Haptic Robot

Final Proposal

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DISCLAIMER

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EXECUTIVE SUMMARY

The Haptic Robot Senior Capstone Project is sponsored by Dr. Reza and aims to develop a three degree of freedom robot arm for the goal of aiding in rehabilitation for stroke and nerve system failure patients. The project is in the early stage of development in terms of the design process. The team is gradually developing an effective basis for the design model starting with conceptual designs that meet the client (Dr. Reza) and engineering requirements. The following report will discuss the current process of the design in terms of design requirements, CAD model, finalized testing procedures, and a project implementation plan for future development of the robot. In order to establish a strong base for the design, the team is currently focused on the formation of the basic model that is to be developed in the future, therefore, a finalized CAD model is developed based on the client needs and the logical engineering technicalities involved as well as various testing procedures that will be implemented to ensure positive robot performance meeting the demands of the client and achieving the end goal for the project.

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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). 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, are limited 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 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 $5,000.00 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. Based on current designs of the robot, the team is underbudget and will most likely not need more than $2,000.00 USD.

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 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.

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 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.

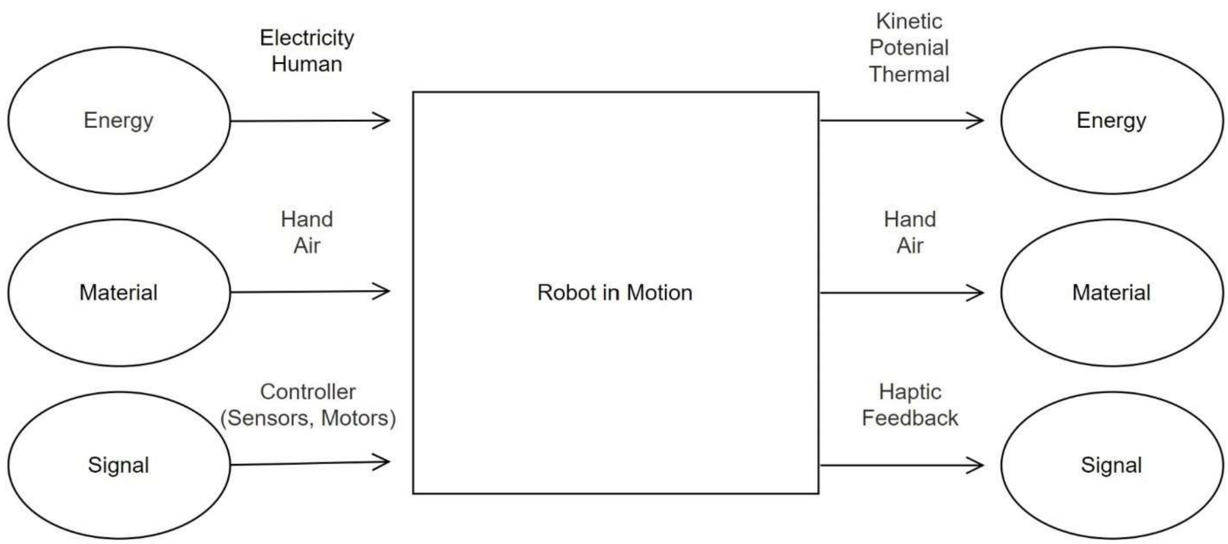

Figure 1: Black Box Model

2.3.2 Functional Model

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 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.

