current process variable. Subsequently, the control input is dynamically adjusted based on proportional, integral, and derivative components, shown in Figure 45 below. This approach ensures a comprehensive and responsive control strategy, effectively mitigating angular momentum-related issues in the shaft and fostering system stability. This portion has not been executed as of DR3 and the goal is to implement this by the final report.

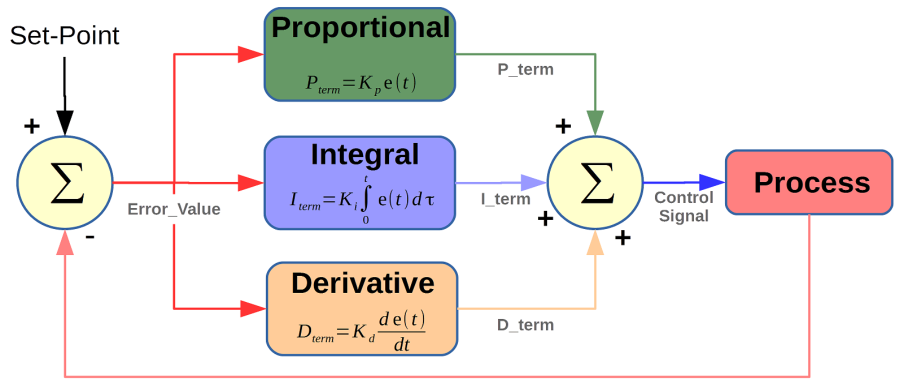


Figure 45: Components of a simple PID controller [36]

FINAL DESIGN DESCRIPTION

Motor and Gearbox Used in the Solution

The motor used in the solution was the UltraPlanetary HD Hex Motor.

The Free Speed of the motor is 6000 RPM and the Stall Torque of the motor is .105 Nm [31.3]. With a 80:1 gear ratio outputted by the REV Planetary Gearbox of 4:1, 4:1 and 5:1. This means that the motor would be able to output 75 RPM of angular velocity and 8.4 Nm of torque. This was achieved with a rev robotics planetary gearbox stack of two 4:1 and one 5:1. This is within the scope change of the project which decreased the angular velocity of the arm from 330 RPM to 70 RPM and the torque from 15 Nm to 8 Nm.

Unsuccessful Outcomes: Motor Selection and Gear Force Analysis of the Initial Design

One critique was the motor. The team wanted to use motors and gears to create a drive train to sustain the specifications of 15 Nm of torque and 300 RPM of angular velocity. A motor was selected that would provide 60 W and needed a 1:10 gear ratio to accomplish this. This wasn’t able to be implemented because of budget and cost overrun, however, there is reason in gear force analysis that this solution would have been suspect.

This solution would be needing gears that have a maximum stress of 450 MPa, and with a 3x Safety Factor, the gears would be running over that maximum stress. This meant that the motor needed to be run at a lower Wattage, which meant lower torque and lower speed and wouldn’t have gotten the team to sustain the specifications of 15 Nm torque and 300 RPM of angular velocity. This meant that the team needed to talk with the stakeholder on decreasing the scope which meant decreasing the angular velocity and the torque sustained by the motor.

With that, new specifications were drawn up and below is evidence that the motor and gear ratio can support this motor.

A lesson learned from this experience would be to look at the budget first before picking parts and doing analysis as this analysis wasted time and effort that could have been used on other topics such as researching PID control.

Encoder Count and the Ability to Parry
The UltraPlanetary Motor has an encoder count of 28 counts/revolution. Using a 80:1 Gear Ratio, the counts per revolution would be 2240. That means that the resolution of the motor would be 0.16 degrees. If we use Figure 46's 0 degree mark as a point of reference and the motor is going clockwise:

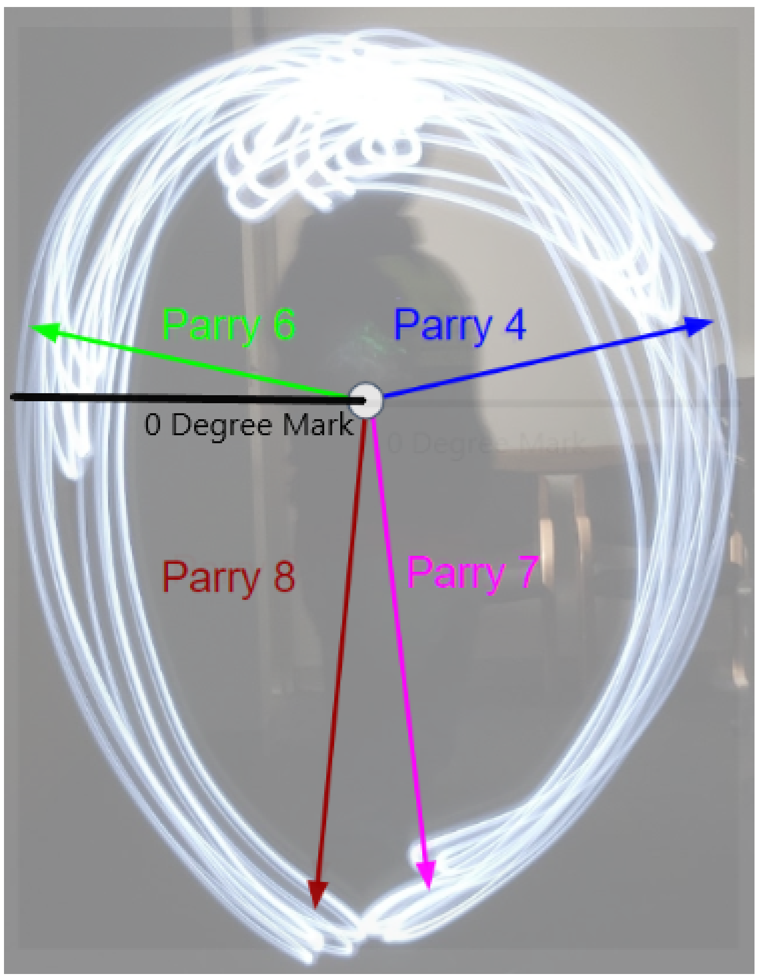


Figure 46: The required stopping angle for each parry is shown.

1. Parry 4 would be at 167 degrees
2. Parry 6 would be at 13 degrees
3. Parry 7 would be at 257 degrees
4. Parry 8 would be at 283 degrees

However, considering that this will try to be a real simulation of fencing, the motor will start from the 90 degree mark and do parries 4 and 7 clockwise from the point of reference. The motor will also do parries 6 and 8 counterclockwise from the point of reference.

With an encoder with a resolution of about 0.16 degrees, each of the parries will be accounted for within the required 3 degrees.

Creating the Arm Out of Aluminum and Shaft Diameter
The forearm and bicep of the product will be made out of aluminum. If one looks back to Tables 7 and 8, the tension force and tensile strength can take the forces that will be created by the motor and gravity. The body portion that won't be requirement critical will be made out of wood to decrease the cost of the dummy. The shaft diameter according to Figure 42 to withstand the force is .442 mm. This is smaller than any shaft sold on McMaster Carr, which means that the team can use a 6 mm shaft for the assembly.

Finally, with the 5mm shaft sizes on McMaster-Carr [24.1], this shaft is larger than the .4 mm shaft that is required to withstand the forces of the motor.

Final CAD
The final CAD of our design is provided below in Figure 47:

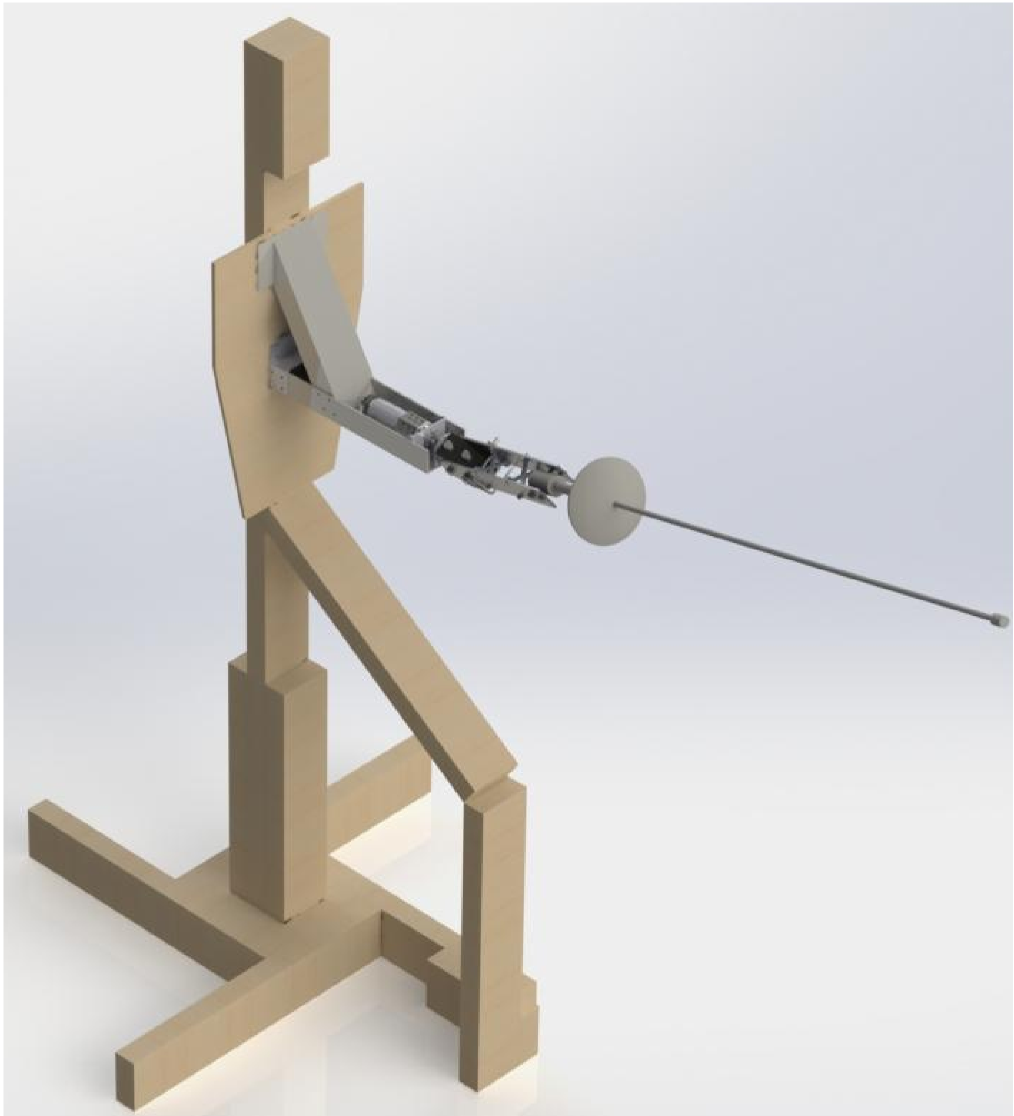


Figure 47: Full CAD of our final design, including the dummy stand with a wide base for stability.

A close view of only the arm is provided in Figure 48 below.

