Haptic Robot

Preliminary Proposal

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DISCLAIMER

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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 and 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 protype 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 remain 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 "soft" touch). However, feedback delays, quantization in sensor readings, and noise can destabilize the system, limiting the admissible feedback gains, 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 [1]). 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 force capacity of ~10 N. These specifications of the robot, although sufficient for small applications such as tele-manipulation, is limiting for more demanding biomedical applications such as a rehabilitation robot. 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 [2] with a price tag of +$75k. However, even the WAM robot suffers from suboptimal haptic rendering performance, mostly due to slow controller update rate (~1.8 kHz) caused by its aged technology.

This project aims to design the next generation of open-source haptic robot, 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, 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)

1. **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.

2. **Affordable- 3**

The budget is given, it is $2,000.00 USD and has little room for flexibility. The client has understood the budget might need to increase depending on part costs that are approved of. The team is now tasked with trying to stay under the budget if possible.

3. **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 benefit. 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.

4. **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 high RPM for this to be achieved.

5. **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.

6. **Flawless Motion- 5**

Similar to stiffness depending on the design on the links, flawless motion requires 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 to meet this requirement. Machining parts so that they do not overlap is also important to lower friction, as well as fastening pieces tight.

7. **No 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.

8. **No 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. To limit friction means to maximize 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.

9. **Produce Force- 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 features 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 reasonable force.

2.2 *Engineering Requirements (ERs)*

1. Decrease Weight

Target goal: <50lbs

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.

2. Tolerance (Reliability)

Target goal: <1% of any requirement

This is a general tolerance for any measurement required by the client or general engineering requirements. This will allow the team to easily calculate and predict how the robot's components will react to loads. By using Matlab Simulink, the team will organize all calculations through a program which will provide useful information for the team to consider. These numbers tell the team if building the robot with specific materials will work or not.

3. Material Strength (Durability)

Target goal: >2 GPa

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.

4. Force

Target goal: >20 N

The robotic arm must produce a maximum force 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 it is possible/ likely we can design for the robot to produce more force.

5. Reduce Friction

Target goal: <1 N

The robot must be able to move freely without 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. If a cable design is used, friction is necessary but can be managed to create more torque.

6. Speed

Target goal: >1m/s

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 minimum 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.

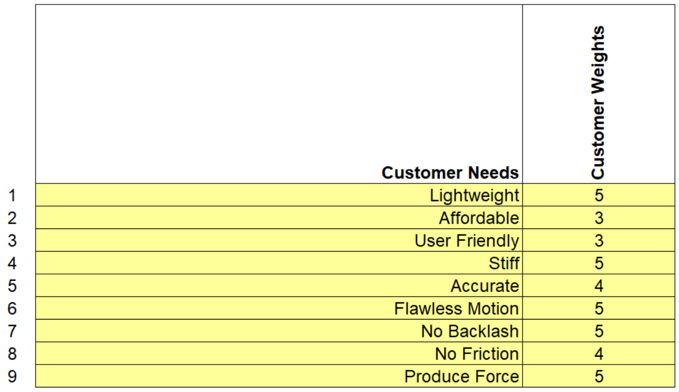
7. Electrical Power

Target goal: >100W

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 use of a mechanical system that is powerful enough to meet other requirements such as the output force of 20 N.

2.3 *House of Quality (HoQ)*

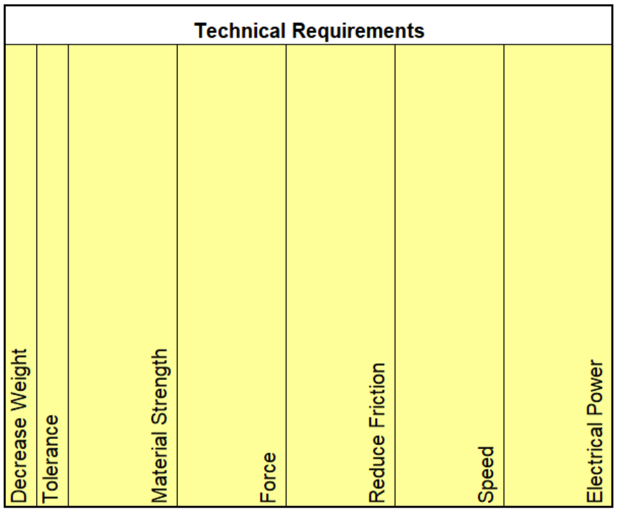
The purpose of the House of Quality (HoQ) is to help clarify the importance of each customer and engineering requirement by weighing and comparing them to each other. The HoQ, located in the Appendices section under Appendix A, shows the entirety of the HoQ process and *Figure 1* below shows the first step which is listing the customer requirements and weighing them according to their importance. The most important requirements the client would like are the weight of the product, flawless motion when in use, and it has to produce a certain amount of force to be used in rehabilitation.



	Customer Needs	Customer Weights
1	Lightweight	5
2	Affordable	3
3	User Friendly	3
4	Stiff	5
5	Accurate	4
6	Flawless Motion	5
7	No Backlash	5
8	No Friction	4
9	Produce Force	5