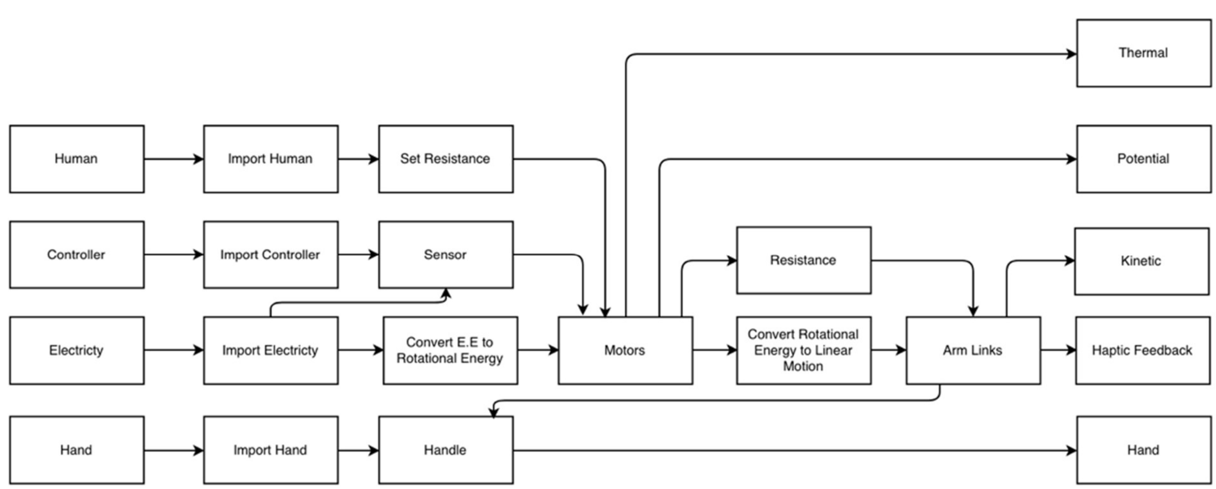

Figure 2: Functional Model

2.4 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 must 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 3: 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 4: Technical Requirements

		Technical Requirements						
Customer Needs	**Customer Weights**	Decrease Weight	Tolerance	Material Strength	Force	Reduce Friction	Speed	Electrical Power
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 5: 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 6: Technical Requirement Units

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 in relation to 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 Testing Procedures (TPs)

In the following section, the team presents two main testing procedures that are considered essential to measure the potential critical failures of the design. A MATLAB Simulink as well as a Stress Analyses are discussed in the section providing detailed descriptions of each procedure.

3.1 Testing Procedure 1: MATLAB Simulink Analysis

This test is a CAD model test that observes the 3D motion of the design to find critical failure points. It covers the moment of inertia, shear stress, bending stress (etc.). This will require the team to know what materials the design will be made of and have accurate CAD modeling of the device. Engineering requirements such as: tolerance (below 1% for all parts), decreasing weight (under 50lbs), producing force (ability to produce/ resist 20N on the handle in any direction), material strength (minimum of 2 GPa), and speed (minimum 1m/s) will be observed and recorded from this test.

3.1.1 Testing Procedure 1: Objective

The Simulink objective is to test dynamic motion of the design before construction begins. It can save the team resources by figuring out if the design will be viable or not. This Simulink model will also be able to detect static failure points based on different positions the robot is in. All calculations derived from this test will prove useful for justifying the design by satisfying ER's.

3.1.2 Testing Procedure 1: Resources Required

The few requirements for this test are an updated CAD model and MATLAB Simulink, which both can be accessed through NAU computers. This test is useful in that it requires no monetary resources from the team's budget and is simple to go through. However, this test requires much time from the team and will be a major focus for next semester in the beginning.

3.1.3 Testing Procedure 1: Schedule

Based on how the next semester is scheduled by the instructor, this test will most likely take initial priority of the team's focus for the first month. Simulink analysis will take time and patience for the team to go through it with accuracy. The team will work on setting up the analysis within the first or second week of the semester and work on it until the final design is justified mathematically.

3.2 Testing Procedure 2: Solidworks Stress Analysis

The built-in function of stress analysis in Solidworks is a useful tool that provides a visual graph showing the weak points of the various parts of the design. This testing procedure will ensure that the stiffness of the design is met, which includes one of the client's requirements. Stress analysis is an essential part moving forward into the implementation stage of the design where the team would have the potential failure points which are easier to mitigate and adjust to meet the required stiffness.