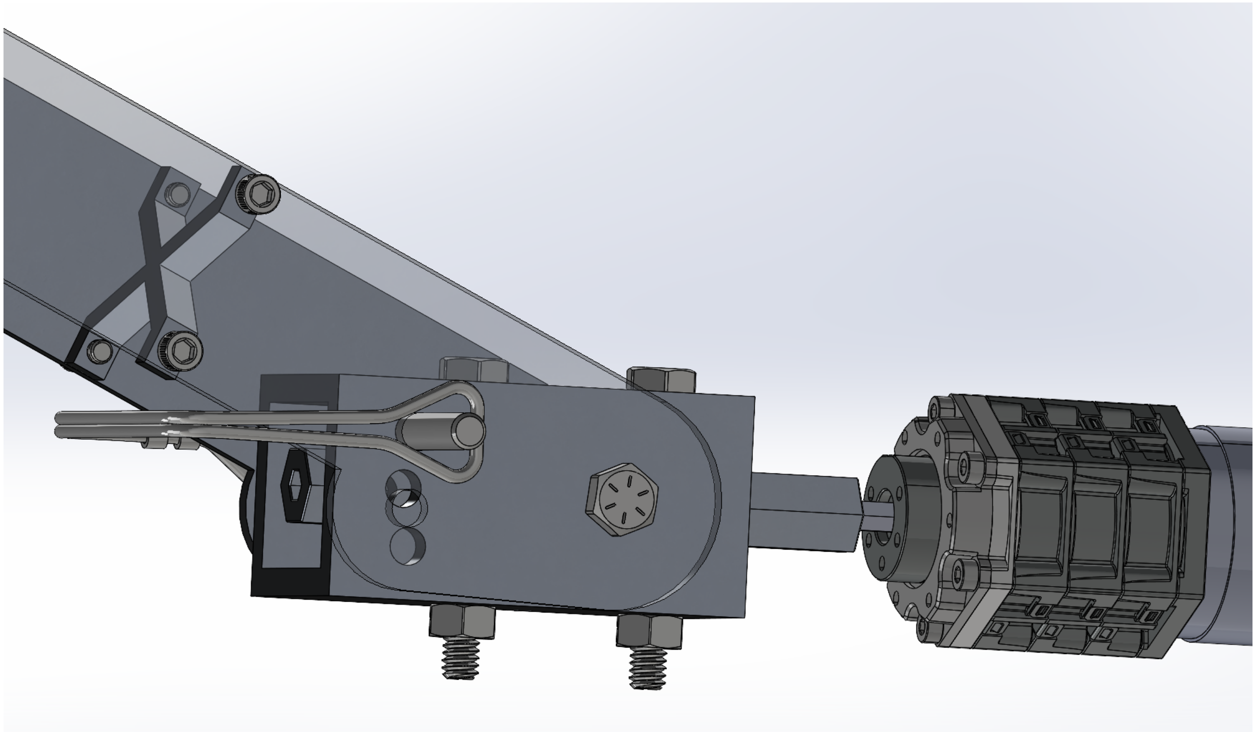


Figure 48: Close-up view of the main arm components, including the X-brace, adjustable pin block, and motor with gearboxes.

A close view of the arm and target interface is provided in Figure 49 below.

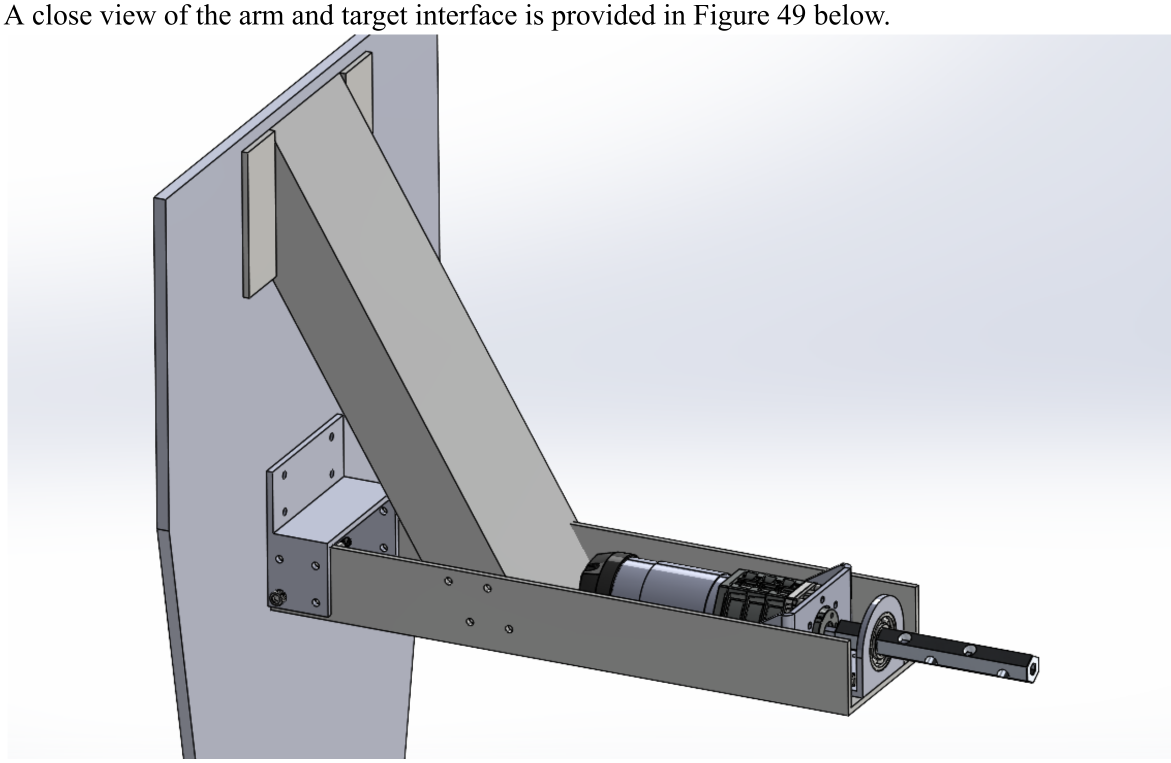


Figure 49: Close-up view of the arm and target interface, including the aluminum u channel “bicep”, brackets, and motor and bearing mounts.

Fabricated Fencing Dummy

Our final fabricated dummy is pictured below in Figures 50, 51, 52

Figure 50: Full fabricated build of the Automated Fencing Dummy.

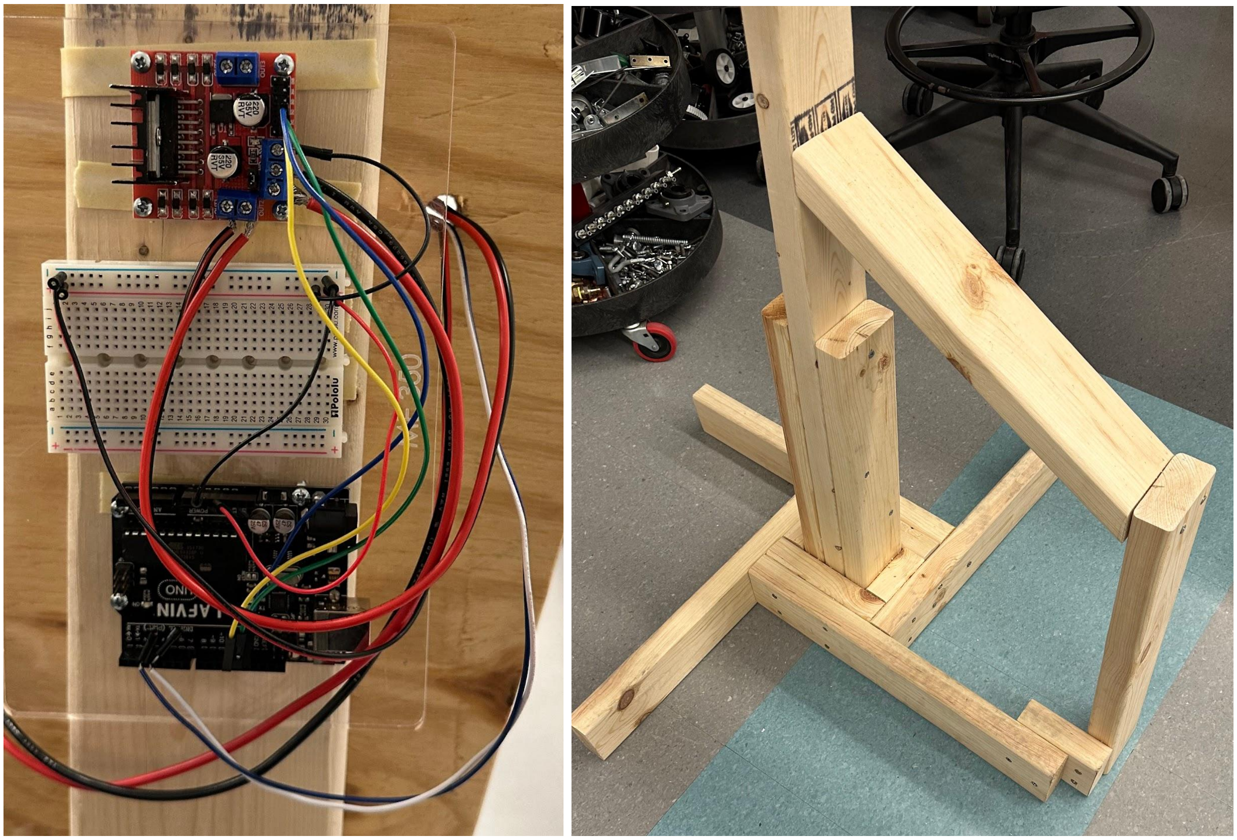


Figure 51: Arduino circuit with motor controller (left) and stable dummy base (right).

Figure 52: Views of the arm and foil joint (top) and elbow joint with motor and gearbox (bottom).

BUILD DESCRIPTION

A full Bill of Materials and assembly plan, along with manufacturing plans and engineering drawings can be found in the appendix.

Relationship Between Build and Final Design

Using calculations and figures from the Final Design Description, this is not going to be a one-off for the sponsor, this will be a general proof of concept that is scaled for the sponsor. Initially, if one looked at the requirements and specifications, the RPM that was initially given was nearly 5x its current value. The torque that was initially wanted was 1.5x its current value. These requirements and specifications needed to be decreased due to costs.

While the requirements and specifications were decreased for the final build, this does not nullify the calculations made for the original requirements and specifications. The calculations used there can be utilized to create a full scale model with appropriate funding and functionality.

VERIFICATION/VALIDATION

Verification

1. **Has to Follow US Fencing Safety Standards**

According to US Fencing Safety Standards, a good fencing jacket is able to withstand 5000 N of force from a foil hit [38]. While the dummy isn't meant to hit a fencing jacket, there might be times that a student that is using the dummy will be hit by the dummy due to them standing too close to the device. With this, the standard of withstanding 5000 N of force must be followed.

To accomplish this, the team first will use engineering analysis with the arm. As the arm can go 75 RPM, the mass of the arm is ~1.5 kgs and the radius from the center of rotation would need to be empirically measured. The RPM and the mass of the arm are known, however the radius from the center of rotation can still be changed. This means that one can use the equation below to find the force that is transmitted by the tip of the foil to a person. This is a virtual test that can be replicated.

$$F_c = \frac{m(r\omega)^2}{r} \quad [9.1]$$

Next, the team can use a physical test to determine whether or not someone will be hurt by the dummy. This test can be accomplished with a Force Gauge and a target. When the dummy hits the force gauge, the force centripetal can be seen from the Force Gauge.

2. **Accommodate a Wide Range of Users Ages 13+**

The dummy must accommodate a wide range of users, including different heights, skill levels, and right and left handedness. This is validated by the dummy meeting the following requirements:
- Based forearm length, height, and range of motion on an average build fencer.
- Left/Right handedness is accommodated by a centered dummy
- Fencer height modeled off of 5'9" in the en garde position, a typical opponent anyone could expect.
- Adjustable speed of parry to accommodate skill levels.

3. **Elbow Rotation**

The verification testing plan for the elbow joint specifications, encompassing pronation and supination parameters (83 degrees RoM, 10.3 Nm Max Torque, 38 rad/s Max Speed for pronation; 100 degrees RoM, 10.8 Nm Max Torque, 33 rad/s Max Speed for supination [Men]), seeks to evaluate the joint's fidelity to the typical movement, speed, and torque exhibited by the human elbow and wrist during parry motions. The comprehensive testing protocol involves pronating and supinating the elbow joint for parry maneuvers 4, 6, 7, and 8. Utilizing a camera and protractor, the range of motion at extreme positions will be precisely measured. Slow-motion video analysis from front and side perspectives will be conducted, with timestamps correlated to arm angle, facilitating the determination of parry speed. The torque exerted by the dummy arm during parrying will be measured with a force meter, and subsequent torque calculations will be compared against specifications. The testing approach combines various methodologies, such as measurements, video analysis, and feedback from fencers, ensuring robust data cross-validation. Although confidence in the testing methods is reasonably high, a contingency plan involves repeating tests in the presence of inconsistencies or discrepancies, and iterative adjustments may be necessary if the design does not align with specifications or expectations.

4. **Forearm Angle Adjustment**

The verification testing plan for the elbow joint specifications focuses on the joint's ability to facilitate both flexion (moving up) and extension (pushing back) movements, with a rotational range of -90 degrees $\leq x \leq 80$ degrees, adjusted to the necessary angles for completing parries 4, 6, 7, and 8. The testing plan involves motion capture analysis to determine the forearm angle for each parry, complemented by protractor measurements of the flexion and extension joint to assess whether the specified angles are achievable. This protractor-based approach is selected for its simplicity and clarity in validating forearm angle adjustments.

