Haptic Robot

Final Report

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DISCLAIMER

EXECUTIVE SUMMARY

The Haptic Robot capstone project focuses on the analysis, development, and modeling of a three-degrees-of-freedom haptic rendering robot that is utilized to aid in the rehabilitation of stroke patients with minor nerve-damaged tissues. The design provides 3D motion while maintaining the important client requirements of lightweight, stiffness, and speed. The team generated conceptual models based on the technical methods that helped the team narrow the possible designs to be considered in moving forward with the project development. As the final design is concluded based on the QFD results, the team established an effective layout plan for the second semester's manufacturing and design completion. The team utilized multiple resources to build the product while implementing design iterations to meet client and engineering requirements. After completing the milestones set by the team in the early stages of the project development, the final design shows efficient and optimized results based on the project requirements set by the client.

ACKNOWLEDGEMENTS

The haptic robot team would like to thank our client Dr. Razavian for sponsoring the team's project and allowing access to the robotic lab for the team to work and store the haptic feedback robot. We would also like to thank our instructor Dr. Willey for giving the team guidance and constructive feedback along the way. The haptic robot team also wants to say thank you to Dr. Wood and the machine shop staff for helping us produce all our machined parts and providing tools for the team to work.

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1 BACKGROUND

1.1 Introduction

Haptic technology has been very effective in many different industries such as the medical field which provides rehabilitation aid for post-stroke patients. Our team is assigned to the haptic robot project which is to be developed from scratch as a new original design. The important objective is to develop a robot that is mechanically capable of 3-dimensional movement as well as being lightweight and easy to control providing haptic feedback to the user. Dr. Reza is the sponsor of the project as well as the client, and he is interested in developing the robot mechanically adding an AI control system for the robot is the end goal for future development. Upon completion of the project, the robot will be used in various ways and will be ready to be used for rehabilitation centers for any patients with nerve system disabilities/weakness. The scope of the design is focused heavily on developing a model that is safe, quick-moving, lightweight, and has rehabilitative capabilities. Research of stoke patient exercises as well as current existing robots will help the team formulate a prototype by the end of the semester and have a strong model before building the actual product.

1.2 Project Description

Following is the original project description provided by the sponsor. “Haptic rendering, or force feedback, is the use of a robotic interface to provide touch sensation about a virtual environment to a user. The applications of haptic rendering are diverse; for instance, an operator can remotely manipulate objects via a robotic avatar while receiving a sense of touch from the manipulated object. Another important application of haptic robots is in neuromuscular rehabilitation, where safe and reliable force modulation by a robot has been shown to accelerate recovery. However, despite vast areas of application, the development of a robotic interface to reliably and accurately "render a haptic scene" has remained a major engineering challenge.

For haptic rendering applications, an ideal robot should have a very high bandwidth, which leads to contradictory design requirements. On the one hand, the robot should have low inertia (to be able to move fast), and on the other hand, exhibit high mechanical stiffness (which makes it heavy). The motors that drive the robot must also be low inertia with low electrical impedance while exhibiting high torque. Aside from these hardware requirements, significant control challenges must be addressed as well. The feedback control gains should be set as high as possible to increase the bandwidth of the system (i.e., being able to simulate a "crisp" contact and touch as opposed to a "soft" touch). However, feedback delays, quantization in sensor readings, and noise can destabilize the system, limiting the admissible feedback gains, and thereby degrading the quality of haptic rendering. Because of all these challenges, high-quality haptic robots are still too expensive (>$50k) to be widely available for most applications.
The goal of this project is to design a haptic robot that addresses some of the challenges mentioned above. A good starting point is to examine an existing open-source design (WoodenHaptics). This robot is a small 3D haptic robot designed for expert engineers and non-expert enthusiasts. The basic design has a working space of approximately 20 cm (sphere diameter) and a force capacity of ~10 N. These specifications of the robot, although sufficient for small applications such as telemanipulation, are limited for more demanding biomedical

applications such as rehabilitation robots. A capable rehabilitation robot needs to have >50 cm workspace (comparable to human reach) and >20 N force capacity. An example of such a robot is WAM® by Barret Technology with a price tag of +$75k. However, even the WAM robot suffers from suboptimal haptic rendering performance, mostly due to the slow controller update rate (~1.8 kHz) caused by its aged technology.

This project aims to design the next generation of open-source haptic robots, capable of providing high-quality haptic rendering, without sacrificing force capacity, workspace size, and control performance. In addition to the series two-link robot design (as in both examples), parallel mechanisms, cable-driven, or perpendicular sliding joints may be considered. The following are the design requirements.

Mechanical

- Move-in 3D
- Workspace larger than a sphere of 50 cm diameter
- Uniform continuous force capacity >20 N in all directions
- Low inertia
- High mechanical stiffness
- Low friction (high back-drivability)
- Zero backlash (no "play")
- Cost-effective and easily reproducible design

Electromechanical

- High bandwidth in power electronics (>10kHz)
- Low motor inertia
- Cost-effective components

Controller/Software

- High-resolution sensing
- Low-latency communications (<100 us)
- Fast update rate (>5 kHz, ideally 10 kHz)
- Cost-effective components

Estimated Costs

- Three actuators + power electronics, ~$500 each: ~$1500
- Three optical encoders, ~$100 each: ~$300
- Data acquisition card: ~$700-$1500
- Mechanical hardware, prototyping, and/or machining: ~$1000
- Optional additions:
- NI CompacRio controller $8000-$15000
- High-quality IMU: guesstimate ~$1000
- Force sensor: ~$8000

2 REQUIREMENTS

Project requirements are set by Dr. Reza Razavian to develop a lightweight robotic arm with three degrees of freedom to be used for patient rehabilitation with motor skill impairments. For the project, the team has taken into consideration customer requirements and the engineering requirements of the project. Some of the customer requirements have been translated into engineering requirements so that the team can set specific goals the final design must meet. The specific customer requirements are listed below and are rated based on what the team and client agree is most important, with a rating of 5, to least important, a rating of 1. The engineering requirements are listed further down and are equally important. They have specific goals to be met that are calculable for efficient evaluation of the design.

2.1 Customer Requirements (CRs)

CR1: Lightweight- 5

The robot must be relatively lightweight so that the arm can move quickly with ease. This is more to decrease the moment of inertia from any movement. Links/arms being lightweight will help maintain the structural integrity of the robot and enable it to move fast with ease.

CR2: User Friendly- 3

For the robot to be effective it must be easy to use. This entails safety as well as simplicity for the user to gain rehabilitative benefits. The robot will use minimum parts/outer casing to reduce pinch points and other potential harm that could be caused by the robot moving. The handle will be a sphere or a different ergonomic design, so the user is comfortable.

CR3: Stiff- 5

Depending on how the robot links are designed, the material needs to be stiff standing. It must not move easily from being pushed or wobbled. Between the material properties and the link connections, the robot must be locked in place unless it is intentionally moving. Notably, motors must have a higher torque rather than only a high RPM for this to be achieved.

CR4: Accurate- 4

Motors need to be able to have a program work in tandem with their controllers so that they can move the handle to any point in space required. 3 degrees of freedom are required for this to be achieved, which means there must be a minimum of 3 motors. The motors and controllers must be high quality enough to have superior accuracy.

CR5: 3D Motion- 5

Similar to stiffness depending on the design of the links, flawless motion requires a unique design so that there is minimalized friction within the mechanical system. Gears can cause friction, depending on type, quality, and size. Looking into other subsystems to turn links in a degree of motion may prove useful in meeting this requirement. Machining parts so that they do not overlap is also important to lower friction, as well as fastening pieces tight.

CR6: Reduced Backlash- 5
Gears are known for causing backlash since making them mesh perfectly is almost impossible. Not only do gears wear down over time, but they also need to be lined up in points in 3D space with each other to maximize efficiency. It may prove difficult to purchase gears that increase torque and do not cause backlash, even over time.

CR7: Reduced Friction- 4
To have flawless motion, there needs to be little to no friction, so gears are yet again difficult to use and satisfy this requirement. Limit friction means maximizing the power output and speed response with the robot. If the arm is moving from rest, having no friction between parts will also make it more user-friendly so the force required to move the robot is more accurate to the desired setting.

CR8: End Effector- 5
The arm of the robot will hold the handle at the end and needs to be able to replicate a physical therapy exercise. This is the haptic rendering feature of the robot, where it can respond to force input and give a resistance output. Electrical energy needs to be turned into mechanical energy at the motors, then transmitted through the arms to the user, so the energy the user experiences needs to be a reasonable force.

2.2 Engineering Requirements (ERs)

Decrease Link Weight - 1
Target goal: < 7 lbs ± 0.5
The client requires the finalized product to be lightweight, at least the robotic part. The base of the robot will hold the most weight so that the moment of inertia will not cause the robot to tip over and fall. This is why there is a weight limit of 50 lbs.; so that the robot is light enough to relocate if needed, but heavy enough to resist tipping while the robot arm is moving.

Factor of Safety - 2
Target goal: 1.5 - 2 ± 0.01
Material strength is important for the robot to last rough usage over time. A higher material strength provides resilience against such usage permanently damaging the robot, so tough motors as well as strong housing for the robot's components are important.

End-effector Force - 3
Target goal: > 20 N ± 0.01
The robotic arm must produce a maximum force of around 20 N to have capabilities of therapeutic value. With an average finger push being around a Newton, our client has instructed us that 20 newtons will be enough for physical therapy purposes. This requirement is a minimum, so we can likely design the robot to produce more force.

Reduce Torque Resistance - 4
Target goal: < 1 N ± 0.01
The robot must be able to move freely with minimized friction to prevent wasted energy and speed reduction. This will be accomplished by not using gear systems (unless necessary) as well as having the fewest moving parts possible. Using a pulley design will reduce the backlash as well as the friction that is caused by torque resistance and bearing rotation.

End-effector Speed - 5
Target goal: > 1m/s ± 0.01
Speed and accuracy go hand in hand between customer and engineering requirements. The team must design a robot with an arm that can move at a minimum of 1 m/s speed to an accurate position in 3D space. This requires a superior controller for the motors as well as a coordinated program to maximize robot usage.

Max Rated Power - 6
Target goal: > 100W ± 0.5
With the requirement of having 3 degrees of freedom, our design will use 3 different motors. This will require a lot of power, along with the controllers for each motor. With this engineering requirement, the team is ensuring the use of a mechanical system that is powerful enough to meet other requirements such as the output force of 20 N.

2.3 Functional Decomposition

To have a solid understanding of the conceptual generation and selection, the team established a Black Box Model along with a functional decomposition that goes into detail about how the model of the project works. The Black Box Model is the larger idea of the robot's main systems as inputs and outputs, and it is essentially a basic model showing visually how energy, material, and signal are the inputs and showing what is produced because of that as outputs. Furthermore, the functional decomposition of the Black Box Model is shown on a work diagram that explains what every input produces and what kind of energy respectively.

2.3.1 Black Box Model

The Black Box Model (BBM) represents the inputs and outputs of the haptic robot by going into general detail about the energies, materials, and signals. The input and output in the black box will be the same on both sides. The left side starts with energy that will be inputted through a battery that can then be turned on by a human. This results in kinetic energy, potential energy, and thermal energy through the movement of the robot. The next input would be material which would include hand and air. This will result in the same output as the material does not change with the robot's motion. The last input would be the signal, this would mainly include the controller and its sensors and motors. The output for the signal would allow for haptic feedback from the robot. With the BBM completed shown below the team will be able to understand the general inputs and outputs that will then be analyzed in detail through a functional model.

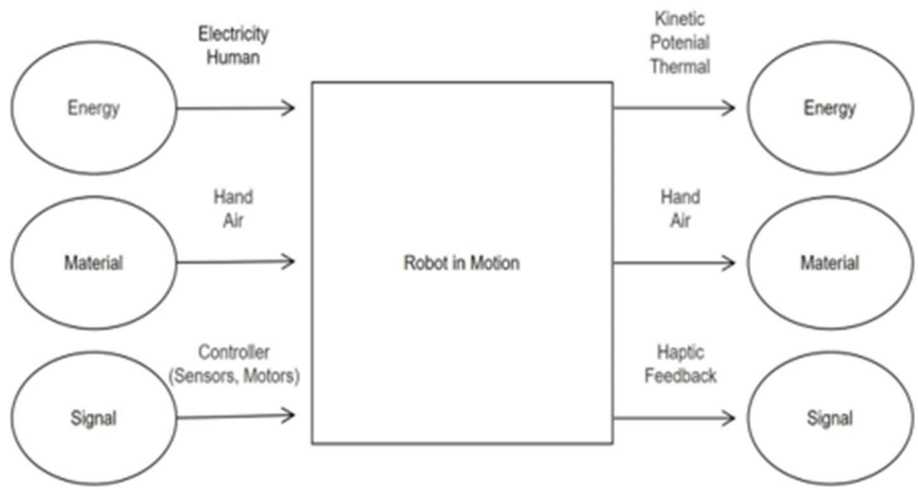


Figure 1: Black Box Model

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The functional model is a detailed structured representation of the functions within the modeled system of the black box model. The functional model below represents each sub-system of the team's final design. Starting with the electricity, it gets imported and is then the electrical energy can then be converted to rotational energy which will then go into the motor. The second is human where a human is imported into the system where they will apply electrical energy to also be converted into rotational energy. The next is a hand which is used to hold onto the handle which is connected to the second arm link of the robot. The last and probably the most technical part is the controller which will apply resistance to the motor that will then convert the rotational energy to the linear motion of the arm link. With the handle and the arm link the system will provide haptic feedback.

Overall, this functional model will aid the team during the project by allowing them to understand all the subsystem's inputs and outputs. The team will also be able to understand the process of function designs through the robot's motion. The model helps discover different possibilities of information that might be needed or identify changing opportunities.