3.2.1 Testing Procedure 2: Objective

The main objective of this procedure is to assess the possible weak parts of the design such as the joints, links, and motor shafts and how much stress could be put into it until it reaches the yielding point. These parts are predicted to be the weaker points on the design simply because they require high strength to transmit a minimum amount of torque to move the robot. Being able to figure out the actual failure values in these parts is essential to ensure a high-quality design.

3.2.2 Testing Procedure 2: Resources Required

The only resource needed to accomplish this procedure is having access to Solidworks software and being able to use the built-in stress analysis function. An important reason of using this procedure is the easy accessibility to the software and the previous knowledge of the team on using this function.

3.2.3 Testing Procedure 2: Schedule

Before taking further steps into the design process of the project, this testing procedure needs to be done to have an accurate measurement of the stiffness of the robot's material. The test procedure will be implemented at the beginning of the next semester to mitigate any potential failures in terms of the material used for the design.

4 Risk Analysis and Mitigation

For the customer requirements to be met and risk analysis was performed using an FMEA chart. The team used their final approved design to look for protentional failures in the system. We have chosen four sub-systems to look at. Those were motor assembly, pully system, joint assembly, arm assembly and from these the team was able to generate ten potential failures for each sub-system. Which was later condensed into the top ten failures that require the most attention. The team considered these the biggest failures to overcome and because of these potential failures design changes were implemented, which the team worked through to find the best possible solution for each.

Table 2: Shortened FMEA

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 missalligned	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

4.1 Critical Failures

4.1.1 Potential Critical Failure 1: Pulley Failure

The design model includes three pulley systems that work as the main mechanism of movement for the design and there are possible failures within these systems. Since the three systems are placed in different locations on the robot, potential failures are caused by high torque on the pullies as well as material failure considering the ropes on the pullies are open to any external physical forces. This will cause failure to transmit power throughout the robot arms. Therefore, based on the predicted critical failures that are mentioned, the team will ensure no external forces are interfering with the cables by covering the systems as well as using the appropriate cables sizing and material to ensure stability and strength of cables.

4.1.2 Potential Critical Failure 2: Motor Shaft Failure

If the pinion pully mounted to the shaft of the motor is slightly off or not correctly supported the entire weight of the user and the force feedback are placed directly on the motor shaft. This causes shear on the shaft at the weakest point, which can permanently deform it. With our design, the motor utilizes a coupler to connect to the pinion pully shaft, which allows for the force to be placed on the pully instead of the motor. How we mitigate this risk is by adding bearing to the other side of the pinion pully which will fully support that piece of the assembly.

4.1.3 Potential Critical Failure 3: Binding of Cables

When considering the cable design, we needed to make sure they were placed in such a way that cable could not be ripped off the pullies by the movement of the other motors. Using three motors to get the required three degrees of freedom required some motors to be mounted directly to some link. These placements of motors made sure no damage could occur to the motors or the cable system. By mitigating this failure point we were able to meet the customer requirements and move forward with the project.

4.1.4 Potential Critical Failure 4: Joint Failure

There are three different connections using U-shaped joints that could cause critical failures in the system due to material strain, stress, and/or fracture. The joints are an essential part of the body that gives the ability to transmit torque and power throughout the system and when a slight failure occurs, the whole system isn't able to move. Therefore, using the results from the testing procedures mentioned above the team will ensure that the joints used are made of the appropriate material in order to prevent potential joint failure in the system.

4.1.5 Potential Critical Failure 5: User Pinching

The design moves in 3 different degrees of freedom and has many different pinch points caused by joints and the rotating arms. This on top of the materials used being rigid means pinching is a risk affecting the user. To mitigate this failure, the team will create a shell for the robot to minimize all joint pinching. This will also help keep the joints moving smoothly as fewer particles will touch the joints and cause them to "gum up" from dust or fibers.

4.1.6 Potential Critical Failure 6: Backlash

Backlash was a big problem that the team had to overcome. We considered many different methods to mitigate this problem by using a cable driven system which has no backlash. With cable there can still be potential backlash is the cable stretches over time which would cause the force feedback from the haptic robot to be incorrect or not a still as the client need. This problem, much like the cable failure later talked about, can be mitigated by implementing a design choice to easily replace the cables when it is noticed.