5. **Stability**

The verification testing plan for stability will focus on ensuring that the fencing dummy body must not move or tilt during use. Additionally, the fencing dummy arm and foil must not vibrate or oscillate during operation and use. To verify that the dummy doesn't move or tilt, we will construct the dummy with a wide and heavy base, as well as physically test the dummy during operation to verify no movement. In order to verify that there is no oscillation/vibration we plan to utilize our arduino motor controller to code a PID controller that will reduce any oscillations at the motor. We will subsequently monitor and adjust the potential, integral, and derivative gain of the system to keep oscillation to a minimum.

6. **Power**

The verification testing plan for the ability of the arm to get power will focus on the stakeholder's wants as this was mainly something that was asked to be implemented by the stakeholder (I. Rozich, personal communication, September 14, 2023). Therefore, the plan would be to invite Coach Ian for user testing around the time of the final prototype to have him see whether or not the stakeholder likes the accessibility afforded to him.

7. **Portability**

The verification testing plan for the portability of the arm will focus on the stakeholders's wants. This means that the plan would be involving Coach Ian for user testing around the time of the final prototype. For this, he will see if he can get the dummy into his car for transport. The team will also simulate his co-coaches in helping to carry the prototype and see if it is feasible to transport the prototype from the parking lot to the building.

8. **Ease of Service**

To verify the dummy can be serviced easily, our concerns involve accessibility of the fasteners, and types of tools used. To solve this, we use standard hex sizes, and reduce the number of different bolt types used. The components are also serviceable from the outside, meaning the bolt head is not obstructed by any other components.

9. **System Controls**

To verify the system controls, we determine if the Arduino accurately and repeatedly produces results that are similar to a real fencer. We plan to test the lame conductivity extensively and ensure they only lead to the desired outcome of each parry. Also, the foil must stop within a certain range of angles ($\pm 2°$) for each parry using the PID control. This is shown in Figure 46:

10. **Durability**

All major dummy components must be able to withstand all forces and torques, as well as last at least 5 years. We have previously done engineering analysis in order to justify and verify the appropriate materials for our design to withstand the forces and torques. To verify that our design will last 5 years, we plan to use various tools for regulatory compliance testing of all of our pre manufactured parts. Additionally, after constructing the prototype, we plan to continuously visually inspect the prototype to ensure that there are no ensuing part failures.

11. Budget

To verify the dummy is within our required budget, we have totaled the cost of parts ordered. This total ($330.09) is below our $400 budget provided.

12. Simulates Fencing Drilling Exercises

The dummy must accurately simulate parries 4, 6, 7, and 8. We will test this by conducting long exposure photography in a similar fashion to the earlier analysis using the actual dummy, and compare the traces. User feedback from fencing students that test the dummy will also be key in ensuring accurate simulation of parries. Analytic testing includes a comparison of CAD traces to the long exposure images of Alex.

13. Setup

The dummy must be able to be set up in under 20 minutes. This will be verified by having a group of five fencing students/fencing coaches set up the fencing dummy and be timed. If all individuals are able to set up the system within the 20 minute time limit the specification will be met.

A prototype was created to be completed at the expo date on November 30th. This provided a lot of preliminary verification giving indications of the target's stability and the movement of the arm. Due to time limitations, comprehensive testing to confirm and validate the specified criteria could not be conducted. Nevertheless, numerous design choices were informed by engineering analysis, incorporating calculations with safety factors and CAD information. This analysis supports the theoretical robustness of the design.

Validation

The validation plan involves engaging five fencers with varying skill levels, heights, and ages to interact with the fencing dummy and perform rotation parries (4, 6, 7, and 8). Many trials will be conducted, during which the fencers will be specifically instructed to focus on assessing the speed, torque, range of motion, human movement resemblance, and stability of the dummy. Durability will be monitored after each trial, and videos will be recorded for further analysis. The selected fencers include Coach Ian and four students or coaches with diverse demographics, ensuring a comprehensive evaluation. The testing will be repeated with participants directed to compare different parry types (4, 6, 7, and 8). This rigorous validation process aims to assess the robot arm's performance in replicating real-world fencing scenarios and its versatility in accurately mimicking various parry maneuvers, addressing a broad spectrum of fencing needs. The inclusion of diverse fencers and specific performance metrics enhances the thoroughness and reliability of the validation outcomes.

DISCUSSION

Problem Definition

If allowed more time and resources to lend on this project, there are several ways in which it could be improved upon. The first improvement made would be to incorporate a better user interface. We would finalize our design concept of the split lamé, that dictates rotational direction based on which side the foil makes contact with. We would likely have to purchase a fencing box as it is the unit necessary for electronically detecting contact between the foil and lamé. Furthermore, this fencing box would need to be wired up and integrated with our arduino so that the entire process can be autonomous.

Our next design improvement would be to alter the robot to accommodate for the 3 part sequence of parry, riposte, and recover. In order to do this, we would need two additional degrees of freedom. One would be at the elbow to control the forearm angle, and the other would need to allow for horizontal, linear extension. The elbow joint would likely be controlled and adjusted with a motor, while the extension of the arm could use various actuating systems such as a motorized rack and pinion or a pneumatic piston. Both of these additional degrees of freedom would need technical benchmarks or metrics for comparison and engineering analysis, in order to justify a specific design.

Design Critique

Given the project's tight timeline within a single semester, our team opted to significantly narrow down the scope of the fencing dummy. Despite achieving considerable progress over the four-month period, there remains additional work ahead.

1. **Target with Arm Interface:**

Constructed from wood and outfitted with fencing gear, including a mask and lame, the target exhibited strengths in stability, surprising, given the cost-effective materials and straightforward manufacturing. Stability emerged as a crucial factor in target design, leading to the selection of a bulky and wide base. While this base minimized movement during arm-actuated parry motions, we identified a potential issue when users lunged and stabbed the target, causing horizontal displacement. To address this, options such as fastening the target to the floor or wall (observed in benchmarked solutions) or placing sandbags on the supporting base pieces were proposed for future improvements.

Its humanoid form, featuring the torso, head, leg, and bicep in the en garde position, was noteworthy. However, a drawback of the design was the absence of padding, a feature observed in benchmarking designs using foam and pleather. Following Coach Ian's advice, we considered dressing the dummy in layers of old clothing to provide necessary padding and prevent potential damage to the fencing blade upon repeated contact.

Examined in the concept selection segment under "Lamé User Interface," consideration was given to the method through which users would interact with the dummy to trigger specific parries. However, owing to time limitations, this concept was not fabricated.

Initially contemplating a left and right-handed adjustment mode, we heeded Coach Ian's suggestion and centered the arm and leg, aiming for a versatile approach. The need for accommodating dominant hand preferences could be revisited in future iterations.

The arm interface performed as intended, but further validation is required to assess the durability of supporting components, especially concerns about potential wood yielding under the aluminum brackets.

In the haste to design and manufacture the arm interface for the expo and judicious resource utilization, certain unconventional decisions were made regarding the brackets linking the wood target with the aluminum U-channel. Future iterations should prioritize a more refined and elegant approach to supporting the arm pieces.

Overall, the manufacturing and assembly of the target and arm posed minimal issues, with the primary challenge being the placement of bolts in confined areas beneath the "bicep."

2. **Foil Attachment**

One design oversight occurred in the method of attachment of the foil to the forearm. Based on CAD online, we had planned to bolt the foil directly to the forearm. However, upon receiving a foil Coach Ian was willing to give us, we discovered that the handle did not match the CAD we used. It was similar, so with a few modifications and an additional bracket piece, we were able to mount it rather hastily, but sturdy enough to perform well.

3. **Reduced Scope**

With the reduction of scope, we had to forgo the ability for a lunging riposte movement of the dummy. This limits the functionality of the dummy, as a full parry, riposte (lunge), and recover (retract lunge) movement is not possible. Again, this was excluded due to the time constraints. This would have been a very attractive feature to have on the dummy, and could become a future project for another 450 team. Along with the loss of riposte feature, we opted for the manually adjustable forearm angle. While this worked well and was very sturdy and simple, another actuator to change this autonomously would improve the performance of the dummy. If it could change the angle of the forearm via a command from the Arduino, the user could reduce unnecessary manual interaction time, and would have a more streamlined practice session. This could again be achieved by another project group using some form of actuated motor and transmission system.

Risks

1. **Burnout of the Motor**

One large risk that is involved with the motor would be burnout due to using the motor too much. In the design exposition, one of the team members noted that the motor would make a high-pitched noise get warm (Sorgenfrei, personal communications, November 30, 2023) . These are the telltale signs of a motor being worked too hard and means that there is too much torque or RPM that is being transferred to the arm.

To decrease the burnout, one could either use a different motor and gear train, or decrease the power that is being fed to the motor. This was done during the exposition to decrease the high-pitched noises and heat coming from the motor. Additionally, to decrease burnout, one could use the dummy moderately.

2. **General Safety With Using Fencing Foils**

One of the large problems with using and demonstrating this dummy during the exposition was the cramped nature attendees were experiencing. This opened the eyes of the team to safety precautions that fencing clubs need to take when using this device. One, everyone needs to wear a mask or eye protection when using this device as even the miniscule amount of force that this device will create can cause eye damage. Two, as much as possible, this device should be used in an open room where there is enough space to not be hit by the foil that this dummy wields except for the few people practicing with it.

REFLECTION

Now that we have reached our project and design conclusion, we can reflect on the global and societal impacts of our project. In the sections below we will outline how our perspectives on the impact of our project have changed.

Relevant Factors

Public health, safety, and welfare are crucial factors to this project as we need to ensure our design is safe to use by the public. This may include meeting US Fencing Safety standards, removing pinch points, and ensuring that there are no sharp edges. While global context may not be the most crucial of factors as fencing is a niche sport, this product could prove to be beneficial by providing access to more training tools to people all over the world. Social impact is a very relevant factor as we tried to keep manufacturing, use, and disposal in mind with our design. Our design is made up primarily of wood and aluminum, both of which can be recycled and or disposed of without harm to the environment. Additionally, its use should focus on enhancing inclusivity in fencing training, ensuring accessibility for students with varying abilities. Economic impact is relevant to our project as our fencing robot could potentially reduce coaching costs by attracting more students with better equipped training facilities. Lastly, in order to characterize the societal impacts of our design, we used a stakeholder map for stakeholder analysis as seen in the appendix, as well as eco-audits on our design to determine factors such as energy consumption and end-of-life disposal.

Ethics

In the pursuit of designing a robotic system for fencing drills, our team encountered several ethical dilemmas that warranted careful consideration. These challenges pertained to ensuring the safety and inclusivity of the product, addressing potential marketplace ethical concerns, and aligning personal ethics with professional expectations.

Safety and Inclusivity:

The primary ethical concern centered around creating a safe and inclusive robotic system. Given the intended use by fencing students, including children and inexperienced individuals, the device had to adhere strictly to safety standards. We faced the ethical dilemma of balancing functionality with safety, especially concerning the automated sword-wielding feature. Our commitment to safety prompted a thorough evaluation of potential risks and the implementation of safety measures to mitigate them.

Market Entry Ethical Issues:

Considering the possibility of the product entering the marketplace, we foresaw ethical issues related to marketing and user accessibility. Ensuring transparent communication about the product's capabilities, limitations, and potential risks became paramount. Ethical marketing practices and providing clear guidelines for the intended use are crucial to prevent misuse or misinterpretation of the robotic fencing system.

Personal Ethics vs. Professional Expectations:

As engineers and members of the University of Michigan community, our personal ethics aligned closely with the ethical standards upheld by the university. However, we recognized the need to bridge personal values with the professional expectations of a potential future employer. Striking this balance involved maintaining transparency, integrity, and a commitment to safety throughout the design and development process.

Stakeholder Collaboration:
Ethical considerations extended to our relationship with stakeholders, Coach Ian Rozich, Professor Wenda Tan, and the fencing community. Open communication, transparency in decision-making, and responsiveness to their input were essential in upholding ethical standards in collaborative endeavors.

Managing ethical considerations in our project involved a meticulous approach to safety, transparency, and alignment with both personal and professional ethical standards. These considerations were not only integral to the design process but also laid the foundation for responsible deployment if the product were to enter the marketplace.