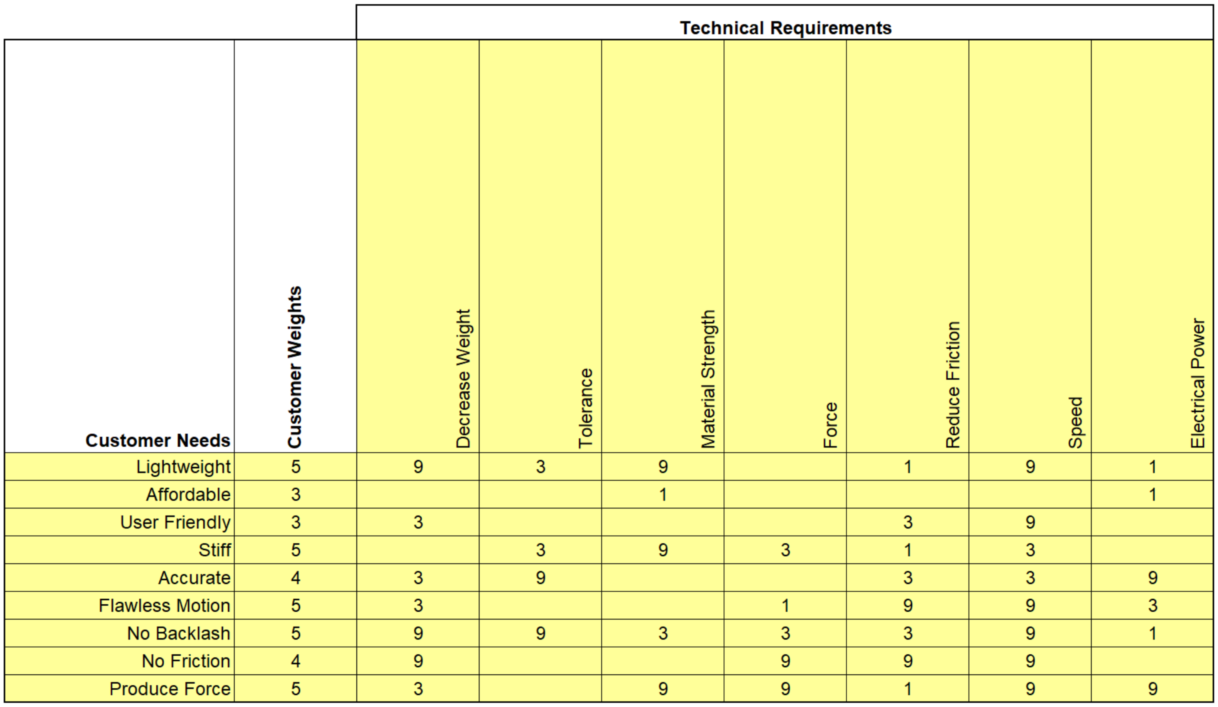
Figure 1: Weights of Customer Needs

Figure 2 shows the technical requirements needed to create a successful design. The customer requirements and technical requirements are graded using a correlation scale. In *Figure 3*, you will find how the team compared the technical and customer requirements using a single number in each box. If the box shows a nine, the two are highly correlated to each other, a three means they are moderately correlated, a one shows no correlation, and if the box is left blank it is a zero and that means there is no correlation between the two.



Technical Requirements						
Decrease Weight	Tolerance	Material Strength	Force	Reduce Friction	Speed	Electrical Power

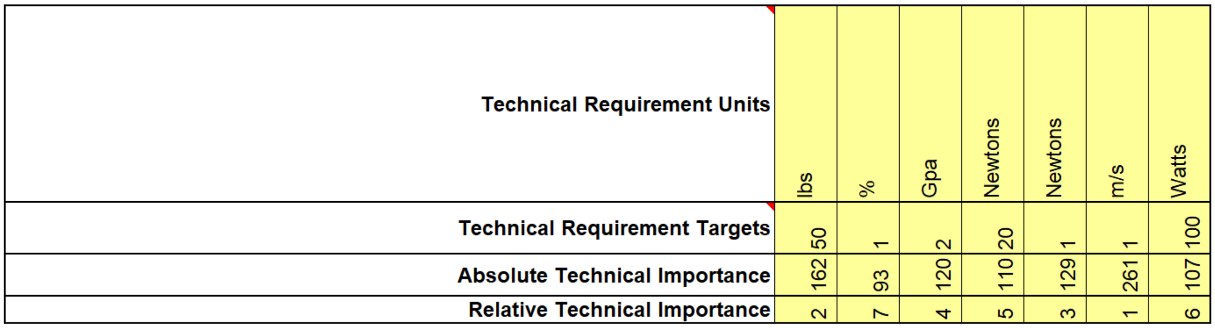
Figure 2: Technical Requirements



Customer Needs	Customer Weights	Decrease Weight	Tolerance	Material Strength	Force	Reduce Friction	Speed	Electrical Power
		Technical Requirements						
Lightweight	5	9	3	9		1	9	1
Affordable	3			1				1
User Friendly	3	3				3	9	
Stiff	5		3	9	3	1	3	
Accurate	4	3	9			3	3	9
Flawless Motion	5	3			1	9	9	3
No Backlash	5	9	9	3	3	3	9	1
No Friction	4	9			9	9	9	
Produce Force	5	3		9	9	1	9	9

Figure 3: Grading of Technical Requirements & Customer Needs

After grading the technical requirements and customer needs, the last step of the process is to calculate the absolute and relative technical importance of each technical requirement. This shows which technical requirements the team needs to focus the most on throughout the design and testing process. In *Figure 4* below, you will find the relative and technical importance values. This figure also shows the target values for each technical requirement as well as the units for each. The first target value is 50lbs which falls under the decrease weight category. A very important customer need is a lightweight design, and after speaking with our client, the consensus was a goal weight of 50lbs with hopes to have an even lighter design. This allows the robot to move quicker as well as be easily transported if needed. To reduce weight while keeping a material strength of 2 GPa, the team feels carbon fiber would be the best option to use as the material for the robot. The robot must produce some sort of force to be used for rehabilitation therefore the client gave the team a target value of 20 N of force. The client also wants the user to be able to do one full arm movement across the body in approximately 1 m/s therefore in order to do so, the robot must have very little friction leaving the groups target value for friction 1 N and speed 1 m/s. Overall, the team would like to have a tolerance value no greater than 1% which allows for a high quality product and avoids any damage to the robot. Finally, the power output must be around 100 watts in order for the robot to perform up to the client's standards.



Technical Requirement Units	lbs	%	Gpa	Newtons	Newtons	m/s	Watts
Technical Requirement Targets	50	1	2	20	1	1	100
Absolute Technical Importance	162	93	120	110	129	261	107
Relative Technical Importance	2	7	4	5	3	1	6

Figure 4: Technical Requirements units, targets, and importance

3 DESIGN SPACE RESEARCH

Research is the fundamental step to start every engineering design and there are various existing designs that relate to the team project. The different sources that the team have chosen to be the main references for this project depend heavily on the important conceptual components that are considered to establish a strong basis in the project development. The following section provides insight on the sources that the team is using as a guide to learn and inspire from to optimize the design process in the project. In addition, the content of this chapter includes the individual literature reviews by each team member, benchmarking of the design, and the functional decomposition of the model.

3.1 Literature Review.

Below are the presented references based on categories that relate to the project which includes what each team member has been assigned to research and the important sources found relating to the team's project. In every sub-section of this content is team members' names, research category, and the relevant sources found along with a summary on every source.

3.1.1 Logan Schubert – Material

A big part of this project is determining the material that would be used for the haptic robot. Using references to obtain a better understanding of what materials other companies use and why they use them. This is important because using a heavier metal wouldn't allow the robot to have enough traction or using plastic for its light weight but won't have the material strength to handle the load that would be applied to the robot while in motion. In this section of the literature review will focus on the types of materials that would structure the robot and help the team determine the material for our design.

Reference 1: "Structural Materials for Robots" [32]

This source offers all the pros and cons for all types of materials. This website would be useful for our team because it would allow us to better understand what the different materials are used for in certain scenarios. This doesn't give the price of the material unfortunately but provides strength material information. For example, it tells if the material would be easy to machine if you were trying to shape or machine a part. It even gives information on the different types of plastic that could be used and the different stresses that it can handle. It also provides property tables for all the materials that are listed on the website which would help the team with future calculations.

Reference 2: "Design of a 7 degree-of-freedom Haptic" [31]

In this research proposal by Vanderbilt University explains the ins and outs of their design process of their haptic robot. This not only includes the design process but also the material they used to create the links for their robot. This will be helpful to the team because it will provide different options for creating the links material wise. For example, in this report they used a Derlin Acetal Resin that has a low weight and high stiffness. This is a type of plastic that has a very strong yield strength and density ration where the strength-to-wight ration is so high that it has a high value for a plastic material. Not only is this source useful by providing different materials but it provides many examples of drawings with multiple types of exploded views.

Reference 3: "Polymer Chemistry for Haptics, Soft Robotics, and Human-Machine Interfaces" [30]

This source was provided by the National Science Foundation. It provides information about the expansions of different types of polymer chemistry for haptics. This report highlights several applications of polymers which have shown a lot of potential in haptics showing different types of polymerization techniques. This will help show the advances in technology and chemistry that could be used for future haptic robots if we decided to continue this path with robotics. For example, this progress report goes over the types of haptics that involve touch like if you were to use a scree protector for your phone and put it on a robot hand for touch. These are super advanced techniques that will be used to broaden the haptic and robotics fields.