4.1.7 Potential Critical Failure 7: Loose Fittings

All parts of the robot must be fastened tight to their respective positions so that there are no failures in parts lining up correctly. This affects the pulley systems, the motor subsystems, the arm links, and the joints equally so that parts will wear down faster, misalign, produce unwanted wobbling, and cause other failures within the design. For this failure, the team will tighten all fittings as hard as possible without damaging the design as well as look into different kinds of fasteners to use on respective subsystems for maximum efficiency of space.

4.1.8 Potential Critical Failure 8: Cable Failure

When researching possible solutions to the transfer of power from the motor the team came across the use of cable to transfer the power of the motor to different links. The team noticed that the entire weight of the resistance would be placed on the cables which is used enough over time can begin to stretch or even fail completely. To mitigate this failure point research into the life span of cable is being investigated, we have also implemented a design change to easily replace the cables when needed.

4.1.9 Potential Critical Failure 9: Motor Positioning

Motor positioning is critical for lining up the pulley system as well as mitigating the moment of inertia as the robot arm moves. If motor placement is misaligned as well, then the subsequent shafts and bearings in the through linear axis may also have friction with each other and cause damage to themselves. We will mitigate this risk by mounting the motors in open areas with enough space to work, as well as lowering all motors on the moving pieces to minimize the moment of inertia from the weight.

4.1.10 Potential Critical Failure 10: Motor Failure

If too much force is applied to the robot arms, the motors will eventually fail and give way to that incoming force. This can result in the arms rotating in the opposite way, which then mitigates the purpose of the robot. To decrease the chance of this failure, a high-torque cable and pulley system is implemented to prevent change in the robot's arm positioning. The motors will need to work more by requiring more revolutions to achieve the same arm movement, but it will prevent small-force applications from being able to cause the motors to fail by rotating the wrong way.

4.2 Risks and Trade-offs Analysis

The team's robotic design went through extensive redesign to meet the customer and engineering requirements. Backlash is one of the risks that cannot be completely avoided but we can mitigate this potential weakness in our design by some strategic design choice. The team has solved this issue by making use of a pulley system, which has no backlash. In previous designs we had considered mounting the motors next to the joints of the robot which would use a gear reduction to achieve the required torque output. The issue with this is gear boxes have a bit of backlash where the gear mesh which would not meet a requirement set forth by the client. By mounting the motor lower the team was able to transfer the power of the motor up to the required joint which fixed a few problems for the team. With the new design, the robotic arm is reliant on the strength cable. The cable can stretch over time, but by designing the cables in the system to be easily replicable, this risk is significantly reduced. This a trade off the team is willing to take as the many benefits of this design outweigh the negative drawbacks. This was the biggest issue the team had to overcome, more explanation on design is shown in the next section.

5 DESIGN SELECTED – First Semester

In this section of the report, the final semester design will be presented and explained. A few engineering calculations will be shown to justify the new design. The current design has many changes so why these changes were made will also be discussed. A CAD model is shown with an exploded view and the parts will be discussed also going over the materials used. The prototype is missing a few components with good reasoning which will lead to the schedule of the upcoming Fall semester.

5.1 Design Description

5.1.1 Design Growth

In the beginning of the summer the team knew we needed a haptic robot but had didn't have any previous experience of what it would look like. After a couple of weeks of general robot designs the client agreed on a 3-degree robot. After many more weeks a haptic robot with carbon fiber links and motors within the carbon fiber was created. In this design, the motors to run the base and first link were inside the robot for more of the aesthetic. The carbon fiber tubes would allow room for the motors and have the material strength the client wanted. This design can be seen below in *Figure 7*. At this point in the design, we felt that with the motors in the link they would still be able to have enough torque to move the links, but this would soon change.