Cultural privilege, identity, and stylistic similarities between team members
Each team member did not really use their cultural privilege to exact an influence on the final design. However, each team member's identity and stylistic similarities definitely exacted an influence. For example, two of the members of the team have done fencing in the past. This means that some of the validation was already being accounted for when designing the device. Additionally, for the end user, the two members somewhat were designing this device for the more senior end-users rather than the beginners that the stakeholder wanted the team to design for. This meant that the stakeholder and the other two members of the team had to hold both of them back and remind these two fencers that beginners were going to use the dummy too.

There weren't any notable differences between each team member with respect to their design. Each team member approached the problems similarly, with the various members talking to the stakeholder/sponsor a lot to get their input on a design question. After talking to the sponsor, each member would meet back together and a convention would be called to discuss how the sponsor's wants would be implemented.

Cultural privilege, identity, and stylistic similarities and power differences with sponsor
While the team members themselves wouldn't have that input on the requirements and specifications, the sponsor with their identity had the most influence on the design. With the fact that the stakeholder is a coach who intends to use this dummy, the end-user and the coach's input set the tone of what the dummy should be doing and the initial design requirements and specifications. Much of the project was guided as the team would refer design questions to the coach. That coach's input would guide the answers that would be present in the solution.

Inclusion and Equity
Throughout the semester, the team seeked to include as much input as possible from each team member, the stakeholders, and end users. Power dynamics were balanced between team members, and input from positions of authority such as professors were taken seriously. As the team was ultimately the one with the final say, what we chose would shape the project, so it was important to disallow personal opinions to take over direct feedback from end users and stakeholders. Each team member also had an equitable opportunity to speak up and challenge a design decision if they thought it was not in the best interest of the public, the stakeholders, or the end users. When developing concepts, initially no concept was too far-fetched; we considered everything. Many discussions would narrow down to a solution we all agreed upon. This allowed us to incorporate many diverse viewpoints into generated concepts in our design.

RECOMMENDATIONS

A recommendation that can be done is finding a motor that is more powerful. Attached in the appendix are the calculations for a gear train that would be able to harness the power of that motor and that would be able to have the same torque and RPM as the original requirements and specifications. This would allow the dummy to more accurately simulate human movement and forces. It is also important to store the dummy safely, as we noticed the foil tip is difficult to see when extended. Safety factors should be taken into consideration, and users should be aware of the range of motion and only be near it when practicing.

CONCLUSION

This report details the process and challenges involved in designing an automated fencing dummy. This device will provide an engineering solution capable of simulating fencing drills, specifically executing parries 4, 6, 7, and 8. The design project, which is commissioned by Coach Ian Rozich and Professor Wenda Tan, aims to introduce a safe, accessible, and autonomous fencing simulator for practical use within Plymouth Fencing Academy.

The main challenges identified include the complexity and time-constrained nature of the design, the multidisciplinary aspects of the project spanning mechanical engineering to coding, and sourcing materials within a tight budget and time constraint. To deal with these, we outline several strategies, including clear role assignment, a structured project plan, modular development, and comprehensive systems understanding.

We have provided a comprehensive analysis of pre-existing technologies, their capabilities, and their shortcomings, leading to the conclusion that a novel solution would be necessary. Initial obstacles were centered around complex applications of mechatronics, control systems, and certain knowledge gaps. This report outlined plans to address these issues, including consulting guides and materials on the necessary topics, thoroughly understanding relevant safety standards outlined by the International Fencing Federation and USA Fencing, and the application of mechatronics systems like motor controls and programming systems.

Our team started with a basis of design, exploring nearly 200 uniquely creative ideas before focusing on creating a humanoid robotic arm, with two degrees of freedom enabling elbow rotation and forearm angle adjustment. The arm was ideated upon using morphological analysis and function decomposition. Multiple joint mechanisms were analyzed, with independent actuators receiving the highest ranking. For setting the forearm angle, we selected the pin and hole mechanism. Servos were initially considered for a rotational elbow joint, but we selected a motor due to wider motion range, higher torque options, and lower cost.

We conducted analysis of the forces and torques acting on the design to allow further guidance on material and motor decisions. Force analysis was completed to ensure a strong material was selected for each component. We then chose a motor that met our torque and RPM requirements. This was accomplished using a combination of gearboxes. The chosen design incorporates a motor for elbow rotation and a pin-in-hole mechanism for manual forearm angle adjustment.

The final stages of this project included manufacture and assembly. Complete manufacturing plans and engineering drawings were produced for each component. Each component was then machined, assembled, and tested. The Arduino code was tested and tweaked with a PID controller to fit the requirements. As we confirmed our final product meets the requirements, we documented this and prepared to use it in a real practice setting at Plymouth Ann Arbor fencing club with Coach Ian Rozich for further verification and validation.

ACKNOWLEDGEMENTS

We would like to convey our heartfelt thanks to Coach Ian for his invaluable guidance in clarifying the design requirements and offering insights into fencing techniques. We appreciate his generous provision of fencing gear, which proved essential in developing the prototype. Additionally, our gratitude extends to Professor Tan for his insightful guidance in managing logistics and addressing engineering challenges throughout the ME 450 class. The expertise and unwavering support from both Coach Ian and Professor Tan have been instrumental in shaping the success of this project.

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APPENDICES

APPENDIX A. TEAM MEMBER BIOGRAPHIES

Steven Majors is a senior in Mechanical Engineering. He is from Howell, Michigan. He wanted to pursue mechanical engineering due to his engineer dad starting a FIRST Lego League team in 2013. This led to him moving up to FIRST Robotics Competition in high school, even becoming a robot driver. He enjoys working through engineering challenges, coming up with solutions, and testing them to get a final working product. He plans to pursue a masters in mechanical engineering through the SUGS program here at University of Michigan. He also is interested in research, and is part of a team using High Energy Diffusion Microscopy to examine the grain structure of light metals and the effects of treating it using heat, electricity, or magnetic fields. He has two dogs back at home, enjoys running, disc golf, and watching football.

Evelyn Sorgenfrei is a senior in Mechanical Engineering from Bloomfield Hills, Michigan. She participated in FIRST robotics from middle school to high school where she got inspired to pursue an engineering degree. In her previous engineering roles, she has applied her design and engineering skills to various domains, such as robotics, access machinery, prosthetics and Agriscience. She is passionate about creating innovative solutions that address global challenges and improve the quality of life for people and the environment. She plans to go into industry after graduating in December of 2023. She enjoys mountain biking, baking, gardening and reading.

Alexander Elan Agraviador Encarnacion Amis Llamelo Constantino is a senior in mechanical engineering from Rockville, MD. He will be graduating in March 2024. Previously, design and engineering skills were used in robotics, coding and CAD for automotive and general operations engineering tasks. One previous experience was working on a project relating to the time it takes to create supply chains of various military parts. Currently, he is modifying the design of the B and A-pillars of an autonomous electric vehicle. He enjoys working in various domains and his overall goal is to improve designs in transportation, whether it be in the aerospace, automotive or railroad industries. He plans to go to industry and then a masters programme.

Ethan Hensley is a senior in Mechanical Engineering originally from Linden, Michigan. He will be graduating from the University of Michigan in December 2023 with a bachelors in Mechanical Engineering. He has passions in automotive engineering, mechatronics, and aeronautical engineering. He was inspired to be an engineer after owning, repairing, and maintaining his first, and subsequent cars. Additionally, constructing his own mini bike created further interest in the field of engineering. This led to him attending the University of Michigan Flint, after graduating from Linden High School, then transferring to the University of Michigan Ann Arbor. He is unsure of exactly which field of engineering he'll be in after graduation, but is ultimately passionate to design solutions that will help others. He has two ferrets and enjoys playing video games with friends, kayaking, and collecting vinyl records.

APPENDIX B. BUILD PLAN

Detailed Materials and Parts

We tracked all of the components necessary to build the dummy, and compiled a Bill of Materials. This is provided below in Table 10 and 11 [2.1, 24.1, 31.1, 31.2, 31.3, 38.1]:

Table 10: Bill of Materials

Part No.	Part Title	Material	Dimension(s)	Supplier	Quantity	Price
1	Elbow Mount	Aluminum	1.5x1.5x3 1/8" thick	McMaster	1	$10.65
2	Forearm	Aluminum	11x2.75x.125	McMaster	2	$23.07
3	X Brace	Aluminum	1.5x1.5x.25	McMaster	2	$11.70
4	Clevis Pin	Steel	2 3/16", 1/4 ⌀	McMaster	1	$2.48
5	Hex Nut	Steel	1/4-20	McMaster	5	$0.45
6	Hex Bolt	Steel	2" 1/4-20	McMaster	5	$2.67
7	Hex 1/2" to 5mm shaft	6061 aluminum	36" long, 1/2" hex, 5mm hex inner	Rev Robotics	1	$12.00
8	Target Screws	Steel		x50 room	<30	$0.00
9	Target Base	2 by 4	20"	Lowes/Home Depot	8	$3.28
10	Target Vertical	2 by 4	62"	Lowes/Home Depot	1	$11.68
11	Target L Spacer	2 by 4	4.5"	Lowes/Home Depot	4	
12	Target S Spacer	2 by 4	3.5"	Lowes/Home Depot	2	
13	Target Torso	Plywood	11.5"(top), 7" (bottom) x 18" x 1/8"	Stevens House	1	
14	Target Padding	Sweatshirts		All		$0.00
15	Aluminum Brackets	Aluminum Sheet	1/8" x 5" x 8"	x50 room	1	
16	Power Supply			x50 room		$0.00

17	Motor and Gearbox Kit	Steel, Nylon	37mm diameter	Rev Robotics	1	$45.00
18	UltraPlanetary Cartridge 4:1	Steel, Nylon		Rev Robotics	1	$11.50
19	H Bridge	Electronic	1.5"	x50 room	1	$0.00
20	Face mounting brackets	5052 aluminum		Rev Robotics	1	$7.00
21	13.75mm (1/2" ThunderHex ID) x 1.125" OD x 0.313" WD (Flanged Bearing)	Stainless Steel	13.75 mm for 1/2" Thunderhex	VEX Robotics	2	$3.99
22	Set screws	Steel	6-32 5/32"	McMaster	2	$9.72
23	U channel	Aluminum	4'	McMaster	1	$46.31
24	8-32 Bolt	Steel	3.5"	McMaster	3	$7.87
25	8-32 Nut	Steel		McMaster	1	$4.60
26	8-32 Bolt	Steel	1/2"	McMaster	1	$7.00

We added the cost of all purchased parts in Table 11 below:

Table 11: Cost summary of BOM purchased materials

Purchased Part No.	Qty	Price/Unit	Supplier Part No.	Cost
1	1	$10.65	6546K22	$10.65
2	1	$23.07	89015K236	$23.07
3	1	$11.70	9246K423	$11.70
4	1	$2.48	98416A013	$2.48
5	1	$8.95	95462A029	$8.95
6	1	$13.37	92620A551	$13.37
7	1	$12.00	REV-41-3205	$12.00
17	1	$45.00	REV-41-1600	$45.00
18	1	$11.50	REV-41-1602	$11.50
20	1	$7.00	REV-41-1625-PK2	$7.00
21	1	$3.99	217-4006	$3.99
22	1	$9.72	91375A182	$9.72
23	1	$46.31	9001K83	$46.31