Reference 4: “Assessment of the suitability of industrial robots for the machining of carbon-fiber reinforced polymers” (CFRPs) [29]

In this article the author goes over the in-depth assessment of machine of carbon-fiber polymers for industrial robots. This will help the team learn more about using carbon fiber for the material of the robot as we are thinking of using this material. The highlights of this article include the delamination in robotic trimming that occurs from the speed of machining and hoes into detail about how the fibers of the carbon fiber react to the trimming. Machining these parts to build are robot are a large part to this design so understanding the ins and outs of how the material will fracture due to the cutting of certain pieces. It is found from this report that delamination occurs mostly when the feed rate and cutting velocity of the material are at a high.

Reference 5: ‘Processing, structure, and properties of carbon fibers” [28]

In this report the author goes over the history of carbon fiber from when filaments were first known. It talks about the processing, structure, and properties of carbon fiber which would be very useful in information needed for future calculations. The team can use this report to determine if the carbon fiber would be best fit for our robot based on the strength and modulus of the material. In specifics from the report, they speak mostly about the production of PAN based carbon fibers and how they stabilize in air and carbonization in the environment.

Joshua Dufek - Haptic Robots

For the team to understand what kind of robot to design, looking into current haptic robots will be crucial. Joshua has searched for various haptic designs to learn and facilitate different ideas for the team to consider. Most robots researched use expensive parts and reside well outside the given budget due to their high quality. This section will focus on the variety of mechanisms used to move the designed robot as well as unique aspects for the team to consider from each design.

Reference 1: “Wooden Haptics” [1]

This source is a website link that has other links to videos and a pdf of the wooden haptic device. It is useful to the team because it demonstrates usage of a computer program to achieve realistic physical properties of multiple objects. The pdf shows “Wooden Haptics” have designed a haptic arm robot that holds a notable red ball on the end for the user to grab. The mechanism for the movement is a pulley/capstan design, consisting of multiple high-tension cables. This design is somewhat lightweight and is very accurate with no backlash due to the cable. It uses wooden parts cut from plywood sheets and metal fasteners like screws. There are built in sensors based on the motors movement that provide the haptic feedback. Main takeaways from this source are the pulley/capstan design and wooden material for the structure, which is a very lightweight/cheap option to consider.

Reference 2: “Haptic Grip Handle” [16]

There are different ways someone can benefit from haptic response in a robot. This source is an article on the pressurized handle grip and the usefulness of the design. This handle has multiple pressure sensors that give feedback to a computer when it is squeezed by the user. It can increase its internal pressure to create more resistance from being squeezed. The purpose of the design is to be compatible with numerous computer programs for rehabilitation of stroke patients, such as constant pressure gripping and even video game simulation exercises. The handle can only work with flexion of the fingers and hand joints, which limits its use. The handle device shows the team a way to make the haptic robot function, by gripping and squeezing a handle as an exercise.

Reference 3: “Five-Fingered Haptic Robot” [9]

This source is an article on a five fingered haptic feedback robot. It is similar to a hand in that it records movements from a person’s hand and renders it in a program to replicate the motion. The producers of the “HIRO II” design stated, “we concluded that the desirable attributes for a haptic interface include the following: The haptic interface must be safe, function in a wide space, and present not only three-directional force at the contact points but also the weights of virtual objects,” (unknown, 2021). Our team’s model may consider utilizing sensors so that the robot can respond to the force input instead of only having a program for movement. The HIRO III also uses multiple joints to achieve the 15 degrees of freedom, some of which rely on small gear systems. The links in the HIRO III’s hand and our current model are very similar in shape, different in size. Overall, this source shows the team how we can build a robot with multiple links connected to each other and have the required 3 degrees of freedom. It has also given insight into how we can incorporate sensors into our model for further haptic feedback.

Reference 4: “HIRO II haptic robot” [15]

This source is a thesis on a pre-existing 3-degree of freedom robot added to a new 4 degree of freedom design to create a 7 degree of freedom medical haptic robot. It was built so that it gives a minimum 2 N of force in any direction because 2 N is not enough to injure a user. This is a requirement the team has taken into consideration for the design. Additionally, “low inertia is critical to provide a sense of transparency to the user” (Marince, 2015), another key requirement our client has demanded from our design. The base robot uses a parallelogram design where the second and third motors move the same main link. This design is something the team has also considered as it would keep the motors down low and reduce the moment of inertia while the robot is in motion.

Reference 5: “Haptic robotic arm (IRJET)” [2]

The last source is a small article on the design of a haptic robot arm on top of a set of wheels. It uses a few different sensors that signal a computer program where the horizontal/vertical inclination the arm is currently at and the current bend of a claw. These sensors might prove useful to our team’s design since we still need to figure out how the robot will know when to turn, extend, or retract based on its position in 3D space. The haptic robotic arm uses a microcontroller to give commands to the robotic arm based on what the user of the haptic glove is doing. This allows the robot to pick up and move lightweight items while the user is far away from the robot. Although our design will most likely use a responsive system to move, this design using a haptic glove is still useful for motor movement when commanded properly.

3.1.2 Christopher Hernandez - Rehabilitation

The main goal for this robot is to be used for people who have had a stroke, had cerebral palsy, or just need some form of arm rehabilitation. In this section, Chris provides information on the effects of cerebral palsy as well as stroke survivors, how they undergo rehabilitation, and some of the different current tools used during the rehabilitation process. This section gives the team insight on how to go about their design and keeps in mind what the main goal for this product is.

Reference 1: “What is Cerebral Palsy?” [13]

This reference is relative to the project because it provides information on cerebral palsy and what those with the disorder go through on a daily basis. Cerebral Palsy is caused by abnormal brain development that affects a person's ability to control their muscles, as well as maintain their balance and posture while trying to move. Another side effect of CP is stiff muscles causing spasticity, not allowing a person with CP to properly gain strength in their muscles with certain workout exercises. This robot would be able to assist those with CP during their rehabilitation exercises by giving them more control of their body while getting stronger as time goes on.

Reference 2: “Physical Therapy for Cerebral Palsy” [10]

This article goes over the goals for Cerebral Palsy patients during their rehabilitation process. By performing positive actions, the brain is able to make adaptive changes to make those actions permanent. While CP is an ongoing condition that will never be 100% irreversible, doing rehabilitation exercises allows those with CP to perform their day-to-day tasks more efficiently. Some of the exercises include stretching, range of motion exercises, and strengthening exercises. This robot will help aid those with CP in all of these tasks to help them live a better life despite their barriers.

Reference 3: “Stroke Exercises for the Full Body” [12]

This robot can also be used to help those who have suffered from a stroke regain the strength in their muscles. After suffering a stroke, one of the most common effects is paralysis in one side of the body. This will affect a person's day-to-day activities therefore they must regain the strength in their body through rehabilitation to get back to their normal selves. Some of the exercises used during the rehabilitation process include circular arm motions with a weight, pushing of weights, and cross body arm exercises. The robot being designed for our client will be beneficial in the rehabilitation process because it will be able to produce a force which acts as a resistance to allow the user to build their strength. The robot will have three degrees of freedom allowing it to move in any direction for any exercise and as the user gets stronger, the force applied can increase to help gain full muscle recovery.