Figure 7: Preliminary CAD Design

There were a lot of major changes that happened from the preliminary to final report design. Starting with the carbon fiber tubing, after our second presentation we found that cutting carbon fiber can be very toxic and harmful to your lungs. Another thing about the carbon fiber was that it was too large, expensive, large, and almost impossible to cut so the team went with a 0.75in aluminum rod that would be almost 10x cheaper and would allow it to cut it without dying. The three aluminum rods are attached by universal joint (U-joint) that would have a block in it to prevent it from moving in the direction it shouldn't. We never had a sound joint system for our robot so that was a huge step in getting the robot to move in 3 degrees of freedom.

To power the links, we originally had two of the motors in the base to run the base and first link and a third motor on the outside ran by a pulley system from the inside of the carbon fiber tube. This all changed when we found that there wouldn't be enough torque from the motors in these positions to move the links so now each of the motors has a pulley system that would have enough torque to run the links properly. The way it works is that each motor has multiple bearings with a 1in 3D printed reel at the bottom of the links or for the base it would be facing down to the base. There's an 8in 3D printed reel placed at all the joints connected with a 5mm cable wire for the pulley system. The two motors placed on the joints are attached using an L-bracket that would attach the motor to the link so that as the arm moved so would the motor. The motors are bracketed down by a 3D printed piece to prevent the motor from spinning or moving which can be seen in *Figure 8* below.

Overall, this was a huge design change within a week and there are still a couple little things that need to be looked at just a little more or just touched up. For reference, all the colored pieces in the new design model are 3-D printed parts. Also, we went with more of a skeletal design that would allow us to meet the engineering and customer requirements because we aren't working with aesthetics. The skeletal design would allow us to design sleeves for the links or even boxes for the motors so that the robot would not get damaged with future use.

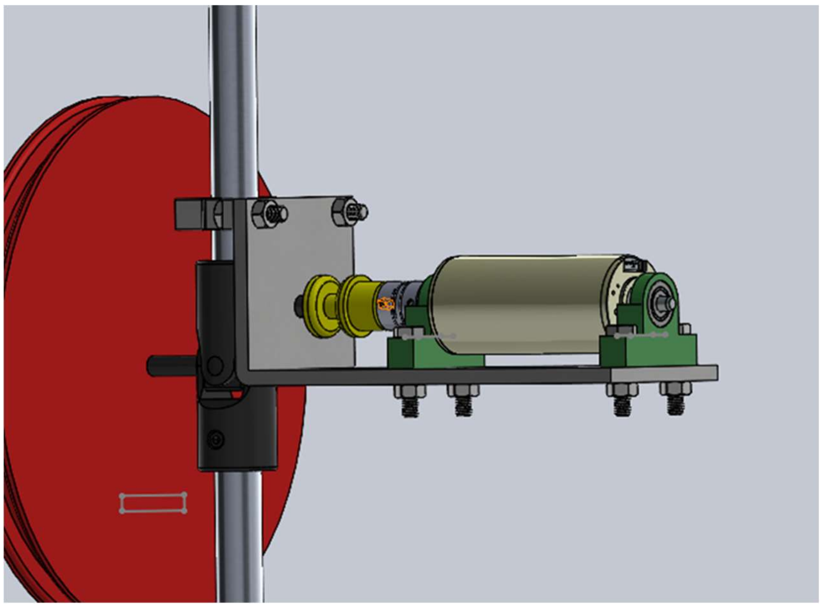

Figure 8: Final CAD Motor Closeup

5.1.2 Prototype Design

After the design and building process of the prototype we found that it shows proof of concept the way we wanted it to. It's always harder presenting and telling the audience how it is going to move than showing them a design that moves in 3 degrees of freedom. There were a few important design aspects that we learned after playing with the prototype for a little bit. The first being the overall extension of the robot is a little too much and the team would like to shorten the first arm a little bit. The handle should also be attached to the last link so that as the robot moves the handle will be able to move itself. For example, in the prototype the tennis ball at the end is on tight and as you move your arm and move your hand to a more comfortable position in that specific movement the ball doesn't move properly making it uncomfortable for the hand to move after a while. Another consideration is the size of the large reel that will be printed for the final design. The current size is 8 inches and as the second link moves down there is a possibility that the user's hand could be pinched in the cable so decreasing the size would help the team out greatly. While building the robot we found that it’s going to take a very long time to construct. Especially, when getting specific parts printed or ever letting parts cure like threads to the joint's connections. This can be resolved by accounting for the cure time and print times when building and doing model reconstruction if needed. The final summer prototype can be seen below in *Figure 9*.