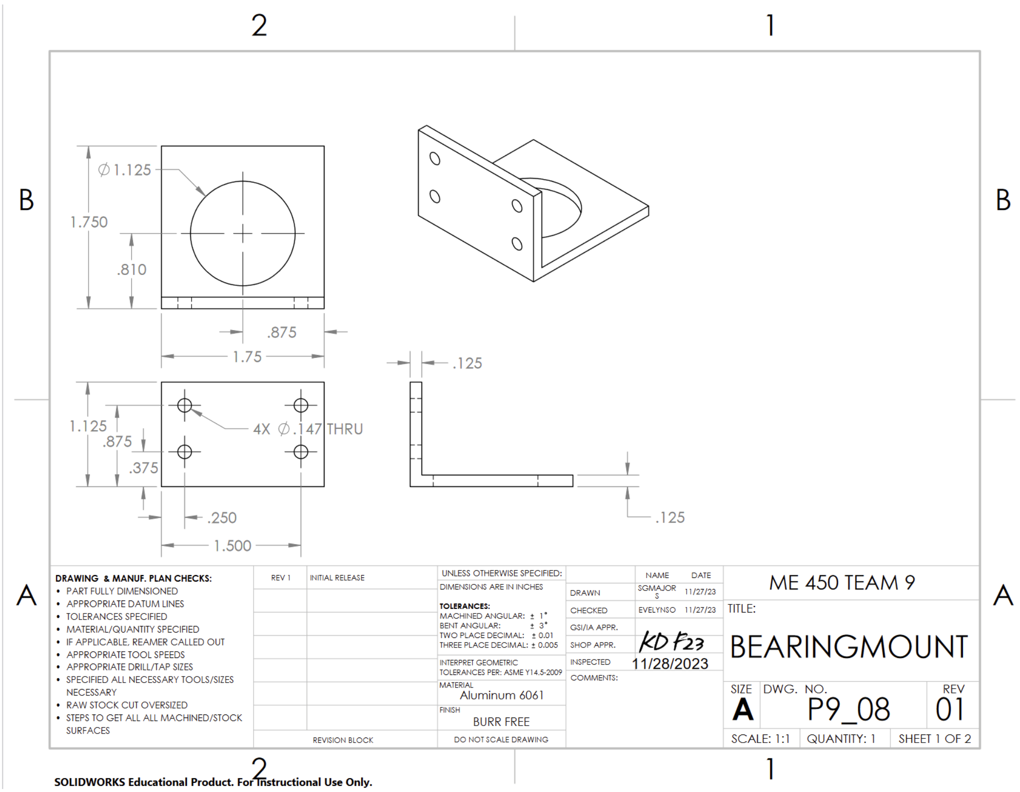
24	3	$7.87	91251A186	$23.61
25	1	$4.60	90631A009	$4.60
26	1	$7.00	90128A194	$7.00
9 thru 12	3	3.28		9.84
Shipping (REV)	1	$18.65		$18.65
Shipping (McMaster)	1	$40.53		$40.53
Tax (McMaster)	1	$9.65		$9.65
Shipping (Vex)	1	$19.83		$19.83
Tax (Vex)	1	$0.48		$0.48

Total Cost	$339.93

Manufacturing Plans/Engineering Drawings

Below are manufacturing plans and engineering drawings for each component. These would each be manufactured before following the detailed fabrication plan to reproduce our dummy.

1. **Bearing Mount**



MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/8" Aluminum L channel

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	cut stock to 1/8" oversize	horizontal bandsaw			
2	mount in mill vice	mill	vice, parallels		
3	find datum	mill	vice, parallels	edgefinder	1000
4	bring material down to length 0.030 passes, 0.010 last pass	mill	vice, parallels	3/4" extended endmill	800
5	centerdrill mount hole	mill	vice, parallels	centerdrill #2	1200
6	drill mount hole	mill	Vice, parallels	#26 drill bit	1500
7	repeat 5-6 for other 3 holes				
8	mount in mill vice for face drilling	mill	vice, parallels		
9	find datum	mill	vice, parallels	edgefinder	1000
10	centerdrill bearing hole	mill	vice, parallels	centerdrill #5	1200
11	Drill hole using stepper bit to just smaller than 1.125	mill	Vice, parallels	stepper bit	
12	Use mill boring bar to get final diameter	mill	vice, parallels	boring bar	

talk to shop staff for help with these steps

SHEET 2 OF 2

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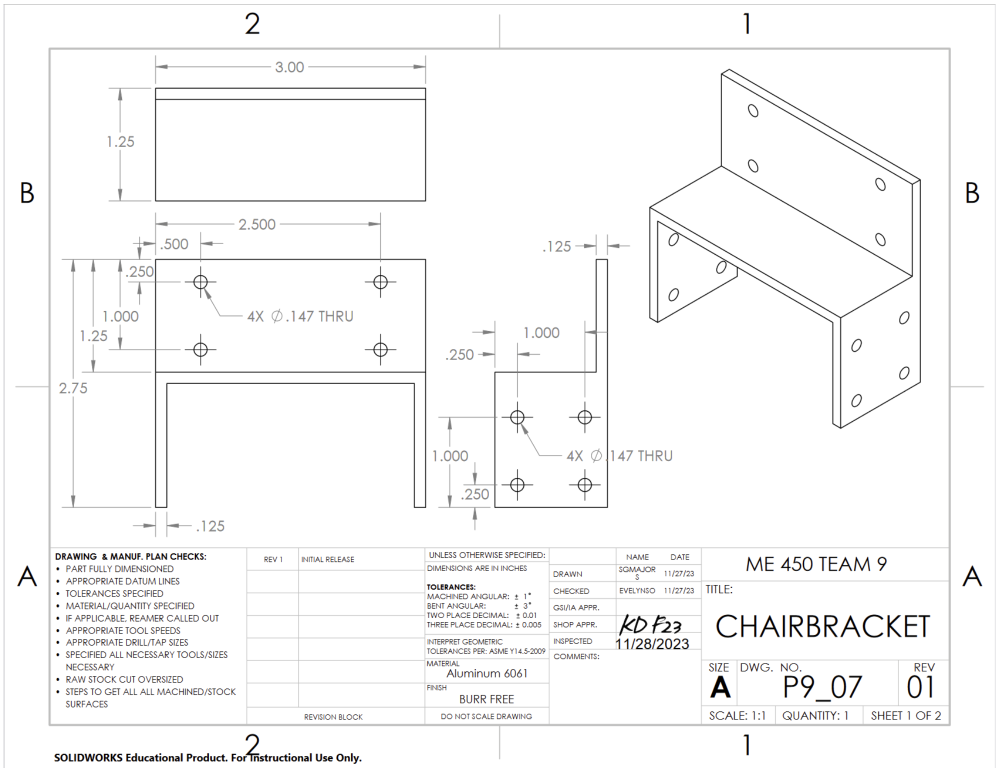
2. Chair Bracket



MANUFACTURING PLAN

RAW MATERIAL STOCK: 1.5" by 3" U channel, 0.125" thick

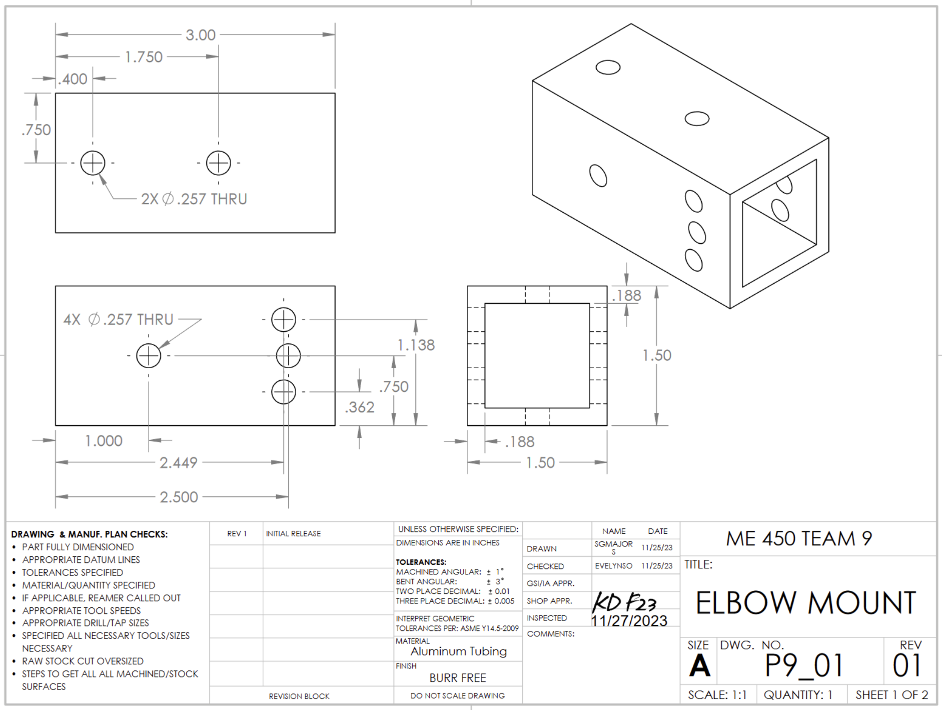
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	cut stock to 3 1/8"	horizontal bandsaw	vice		
2	bring part to length, 0.03" passes, 0.01" final pass	mill	vice	endmill	1000
3	remove 1.5" of the tabs, leaving 1.5" of U channel, and 1.5" of just the flat bottom piece	vertical bandsaw	pusher		
4	file edges			file	
5	bend flat bottom 90 degrees to form chair shape	brake press			
6	clamp in vice for bottom piece holes	mill	vice, parallels		
7	find datum	mill	vice	edgefinder	1000
8	center drill	mill	Vice, parallels	center drill #2	1200
9	Drill hole	mill	Vice, parallels	#26 drill bit	1000
10	repeat 8-9 for 3 other holes				
11	clamp in vice for side holes	mill	vice, parallels		
12	find datum	mill	vice	edgefinder	1000
13	center drill	mill	Vice, parallels	center drill #2	1200
14	Drill hole	mill	Vice, parallels	#26 drill bit	1000
15	repeat 13-14 for 3 other holes				
16	flip and clamp in vice for other side holes	mill	vice, parallels		
17	repeat 11-15 for other side holes				

From our experience here in the shop, this part is likely to crack or break when bending at this angle, so you'll need to heat the material up to anneal it before bending, and it still may not turn out right. alternatively, you can split this part into two, the U channel and a plate that is either threaded or welded together. consider your options.

SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.

3. Elbow Mount



SOLIDWORKS Educational Product. For Instructional Use Only.

MANUFACTURING PLAN

RAW MATERIAL STOCK: 1.5" SQUARE ALUMINUM TUBE, 0.188 WALL THICKNESS

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	cut to rough length, 3.1"	horizontal bandsaw	vice		
2	bring part to length, 0.03" passes, 0.01" final pass	mill	vice	3/4" endmill	500 ~~1000~~
3	Clamp into mill, find datum	Mill	Vise, parallels	edgefinder	1000
4	center drill	mill	Vise, parallels	center drill #2	1200
5	Drill hole	mill	Vise, parallels	F drill bit	1000
6	Repeat 2-3 for other hole on top face				
7	Turn and repeat 1-4 for 4 holes on side				

SHEET 2 OF 2

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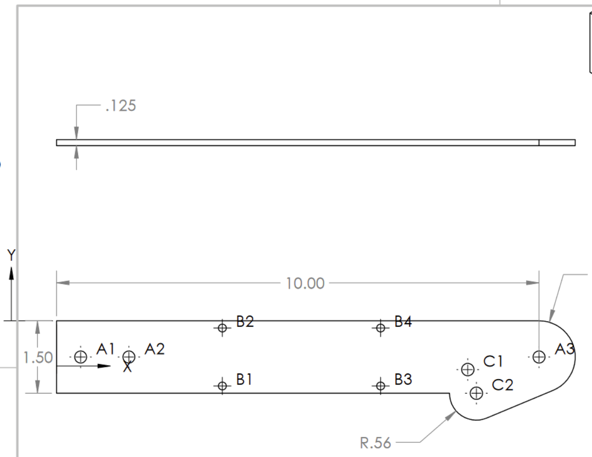
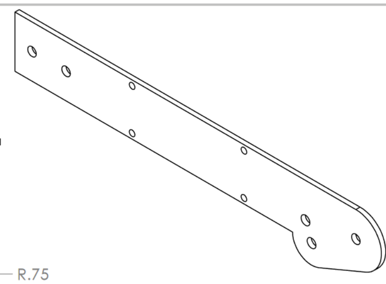
4. Forearm

2 1

B





TAG	X LOC	Y LOC	SIZE
A1	.500	-.750	∅.25 THRU
A2	1.500	-.750	∅.25 THRU
A3	10.000	-.750	∅.25 THRU
B1	3.437	-1.350	∅.16 THRU
B2	3.437	-.150	∅.16 THRU
B3	6.717	-1.350	∅.16 THRU
B4	6.717	-.150	∅.16 THRU
C1	8.523	-1.010	∅.26 THRU
C2	8.701	-1.500	∅.26 THRU

A

DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009
MATERIAL Aluminum 6061
FINISH BURR FREE
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SGMAJORS	11/14/23
CHECKED	EVELYNSO	11/14/23
GSI/IA APPR.		
SHOP APPR.	KD F23	11/27/2023
INSPECTED		
COMMENTS:		

ME 450 TEAM 9

TITLE: FOREARM

SIZE A | DWG. NO. P9_01 | REV 01

SCALE: 1:2 | QUANTITY: 2 | SHEET 1 OF 2

2 1

SOLIDWORKS Educational Product. For Instructional Use Only.