Reference 4: “Resistance Training” [14]

The best way to describe the use of this robot is using resistance bands during the rehabilitation process. Using resistance bands allows the body to recover in a cheap, user-friendly way. By creating this robot, there is more stability, meaning if the user has a muscle spasm, the robot will be in more control allowing for a safer recovery process. Often times when a stroke or CP patients are doing their recovery exercises, they can have a muscle spasm causing a resistance band to snap which could lead to another injury. This product reduces that risk factor and can help with a quicker recovery by eliminating any potential injuries.

Reference 5: “Robotic Device for Post Stroke Rehabilitation” [11]

As mentioned previously, those who have suffered from a stroke lose some or all mobility in one side of their body. This forces physical therapists to exert energy while working with their patients through every exercise they do. This article goes into detail as to why haptic robots are the future for rehabilitation as well as how they will be implemented for those who have suffered from a stroke. Most of the exercises stroke patients undergo are recreating muscle memory. By using a robot during these exercises, it cuts down on costs, as well as creating a more personal rehabilitation process for the user. This process also allows the physical therapist to monitor the motions of the patients because they are not focused on doing the exercises with the patient allowing them to have a quicker and more effective recovery.

3.1.3 Rakan Alanazi - Degrees of Freedom in Robotic Arm

In this section, Rakan provides an insight into the resources that are considered essential in the research stage of this project. The content of the sources focuses on the degrees of freedom related to the team’s project which is set by the client to be 3 degrees with two linkage and a rotary shoulder as well as vertical and horizontal axial movement for the main links giving the robot arm 3-dimensional movement.

Reference 1: “Design of a Three Degrees of Freedom Robotic Arm” [17]

The purpose of this research is to design a 3 degree of freedom robotic arm that is actuated using servo motors which are controlled by a code iteration in Matlab. The robotic arm is designed to pick up and move light objects to different positions as the main objective of the robot. As the team is required to design a 3 degree of freedom robotic arm, this source carries effective information about math concepts, physical measurements in terms of dynamical motion, and fundamental operators to design a functional robotic arm.

Reference 2: “Design and Development of a Competitive Low-Cost Robot Arm with Four Degrees of Freedom” [18]

In this research design, the authors documented every specific engineering step taken and considered designing a 4-degree-of-freedom robot arm that accomplishes the tasks of moving items to different positions. In the research paper, it was apparent that the engineers chose a 4 degree of freedom to accommodate for economic and complexity limitations. Therefore, the team can use the information provided in this source to improve design ideas in terms of using accurate joints, links, and other components to achieve the required degree of freedom for the model.

Reference 3: “Development of a Hand-Assist Robo with Multi-Degree-of-Freedom for Rehabilitation Therapy” [19]

This source provides a deeper insight into the development of an arm robot that aids in rehabilitation. It is a very complex model; however, it is an effective source to use during the design process since the content of the research covers 18 DOF which ensures that any minor issues the team experiences are already covered in the content of this source. The team’s project carries the same end goal as the design of this source which is aiming toward rehabilitation and sensor feedback for the user.

Reference 4: “Unraveling Degrees of Freedom and Robot Axis” [20]

In this source, the author gives valuable information about the directional motion of the different robot parts based on the number of degrees of freedom. It is helpful for the team to understand what kind of axis produces a certain direction as it would improve the fundamental understanding of the functionality of the robot arm. The author of this content defines the motion effect of every axis between 1 & 6 and what type of movement it would produce.

Reference 5: “Everything About the Degrees of Freedom of a Robot” [21]

Understanding the meaning of a degree of freedom is essential in robotics in general and in this project specifically as it is one of the requirements that cannot be altered. In this journal post, the author thoroughly explains the idea of degrees of freedom and the necessary formulas that could be used when calculating the effects of DOF on the motion of the robot. The content goes in detail about determining the directions of movement in the different axis and how it can be effective. In addition, this source provides useful information about how the joints can affect the motion of the robot and the issues that it could have on the reduction of degree of freedom.

3.1.4 Thomas Filippini - Inertia in Robotic Arm and How it Relates to Motor Placement

When considering designs for a haptic feedback robot motor placement becomes a design challenge. As the robot moves through space inertia becomes a factor in functionality of the robot. The higher the inertia, the higher the strain that is placed on the links of the robot. Discussed in this section will be the advantages and disadvantages of certain motor placements as well as how inertia is effect.

Reference 1: “Rotational-Linear Parallels”

To give some background moment of inertia is a constant distribution on mass at a distance (24). The equation that defines the moment of inertia is mass times the radius of the length squared. This will be the force acting on the robotic arm when in motion. The longer the arm the bigger this force is going to be, same goes the mass at the end of the arm the larger the mass, the larger the force. Taking this factor into consideration the team will have to be mindful of the overall design on the robotic arm. As the design has to be feasible to produce the required torque need to support both the weight of the arm and the resistance being applied by the patient.

Reference 2: “Internal Forces of Robots and Manipulators”

This article investigates the how models are used to analyze internal for on a multi-link robot. Discussed in the article is the use of a “Point Mass Model” for inertia force analysis. For the convenience of the model concentrated masses are placed on the structure to replace rigid links which allows for a physical skeleton model to be created (26). From this the model can be dynamically analyzed which is shown throughout the paper. The author is also able to use vector coordinates to produce accurate position in space to be further analyzed. This is something to consider as the team further analyses the force experienced on the robotic arm. When the team starts implementing designs with different materials and mechanism well will be able to take into consideration the methods used in previous analysis. This will allow for the team to further optimize the design as the progress of the project continues in the latter half of the project.

Reference 3: “Design optimization on the drive train of a lightweight robotic arm “

Since inertia becomes a factor on the force that joints in a robotic arm experience optimization of the drive train come in focus. This article investigates the key components that make the performance of the robotic arm as optimal as possible like transmission of power from the motors, gears being used and the mother themselves. The first step was design consideration, the author of this article chose to create a five degree of freedom robotic arm. Next was designing the drive train on the joints of the robotic arm to produce the required torque. Using this formula where ρ is the gear ratio, Jg is gear inertia respect to motor axis, Jm is inertia of the motor and η gear efficiency. (x).

$$\tau_{m,i} = \left\{ (J_m + J_g)\ddot{\theta}(t)\rho + \frac{\tau(t)}{\rho\eta_g} \right\}_i; \quad i = 1,\ldots,5$$

Figure 5: (Description)

By optimizing gear and motor selection the author was able to achieve the desired output by using the MSC.ADAMS simulation package and optimization with a MATLAB algorithm. These aspects are areas to consider as we continue to develop and test concept ideas as the team gets further into the development of the project.