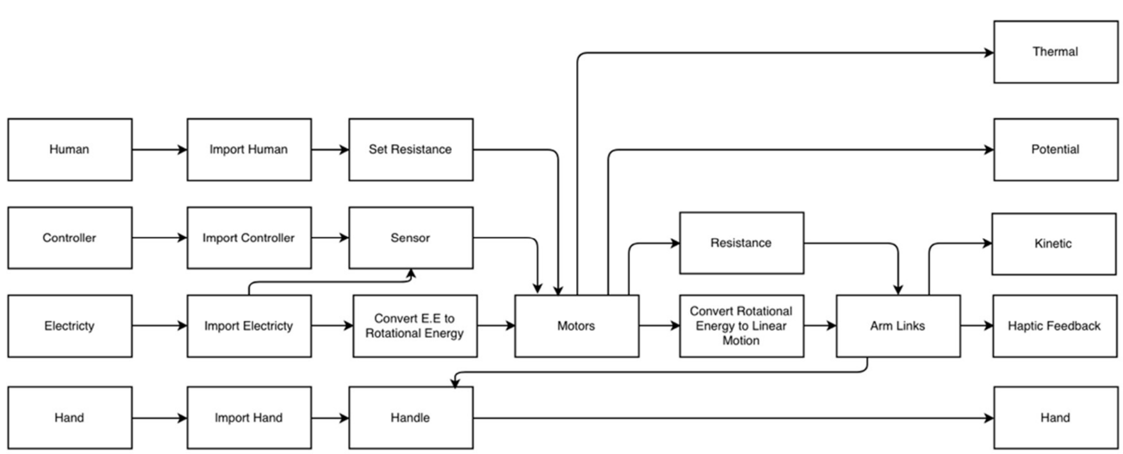


Figure 2: Functional Model

2.4 House of Quality (HoQ)

System QFD

		Decrease Link Weight	Factor of Safety	Force	Reduce Torque Resistance	Speed
1	Decrease Link Weight					
3	Factor of Safety	-3				
4	Force		9			
5	Reduce Torque Resistance	9		1		
6	Speed	9	-3	-9	9	
7	Max Rated Power	1		-9		-9

Legend		
A	Wooden Haptics	woode nhantic pen.co
B	HIRO II	
C	Haptx	haptx.c om/rob

	Customer Needs	Customer Weights	Decrease Link Weight	Factor of Safety	Force	Reduce Torque Resistance	Speed	Max Rated Power	1 Poor	2	3 Acceptable	4	5 Excellent
			Technical Requirements						**Customer Opinion Survey**				
1	Lightweight	5	9	9		1	9	1		C	B		A
2	Affordable	3		1				1	BC		A		
3	User Friendly	3	3			3	9						ABC
4	Stiff	5		9	3	1	3			A	B		C
5	Accurate	4	3			3	3	9			AB		C
6	3D Motion	5	3		1	9	9	3		B	A		C
7	No Backlash	5	9	3	3	3	9	1				AB	C
8	No Friction	4	9		9	9	9			B		A	C
9	End Effector	5	3	9	9	1	9	9	B		A		C
	Technical Requirement Units		lbs	NA	Newtons	Newtons	m/s	Watts					
	Technical Requirement Targets		50	1.5	20	1	1	100					
	Absolute Technical Importance		162	120	110	129	261	107					
	Relative Technical Importance		2	4	5	3	1	6					

Figure 3: QFD

The haptic robot team is aiming to meet all the customer requirements. Through the five tests, the team has planned to gain insight into the weight, backlash, force output, and range of motion, which will allow for adjustment in the design. Most importantly by meeting the customer requirements, the team will meet the engineering requirements such as decreasing weight, reducing torque resistance, meeting speed and force requirements, and obtaining the max rated power for the system. As shown in the attached QFD the team has placed weights to the level of importance for each engineering requirement and how they relate to the customer requirements. The client has also placed weights on the customer requirements to indicate what they place as the most important for the group to achieve. For a further breakdown, to see specifically how each engineering requirement relates to the customer requirements, refer to ***Figure 3.*** Each testing plan will test the corresponding requirements to ensure the team is meeting the goal of the project.

2.5 Standards, Codes, and Regulations

The team used the National Society of Professional Engineers (NSPE) Code of Ethics as a guide to ensure the design is within the limits of the established codes of ethics and to provide a safe, trustworthy, and appropriate design for the client. An important fundamental canon that is chosen to be an essential code in the team's design according to the NSPE is to "Act for each employee or client as faithful agents or trustees" [1]. Every step that the team has taken in the development of the design has been thoroughly discussed and presented to the client to ensure that the code of ethics mentioned is implemented during the design process. Another important code of ethics that is used as a guide by the team is from the NSPE Professional Obligations that states, "Engineers shall be guided in all their relations by the highest standards of honesty and integrity" [1] which applies to the team's efforts to have an original design plan that is based on team members knowledge and client and engineering requirements. In addition, using any external sources for guidance is always referenced and mentioned appropriately about the team's project.

Table 1: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
NSPE (I-4)	Fundamental Canons	Ensures that any work done in the project is discussed and approved by the client.
NSPE (III-1)	Professional Obligations	Used as a guide to provide quality work with original ideas that are based on honest efforts and high integrity

3 DESIGN SPACE RESEARCH

3.1 Literature Review

The following section provides the literature references that the team utilized to aid in the understanding, analysis, and development of the project. The main categories that the team focused on are related to the material, haptic rendering robotics, rehabilitation, degrees of freedom in robotic arms, and the relation of inertia on robotics arm to motor placement. The team compiled a rich combination of literature and benchmarking resources to be used as references in design calculations and development. Based on the research done, the team understood the market's existing products which helped in the ability to innovate, expand, and even reference some of the team's design components. The literature review was an essential design step in the team's ability to design the required properties of the robot.

3.2 Benchmarking

Previous to any concept generation for the project, the team committed to an appropriate amount of extensive research in the area of robotics, specifically motorized robotic arms. Based on the client requirements, the team considered the WoodenHaptics robot in ***Figure 4,*** to be the main inspiration for the development of the conceptual designs. There are various designs considered competitive carrying advanced technological parts; however, most of the products are heavier than the required weight for the team's design which concludes that the finalized design in this project will be more competitive in the market ensuring light equipment with the same and/or higher amount of accuracy of motion and stiffness.

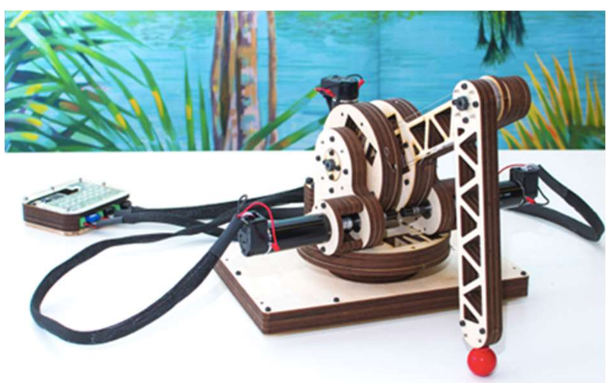


Figure 4: WoodenHaptics Robot

3.2.1 System-Level Benchmarking

Expanding on the benchmarking research, the team compiled three important existing designs that relate to the team's project. The following section presents the different models considered and how they're related to our design as well as a summary of the overall mechanism of each model.

3.2.1.1 Existing Design #1: WoodenHaptics

The following design is heavily related to the team's project based on the overall structure and the mechanical system it utilizes. Similar to the Wooden Haptics design, our robot must move with 3 degrees of freedom. Ours, however, must move more than Wooden Haptics because that design is limited by the mechanisms used to extend and retract the arm. Having 3 degrees of freedom and being able to move in 3D motion while remaining lightweight, this product is to be considered a strong reference that will inspire the project's development. One of the most important customer requirements for this project is to design a lightweight robot that can withstand a large amount of force. One of the toughest parts of the project is generating ideas for not only the placement of the motors but also how each link will be actuated while in use. The Wooden Haptics robot is our greatest inspiration for this project because of the unique pulley system it has. By using a pulley system, the team will be able to actuate each link of the robot while remaining relatively lightweight. There have been multiple discussions about the placement of the motors in the design and both the team and client feel placing a motor within the second link would reduce the speed and potentially the accuracy of the robot. There could also be some sort of backlash within the design if the third motor was in the second link, meaning that when the robot was not in use it could move after being let go. Having little to no backlash in the design is a very important customer requirement because it could potentially affect the accuracy of the robot. In the end, we have effectively used the cables between pullies as belt systems to meet our customer requirements.

3.2.1.2 Existing Design #2: Haptx

The Haptx design shown in ***Figure 5****,* is a complex version of the team's design, it carries advanced technology in the haptic feedback robotics. This design operates on sensor feedback to the user where the robot's arm movement is dependent on the user's hand movement. In this case, the robot is designed to operate in other fields of the industrial technology world where its precision can help the user perform delicate tasks such as picking up an object and moving it within the range of motion of the robot. Haptx robot isn't reliable for rehabilitation since the user isn't physically able to feel the force produced by the movement of the robot; however, due to its advanced operators, the team's design can be positively influenced by the conceptual design of this robot arm.

Figure 5: Haptx Robot

3.2.1.3 Existing Design #3: HIRO-II

The team's design will be actuated using motors supplying power to the joints which relates HIRO-II shown in ***Figure 6***, to the current model the team is working on. Having the same degrees of freedom, the HIRO-II robot is one of the most important benchmarks in the team's project. This robot interacts with the human by sensing the hand fingertips producing feedback to the user with the appropriate force.

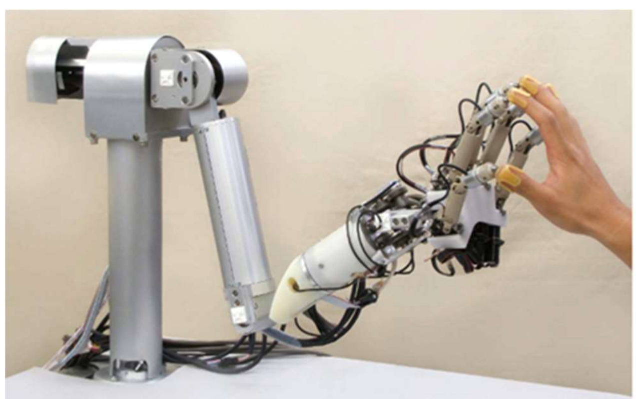


Figure 6: HIRO-II Robot

3.2.2 Subsystem Level Benchmarking

The following section contains the three different subsystems that are considered essential components in the development of robotic arms. It is important to consider these designs to compare with the team's design based on the criterion and weight of the technicalities. The subsystems that will be reviewed are the types of links, the types of handles, and the motor placements. These three subsystems are crucial to the team's design as they are the main systems that will provide an excellent user experience.

3.2.2.1 Subsystem #1: Links

The first subsystem to be introduced is the links of the robot and how they will be placed to maximize the performance of the robot. There are several different styles of robots on the market with different link systems that help the robot perform its tasks. The link system design is very important because it can affect how the robot performs as well as increase or decrease the weight of the robot. If the link system is bulky and gets in the way of itself, it can slow the robot down from completing tasks. With the accuracy and speed of the robot being some of the highest weighted customer requirements, it is important the link system is lightweight and helps the robot move flawlessly.

3.2.2.1.1 Existing Design #1: WoodenHaptics Robot

The WoodenHaptics robot has two links with a rotating base to ensure 3D movement for the user. Two links are attached to the base of the robot which allows the robot to move in any direction. The rotating base as well as the two links are cable-driven which allows for the robot to be extremely lightweight at the links. This ensures the motors to power the robot can remain at the base and still perform up to the user's standards. This robot's link system relates to our project because it aids in creating a lightweight design, with minimal backlash, and still allows for three degrees of freedom, all of which are customer requirements given by the team's client. The team will use this robot's link system as a means of inspiration with the hopes of implementing a pulley system into the design. The robot designed will differ from the WoodenHaptics robot as the team would like to hide the pulley system within the tubing used for the links [1].

3.2.2.1.2 Existing Design #2: Haptx Robot

The Haptx robot’s link system is very different from the WoodenHaptics robot. The Haptx design still has a rotating base with two links but there are motors within the joints connecting the links. This design is significantly more complex than that of the WoodenHaptics robot but relates more to the team's design as far as link placement goes. The team would like to implement a pulley system while keeping a design similar to the Haptx Robot. The robot being designed will have a rotating base with two links and joints similar to the Haptx Robot while implementing a pulley system to the design. The Haptx robot appears to be extremely heavy which may decrease the speed of the robot therefore the ream will use carbon fiber tubing as the material for the links. The Haptx robot will continue to provide insight to the team as the design process moves along allowing us to have a reference to look back to if we lack creativity during the design process [7].

3.2.2.1.3 Existing Design #3: HIRO-II Robot

The last and final existing design that is relative to this project is the Hiro-II Robot. The Hiro-II robot also has a rotating base with two links attached to it but builds from top to bottom rather than bottom to top. This means that the first link of the robot is roughly 300 mm from the stationary base of the robot. The links of this robot contain motors within them which will cause them to be heavier at the links. The team can implement the information from this design because the way the links are connected is completely different than the first two existing designs. The links are connected in a way that creates a relatively straight arm coming from the rotating base. This leaves less room for error and allows the robot to not get in the way of itself. This robot will be referenced during the design process as the team continues to decide how they would like their links to be placed within the design. [15]

3.2.2.2 Subsystem #2: Handles

The handle of an arm robot is considered an important component of a design simply because it is the first human-robot interaction. Handles vary in size, shape, and even purpose as some handles are designed to pick objects such as grips while other handles are designed to be held and moved by human body parts such as a hand.

3.2.2.2.1 Existing Design #1: WoodenHaptics Robot

As shown in ***Figure 4*** the handle of the WoodenHaptics robot is a simple design of a ball knob handle which indeed relates to the client's preference of the type of handle needed for the team's model. A ball knob handle isn't meant to aid the wrist nerve system specifically as much as it is effective in whole-hand motion. In other words, being able to have a strong grip on the handle aids in easier movement of the human hand as a whole-body part motion.

3.2.2.2.2 Existing Design #2: Haptx Robot

The Haptx robot handle motion and/or structure is different from the other two benchmark designs. The purpose of its handle is to perform operations without the physical involvement of the human interface. In this case, the handle doesn't serve the development of the team's model, but it is an advanced method in which the team can generate ideas in terms of the robot's sensors and control system feedback abilities.

3.2.2.2.3 Existing Design #3: HIRO-II Robot

In the third design of the benchmarking results, the handle used in the robot serves the purpose of interacting directly with the human hand. HIRO-II robotic arm is the closest to the team's design in terms of the end-effector/handle objective where it senses the human hand movement and gives appropriate feedback force to the user resulting in the aid of hand movement. However, the handle design of this robot is limited to the wrist interaction with the human while the team is focused on whole-hand interaction with the robot handle.

3.2.2.3 Subsystem #3: Motor Placement

In this project, many technical challenges affect the motion of the robot. One of these challenges is the motor placement and since the client has already provided two of the three motors needed to run the model, the team must establish a mechanical system capable of controlling the movement of the robot while being lightweight. The optimate solution is to place all motors in the base to ensure smooth movement; however, the connection of the links and motors is the challenge in this case. Below are descriptions of the motor placements of each of the benchmark products that are considered to be the top designs for the team's project development.