2 1

B

MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" AL PLATE

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Waterjet, all holes are free fit, tolerance not tight	Waterjet	Clamps		

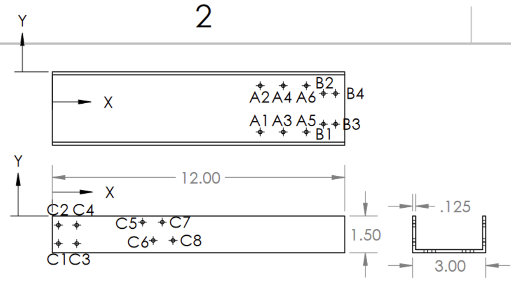
A

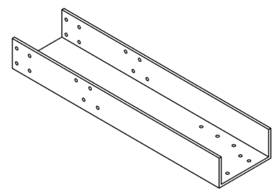
SHEET 2 OF 2

2 1

SOLIDWORKS Educational Product. For Instructional Use Only.

5. Lower Bicep





TAG	X LOC	Y LOC	SIZE
A1	8.534	-2.458	∅ .147 THRU ALL
A2	8.534	-.568	∅ .147 THRU ALL
A3	9.479	-2.458	∅ .147 THRU ALL
A4	9.479	-.568	∅ .147 THRU ALL
A5	10.423	-2.458	∅ .147 THRU ALL
A6	10.423	-.568	∅.147 THRU
B1	11.125	-2.138	∅.147 THRU
B2	11.125	-.888	∅.147 THRU
B3	11.625	-2.138	∅.147 THRU
B4	11.625	-.888	∅.147 THRU

TAG	X LOC	Y LOC	SIZE
C1	.250	-1.125	∅ .147 THRU ALL
C2	.250	-.375	∅ .147 THRU ALL
C3	1.000	-1.125	∅ .147 THRU ALL
C4	1.000	-.375	∅ .147 THRU ALL
C5	3.702	-.250	∅ .147 THRU ALL
C6	4.142	-1.000	∅ .147 THRU ALL
C7	4.514	-.250	∅ .147 THRU ALL
C8	4.954	-1.000	∅ .147 THRU ALL

DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1 — INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009
MATERIAL: Aluminum U Channel
FINISH: BURR FREE
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SGMAJOR S	11/25/23
CHECKED	EVELYNSO	11/25/23
GSI/IA APPR.		
SHOP APPR.	KD F23	11/27/2023
INSPECTED		
COMMENTS:		

ME 450 TEAM 9

TITLE: LOWER BICEP

SIZE: A — DWG. NO. P9_04 — REV 01

SCALE: 1:4 — QUANTITY: 1 — SHEET 1 OF 2

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MANUFACTURING PLAN

RAW MATERIAL STOCK: ~~1/4" AL PLATE~~

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Clamp into mill, find datum	Mill	Vise, parallels	edgefinder	1000
2	center drill	mill	Vise, parallels	center drill #2	1200
3	Drill hole	mill	Vise, parallels	#26 drill bit	1500
4	Repeat 2-3 for all A and B holes				
5	Remove, turn, and clamp to drill side holes (C), repeat 2-3				

talk to he shop staff about how to secure this part in the vise, you have a chance of potentially damaging the part due to its length and shape

SHEET 2 OF 2

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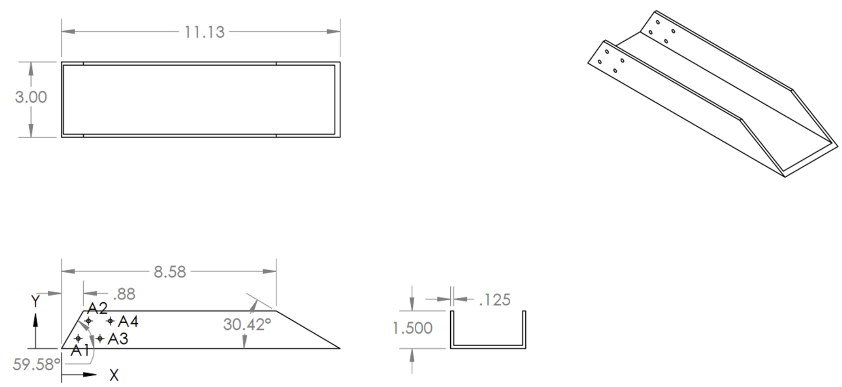
6. Support Bicep



TAG	X LOC	Y LOC	SIZE
A1	.670	.400	∅ .147 THRU ALL
A2	1.081	1.100	∅ .147 THRU ALL
A3	1.540	.400	∅ .147 THRU ALL
A4	1.951	1.100	∅ .147 THRU ALL

DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1 — INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009
MATERIAL: Aluminum 6061
FINISH: BURR FREE
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SGMAJORS	11/27/23
CHECKED	ETHENSLE	11/27/23
GSI/IA APPR.		
SHOP APPR.	KD F23	11/28/2023
INSPECTED		
COMMENTS:		

ME 450 TEAM 9

TITLE: SUPPORTBICEP

SIZE: A — DWG. NO.: P9_05 — REV: 01

SCALE: 1:4 — QUANTITY: 1 — SHEET 1 OF 2

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I would recommend doing this at the end, you won't be able to find your datum with the edge finder if you cut off the sides first

MANUFACTURING PLAN

RAW MATERIAL STOCK: 3" by 1.5" U channel, .125 thick

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	cut to rough length, 11.2"	horizontal bandsaw	vice		
2	bring part to length, 0.03" passes, 0.01" final pass	mill	vice	extended 3/4" endmill	500 ~~1000~~
3	cut to rough angles	vertical bandsaw	angle measurement (protractor, etc), pusher		
4	fix in vice for 30.42 degree face	mill	vice, angle blocks		
5	face part to length, 0.03" passes, 0.01" final pass	mill	vice	face mill	1000
6	repeat 4-5 for other angle				
7	orient to drill holes	mill	vice, parallels		
8	find datum	mill	vice	edgefinder	1000
9	center drill	mill	Vice, parallels	center drill #2	1200
10	Drill hole	mill	Vice, parallels	#26 drill bit	1500 ~~1000~~
11	repeat 8-9 for other holes				
12	remove, deburr			deburring tools	

talk to the shop about how best to secure these parts in the vise, as it is now it has a slight bend risk.

SHEET 2 OF 2

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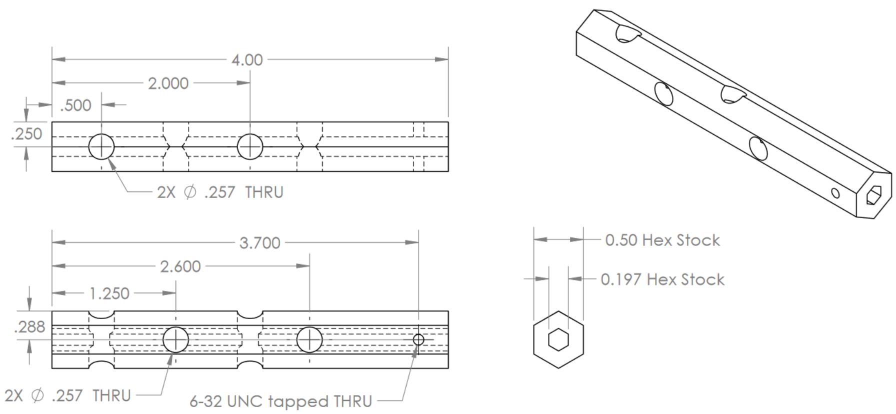
7. Wrist Rod



DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1 — INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL: Aluminum 6061

FINISH: BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SGMAJORS	11/27/23
CHECKED	ETHENSLE	11/27/23
GSI/IA APPR.		
SHOP APPR.	KD F23	
INSPECTED	11/28/2023	
COMMENTS:		

ME 450 TEAM 9

TITLE: WRIST ROD

SIZE: A | DWG. NO.: P9_04 | REV: 01

SCALE: 1:1 | QUANTITY: 1 | SHEET 1 OF 2

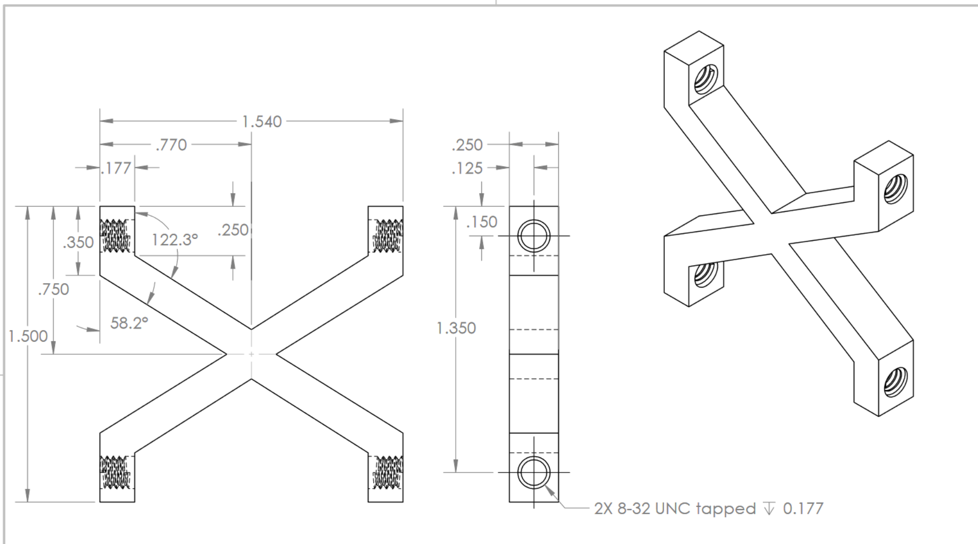
MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/2" Thunderhex, 5mm inner hex

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock to 4 1/8"	Horizontal Bandsaw	vice		
2	Clamp in vice, possibly use axle fixture	Mill	Vice, axle fixture		
3	bring part to length, 0.03" passes, 0.01" final pass	mill	vice	endmill	1000
4	find datum	mill	vice	edgefinder	1000
5	center drill top hole	mill	Vice, parallels	center drill #2	1200
6	Drill hole	mill	Vice, parallels	#F drill bit	1000
7	repeat 5-6 for other top hole				
8	remove, rotate, and clamp in vice with axle fixture to drill side holes	mill	vice		
9	find datum	mill	vice	edgefinder	1000
10	center drill	mill	Vice, parallels	center drill #2	1200
11	Drill hole	mill	Vice, parallels	#F drill bit	1000
12	repeat 10-11 for other top hole				
13	center drill set screw hole	mill	Vice, parallels	center drill #1	1200
14	Drill set screw hole	mill	Vice, parallels	#36 drill bit	1600 ~~1000~~
15	tap set screw hole	mill	Vice, parallels	6-32 tap	hand
16	remove, deburr			deburring tool	

SHEET 2 OF 2

8. XBrace



DRAWING & MANUF. PLAN CHECKS:
- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1 | INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009
MATERIAL: Aluminum 6061
FINISH: BURR FREE
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SGMAJORS	11/25/23
CHECKED	EVELYNSO	11/25/23
GSI/IA APPR.		
SHOP APPR.	KD F23	
INSPECTED	11/28/2023	
COMMENTS:		

ME 450 TEAM 9

TITLE: X BRACE

SIZE A | DWG. NO. P9_03 | REV 01

SCALE: 2:1 | QUANTITY: 2 | SHEET 1 OF 2

MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" AL PLATE

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Waterjet outer profile	Waterjet	Clamps		
2	Clamp into mill, find datum	Mill	Vise, parallels	edgefinder	1000
3	center drill	mill	Vise, parallels	center drill #2	1200
4	Drill hole	mill	Vise, parallels	#29 drill bit	1500
5	tap hole	mill	Vise, parallels	8-32 tap	hand
6	repeat 3-5 for other hole				
7	flip and repeat 2-6 for other side				