Reference 4: “Cable driven robotic joint”

This article details a unique design for cable driven robot joint with significant mechanical advantage and zero back lash. This is a design element the team has considered implementing in our design to keep the weight near the base to avoid high inertia. This design uses counteracting pullies which will run one cable and can be easily modified for mor mechanical advantage by either adding in more pulleys or adding in more cables. This mechanism is back drivable which can be used with a motor with an encoder to track position (8). This allows for the robot to be dynamically controlled, which is perfect for the team's needs. One thing to consider when going this route is the mechanism is reliant on the cables themselves, as over time cables can stretch and lose tension. Overall, this is a good design to consider when thinking about motor placement as the power of the motor can be delivered to another point on the robot without the weight of the motor causing inertia and allowing the robot to move faster.

Reference 5: “3D Printed Belt Driven Robot Arm”

In this article the author shows a 3D printed robotic arm which uses a combination of links and belts to provide three degrees of freedom. This article also provides a list of parts that are not 3D printed so it can be recreated at home. The whole thing is run by an Arduino controller and lower standard components (25). The controls are also open source which allows for anyone to modify the program to fit the needs of the user. When looking at this design, it does a really nice job of placing the motors much like the cable driven robot it will allow for the motors to be placed near the base of the arm. Which again keeps the inertia low on the whole system, it also utilizes two different techniques, one being belt to transfer the power of the motor to a mechanism nearby and links connect to farther arms. This design has proven to be helpful with the team's design as it allows us to explore more options to meet the customer's needs.

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 and specifically motorized robotic arms. Based on the client requirements, the team considered the WoodenHaptics robot in *Figure 6,* 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.

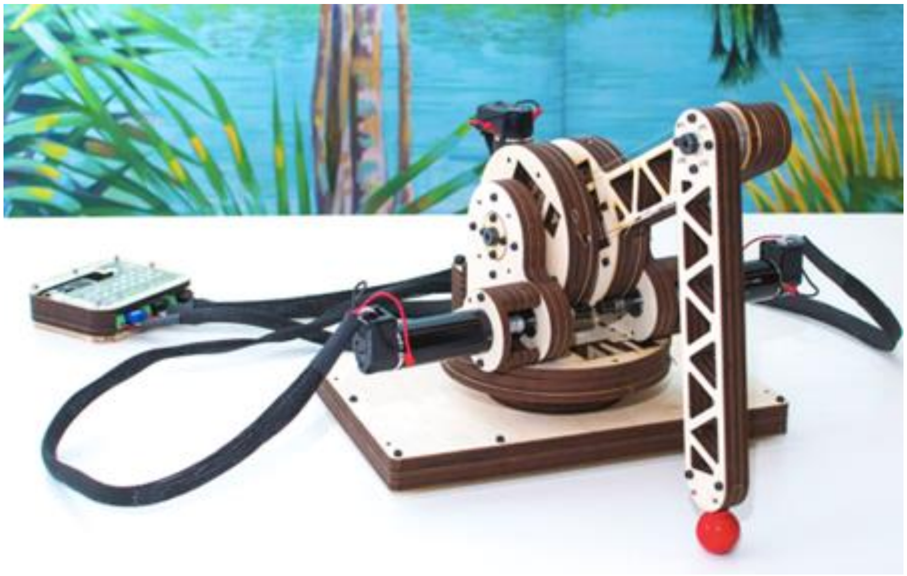


Figure 6: WoodenHaptics Robot

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 brief 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. 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 how each link will be actuated while in use. The WoodenHaptics 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 still 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 the when the robot was not in use it could possibly 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. Overall, the team feels the design of the WoodenHaptics robot would be our greatest inspiration as it checks off a number of boxes when it comes to our customer and engineering requirements.

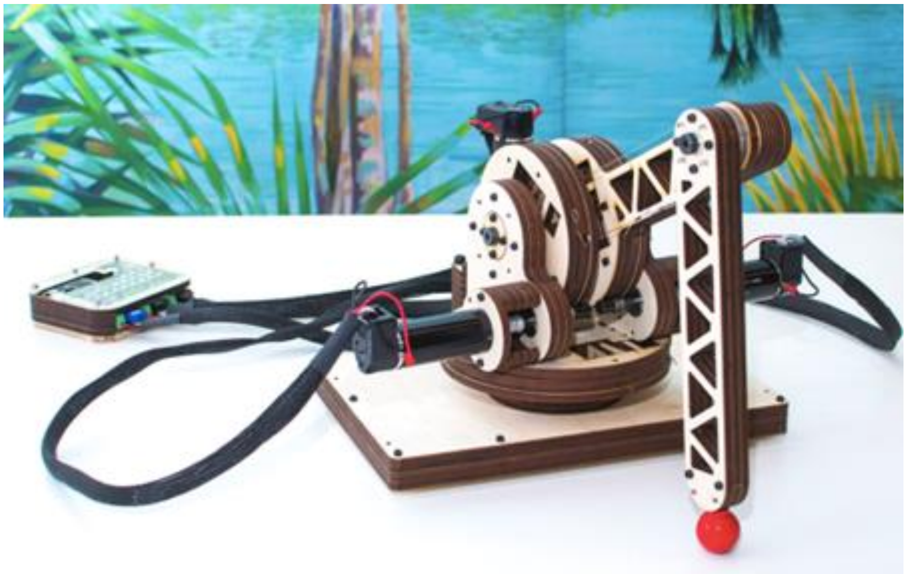


Figure 6: WoodenHaptics Robot

3.2.1.2 Existing Design #2: Haptx

The Haptx design shown in *Figure 7,* 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 7: 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 8,* 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 8: 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 criterion and weight of the technicalities. The subsystem's 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 a number of 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 mov in a flawless manner.

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. There are two links that are attached to the base of the robot that allow 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, 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 for inspiration with the hopes to implement a pulley system into the design. The robot being 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 together. 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 wat 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 object such as grips while other handles are designed to be held and moved by human body part such as a hand.

3.2.2.2.1 Existing Design #1: WoodenHaptics Robot

As shown in figure x 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 from 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 there are many technical challenges that 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 where 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 together. This design was initially used by the group for 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 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 withing 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 very 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 possibly be implemented into the final design of the haptic robot.

3.3 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 in 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.

3.3.1 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 the signals. The input and output in the black box will be the same on both sides. With the left side starting 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.