3.2.2.3.1 Existing Design #1: WoodenHaptics Robot

In this design, the motors used are the same type of motors the team is using for the final model. Brushless DC motors are mounted on the base of this robot to establish a simple but secure motion mechanism for the robot. There are three motors in this design which is exactly the number of motors the team is using the first motor actuates the rotary base of the robot while the other two motors are connected to each side of the robot actuating the shoulder and wrist of the robot. This is an important implementation of motor placement as it is a simple design actuating all joint connections while no issue is occurring by placing all motors at the base.

3.2.2.3.2 Existing Design #2: Haptx Robot

As previously stated, the motor placement of the Haptx robot lies within the joints connecting the links. This design was initially used by the group as the main form of inspiration. After speaking with our client, the team has decided to steer away from placing the motors within the joints and or links of the robot. However, since there are three motors in total, the team can use this design as a guideline when it comes to placing the first motor which will actuate the rotating base of the robot. The Haptx robot has a motor within the rotating base and leaves just enough space for that motor. The team is looking into implementing a pulley system on the base of the robot to actuate the rotating base, but the Haptx robot design can still be used if that design fails. Overall, the Haptx robot is a very clean-looking robot that performs extremely well and will continuously be evaluated by the group as the project progresses.

3.2.2.3.3 Existing Design #3: HIRO-II Robot

As previously stated, the Hiro-II robot has a unique design. This robot has a total of three motors that actuate the robot. Two of the motors lie within the back end of the robot, allowing it to have a rotating base as well as actuate the first link of the robot. The third motor lies within the first link of the robot and that motor is used to actuate the second link of the robot. This design can be used by the team to give a different perspective when it comes to the placement of the motors for the robot. No other design has the motors on the back end of the entire link system therefore if the team runs into any errors with motor placement, this design can be implemented into the final design of the haptic robot.

4 CONCEPT GENERATION

In the following chapter, the team presents the conceptual generated designs based on the benchmarking results, customer and engineering requirements as well as the types of system mechanisms used to finalize the design. In addition, the content is focused on the top three full designs that the team resulted in based on the conceptual rankings of each design model.

4.1 Full System Concepts

This section will discuss the designs the team considered during the design process of the project. Below the team has compiled three designs, each varying in different aspects.

4.1.1 Full System Design #1: Belt-Driven Links

To move the links, we came up with 3 different ways to use motors provided by the client. The belt system would use pullies with different step sizes for an increase in torque to meet client and engineering requirements. The motors would be placed in housing, attached to a coupler shaft that has the first belt around it. That belt would then go towards the first pulley, which has a larger diameter than the coupler shaft. On the same axis that the pulley is resting, there would be the start of another pulley system. This design would allow multiple reductions in speed but an increase in torque, so one motor could end up moving a joint at a much lower speed but much higher torque. This design is very similar to how a gear train works, which is our next system design.

4.1.2 Full System Design #2: Differential Gear System

Our team came up with a design that could house motors within the links and still have the motion required. This system would use a gear train within carbon fiber tubing, so all pinch points and components would be hidden. It was a compact version of a pulley design since the gear train would be smaller and in the links themselves. Due to the motors turning in the long axis, we created a "differential" styled system that would use bevel gears at the end of the top link gear train. However, this system was not ideal for two main reasons: cutting carbon fiber was hazardous since the dust particles are considered very toxic, and the only other option would be 3D printing all the tubing, which would most likely cause us to exceed the budget. To make it easier to engineer, the gear train was later considered to be external, but due to the client's requirement of no backlash, we needed to change our design to not involve gears.

4.1.3 Full System Design #3: Solid Joint Assembly

The final system would have been similar to the gear system, where the motors are housed within carbon fiber tubing. The motors wouldn't have used a gear or pulley system to increase torque in this system, which would have failed the engineering requirement of resisting 20N of force at the end effector. Essentially all components would be housed, and the robot wouldn't be very strong. This is similar to the Wooden Haptics robot where it can't resist motion very well, but it can move freely. The motor for the last link would need to be at the top of the robot, at the joint, so it would have a large amount of momentum caused by the weight from that motor alone. The team figured the robot would fail with the design without some sort of counterweight system attached to the robot, and the client agreed.

4.2 Subsystem Concepts

The following sections provide detailed conceptual subsystems that the team considered to be important for the design modeling. Based on the customer requirements and the engineering analysis, these subsystems will be effective in terms of weight, speed, and accuracy.

4.2.1 Subsystem #1: Motor Placement

The motors that the team is using for this project carry a somewhat heavy load (300-800 grams) which impacts the movement, balance, and overall weight of the model. Considering motor placement to be analyzed as a subsystem, the team constructed 3 distinct designs aiming to provide an expanded conceptual framework when mounting motors on the robot.

4.2.1.1 Design #1: All on-base platform

In this design, all motors will be placed on a rotating base to decrease the moment of inertia and enable the design to move faster. The connections between motors and the links will need to be strong, given that they are a longer distance apart. It requires the team to come up with a unique mechanism, such as a pulley or capstan design, for the motors to work with.
Pros: the moment of inertia is minimized by having motor placement low, parts are cheaper, parts are lighter, and the robot arm can move faster.
Cons: connecting motors to links can be difficult, and torque against motors could increase.

4.2.1.2 Design #2: Two on the base platform, one in link 2

This design places 2 motors at the base and 1 motor inside the first link. This allows easier mechanical energy transmission to the second link because the last motor is placed near it. Connecting the motor to the second link requires a design that runs up the first link.
Pros: the second link is actuated more easily, and the moment of inertia is relatively low.
Cons: speed must be reduced slightly, and intricate design is required to allow the motor in the first link.

4.2.1.3 Design #3: All three in robot links

Having motors in the joints/ links requires more bearings but it provides a smoother design with everything mechanical being concealed. It has motor 1 in the first vertical piece, then another in the first horizontal joint, and a last motor in the last horizontal joint. It is similar to some of our team designs and can be seen inside of them.
Pros: all parts are concealed, minimal pinch points, smooth exterior design.
Cons: moment of inertia is maximized, more parts required.

4.2.2 Subsystem #2: Types of Links

4.2.2.1 Design #1: Aluminum Arm

Aluminum offers a cheaper design while maintaining structural integrity. It is almost always available to purchase and can be machined easily. Having aluminum links makes the design heavier, so most likely this will be simple aluminum arms, not tubes.
Pros: affordable, strong, easily edited by machining the parts.
Cons: components are exposed, not smooth-looking, and a heavier material option.

4.2.2.2 Design #2: Carbon Fiber Tube

Carbon fiber is known for its strong material properties and being lightweight. It is more expensive but can be purchased from many manufacturers in different forms. It is harder to work within a machine shop setting, so it requires a higher level of care.
Pros: strong, lightweight, houses components
Cons: expensive, difficult to edit using machine shop.

4.2.2.3 Design #3: Wooden Arm

Wooden parts are the cheapest option but provide less structural support. The team could use wood to create housing for components or just make an arm like the "Wooden Haptics" design. It is strong but also heavy, to achieve a sturdy design.
Pros: cheapest option, multiple designs can work, easy to machine with.
Cons: may or may not house components (link weight depends on this), not as strong as other options.

4.2.3 Subsystem #3: Motion Mechanism

4.2.3.1 Design #1: Gear Assembly

A gear assembly requires many specific gears to be purchased with one another so that they mesh correctly. To get a higher torque from the motors, a gear system is easy to use. They create pinch points and must be housed in a case of some kind.
Pros: lowers motor rpm and increases torque easily, sometimes found easily in the market.
Cons: must be housed, expensive, requires multiple unique parts, can have backlash.

4.2.3.2 Design #2: Pulley/Winch Assembly

A pulley assembly would use a high-tension steel cable and most likely represent a winch system. It can be external or internal if designed correctly. There are fewer parts required, so it is less expensive.
Pros: simpler and less expensive, parts are more available, no backlash, lightweight.
Cons: may produce heat in cable, requires strong support for cable to wrap on.

4.2.3.3 Design #3: Solid Joint Assembly

The solid joint assembly would have motors attached to couplings, which are attached to the links. Most likely they will be internal and are very simple. This can be a cheaper option, but it requires specific bearings to mount the motors to the links.
Pros: a small number of parts, simple design, no backlash.
Cons: specific bearings required, can become expensive depending on the coupling system.

5 DESIGN SELECTED – First Semester

In this section the team shows the process of narrowing down the design the team created, utilizing a decision matrix and Pugh chart to score each design which provided the team with an understanding of why each design has advantages to satisfy customer and engineering requirements.

5.1 Technical Selection Criteria

The team started with a Pugh chart filled with the concept design brought forward by the members of the group. Four new designs were generated with one design being used as our datum. The datum was chosen for being the team's initial design that met the customer requirements and based on the team's initial ideas this was the working model to improve upon. In the team's Pugh chart, these four designs were scored on the criteria of cost, lightweight, range of motion, durability, accuracy, speed, and stiffness. The team had based cost, range of motion durability, speed, and stiffness with a score weight of three. The most important aspects of the design were being lightweight and speed because of the robot arm being used for rehabilitation. From the scores, the team found that designs two and four scored the highest with a six in the final weighted score. These two designs excelled in nearly every category with design two's drawback being cost and design four's being accuracy. From this, the team was able to eliminate one design that being design number one with the three remaining being used for the decision matrix to continue further grading.

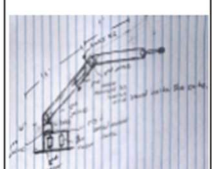
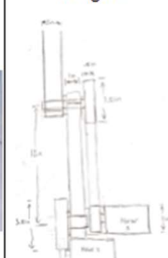
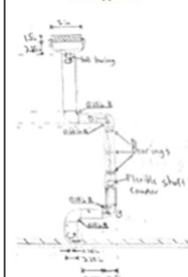
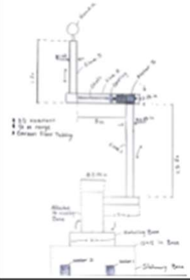
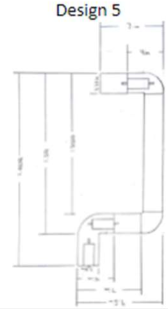
Concept → Criteria	Design 1 	Design 2 	Design 3 	Design 4 	Design 5 	Imprortance Rating
Cost	S	-	-		Baseline	3
Lightweight	-	S	S	S	Baseline	9
Range of Motion	-	S	S	S	Baseline	3
Durability	-	S	-	S	Baseline	3
Accuracy	S	+	+	-	Baseline	3
Speed	+	+	S	+	Baseline	9
Stiffness	-	-	+	S	Baseline	3
∑+	1	2	2	1		
∑-	4	2	2	1		
Net	-3	0	0	0		
Weighted +	9	12	6	9		
Weighted -	-18	-6	-9	-3		
Final Weighted	-9	6	0	6		

Figure 7: Pugh Chart

To narrow down the design further a decision matrix used designs two, three, and four were chosen to continue based on the initial evaluation in the Pugh chart. This time the team graded the designs more in depth with the same criteria as before. The criteria this time have different weights for the importance to the overall design. The team placed lightweight, range of motion, and stiffness the highest at twenty percent each because these make the robotic arm viable for rehabilitation to provide the correct resistance for any motion needed. Speed has the next highest weight at fifteen percent, as the team valued making sure it could match the speed of the patient. Durability and accuracy are weighted ten percent because this isn't a machine that will take much damage in its use and does not need to be used in a way that will require the robotic arm to reach specific points in space. The lowest weight category was cost at five percent, the team valued being able to produce a robotic arm for our client, even if that meant going over in price. Scoring the design based on these weights we can see that design three scored the lowest with an overall weighted score of 85.75. Its highest categories are range of motion and speed at one hundred and ninety respectively. It suffered the most in cost and did not have as high scores in speed, durability, and being lightweight as the other designs did. Coming in second was design number two with an overall weight score of 88.5. Design number two scored a ninety-five for both speed and cost, placing it amongst the best of all designs, while scoring a one hundred in range of motion. The best-scoring design was number four with an overall weighted score of 89.25 placing it at the top of all designs currently considered. This design scored the highest in nearly all categories with the standouts being lightweight, accuracy, and speed.

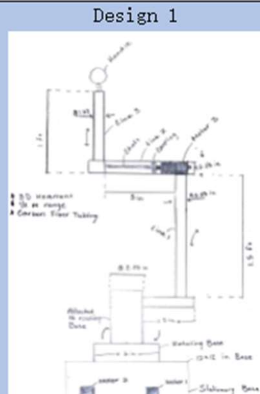
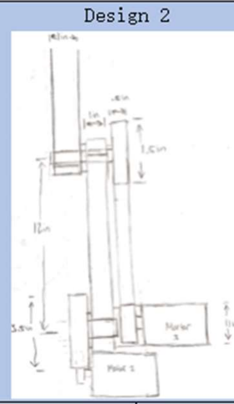
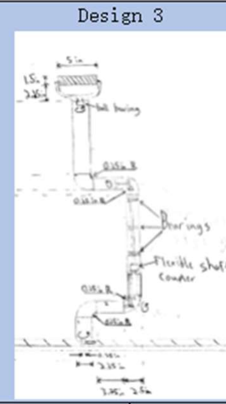
Criterion	Weight	Design 1		Design 2		Design 3	
							
			Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Cost	5	85	4.25	95	4.75	75	3.75
Lightweight	20	90	18	80	16	85	17
Range of Motion	20	100	20	100	20	100	20
Durability	10	75	7.5	75	7.5	70	7
Accuracy	10	90	9	90	9	90	9
Speed	15	90	13.5	95	14.25	80	12
Stiffness	20	85	17	85	17	85	17
Total	100	Sum:	89.25	Sum:	88.5	Sum:	85.75

Figure 8: Decision Matrix

5.2 Rational for Design Selection

The team concluded the top two final designs for the Haptic Robot capstone project which are full system design 1 & 3 which are discussed in sections 4.1.1 & 4.1.3. The team processed the designs through conceptual analysis using the Pugh chart weightings in ***Figure 7*** and narrowing the top three designs to be ranked in the Decision Matrix in ***Figure 8***. In addition, the top designs were ranked using the decision matrix which is based on the requirements needed for the project. The criterion of each of the conceptual analysis charts is weighted based on importance that is affected by both client and engineering requirements. To conclude, the team aims toward the development of design 4 in section 4.1.3 as a final model for the project; however, the final design might be adjusted due to further analysis and client feedback on some parts of the model such as motor placement and link connections.