SHEET 2 OF 2

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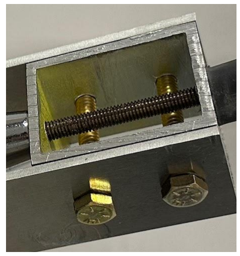
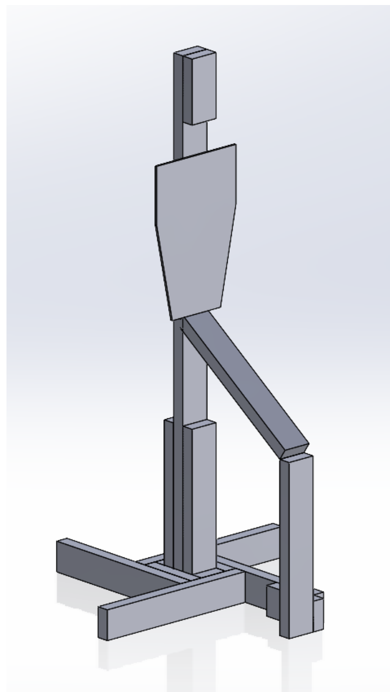
9. Foil Attachment

a. Using 1.54” x 1.5” aluminum stock, cut it to 1.5” of length using a bandsaw and debur
b. Using a hand drill, drill four holes into the foil attachment that can fit a 0.25 through screw
c. Bolt foil to the attachment



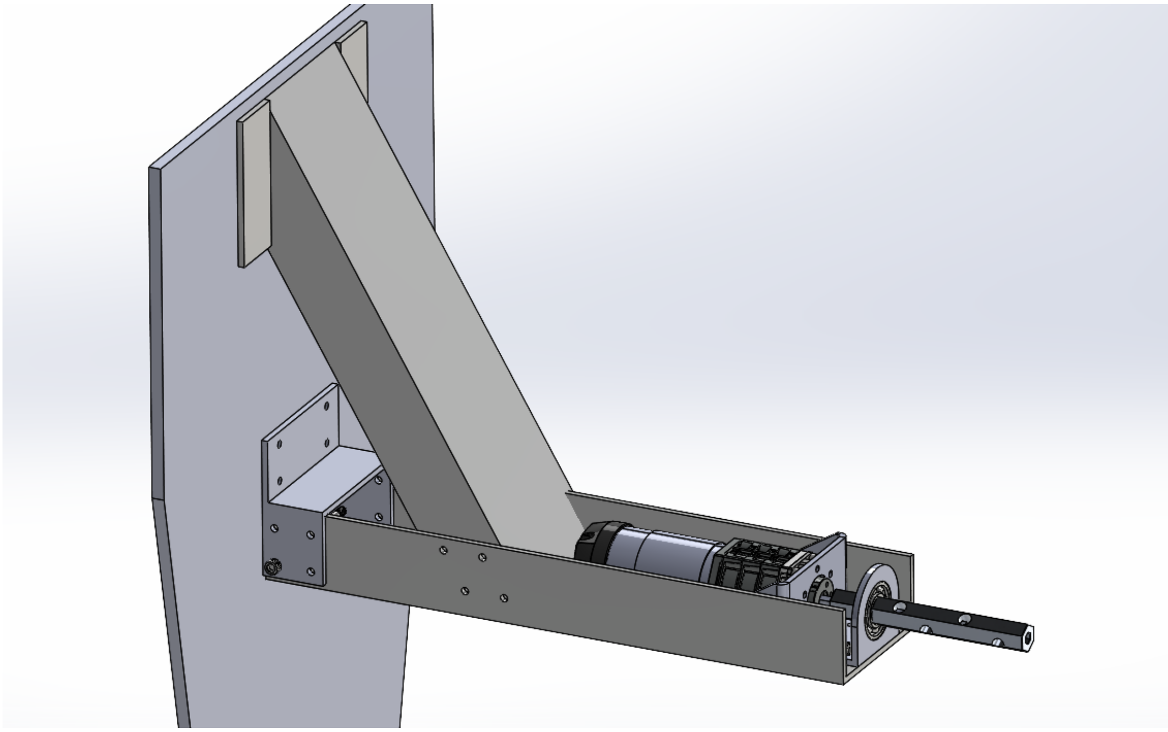
Detailed Fabrication Plan
Target:

1. The team would recommend starting with the base first. To assemble the base, first lay out the 4 2x4s, the 4 L spacers which make up the base in the format that is detailed in this picture. This will be the desired result.



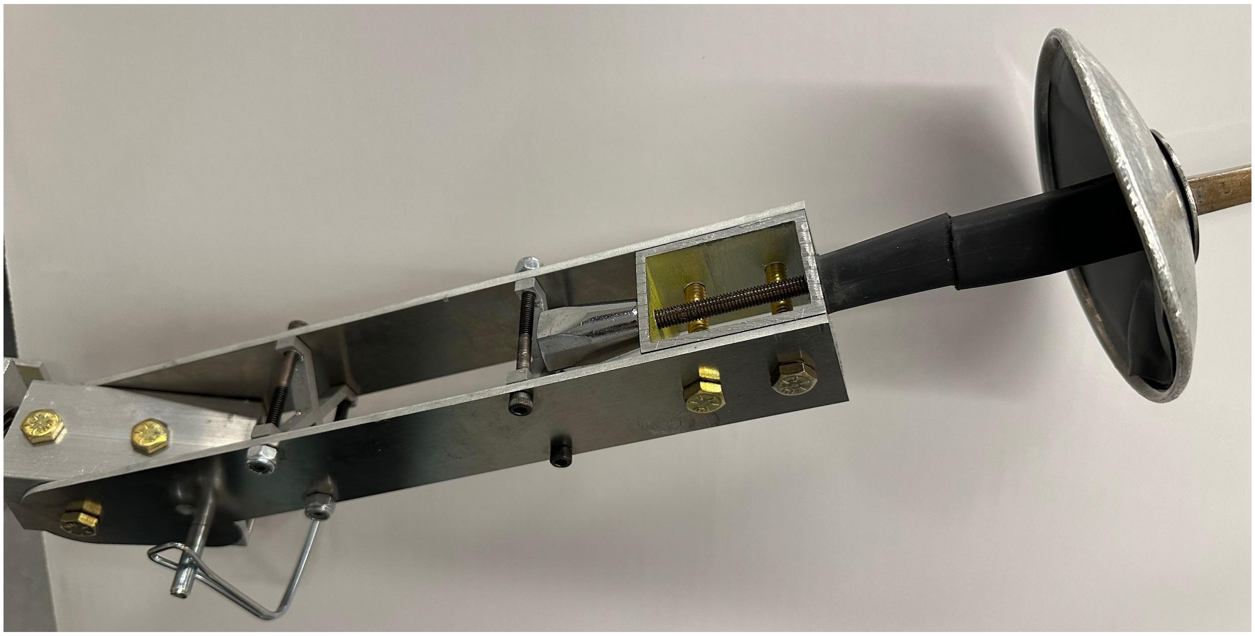
2. The team would recommend that two or three people are present when assembling the base. The first person would be drilling the holes using a drill and a bit which accommodates the wood screws present on the Bill of Materials
3. Using the picture as a reference, take two of the 4 2x4s and place them next to each other perpendicularly. This will be a frame of reference for you to place the rest of the materials needed such as demonstrated in the picture. Note that there is one spacer that isn't going to be in the base. This will be added later.
4. Drill each of the parts into place using the selected drill, drill bit and wood screw
5. Put the target vertical and 2 2x4s next to one another and drill them together. Note, when drilling these together, both sides should not be drilled. Only drill one side so that the target vertical can slot into the base and one can use the drill and screws to structurally support the target vertical
6. Drill one of the S spacers at the end of one of the base extensions. This will serve as the first part of the 'leg'.
7. Drill one of the long 2x4s up at the end of one of the base extensions next to the S spacer.
8. Diagonally check how long one of the 2x4s are and see if it fits nicely such as in the picture.
9. If not, one can cut it to length so that it diagonally fits and is easy to drill
10. Drill the 2 2x4s together so that it looks like the figure
11. At the top of that 2x4, drill the plywood torso in.

Bicep:



1. Drill the chair bracket to the plywood backing as shown. Use pilot holes instead of normal drilling so that the plywood doesn't crack.
2. Put the lower bicep on and see if it fits
3. If it does, start joining together the chair bracket and the lower bicep together using the nuts and bolts.
4. When it is fastened, put the upper bicep on and match it to the hole
5. Drill a hole through the upper bicep as shown
6. Drill the upper bicep to the plywood backing
7. Place the bearing mount on the correct holes at the front of the motor
8. Press fit the bearing into the bearing mount

Forearm:



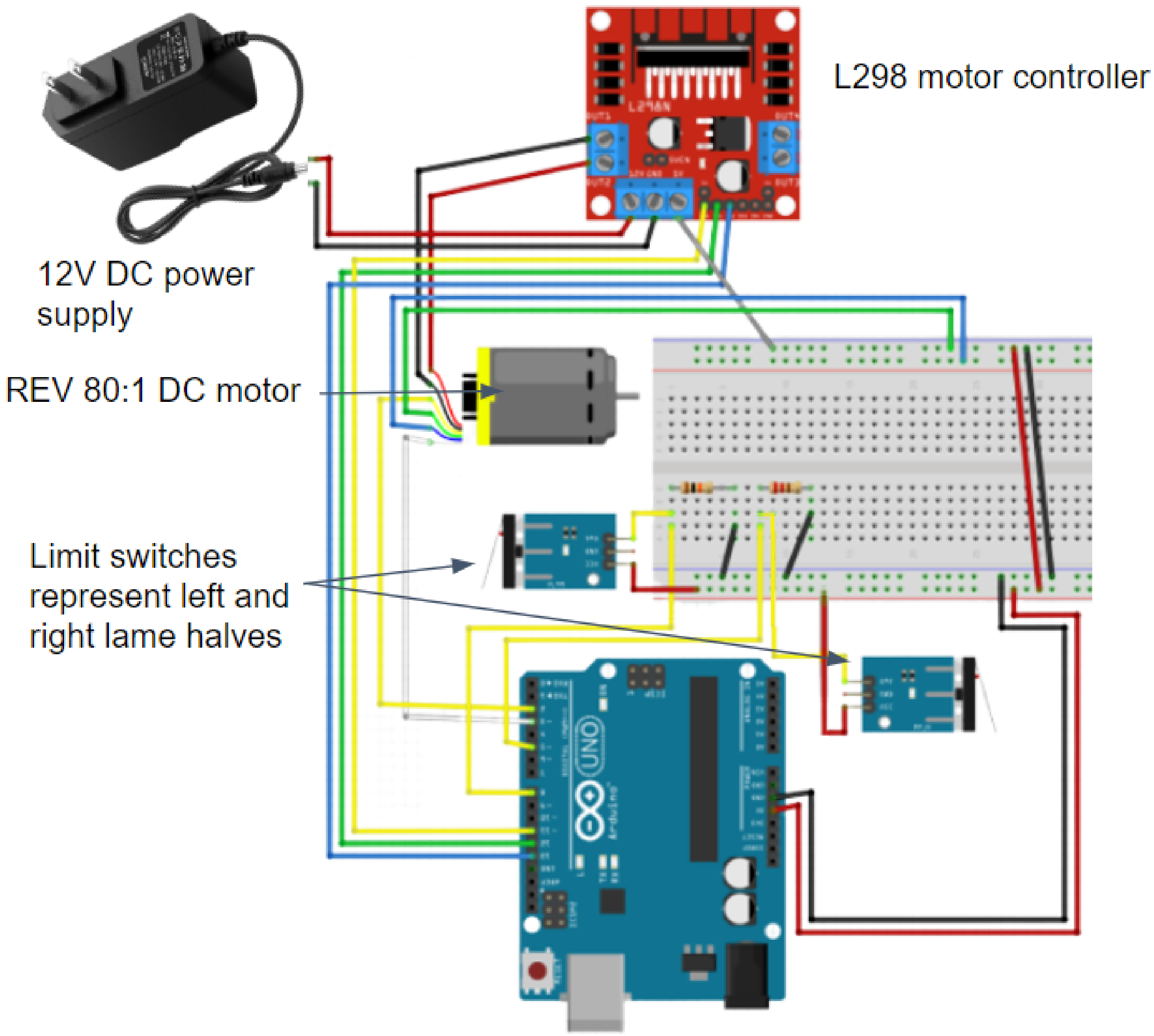
1. Using nuts and bolts, fit the x brackets into one of the two portions of the forearm
2. Fit the the other portion onto the x-brackets and using nuts and bolts, join them together
3. Join the foil attachment on to the top of the forearm
4. Join the pin and hole and elbow mount at the bottom of the forearm using screws

Motor Assembly:

1. Screw the gearboxes on the motor together with the 4:1 first, the 4:1 second and the 5:1 finally
2. Fit the hex shaft into the motor
3. Put the motor into into the bicep
4. Attach forearm to the motor

Arduino and Power Supply Setup:

1. Using this starter code, upload it to the Arduino board
2. Wire the power supply and put it into the Arduino and breadboard
3. Thread the wire through the bicep support and attach it to the breadboard
4. Press the run button on the Arduino program
5. Run the power supply.