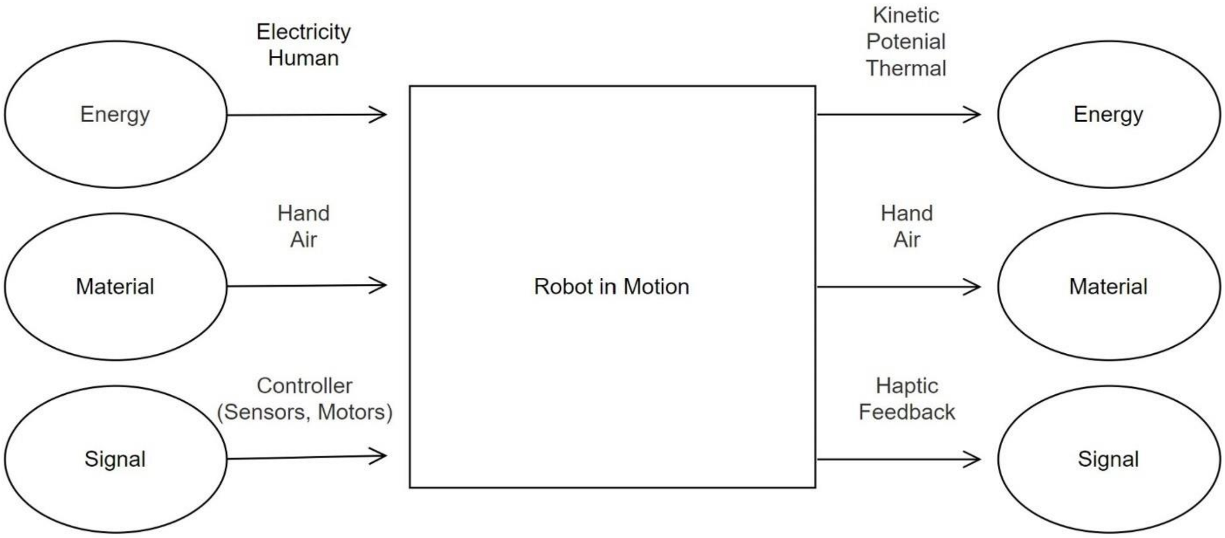


Figure 9: Robot Black Box Model

3.3.2 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 of the subsystem's input 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.

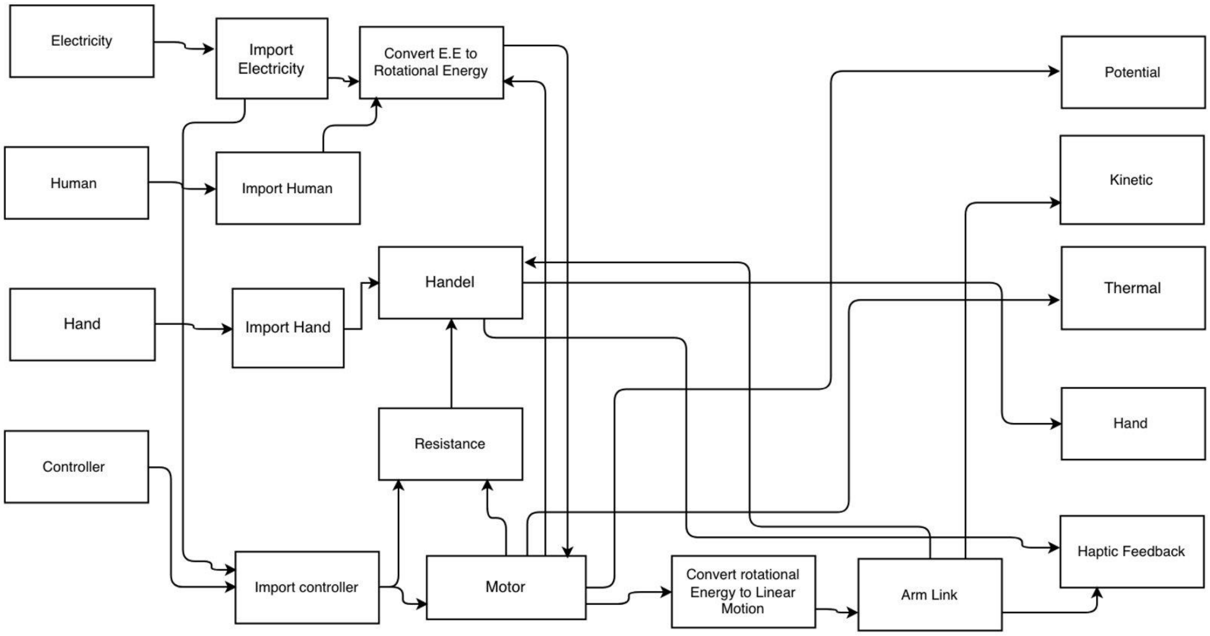


Figure 10: Robot Composition Model

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

This design uses the concept of using belts to translate the power of the motor to their respected links to provide the required three degrees of freedom. The first motor is mounted on a base extension to give it clearance and utilizes a belt to turn the attached link which holds the arms of the robot. From this first link which extends out to give clearance for the second motor to be mounted which will power the first arm of the robot. Then mounted on the other side of the joint for the first arm is motor number three which with the use of a belt can reach the gear for the second arm which will provide us with the total degrees of freedom needed. The disadvantage with this design is the arm of the robot is reliant on the fiction that the belt can hold. There is a chance for slippage which could cause the torque output not to be fully utilized. The advantage is using the belt system is that it keeps the moment of inertia low, allowing for faster movement of the arms and less strain on arms and joints when operational.

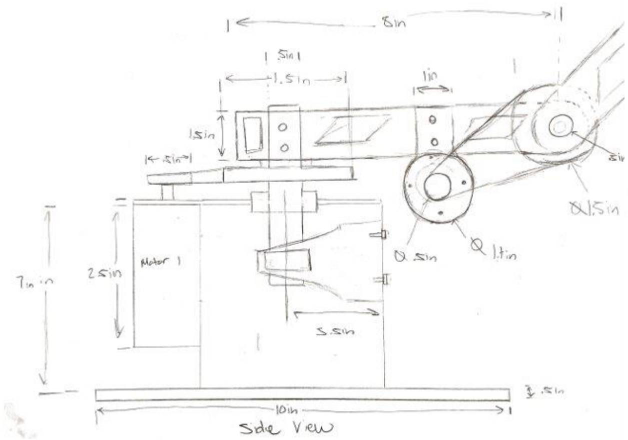


Figure 11: Tommy's design

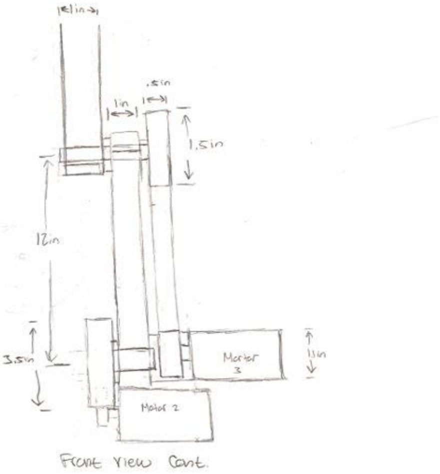


Figure 12: Tommy's design p.2

4.1.2 Full System Design #2: Differential gear system

This design utilizes a gear system for moving the robot links and has motor placement relatively low to reduce moment of inertia as the arm moves. The main feature is having a long shaft in the first link to transmit mechanical energy between the motor to a driven gear, which will rotate the second link. All parts are concealed in a carbon fiber tube housing, which reduces pinch points as well as makes the design look more professional (no loose wires or exposed mechanical parts). The top handle will be a rubberized grip handle, with an ergonomic shape for comfortability and ease of use. Motor 1 is placed vertically in the bottom joint, allowing for horizontal rotation. Motor 2 is located horizontally in the bottom joint, allowing the first link to rotate vertically. Last, motor 3 is placed vertically in the first link and has a long shaft with a pinion gear at the end to connect it to a driven gear. This allows the second link to have independent vertical rotation of the first link. Pros of the design: low moment of inertia based on part placement, comfortable handle, simple exterior features, quick-moving design. Cons: expensive and specific parts required, many parts required, long shaft increases torque against motor 3, all parts need to be placed carefully and accurately for gears to line up correctly.