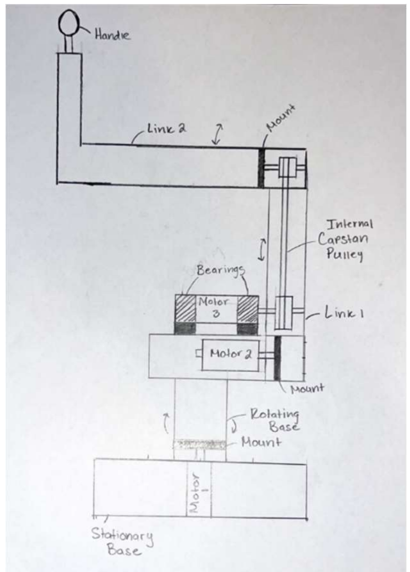


Figure 9: Final Design

6 Project Management – Second Semester

6.1 Gantt Chart

The team utilized the Gantt chart throughout the entire semester with minimal changes to the order of events in which we did everything. The summarized outline for the Gantt chart comes down to the main deliverables that were provided by our instructor on the first day of the capstone. There were three main deadlines the team needed to hit which were the 33%, 67%, and 100% builds. The team used these dates as a guideline to break down the schedule and create even smaller Gantt charts throughout the semester. This helped us stay on track with everything that needed to be done when it came to building the actual robot, but there were still some deadlines that were not completed along the way. The Gantt chart for the entire semester can be overwhelming to look at therefore the smaller scheduling made the group much more efficient every week. If the team could do the project over again, we would focus on starting homework for other classes much sooner so we could give our undivided attention to our capstone project in hopes of catching some of the mistakes we made along the way.

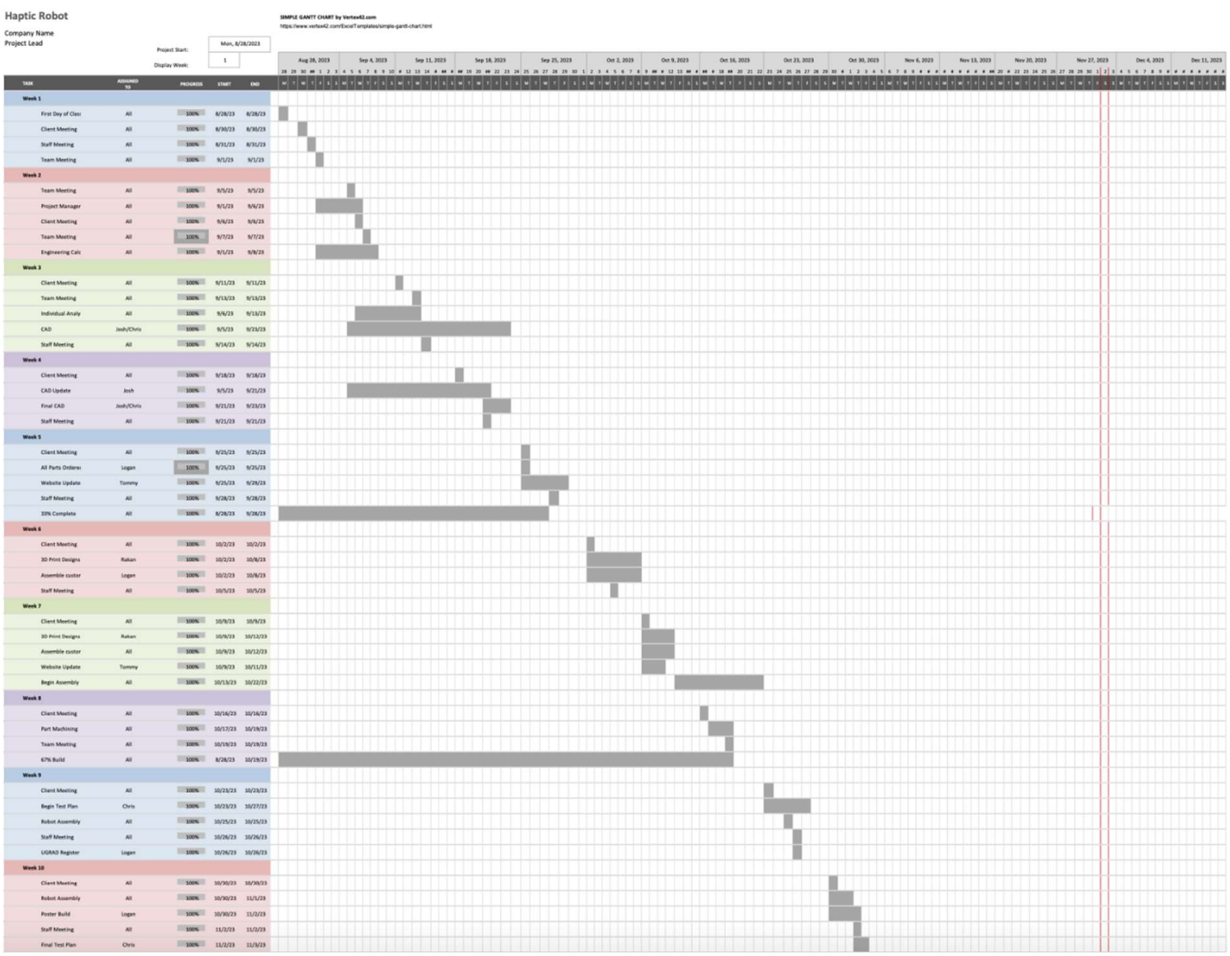


Figure 10: Gantt Chart

6.2 Purchasing Plan

The team's BOM used a table-like format to show exactly how much each part is going to cost. It is organized by the item and what the item does, then if it was in our possession or not, who sells the item, if it needs to be manufactured, the time to manufacture (purely estimated), part number (if applicable), quantity, total cost, and cost per unit. We have the entire bill of materials in **Appendix A**. For our entire BOM, we have all parts in hand, so all the boxes are a green color. A sample picture of our BOM is posted below.

Bill of Materials (BOM)

Item #	Item	Item Description	In Hand/In Progress/ Not In Hand	Vendor	Make/Buy	E.T. Make (hr)	Part Number	Quantity	Total Cost ($)	Cost Per Unit ($)
1	Motors	EC Maxon Brushless Motor	In Hand	Maxon	Buy	0	283873	3	$1,963.50	$654.50
2	Flange 3/4" Bearing	Base Bearing	In Hand	Amazon	Buy	0	60355K297	1	$12.25	$12.25

Figure 11: BOM Snip

Our Bill of materials has been organized in this way to give us the best representation of what the material is sourced from. There were some problems conveying our BOM to the audience since the table is cramped, so changing the table by shortening the number of columns might improve read quality. The one we created, in the beginning, was very simple and didn't have as much detail, but perhaps we have put too much detail in ours. Other than purchasing, we needed to create some parts using a stock piece such as aluminum, the manufacturing plan covers that important aspect.

6.3 Manufacturing Plan

The manufacturing of our robot consisted of two types: machining metal using the NAU machine shop, and 3D printing unique parts that would be impossible to find on the market. Our build progressed throughout the semester by the specific percent of build benchmarks and status updates within 486C. Our BOM (shown below) has all the different machined parts color-coded based on whether it was considered manufactured or not. **Appendix B** has the entire manufacturing plan the team used during the construction of this project.

Manufacturing Plan

Item	Item	Item Description	Vendor	Make/Buy	E.T. Make (hr)	Part #	Quantity	Image	Total Cost ($)
1	Motors	EC Maxon Brushless Motor	Maxon	Buy	0	[illegible]	3		$0.00
2	Steel Cable	For Pulleys	Client	Buy	0	NA	1		$0.00
3	Hex Bearings	Link Bearings for knuckle	McMaster-Carr	Buy	0	[illegible]	[illegible]		[illegible]
4	Hex Nut	1/4" - 20	Home Depot	Buy	0	[illegible]	[illegible]		[illegible]
5	8mm Shaft	Used for the 8mm and 4mm pulley reels. Steel	McMaster-Carr	Buy	3	NA	3		$0.00
6	Coupler	Connects the motor shaft to the coupler shaft	MISUMI	Buy	0	[illegible]	3		[illegible]
7	Coupler Screw	Used to tighten the coupler to the shaft	MISUMI	Buy	0	[illegible]	12	NA	$0.00
8	Pulley Set Screws	Used to tighten the driven pulleys down (d = 6.35mm, L = 26 mm)	MISUMI	Buy	0	[illegible]	[illegible]		[illegible]
9	Wood Base (MDF)	Holds the robot	Home Depot	Buy	2	NA	1		[illegible]

Figure 12: Manufacturing plan

For the 33% build, our team purchased hardware and 3D printed several pullies that we had designed in SOLIDWORKS to show proof of concept. We then started to put in machine shop orders for aluminum stock to be cut into the various necessary parts for our robot.

By the 66% build, we had several aluminum parts completed such as the motor housing, the first link, and multiple reduction hex shafts that were turned down. We also had all our pullies printed by the idea lab in stronger material since our previous ones seemed a bit weak. We also got rid of the initial pullies on the coupler shaft so that we could have an even higher reduction in speed and greater torque output.

When it came to the 100% build, we had all parts machined and the entire robot assembled, other than the cable since we knew we needed to figure out how we could tension the cable effectively. All aluminum parts were completed by this benchmark and were cut on various machines such as the Haus and the lathe. The press-fitting was also done in the machine shop and was tasking, to say the least since our bearing tolerances were not specified by the manufacturer.

The main difference between the previous semester's plan and what happened was the number of hours spent editing parts. We anticipated having to go to the machine shop and put in orders along with our work on the parts for the robot to turn out how we wanted it. In the end, we spent much time planning how the manufacturing would go, but we had to edit much on our own based on tight fittings and changing materials for the reduction shaft housing.

7 Final Hardware

7.1 Final Hardware Images and Descriptions

Some of the final hardware we used when constructing the project included many off-the-shelf parts such as nuts, bolts, and bearings. Some of the special parts like our aluminum pieces and 3-D printed parts were made from original designs. The team did purchase raw materials for the machined parts and was able to have them CNC machined to produce the final product. The 3-D printed parts were from the NAU idea lab that we sent over from our CAD designs. For pictures of the full hardware and made parts refer to **Appendix B**.

7.2 Design Changes in the Second Semester

7.2.1 Design Iteration 1: Change in motor mounting position discussion

For our first design iteration, the team changed the placement of the second motor. This change moved the second motor, which was mounted on our second arm, down to the base link. By changing the position of the motor this decreases the moment of inertia and makes it easier for the motor that controls the second link to be able to move the arm. One reason for this change was the weight of the motor was a concern during the entire construction process and changing the placement gave our project a better chance of working as intended. With this design iteration, some other changes had to be made, since our second motor is now mounted to the opposite side of the first motor the use of a transfer pulley was needed. The team placed a transfer pulley at the top of the base link using the same shaft that is used to move the second arm, this ensured that the cable would stay in line with the center of the axis and the length of the cable would not change. This ensured the cables would not bind and restrict the movement of the robot's arms.

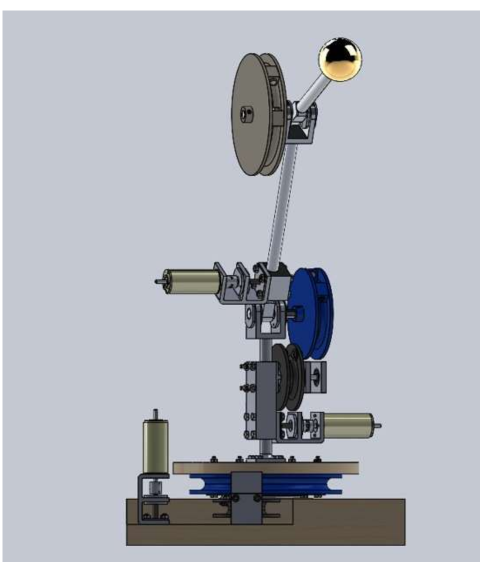


Figure 13: Original Motor Mount

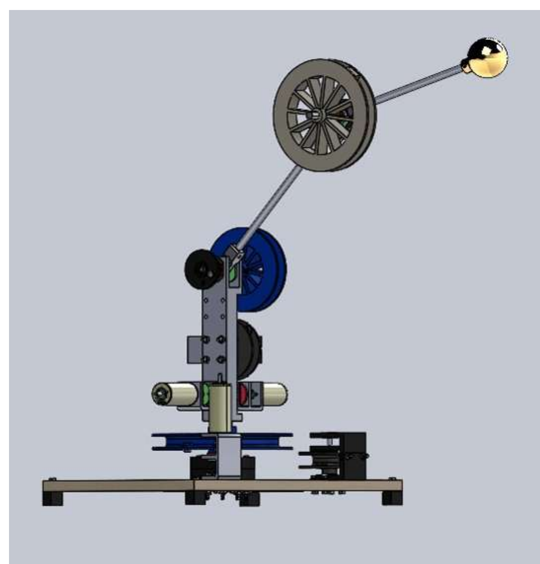


Figure 14: Iteration One

7.2.2 Design Iteration 2: Change in base arm mounting discussion

The second change made during our design process was changing the way the base arm was mounted. Originally the base arm was mounted using a flange bearing that matched the size of our base link. This design choice had too much play in the mount, which made our base link have too much backlash. This was caused by the tolerance between the bearing and the housing for the bearing being too big which resulted in unwanted movement. To fix this problem the team used 3/4in diameter bearings and a custom 3-D printed housing to hold the bearings. By also spacing the bearings ½ in apart inside the bearing housings the team could reduce the amount of backlash in the assembly. This design choice proved to work very well as the team has two points of contact with the base link, creating an even stronger connection than just using a single flange bearing.

Figure 15: Flange Bearing Mount

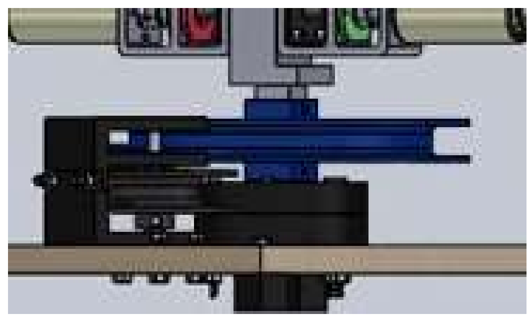


Figure 16: 3-D Printed Mount

7.2.3 Design Iteration 3: Change in Belt/pulley system discussion

For our links, we have discovered, through testing, that the motors are best used when the links are belt-driven. We wanted to use rubber bands to move the links at first, due to the high amount of friction provided by the surface area on the coupler shaft and the pullies. This design came with much backlash, so we then tried using a strong elastic cable, which had a circular cross-section but also had a rough surface. This also had backlash but was less noticeable compared to the rubber bands. To remedy the backlash, we decided to use surgical tubing (this was recommended by an engineer with over 30 years of experience in the field) and then put the cable within the tubing. The tubing would provide friction similar to the belt system that rubber bands do while the cables would eliminate backlash better than anything else tested.