APPENDIX C. ANALYSIS OF CHALLENGES

Our goal is to provide a high quality engineering solution capable of simulating fencing exercises for students to practice simple parry drills within the semester timeline. Designing a system to meet all of the specified requirements, especially simulating fencing drills, ensuring user adaptability, implementing hit detection, and designing a stable, durable, and aesthetically presentable system, can be an extremely complex and time-consuming process. Developing and fine-tuning the mechanical, electronic, and software components to achieve these goals within a short time frame is challenging. There are four main overall project anticipated challenges our team will need to face are prototyping and iteration, coordination of multiple disciplines, sourcing components and materials and integration of complex systems. The three main elbow joint specific anticipated challenges are durability, torque loads and safety of pinch points.

Prototyping and Iteration

Developing a functional prototype often necessitates multiple rounds of refinement and testing. Safety takes on particular importance due to the diverse range of users, including those without specialized training, such as children, who will be interacting with it. Ensuring that the dummy accurately mimics fencing movements while upholding safety standards demands extensive testing, which can be time-consuming.

To effectively address these challenges, a well-structured project plan with clearly defined milestones becomes crucial. This ensures sufficient time allocation and preparedness for each phase of development. Additionally, implementing Modular Development, which breaks the project into smaller, assessable components or modules, facilitates iterative testing of individual elements, eliminating the need to wait for the entire project to be completed.

Coordination of Multiple Disciplines

Designing such a system requires expertise in mechanical engineering, electronics, software development, biomechanics and shop machinery (prototyping). Learning and coordinating the efforts of these specialized skills on a short timeline can be challenging.

Figure 53: Multidisciplinary expertise needed to design fencing dummy.

To overcome these challenges, the roles and responsibilities of each team member need to be clearly delineated. This clarity helps prevent duplication of effort and ensures accountability. Additionally, open lines of communication need to be maintained among team members. Holding regular progress meetings to discuss achievements, challenges, and roadblocks fosters collaboration, allows for timely issue resolution, and keeps everyone informed about the project's status. Lastly, thorough documentation is indispensable for tracking project progress and ensuring continuity (document design decisions, software code, mechanical specifications, and test results). This documentation not only aids in knowledge sharing but also serves as a valuable reference for future iterations or improvements. By combining the diverse expertise of the team members with effective project management strategies, the complexities of designing this intricate system can be navigated while adhering to the tight timeline.

Sourcing Components and Materials

Finding and sourcing the necessary components and materials that fit within the budget and are readily available can be time-consuming. Delays in procurement can have a significant impact on the overall project timeline.

Before initiating the procurement process, a comprehensive build and testing plan that outlines all the necessary components and materials needs to be developed. This plan should specify the quantity, specifications, and sourcing requirements for each item. Having a well-thought-out plan ensures that there is a clear understanding of what is needed, reducing the chances of overlooking critical items. Setting up a procurement schedule that aligns with the project timeline is important. Be sure to factor in lead times for items that may have longer delivery times or are custom-made. Clearly specify the materials and machinery required for the project in the build plan. This not only helps in the procurement process but also ensures that the right components are selected. It can prevent costly mistakes or delays caused by incorrect or incompatible materials. Detailed engineering drawings can serve as a valuable reference during the procurement process. These drawings should include precise dimensions, tolerances, and material specifications. Moreover, utilizing reputable suppliers or online marketplaces that offer a wide range of components and materials is beneficial. Websites like McMaster-Carr are known for their extensive inventory and user-friendly ordering systems. Ordering from a single source can simplify the procurement process, as you can consolidate orders and potentially benefit from bulk discounts or reduced shipping costs. Whenever possible, arrange for components to be shipped all at once rather than in multiple shipments. Consolidating shipments reduces the risk of partial deliveries and simplifies inventory management. It also minimizes the potential for delays caused by missing or late-arriving components. By following these solutions, the procurement process can be streamlined, delays mitigated, and a better control over the project timeline can be maintained.

Integration of Complex Systems

Integrating arm and wrist articulation, hit detection, autonomous controls, and power supply into a cohesive system while meeting safety and durability requirements is a complex task. Troubleshooting and fine-tuning these integrated systems can extend the development timeline.

To surmount these hurdles, the functions and requirements of each component need to be thoroughly understood. This includes arm and wrist articulation mechanisms, hit detection sensors, autonomous control systems, and power supply units. Secondly, how these components interface with each other needs to be analyzed (identify the data flows and dependencies between them). A comprehensive system analysis will help to grasp the intricacies of integration. Thirdly, employment of rapid prototyping techniques to create simplified versions of the integrated system allows for adjustments and refinements before committing to a full-scale build. These prototypes should serve as a quick way to test the feasibility of integration and uncover potential challenges. Lastly, an incremental integration approach should be adopted. Begin by integrating and testing one component or module at a time. This step-by-step approach allows for continuous validation and reduces the risk of bottlenecks or unforeseen issues. These strategies promote a structured and controlled approach to integration, reducing the likelihood of unforeseen delays and ensuring that the final product meets safety and durability requirements.

Durability of Elbow Joint

When considering the difficulties related to the elbow joint mechanism, the primary concern is its ability to withstand the forces exerted during user parries. It necessitates the execution of rigorous strength calculations that encompass all aspects of the joint's mechanics and materials. A crucial component of this solution is the incorporation of a safety factor, which acts as a buffer or margin of safety to account for uncertainties, unexpected variations in usage, and other unforeseen factors.

Torque Loads

An expected hurdle lies in the substantial torque demands imposed on the elbow joint, primarily originating from the fast and strong wrist and arm requirements modeled after human capabilities. As our team intends to employ a gear transmission system, meticulous attention must be dedicated to gear sizing, and the inclusion of a counterweight may prove beneficial in counterbalancing the significant loads associated with both the fencing foil and weight of the humanoid arm.

Safety of Pinch Points

Owing to safety considerations related to the system's use by children and untrained individuals, the issue of potential pinch points within the joints is a cause for concern. To address this, a solution involves enclosing the moving components within protective housings or equipping the joints with flexible barriers to prevent the possibility of injury to small fingers.

By implementing these solutions, we can navigate the complexities, streamline the development process, and achieve our goal of delivering a safe, durable, and functional fencing simulation system within our timeline.

APPENDIX D. PROJECT TIMELINE

We employed a Gantt chart (seen in Fig. 50 below) to formulate a semester-long schedule, which outlined design review deadlines and meticulously laid out the various steps in the design process. Stakeholder meetings and testing are both integrated throughout to assess the effectiveness of the engineering solution. Each task is allocated a task owner to ensure timely completion and proper accountability. While this plan was initially projected to extend until mid-December, it is expected that modifications will be necessary as we collaborate with stakeholders to ensure that project objectives remain aligned with specifications and requirements during both the design and redesign phases.

			DR 1									DR 2						
WBS NUMBER	TASK TITLE	Task Owner	T	W	R	T	W	R	T	W	R	T	W	R	T	W	R	T
			5	6	7	12	13	14	19	20	21	26	27	28	3	4	5	10
1	First Meeting																	
	Meeting with Sponsor	Evelyn Sorgenfrei																
	Requirements & Specifications	Alexander Elan Constantino																
	Background Info	Evelyn Sorgenfrei																
	Assess Challenges	Ethan Hensley																
	Meeting with Coach Ian	Steven Majors																
2	DR 1	Evelyn Sorgenfrei																
	DR 1 Report	Steven Majors																
	Requirement Refinement	Alexander Elan Constantino																
	Information Gathering	Alexander Elan Constantino																
	Ideation	Steven Majors																
	Scope Reduction	Ethan Hensley																
	Concept Selection	Evelyn Sorgenfrei																
	Concept Iteration	Ethan Hensley																
	Final Concept Selection	Steven Majors																
	Engineering Analysis (FBD)	Ethan Hensley																
	CAD Prototyping (Basic with Actuator)	Alexander Elan Constantino																
3	DR 2	Ethan Hensley																
	DR 2 Report	Evelyn Sorgenfrei																
	Torque and Range of Motion Calculations	Ethan Hensley																
	Analysis of Bio-kinematics	Evelyn Sorgenfrei																
	Concept Iteration	Steven Majors																
	CAD Prototyping (Hardware Components)	Ethan Hensley																
	CAD Prototyping (Hardware + Electrical)	Alexander Elan Constantino																
	Build Plan	Alexander Elan Constantino																
	Gathering Materials	Steven Majors																
	Physical Prototyping	Ethan Hensley																
	Experimental Testing	Evelyn Sorgenfrei																
	Testing with Coach Ian	Ethan Hensley																
	Iteration(?)	Alexander Elan Constantino																
4	DR 3	Steven Majors																
	DR 3 Report	Ethan Hensley																
	Design Expo Poster	Steven Majors																
	Gathering Materials	Steven Majors																
	Construction/Prototyping	Ethan Hensley																
	Experimental Testing	Evelyn Sorgenfrei																
	Iteration	Alexander Elan Constantino																
	Verification	Steven Majors																
	Validation	Alexander Elan Constantino																
5	Final Poster Presentation	Evelyn Sorgenfrei																
	Final Report	Ethan Hensley																

		DR 3															Final											
TASK TITLE	Task Owner	W	R	T	W	R	T	W	R	T	W	R	T	W	R	T	W	R	T	W	R	T	W	R	T	W	R	T
		11	12	17	18	19	24	25	26	31	1	2	7	8	9	14	15	16	21	22	23	28	29	30	5	6	7	12
First Meeting																												
Meeting with Sponsor	Evelyn Sorgenfrei																											
Requirements & Specifications	Alexander Elan Constantino																											
Background Info	Evelyn Sorgenfrei																											
Assess Challenges	Ethan Hensley																											
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Verification	Steven Majors																											
Validation	Alexander Elan Constantino																											
Final Poster Presentation	Evelyn Sorgenfrei																											
Final Report	Ethan Hensley																											

Figure 54: Gantt chart schedule with the design process scope. The project spans from September 5th (first meeting and project assignment) until December 12 when the final report is due.

Furthermore, we created Table 12 to outline our more specific, future plans for manufacturing, assembly, and verification.

Table 12: A list of assigned responsibilities and completion dates.

Completion Date	Task	Person Assigned
11/21	Purchase wood for target	Ethan
11/26	Design problem portion of expo poster	Alex
11/26	Design Concept portion of expo poster	Evelyn
11/26	Design process/ context portion of expo poster	Steven
11/26	Requirements and Specifications portion of expo poster	Alex
11/26	Analysis, Verification, Validation portion of expo poster	Ethan
11/27	Cut out target body from plywood	Steven
11/27	Finish Engineering drawing, safety sheets, manufacturing plan etc	Steven
11/28	Screw together and assemble wood target	Evelyn
11/28	Assemble Mcmaster parts, brackets, and motor	Alex
11/28	Submit engineering drawings to be waterjetted	Steven
11/28	Mill out holes and unnecessary material	Ethan
11/28	Begin experimenting with arduino code on motor	Steven
11/28	Assemble arm components	Alex
11/28	Finalize expo poster	Everyone
11/29	Attach arm to target stand with brackets	Evelyn
11/29	Test and finalize Arduino code	Steven
11/29	Final testing of design before expo	Everyone
11/30	Design Expo	Everyone
12/7	Design validation	Everyone
12/12	Final report	Everyone

Ultimately the person assigned to the task is subjective and we plan to help each other so that no one facet of our project falls behind. Considering that we have received all of our shipped parts, I suspect one of the few challenges we may face will be manufacturing our own custom parts in time. In order to ensure that we are effective within our time constraints, we plan to complete and submit the engineering drawings and build plan early so that we can correct any errors should they arise, and manufacture our parts within a timely manner.