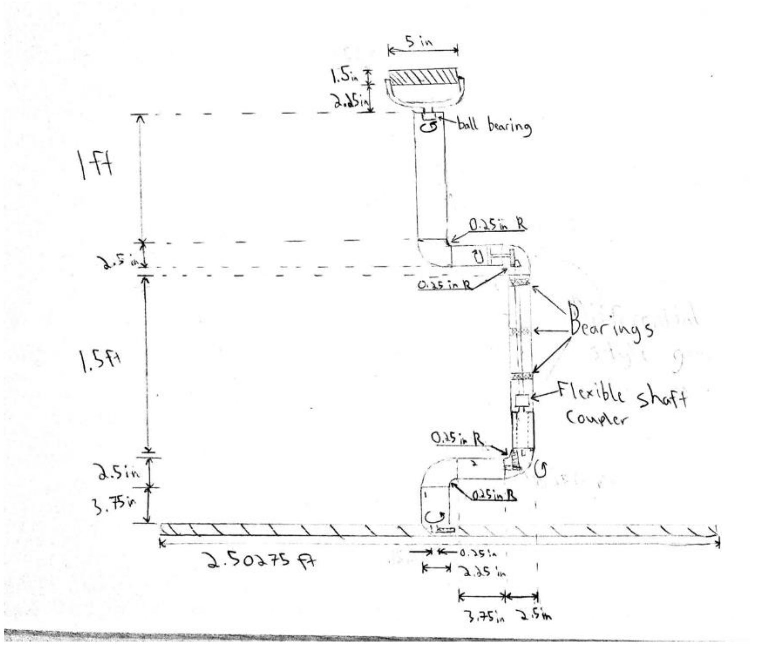


Figure 13: Joshua's final design drawing

4.1.3 Full System Design #3: Solid Joint Assembly

This design features a solid joint assembly where the motors are attached to coupling which are then attached to the links of the robot. The design looks very similar to the previous design however, the shaft is not nearly as long, and there is more space for the motor to fit within the links as the joints are not rounded off. There will be two motors within the base of the design that are hidden in a removeable drawer. These motors will actuate the rotating base of the design as well as feed wires through to actuate the first link of the robot. The third motor will be placed within the second link and will be significantly smaller than the other two, in order to reduce the amount of weight the link needs to hold. This will allow for the speed of the robot to increase as there will be no motors within the first link and very light motor in the second link. The entire robot will be controlled by the ball shaped handle at the end of the second link allowing the user to try and improve grip strength. Pros of the design: all motors are hidden, maintain 3 degrees of freedom, comfortable handle. The cons of the design would include added weight in the second link, slower reaction time due to added weight, and more room for error regarding backlash of the robot.

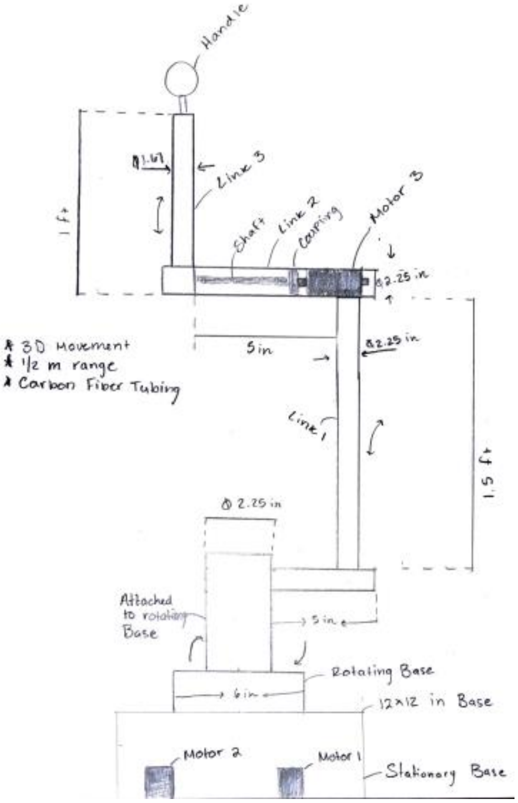


Figure 14: Chris' Design

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 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, the robot arm can move faster.

Cons: connecting motors to links can be difficult, torque against motors could increase.

4.2.1.2 Design #2: 2 on base platform,1 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: second link is actuated easier, and moment of inertia is relatively low.

Cons: speed must be reduced slightly, intricate design required to allow motor in first link.

4.2.1.3 Design #3: All 3 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, 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 with in 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 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: small number of parts, simple design, no backlash.

Cons: specific bearings required, can become expensive depending on coupling system.

5 DESIGNS 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 off 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. While the most important aspects to 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 which with the three remaining being used for the decision matrix to continue further grading.

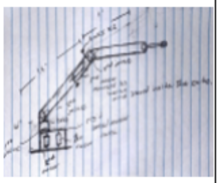
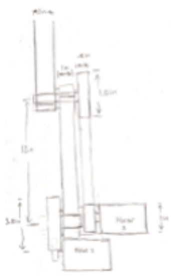
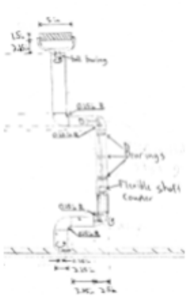
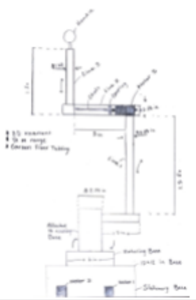
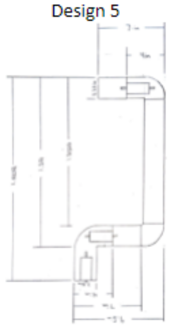
Concept → Criteria	Design 1 	Design 2 	Design 3 	Design 4 	Design 5 	Imprortance Rating
Cost	S	-	-		Baseline	3
Lightweight	-	S	S	S	Baseline	9
Range of Motion	-	S	S	S	Baseline	3
Durability	-	S	-	S	Baseline	3
Accuracy	S	+	+	-	Baseline	3
Speed	+	+	S	+	Baseline	9
Stiffness	-	-	+	S	Baseline	3
∑+	1	2	2	1		
∑-	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 15: Pugh Chart

To narrow down the design further a decision matrix used designs two, three and four were chosen to continue based off 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 had the ability to match the speed of the patient. Durability and accuracy had a weight of ten percent because this isn't a machine that will take much damage in its use and does not need to be use 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 means 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 being 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.