Figure 17: Rubber Band Belts

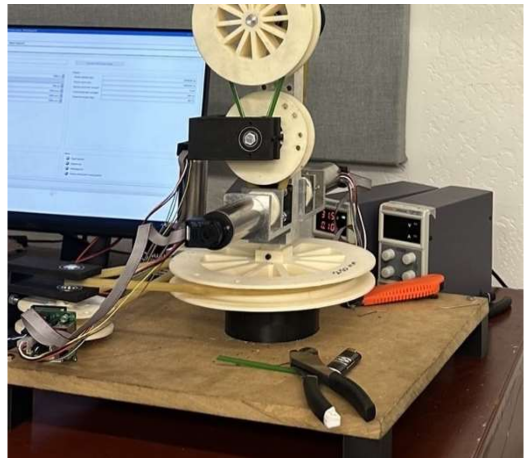


Figure 18: Cable and Surgical Tubing

7.3 Challenges Bested

One of the challenges the team faced when trying to meet the 100% requirements was the time of manufacturing parts. Since we did so much iterating to satisfy the client's needs, we were short on time for most of the parts. When the team started working on this project, we had a design in place we thought would be acceptable and work given the requirements. Two members of our team had taken the advanced machine shop training and decided to start to work on some of the parts that needed to be machined. What we learned is that given the complexity of the parts, the time to manufacture was going to take much longer than expected, which also put us in a time crunch. The team instead opted to have the parts machined using a CNC at NAU's machine shop. This cut the machining time down significantly allowing for the team to produce all the aluminum parts within a week of machining. The next parts that needed to be mass-produced were our 3-D printed parts which took longer due to the printing process being slower. We were able to produce the parts on time but took twice as long to print. Our design required twice as many 3-D printed parts, which was the main cause of our increased total manufacturing time. The team was able to overcome these drawbacks by meeting with the machine shop to ensure the design we had submitted was not only feasible for the machine but would be produced on time.

8 Testing

8.1 Testing Plan

Before testing the robot, the team referenced the QFD to discuss how each customer and engineering requirements could be tested to prove the functionality of the design created. There are eight customer requirements and six engineering requirements that can be put to the test using five different experiments as shown in *Table 2* below. This section of this report will go into detail about the steps taken for each experiment to ensure the team created a product that satisfies their client.

Table 2: Summary of Experiments Relative to Customer and Engineering Requirements

Experiment/Test	DR Relevance
Ex 1 – Weighing Robot	CR1, ER1
Ex 2 – Robot Backlash	CR5, CR6, CR7, ER2
Ex 3 – FEA	CR3, ER2
Ex 4 - Output Force	CR4, CR8, ER3
Ex 5 – Speed and Motion	CR2, CR4, CR5, ER5

8.1.1 - Weighing Robot

Test/Experiment Summary

One of the customer requirements is making the robot as lightweight as possible. This will reduce the strain on the motors, move at the required speed, make it easier to transport, and decrease the moment of inertia. The highest weighted customer requirement is being lightweight which makes this experiment/test an important part of the test plan. All links are manufactured through the machine shop and can easily be weighed using an accurate scale, and then the weights do not exceed 7.5 lbs. total weight for all three links.

Procedure

To find the total weight of the links, the robot must be weighed using an appropriate and accurate scale. Start by removing each of the links for the robot and zero out the scale that will be used. Weigh the first link of the robot and record the weight in an Excel file. Record the weight for the link two more times and take the average as the final weight of the robot link. If you want to dive deeper into this test you can take different scales and weigh the links of the robots with multiple scales, then average the weights. Finally, add up the weights of all three links and ensure they do not exceed the weight the client is looking for.

8.1.2 - Robot Backlash

Test/Experiment Summary

The robot's accuracy depends on how it responds to force. By using a pulley system, we can minimize backlash since the cables will be in high tension. Motors depend on the cables being taut, so minimal backlash will be tested through cable give. Specifically, we will be measuring cable deflection when it is pulled perpendicular to the line of tension. Part of the customer requirements is to build a robot that has little to no friction, little to no backlash, and flawless movement in three degrees of freedom. The factor of safety for this feature needs to be between 1.5 and 2.

Procedure

To test the backlash of the robot, start by marking the robot and either memorizing where that mark is or physically marking the robot with a pencil. Then, move the robot in any fashion you would like and bring the robot as close to its original starting position as possible. Measure the change between the two markings on the robot to see if there is any difference after robot movement. The second test will require more of a human-touch approach. Move the robot in any direction you would like and let go of the robot. Test to see if there is any movement after the robot is no longer being touched by a human. Finally, the last test will measure cable deflection when it is pulled perpendicular to the line of tension. Fix a rod to the robot and move the robot so the rod is perpendicular to its original starting position. Measure if the cable has any deflection

8.1.3 - FEA

Test/Experiment Summary

A finite element analysis of the joint links and predicted material failure on the robot will be tested through SolidWorks by applying at least 20 Newtons of force to the end-effector and visualizing how the links and joints are affected in terms of stress and deflection. The minimum factor of safety has to be at least 1.5 for all parts experiencing force as it is a high-weight customer requirement to have a stiff/strong final design. The only equipment needed is an intermediate level of knowledge on using the finite element analysis function in SolidWorks and knowing how it works in terms of force directions and how it is applied to the part being investigated. The main variable to measure in this test that will affect the results is the material type where the forces are acting. The material is mainly aluminum, but in some parts of the robot, it's 3-D printed PLA which could be an essential part of the robot that needs to be calculated in terms of stress and deflection. The isolation of the part from the assembly to be measured is an essential part of the finite element analysis. The factor of safety is then calculated by running the simulation using the procedure provided below.

Procedure

To start the experiment, the full assembly of the design needs to be opened in SolidWorks and starting from the nearest link to the end-effector, the part is to be opened and the FEA simulation is started. The link is then fixed appropriately with the material of the part specified and run through the analysis simulation with the desired amount of force applied in the appropriate direction and location. The equation to be used in this test is equation 1 below where the factor of safety is equal to the allowable stress over the actual stress the part is experiencing.

$$FOS = \frac{\sigma_{allowable}}{\sigma} \quad (1)$$

8.1.4 - Output Force

Test/Experiment Summary

Force output for the haptic robot is 20 Newtons as set by the client, to meet the therapeutic needs of the user. This amount of output force will allow the haptic robot team to see if our design is capable of handling the forces exerted on the arms during motion. To the output, the haptic robot team will conduct a series of experiments on the end effector of the robot. With various weights attached to the handle, set at 2, 5, and 10 pounds, the team will run the motors at their nominal torque output. The test will be conducted in various orientations that the robotic arm can achieve, ranging from an orientation that produces the highest moment of inertia to a more acceptable range. From this test, the team will understand the limitations of the robotic arm and understand the required power needed to achieve this engineering requirement. This is a great way to see deflection in all the parts of the robot, including the arms, 3D-printed parts, and machine mounts.

Procedure

To conduct the test of force output the team will set up weights starting at 2 pounds at the end effector and running the motors at their nominal torque output of 0.2 Nmm. The test will increase in weight running at the same power. Once these tests are complete, the same experiments will be conducted again at the motor's highest torque output of 0.8 Nmm. The orientation of the robotic arm is important to the test, the team will set the arms in the 'worst case scenario' meaning that the arms will be fully extended to the farthest possible position from the center of gravity for the entire robot. This will great the highest stress on the system and will serve as a starting point to determine the effectiveness in lower-stress positions.

8.1.5 - Speed and Motion

Test/Experiment Summary

The speed for the haptic robot has an engineering requirement set by the team of 1 m/s when the user moves the robot from one side of the body to the other. By ensuring the robot can move at a speed of 1 m/s, the team can guarantee a user-friendly experience while in use, which was the second customer requirement given to the team. To guarantee the robot will be safe for the user, especially because they are recovering from an injury, the robot must be accurate when trying to cover the maximum possible distance the robot can reach. If the robot is not accurate or not able to cover the distance requested by the client, the robot could be unsafe for use. Finally, the robot also needs to be able to move with three degrees of freedom to give the user flexibility when choosing which activities will be best suited for their rehabilitation process. To test the speed and motion of the robot, the team plans to work with a graduate student to create a basic code that will allow the robot to move from one side to the other. By performing this test, the robot can be isolated into individual links to ensure each link can meet the speed and range requirement provided by the client and team. This test can be done using an Arduino mega board and will help ensure the robot that is being built will be satisfactory and run when all components are powered together. During the test, the team will manually time the robot as well as time within the program. The isolated variables for this experiment will be the three links. From this test, the maximum distance the robot can reach will be found, as well as the average speed of the robot when performing simple tasks.

Procedure

To test the speed and motion of the robot, start by writing a code that allows the robot to perform a basic task. Next, connect one motor of the robot to a controller to only test a specific link of the robot. Run the code generated and manually time how long it takes to run through the entirety of the code. Note that the code should also be timing how long it takes to run through the code. Measure the distance of the link from a specific starting point and find the displacement. This will allow you to find the maximum distance the robot can reach at any given point. Input all of the measured values into Excel or MATLAB and calculate the averages for each test. Perform each test a minimum of three times for each link.

8.2 Testing Results

8.2.1 - Customer Requirements Testing Results

After completing all the experiments above, the team was able to decide if each of the customer requirements was met or not. The first customer requirement was a lightweight design, which was tested by finding the weight of each link and summing the totals of each link. The total weight for all three links was found to be less than the customers' desired weight which means that the requirement was met. The second requirement was a user-friendly design which was met because any new user can use the robot with ease and little to no help from an outside party. The robot needed to have a stiff design and the requirement was met because each link was rigid and could support the loads applied to them. The robot needed to be accurate while the user was using it, and it was found that the requirement was met because the robot could move to a specific point in space within the parameters and not fall from its own weight. Along with the accuracy of the robot, it needed to move with three degrees of freedom which it does therefore that requirement was acceptable. The customer asked the team to reduce the backlash of the robot meaning once the robot comes to a stop, the robot does not move anymore. This requirement was also met while performing many different tests for each link. The last two customer requirements were reducing friction and supplying an end effector force. The team feels as if these requirements were met because the robot does indeed produce a force on the end effector and the team worked to reduce the friction within the system as best as they could.

Table 3: Customer Requirement Check

Customer Requirement	CR Met? (✓ or X)	Client Acceptable (✓ or X)
CR1-Lightweight	☑	☐
CR2-User Friendly	☑	☐
CR3-Stiff	☑	☐
CR4-Accurate	☑	☐
CR5-3D Motion	☑	☐
CR6-Reduced Backlash	☑	☐
CR7-Reduced Friction	☑	☐
CR8-End Effector	☑	☐

8.2.2 - Engineering Requirements Testing Results

Table 4 below shows the specification sheet for the Engineering Requirements involved in the project. The first engineering requirement is a decrease in link weight which was tested by summing the total weight of all three links and ensuring they are below 7.5 lbs. The total weight for all three links was 4.19 lbs therefore the team met this requirement. The overall design of the robot needed to have a minimum factor of safety between 1.5-2. The team found this factor of safety by taking the weakest component for the design which was found to have a factor of safety of 6. Since this is the weakest point of the design, the rest of the robot will have an equal or higher factor of safety, therefore the team has met this requirement. The robot needed to provide an end effector force of greater than or equal to 20N. The team was able to produce an end effector force of 12N therefore we did not meet this requirement. The team needed to reduce torque resistance within the design and needed to have a value of less than 1Nm. The team measured a torque resistance of 0.8Nm therefore this requirement was met. Along with producing an end effector force, the robot needed to have an end effector speed of 1 m/s. The team was able to find the robot moves at a speed of 1.047 m/s therefore this requirement has been met. Finally, the max rated power for the robot needed to be less than 100W. After testing the robot, the team found the max rated power to be 65.25W which is well below the 100W mark therefore this requirement has been met.

Table 4: Engineering Requirements Check

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met? (✓ or X)	Client Acceptable (✓ or X)
ER1-Decrease Link Weight	< 7.5 lbs	± 0.5 lbs	4.19lbs	☑	☐
ER2-Factor of Safety	1.5-2	± 0.01	6.5	☑	☐
ER3-End-Effector Force	≥ 20N	± 0.01 N	12N	☐	☐
ER4-Reduce Torque Resistance	< 1Nm	± 0.01 Nm	0.8Nm	☑	☐
ER5-End Effector Speed & Motion	1 m/s	± 0.01 m/s	1.047m/s	☑	☐
ER6-Max Rated Power	100W	± 0.5 W	65.25W	☑	☐

9 RISK ANALYSIS AND MITIGATION

9.1 Potential Failures Identified First Semester

The following section focuses on the finite material element analysis (FMEA) the team has done at the end of the first semester. The FMEA model is an essential design method to address any potential failures in detail for each design component in the robot. The modes of failure in terms of the team's project are mainly mechanical with one electric potential failure.

As shown in ***Figure 19*** below, the shortened FMEA includes the compact results of main subsystem components in the team's design. The critical failures according to the FMEA below are correlated within the range of pulleys and motor performances. The team is concerned about the pulley and motor's ability to transmit the power needed to move the robot's arms due to the slipping of the steel cable used as a tensioning mechanism. Other important potential failures that were considered in the FMEA revolve around the motors' placement on the robot where it could have a high moment of inertia exposing the motor system to potential failure when turned on. Another important potential failure discussed in the FMEA is the binding of cables which is caused by motor placement conflicting with the required range of motion between pulley systems.

FMEA Shortened					
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
Pulley	Mechanical	No power transmission from motor	Cable comes off the pulley and recieve no power		Make sure cables are tensioned and alligned properly using accurate sized cables and material
Motor Shaft	Mechanical	Shear on the shaft, deformation of the shaft	Pinion pully not supported and misalligned	216	Add a bearing to the pinion pulley to prevent strain
Binding of Cables	Mechanical	No movement in arm links, robot motion malfunction	Motor placement in conflict with range of motion needed	200	Correct placement of motors
Joint Failures	Mechanical	Lack of ability to transmit torque to move the robot	Weak material properties and friction within the joint	100	Using strong material to withstand high stress and friction and process joints through a stress analysis
User Pinching	Mechanical	User injury	The rotation of arms and the use of certain joints	120	Create shell around components
Backlash	Mechanical	Delayed motion and inaccurate force feedback	Unneccesary space between pinion and driven gear	504	Use a cable-driven system
Loose Fittings	Mechanical	Design wobbling, misalignment, collapse	Lack of space for proper tightening of fittings or wrong sized fittings used	120	Ensure fitting tightness and use appropriate tight fastners
Cable Failure	Mechanical	Violent motion, loss of power transmission	Cable overtightened causing too much tension and friction on the cable to other parts.	270	Use a stronger cable with high life cycle and design to easily replace the cables
Motor Positioning	Mechanical	Increased moment of inertia	Mounting motors high from the base	294	Place motors as close as possible to the base
Motor Failure	Mechanical and Electrical	Motor system can fail producing friction on parts	Improper mounting of motors and/or wrong placement on the robot	160	Mount motors in open space

Figure 19: Shortened FMEA

9.2 Potential Failures Identified This Semester

For our first semester final design, we thought the joint shaft would have the most torque on it and would be a point of failure. This semester brought many iterations of the robot and with it came different failure points to think about. The new design, when all forces were applied to the main components, showed that our joint key connector piece had the highest risk of failure due to shear. This is because our shafts were a hex shape to best transmit load using the edges. Our piece will be shown in the figure below.

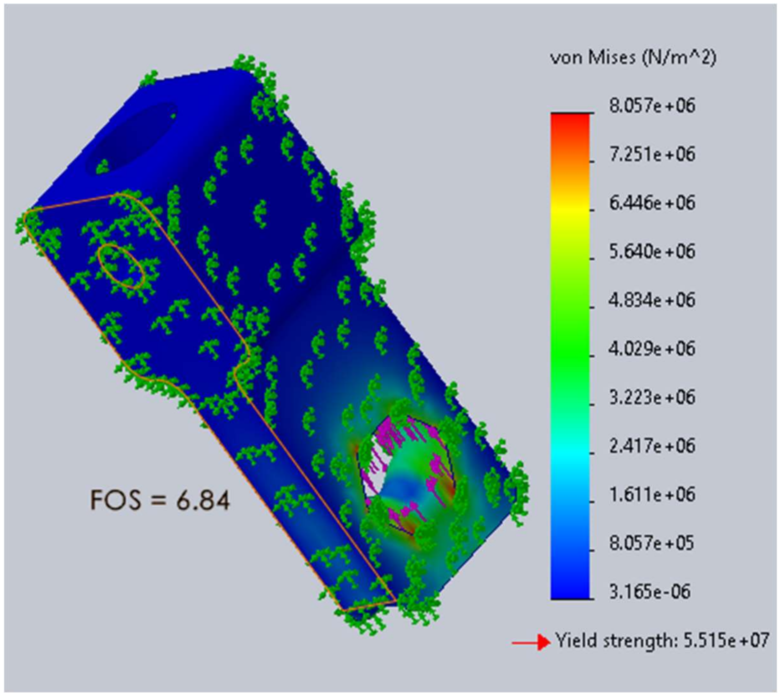


Figure 20: Rod connector FEA using SOLIDWORKS

This piece had the lowest factor of safety of 6.84 compared to all other parts in the design. This is due to the high amount of force resisting motion from the moment. This connector is used at the first joint to transmit the load from the motor and reduction pulley system into the aluminum rod, or the arm. With design iterations comes new potential points of failure, and even then, we stand firm in our final design.

9.3 Risk Mitigation

Throughout the manufacturing and design process over the second semester, the team has done five full design iterations based on potential failures, client needs, and general technical issues. The team has considered the potential failures listed in the FMEA during the design process by optimizing motor placement, ensuring tensioning mechanism functionality, developing appropriate gear ratios, and maximizing output power from the motors. The first iteration of the full system design from the beginning of the second semester is shown in ***Figure 21*** below, the model is simplified by using three pulley systems and one motor mounted higher up on the robot. After analyzing the full system design to be more consistent with the FMEA, the team made changes to optimize results based on client and engineering requirements.

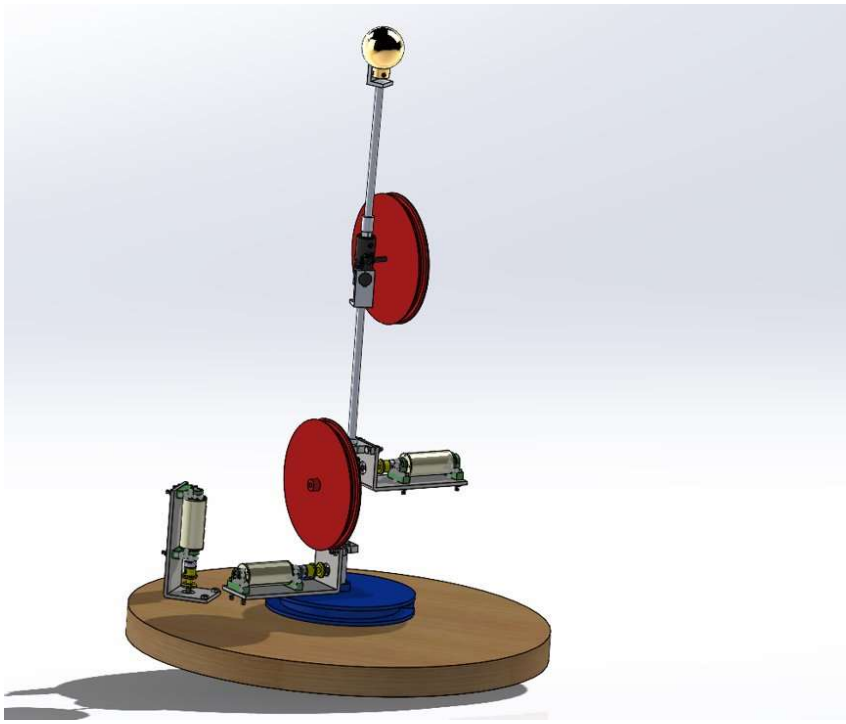


Figure 21: Full Design Iteration 1

As it is known to be an important part of an engineering design process, the team has moved forward with the second iteration of the full system design to minimize potential failures and mitigate any risks that could affect the outcome of the client requirements. In ***Figure 22*** below is the second full design iteration based on the results of the analyses done on the first iteration. The changes made from the first to the second iterations involve the placement of the motors, the addition of more pulley systems for reduction, and a new joint connection design to ensure the stability of robot arms.

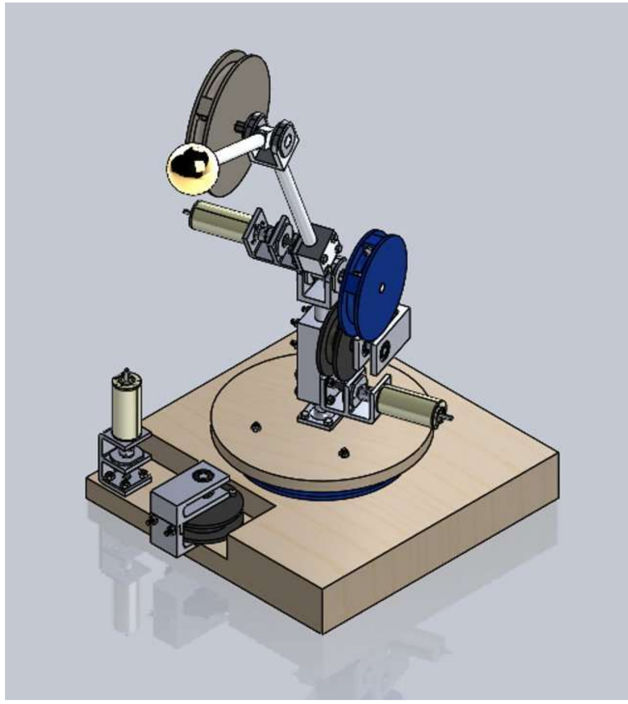


Figure 22: Full Design Iteration 2

Based on the results of the second iteration, the team further optimized the design before starting the manufacturing process by analyzing the model based on the FMEA and client requirements and their relation to the system functionality. The potential failures that were considered in the second iteration are mainly concerning the joint connections, base link mount, and motor placement. These key points were then analyzed further by the team to expand on design ideas and methods to mitigate the risks and come up with technical solutions to the stated issues in the second iteration design.

The final design is completed after the second iteration was analyzed and client approval of new ideas are established and modeled in SolidWorks resulting in the full design shown in ***Figure 23*** below. The team considered the motor placement risks and mitigated the issues by mounting the motors closer to the base and changing the link joints to be hex shaped to reduce backlash and increase linkage strength/safety.

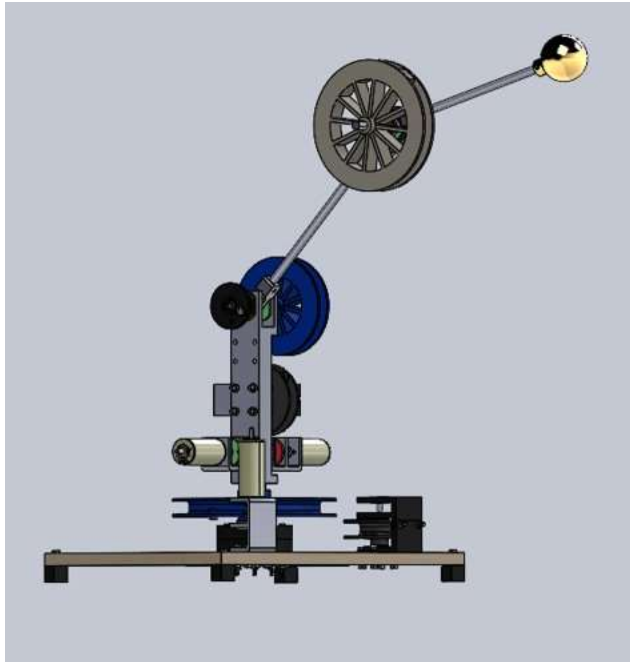


Figure 23: Final Design Iteration

Based on the final design results and testing of robot motion, the team considered many trade-offs with the most important being the tensioning system mechanism as well as the size of the pulleys compared to the 1 mm (about 0.04 in) steel cable that is used by client recommendation. Another important trade-off that the team have made based on client suggestion was using carbon fiber motor mounts to be used for the gear reduction pulleys which resulted in a major system functionality issue when the pulley is tensioned well enough on the shafts causing the mount to bend which effects the motion of the robot as well as the second link having trouble to move due to dysfunctional components. The team mitigated the risk of the carbon fiber mount bending by adding support to the mount using a steel cable tensioned opposed to the bending direction in order to balance the forces acting on the mount.

10 LOOKING FORWARD

10.1 Future Testing Procedures

One future test that could be performed to help validate the design's functionality is having an exact way to measure the backlash and slop in the design. The use of a micrometer to get the exact measurements can help the team understand the quality of the design. For our test we had to measure the backlash as being noticeable to the user, this was a client suggestion as the team had no real way to measure the exact amount of back last.

For our next test, the team would like to be able to measure the exact amount of weight that the robotic arm could lift. The team’s experiment was to use water bottles filled with a certain amount of water that related to a specific weight. This was able to give us a rough estimate of the capabilities, with the arm being able to lift about 2.8 lbs of water. This test would have been nice to apply to other links within our design but was only tested on the link the team had considered the most critical. The way the team had conducted the experiment was for the worst orientation possible which is where the robot would have the hardest time moving. By experimenting with all positions, we could have had a deeper understanding of the position that met the client's requirements.

The last experiment that would have helped with the test would have been to control more than one arm at a time. In our current state, the team can only control one arm at a time, which doesn't allow for the team to see the full action of the robot. When conducting the range of motion test, we had been using the one motor and if we had wanted to hit any dynamic range it would be through using our hands to physically move to a certain position. By not having more than one motor function at a time, we could not produce better videos of the range of motion. A team in the future will be taking over the controlling aspect of the robot to hit specific positions automatically.

10.2 Future Iterations

For future iterations, if a team were to continue the work on the area that needs to be addressed the most is with the cable pulley system. There could be improvement with developing a proper tensioning system or changing the design entirely. During testing, we noticed that slipping was an issue with the pulleys. One way to overcome this would increase the tension within the pulleys, but with the current setup and trying to achieve the required range of motion it can become difficult to develop within the current design. A design of the pulley would help with achieving better results in terms of producing more force output at the end effector. This was the biggest limitation in our design had been the pulleys not functioning as intended.

11 CONCLUSIONS

Six months ago, the haptic robot capstone group was given the challenge of designing and building a three degree of freedom haptic robot that can be used to aid in the rehabilitation process for those who have suffered from a stroke or have cerebral palsy. When the team started their journey, they brainstormed several ideas and ultimately set a goal to design a haptic robot that was lightweight, rigid, used pulley systems, and utilized steel cables instead of belts. The project is very quickly coming to a finish and the final product has been created utilizing all the goals that were set above. The team was able to create a design that moves in three degrees of freedom while remaining relatively lightweight, which was a huge success for the reach requirements that were given by our client. We were also able to utilize a pulley system with steel cables into our design which helped us achieve all our customer requirements and a majority of our engineering requirements. This project was a challenge the group was not expecting but nonetheless one of the best learning experiences we have had at NAU.

11.1 Reflection

This project was originally intended for the use of public health and helping patients who have had a stroke or suffer from cerebral palsy. This robot has been created with the safety of the user in mind regardless of who they are and what they are trying to accomplish while using the robot, therefore the design that has been implemented has safety features such as stoppers implemented into the design. The public health and safety factors were the most important for this project therefore the team spent the majority of their time working towards providing a safe product for the user. The team was able to ensure the product created was safe for use by testing the stops on the robot and ensuring they safely do their job to make the user experience enjoyable for all.

11.2 Resource Wishlist

If the team had the opportunity to do this project over again, we feel we would have more success with a few key items in replacement of current items within our design. The first item we would change would be the type of motor used within the design, we feel as if we could have picked a motor that was better suited for our design which would have made a huge difference in the way the robot functions. The other physical item that is attached to the robot would be a different material for the reduction brackets on the robot, the team originally wanted to use aluminum but there were some manufacturing issues within the machine shop which prevented us from doing so. Finally, any references that would have helped us throughout the entire project. There are not many resources available when it comes to robots using pulley systems. The robot the team created seems to be very unique and there are not many products on the market when it comes to designing a robot with steel cable and a pulley system, most robots use belts and or gears because they have worked so well for so many years.

11.3 Project Applicability

This project has prepared us for our future careers in many ways. Time management was the key part of this project, putting in the hours to ensure everything we worked on looked good and was submitted on time. The design process was key to making sure the team was following steps to ensure a high-quality robot that ran smoothly and met the requirements given by the client. Being able to work with a team allowed us to learn how to communicate and be respectful to each other even if our ideas didn't meet. Working with a client for the first time was a real eye-opener for the entire team as we met with him every week to ensure we were meeting his needs and getting important input on our design process. The most important parts of our robot were manufactured by the machine shop so understanding their needs for design drawings helped us learn what might be needed like this in the future. Overall, this project was an important steppingstone for the entire team to learn and be a part of a design process that will one day help others learn as we did ourselves.