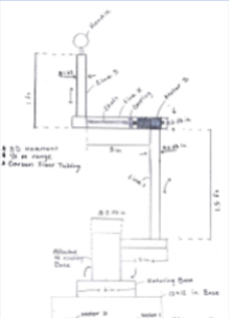
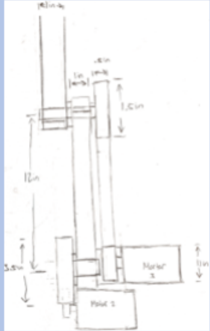
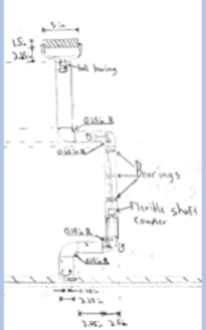
Criterion	Weight	Design 1 		Design 2 		Design 3 	
			Weighted Score	Unweighted Score	Weighted Score	Unweighted Score	Weighted Score
Cost	5	85	4.25	95	4.75	75	3.75
Lightweight	20	90	18	80	16	85	17
Range of Motion	20	100	20	100	20	100	20
Durability	10	75	7.5	75	7.5	70	7
Accuracy	10	90	9	90	9	90	9
Speed	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 16: Decision Matrix

5.2 Rationale for Design Selection

The team concluded the top two final designs for the Haptic Robot capstone project which are full system design 1 & 3 that 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 15* and narrowing the top three designs to be ranked in the Decision Matrix in *Figure 16*. In addition, the top designs were ranked using the decision matrix in appendix 7.2 B that is based on the requirements needed for the project. The criterion of each of the conceptual analysis charts are weighted based importance that effected 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.

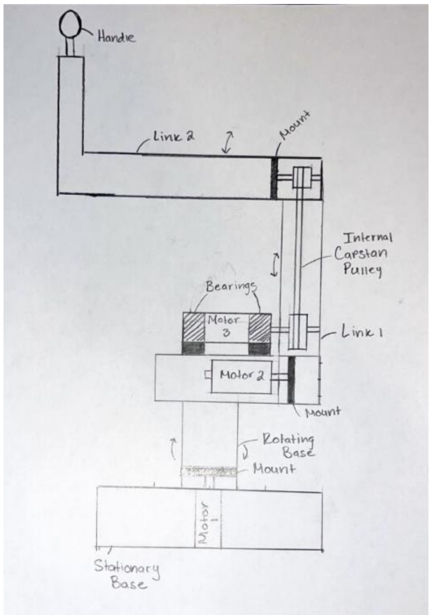


Figure 17: Final Design

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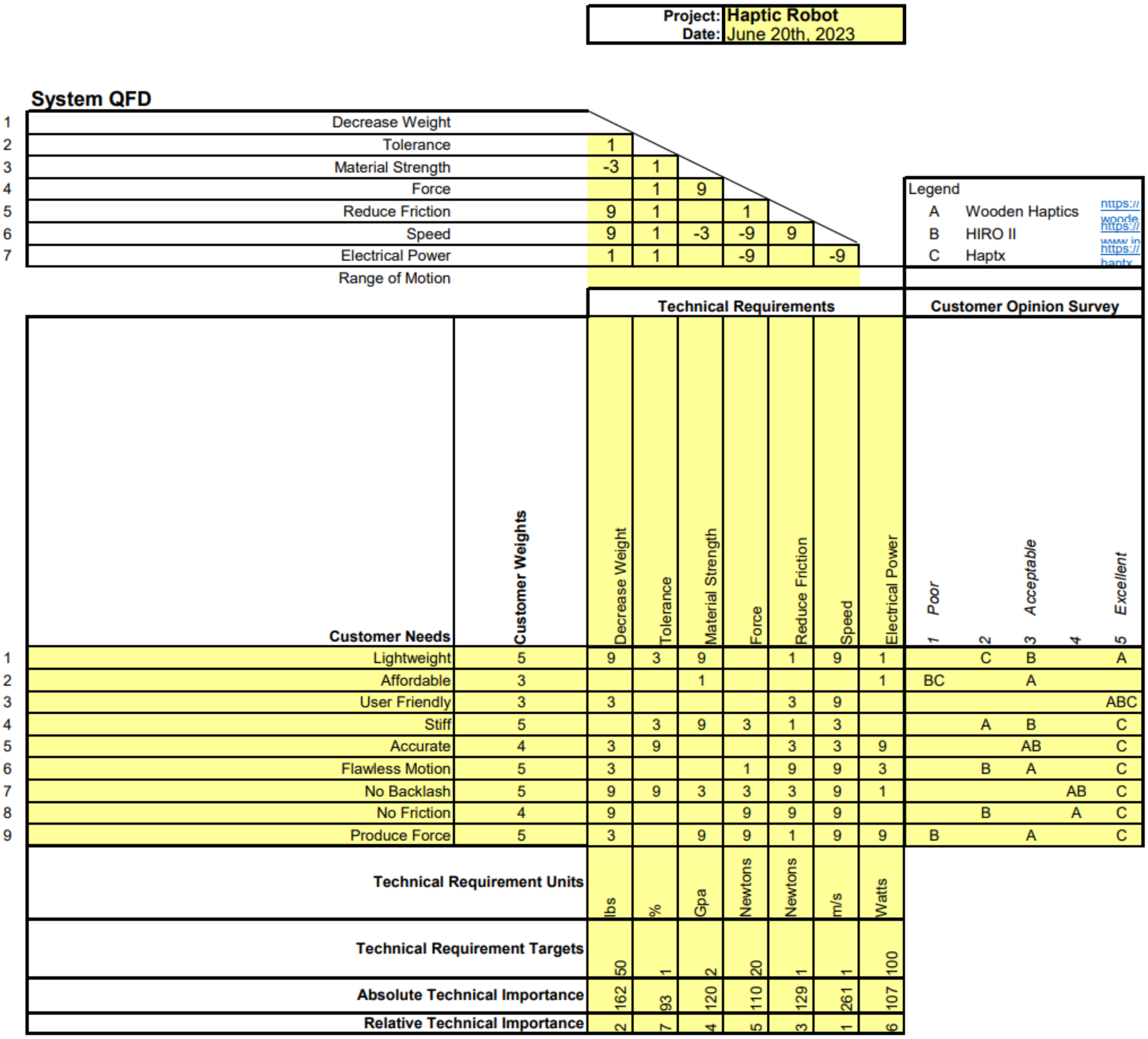
7 APPENDICES

7.1 *Appendix A: House of Quality*

Figure xx: House of Quality (QFD)



Project:	**Haptic Robot**
Date:	June 20th, 2023

System QFD

		1	2	3	4	5	6
1	Decrease Weight						
2	Tolerance	1					
3	Material Strength	-3	1				
4	Force		1	9			
5	Reduce Friction	9	1		1		
6	Speed	9	1	-3	-9	9	
7	Electrical Power	1	1		-9		-9
	Range of Motion						

Legend		
A	Wooden Haptics	https:// woode
B	HIRO II	https:// www.in
C	Haptx	https:// haptx

			Technical Requirements							**Customer Opinion Survey**				
	Customer Needs	**Customer Weights**	Decrease Weight	Tolerance	Material Strength	Force	Reduce Friction	Speed	Electrical Power	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
1	Lightweight	5	9	3	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		3	9	3	1	3			A	B		C
5	Accurate	4	3	9			3	3	9			AB		C
6	Flawless Motion	5	3			1	9	9	3		B	A		C
7	No Backlash	5	9	9	3	3	3	9	1				AB	C
8	No Friction	4	9			9	9	9			B		A	C
9	Produce Force	5	3		9	9	1	9	9	B		A		C
	Technical Requirement Units		lbs	%	Gpa	Newtons	Newtons	m/s	Watts					
	Technical Requirement Targets		50	1	2	20	1	1	100					
	Absolute Technical Importance		162	93	120	110	129	261	107					
	Relative Technical Importance		2	7	4	5	3	1	6					