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13 APPENDICES

13.1 Appendix A: Bill of Materials

Bill of Materials (BOM)										
Item #	**Item**	**Item Description**	**In Hand/In Progress/ Not In Hand**	**Vendor**	**Make/Buy**	**E.T. Make (hr)**	**Part Number**	**Quantity**	**Total Cost ($)**	**Cost Per Unit ($)**
1	Motors	EC Maxon Brushless Motor	In Hand	Maxon	Buy	0	283873	3	$1,963.50	$654.50
2	Flange 3/4" Bearing	Base Bearing	In Hand	Amazon	Buy	0	60355K297	1	$12.25	$12.25
3	Hex Bearings	Link Bearings for knuckle	In Hand	McMaster-Carr	Buy	0	6661K11	10	$104.28	$10.43
4	Hex Nut	1/4" - 20	In Hand	Home Depot	Buy	0	154209	38	$4.52	$4.52
5	8mm Shaft	Used for the 8mm and 6mm pulley reels, Aluminum	In Hand	McMaster-Carr	Make	4	4138N71	3	N/A	N/A
6	Coupler	Connects the motor shaft to the coupler shaft	In Hand	MiSUMi	Buy	0	CPS20-5-6	3	$50.38	$25.19
7	Coupler Screw	Used to tighten the coupler to the shaft	In Hand	MiSUMi	Buy	0	CPS20-5-6	12	N/A	N/A
8	Pulley Set	Used to tighten	In Hand	MiSUMi	Buy	0	PSFJU8	4	$46.86	$15.62

	Screws	the driven pulleys down								
9	Wood Base (MDF)	Holds the robot	In Hand	Home Depot	Make	2	219743	1	$30.00	$30.00
10	1/2" Aluminum Rods	Machined to be shafts for pulleys	In Hand	Amazon	Buy	0	9038k34	3	$33.87	$33.87
11	8mm Bearing	Hold coupler shaft within fin bracket	In Hand	Amazon	Buy	0	5972K91	6	$28.92	$4.82
12	Motor Screws M3x10mm	Holds the robot to Fin Mount 10mm long	In Hand	McMaster-Carr	Buy	0	91290A106	15	$12.04	$12.04
13	1/4" x 2.0" Hex Bolts	Bolts for the motor mount	In Hand	Home Depot	Buy	0	1002626453	24	$4.72	$0.20
14	3/8" x 2" Bolts	Bolts for motor mounts to links and base	In Hand	Home Depot	Buy	0	805386	4	$2.72	$0.68
15	10-32 x 2in Machine Screw	Machine Screws to hold rotating base	In Hand	Home Depot	Buy	0	458052	4	$5.28	$1.32
17	1/4" x 1" Bolts/Nut Set	Bolts for motor mounts and	In Hand	Home Depot	Buy	0	800596	10	$1.90	$0.19

		reduction assembly								
18	1/2" Hex Shaft	Machined to be joint pin for arms	In Hand	McMaster-Carr	Make	2	8875k74	3	$29.09	$29.09
19	1/4" - 20 x 1/4" Set Screws	Set screws for pulleys	In Hand	Home Depot	Buy	0	756279	12	$16.50	$2.75
20	2" Square Aluminium Stock	Used to machine arms out of and motor mounts	In Hand	Online Metals	Buy	0	1120	1	$164.79	$164.79
21	100mm Pulley Reel	Located at the first U-Joint and base of Rod Shaft, 3-D Printed	In Hand	Idea Lab	Make	18	N/A	1	N/A	N/A
22	200mm Pulley Reel	Located next to the 60mm pulley reel, 3-D Printed	In Hand	Idea Lab	Make	18	N/A	1	N/A	N/A
23	150mm Pulley Reel	Located at the second joint at the top, 3-D Printed	In Hand	Idea Lab	Make	18	N/A	1	N/A	N/A
24	60mm Pulley Reel	Located next to the 10mm pulley	In Hand	Idea Lab	Make	12	N/A	2	N/A	N/A

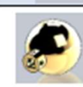
		reel, 3-D Printed								
25	Handle	Swivel Handle, Gold Ball, 3-D Printed	In Hand	Idea Lab	Make	2	N/A	1	N/A	N/A
26	Pully Mount	Machined pulley mount for arms and base	In Hand	McMaster-Carr	Make	24	N/A	3	N/A	N/A
27	Fin Motor Mounts	Attaches to motor and homes pinion pulley	In Hand	McMaster-Carr	Make	9	N/A	3	N/A	N/A
28	Fin Motor Mount Washers	Attaches to motor mounts and holds bearings	In Hand	Idea Lab	Make	7	N/A	14	N/A	N/A
29	Hex Bearing Washers	To Secure Hex Bearings	In Hand	Idea Lab	Make	3	N/A	7	N/A	N/A
30	Wood Base (MDF)	Wood Base square to mount robot on	In Hand	Home Depot	Make	4	N/A	1	$30.00	N/A
31	Second Arm	Machined to be Arm with handle on end	In Hand	Online Metals	Make	7	N/A	1	N/A	N/A
32	First Arm	Machined to be second arm, hold one motor	In Hand	Online Metals	Make	7	N/A	1	N/A	N/A

		mount								
33	Base Arm	Machined to be base arms holds one motor and pulley mounts	In Hand	Online Metals	Make	7	N/A	1	N/A	N/A
34	42mm Intermediate Pulley	Attached in the middle link to connect the middle shaft with the top pulley	In Hand	Team Printer	Make	4	N/A	1	N/A	N/A
		Total				148		194	$2,541.62	

13.2 Appendix B: Manufacturing Plan/Hardware Used

Manufacturing Plan

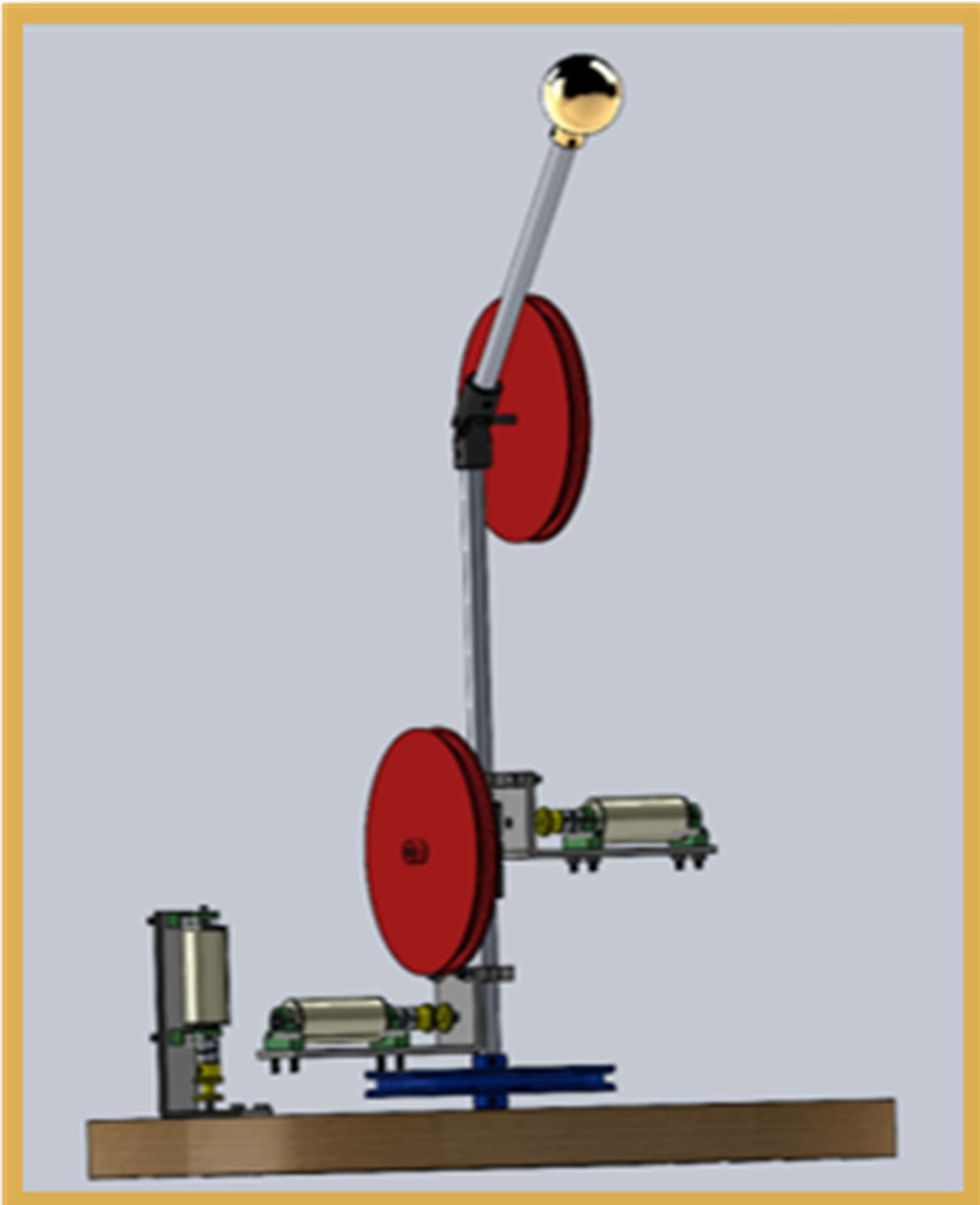
Item	Item	Item Description	Vendor	Make/Buy	E.T. Make (hr)	Part #	Quantity	Image	Total Cost ($)
1	Motors	EC Maxon Brushless Motor	Maxon	Buy	0	283873	3		$0.00
2	Steel Cable	For Pulleys	Chase	Buy	0	NA	1		$0.00
3	Hex Bearings	Link Bearings for knuckle	McMaster-Carr	Buy	0	6661K11	10		$304.28
4	Hex Nut	1/4" - 20	Home Depot	Buy	0	154 209	38		$4.52
5	8mm Shaft	Used for the 8mm and 6mm pulley reels, Steel	McMaster-Carr	Buy	3	NA	3		$0.00
6	Coupler	Connects the motor shaft to the coupler shaft	MiSUMi	Buy	0	CPS20-5-6	3		$50.58
7	Coupler Screw	Used to tighten the coupler to the shaft	MiSUMi	Buy	0	CPS20-5-6	12	NA	$0.00
8	Pulley Set Screws	Used to tighten the driven pulleys down (d – 6.35mm, L –26 mm)	MiSUMi	Buy	0	PSFJU8	4		$2.78
9	Wood Base (MDF)	Holds the robot	Home Depot	Buy	2	NA	1		$30.00
10	1/2" Aluminum Rod	Machined to be shafts for pulleys	McMaster-Carr	Buy	4	9038k34	1		$15.87
11	8mm Bearing	Hold coupler shaft within fin bracket	McMaster-Carr	Buy	0	5972K91	6		$28.92
12	Motor Screws M2.5x0.45	Holds the robot to Fin Mount 16mm long	Maxon	Buy	0	91290A106	15		$12.04

15	13	1/4" x 2.0" Hex Bolts	Bolts for the motor mount	Home Depot	Buy	0	1002 626 453	24	NA	$3.18
16	14	1/4" x 2.5" Bolts	Bolts for motor mounts to links and base	Home Depot	Buy	0	805386	4	NA	$2.72
17	15	10-32 x 2in Machine Screw	Machine Screws to hold Rotatiing base to lazy susan	Home Depot	Buy	0	458 052	4	NA	$1.32
18	16	1/4" x 1" Bolts/Nut Set	Bolts for motor mounts and reduction assembly	Home Depot	Buy	0	800596	10	NA	$1.90
19	17	1/2" Hex Shaft	Machined to be joint pin for arms	McMaster-Carr	Buy	2	8875K74	3		$29.09
20	18	1/4"- 20 x 1/4" Set Screws	Set screws for pulleys	Home Depot	Buy	0	756 279	12		$7.43
21	19	200mm Pulley Reel	Located at the first U-Joint and base of Rod Shaft, 3-D Printed	IDEA Lab	Make	24	NA	1		$34.00
22	20	100mm Pulley Reel	Located next to the 60mm pulley reel, 3-D Printed	IDEA Lab	Make	18	NA	1		$34.00
23	21	150mm Pulley Reel	Located at the second joint at the top, 3-D Printed	IDEA Lab	Make	18	NA	1		$34.00
24	22	60mm Pulley Reel	Located next to the 10mm pulley reel, 3-D Printed	IDEA Lab	Make	12	NA	2		$34.00
25	23	42mm Intermediate Pulley	Reduction pulley used to connect the top pulley with the middle shaft	IDEA Lab	Make	4	NA	1		$40.00
26	24	Handle	Swivel Handle, Gold Ball, 3-D Printed	IDEA Lab	Make	2	NA	1		$34.00
27	25	Bearing Washers	To secure bearing connection on Lazy Susan	IDEA Lab	Make	2	NA	14		$34.00
28	26	Pulley Reduction Washer	To secure the bearing on the pulley mount	Personal Printer	Make	3	NA	1		$0.00
29	27	Pully Mount	Machined pulley mount for arms and base	IDEA Lab	Make	24	NA	2		$400.00
30	28	Fin Motor Mounts	Attaches to motor and homes pinion pulley	McMaster-Carr	Make	9	NA	3		$0.00
31	29	Base Arm	Machined to be base arms holds one motor and pulley mounts	Online Metals	Make	7	NA	1		$0.00
32	30	First Arm	Machined to be second arm, hold one motor mount	Online Metals	Make	7	NA	1		$0.00
33	31	Second Arm	Machined to be Arm with handle on end	Online Metals	Make	7	NA	1		$0.00
34			**Total**			148		184		$936.43

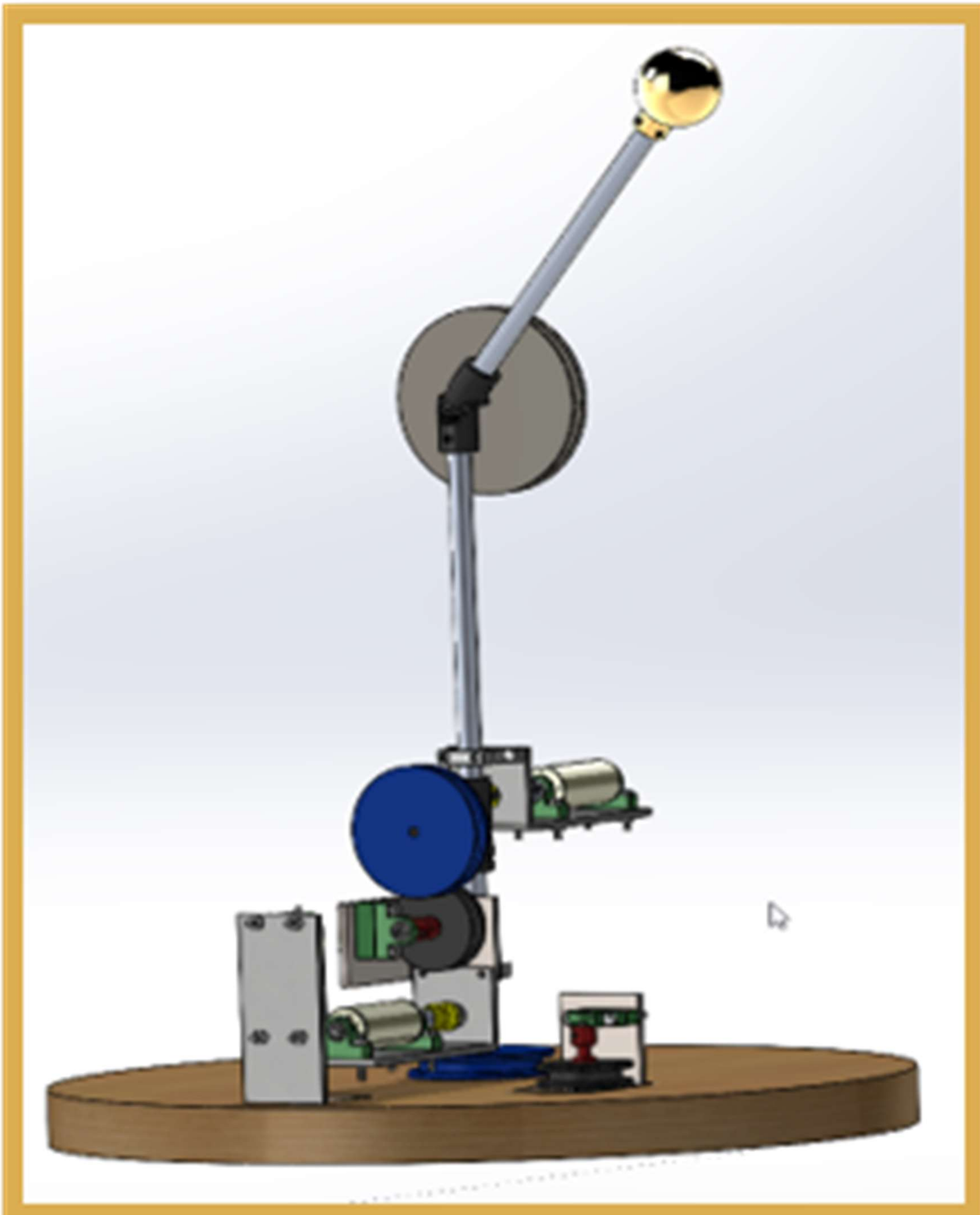
13.3 Appendix C: Design Iterations

13.4 Appendix C.1: Design Iteration One

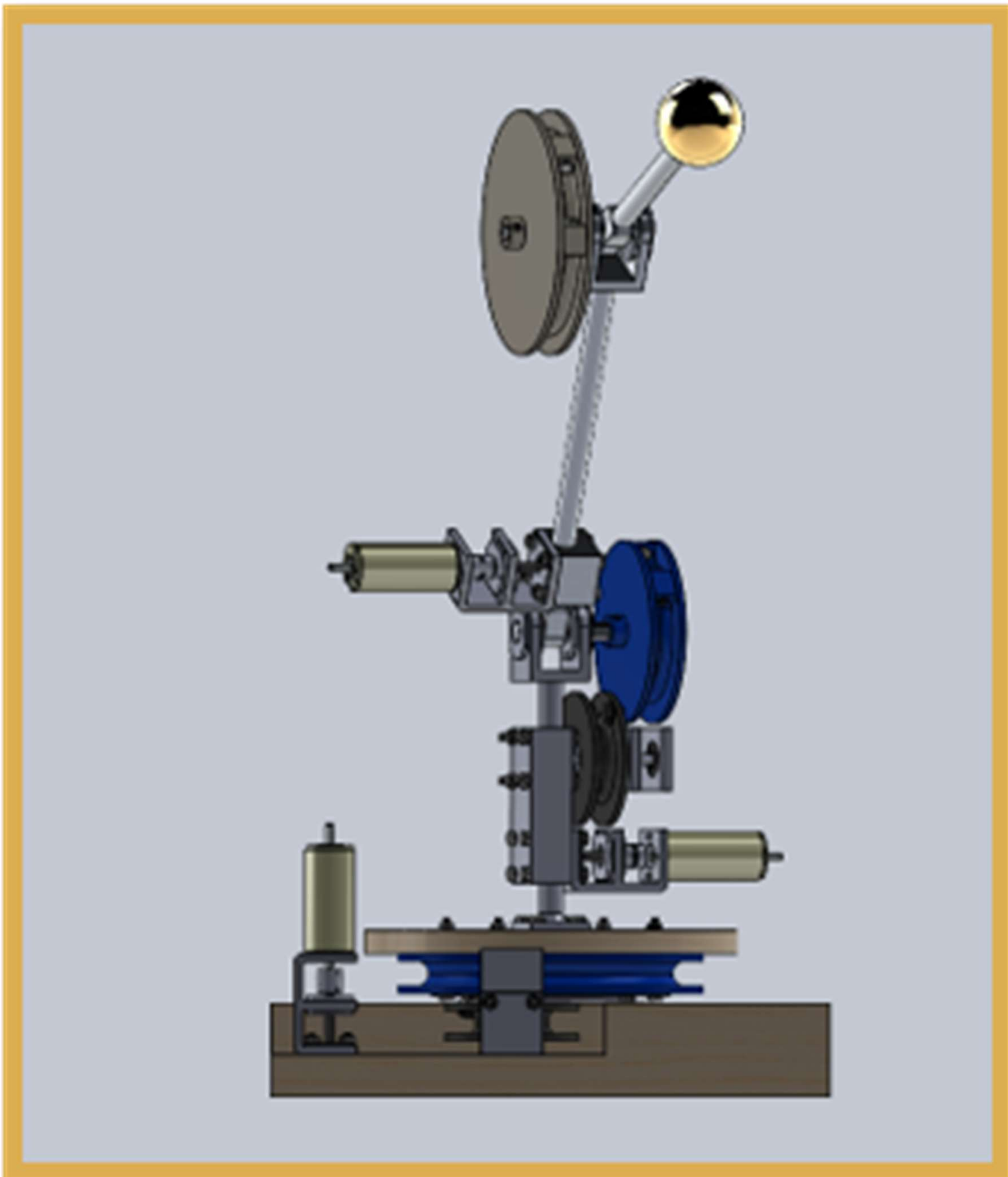
13.5 Appendix C.2: Design Iteration Two



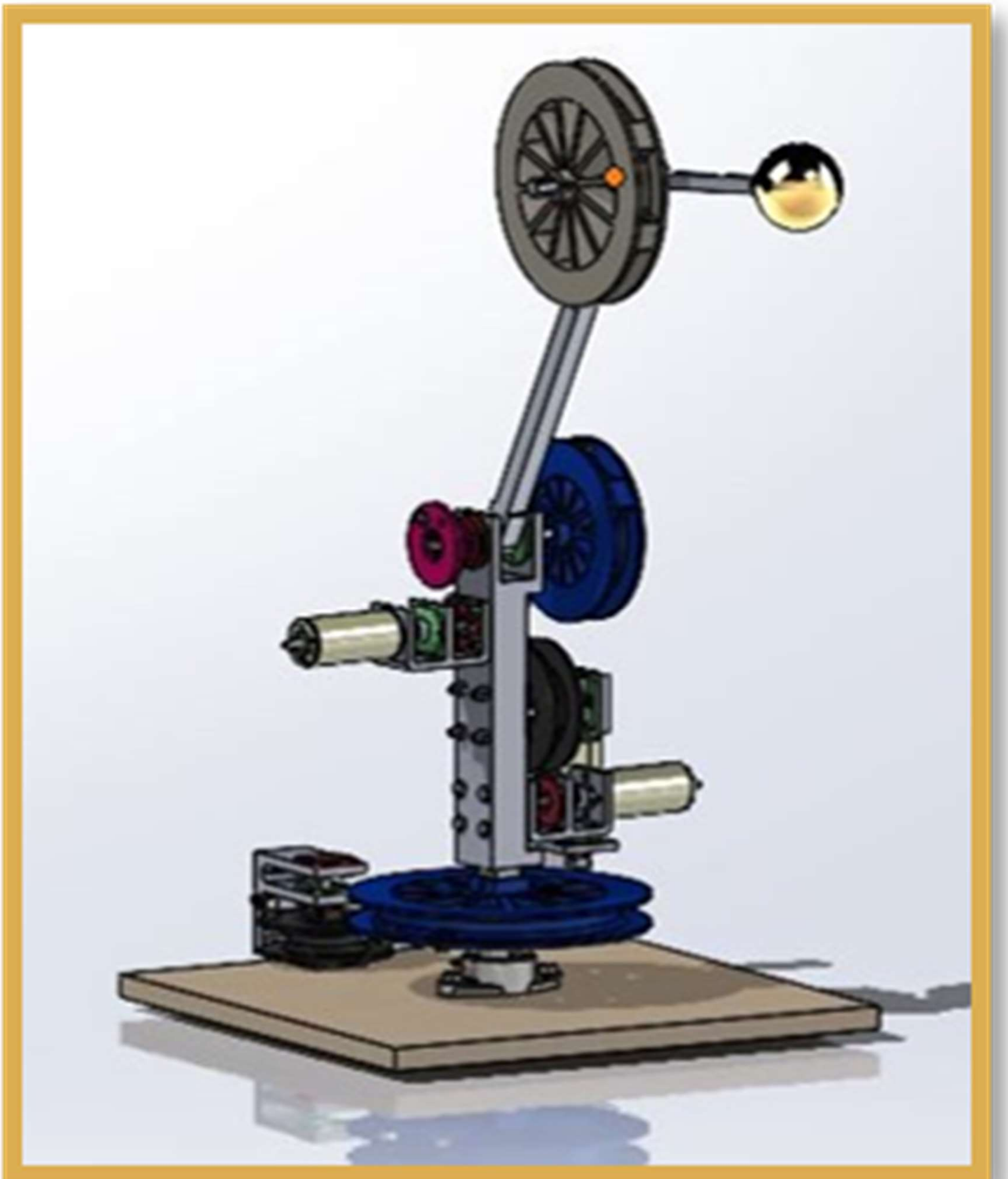
13.6 Appendix C.3: Design Iteration Three



13.7 Appendix C.4: Design Iteration Four

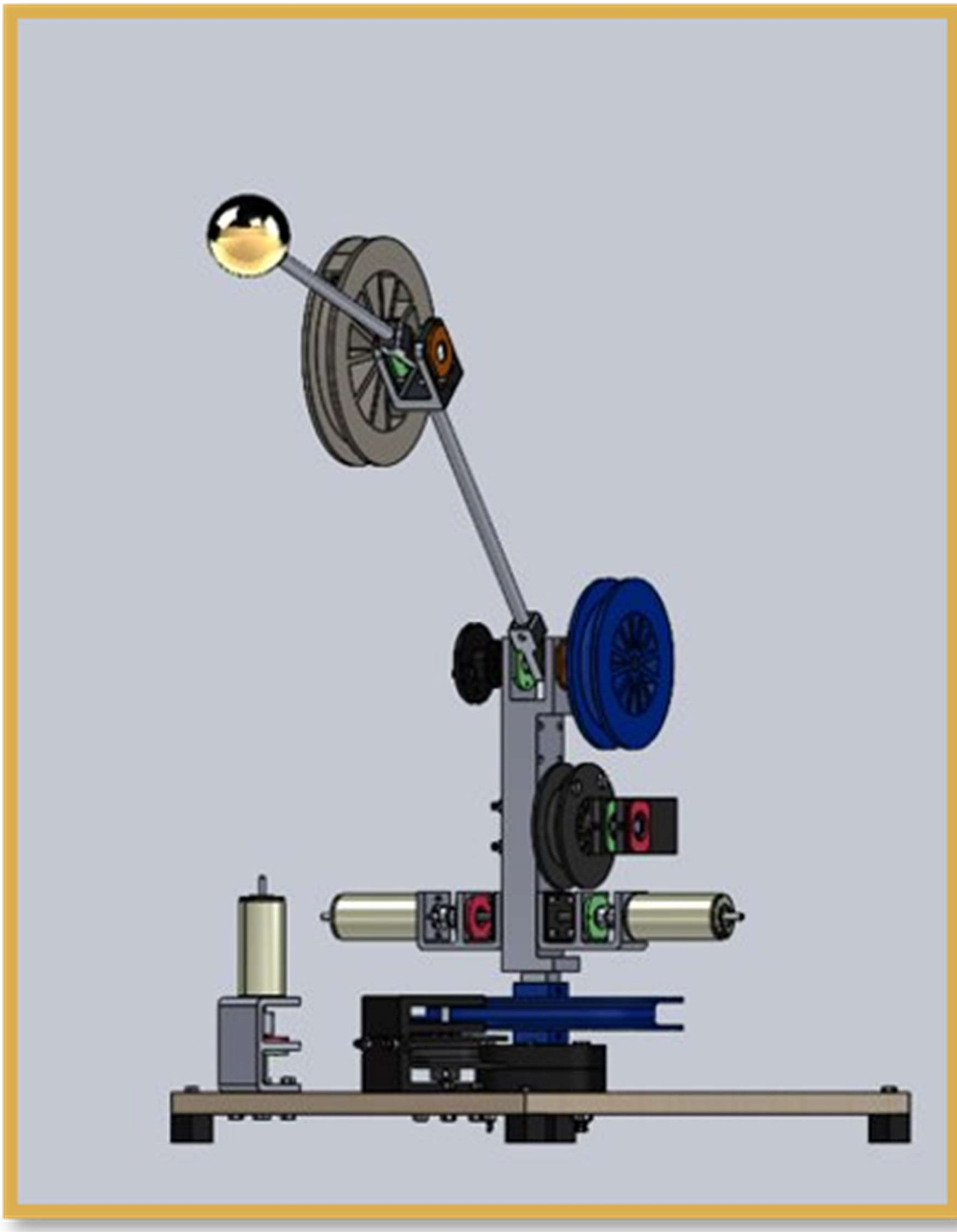


13.8 Appendix C.5: Design Iteration Five



13.9 Appendix D: First Prototype

13.10 Appendix E: Final Design



13.11 Appendix F: Final Design