Figure 9: Current Prototype Build

5.2 Implementation Plan

In order to implement the teams design of the robot, we will finalize the CAD design which will meet all of the customer requirements visually and show the design to our client for any feedback he may have. After completion of the CAD model, the team will create a simulation of the robot using Simulink. This simulation will allow the team and client to run into any errors before even building the robot. With the errors the team runs into, we will quickly be able to fix them by adjusting our CAD model and running the simulation again, all of which is a part of the testing process. It is partially up to the group to write any code for the robot while continuously working with the client to ensure the design is done on time and it works up to the client's standards.

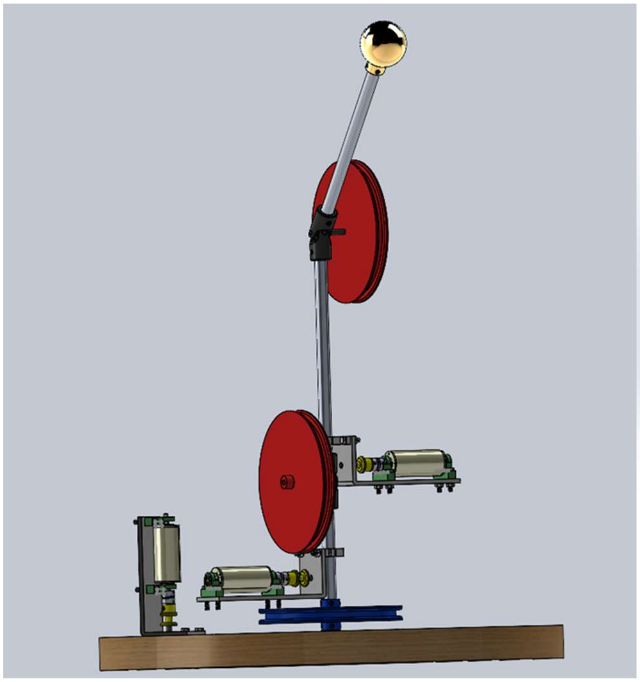

Figure 10: CAD Model

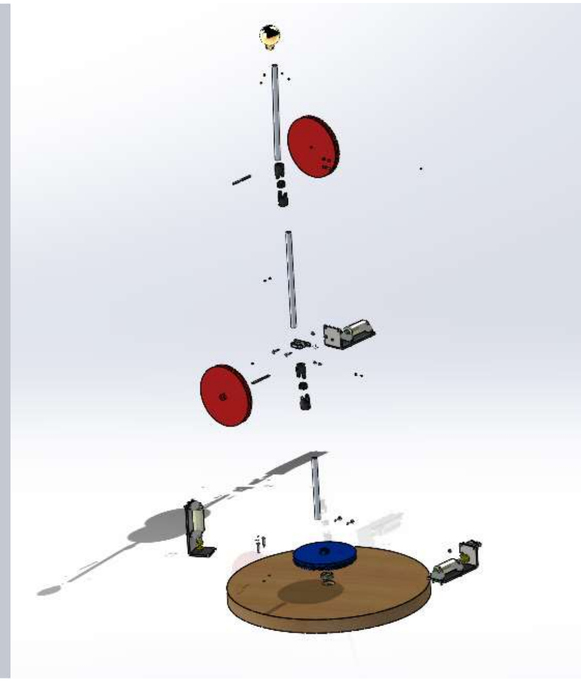

Figure 11: CAD Model Exploded

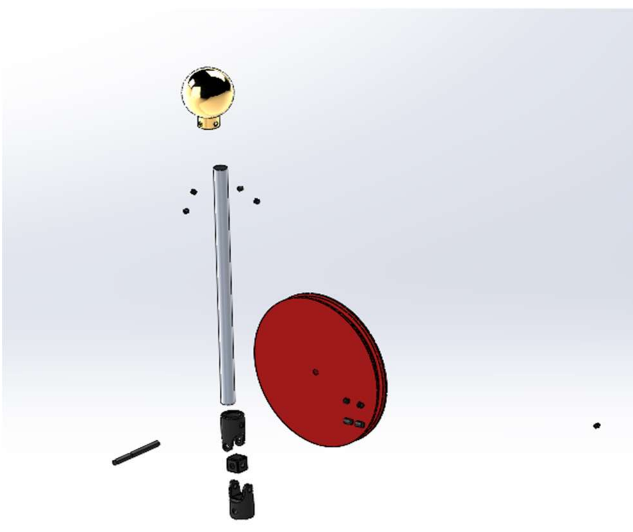

Figure 12: Second Link Exploded

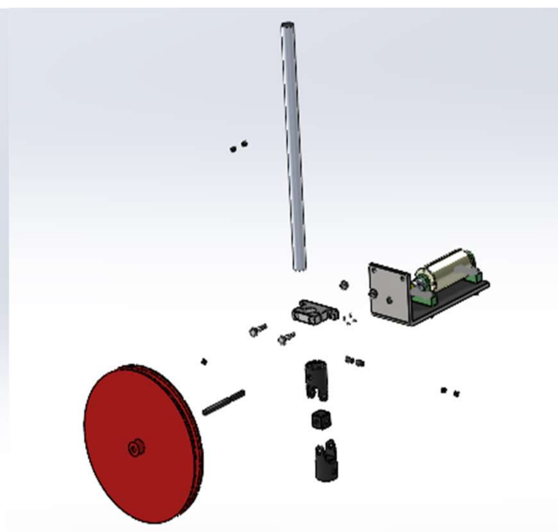

Figure 13: First Link Exploded

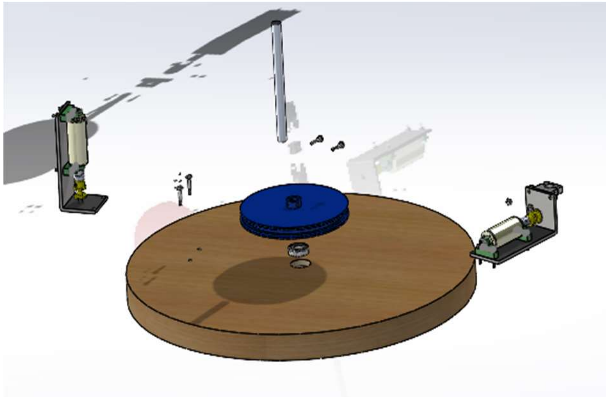

Figure 14: Base Exploded

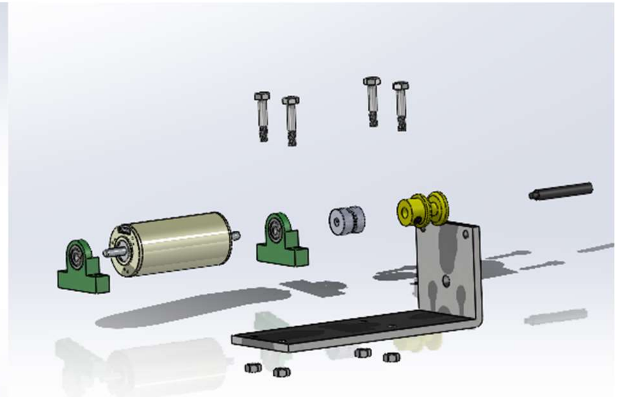

Figure 15: Motor Mount Exploded

As seen in *Figure 9*, the team has already created a physical prototype of the robot which represents how the robot will be able to move in three degrees of freedom per customer requirements. This prototype is very basic and does not contain any motors or pulley systems which will be used in the final design. Therefore, the prototype will be used as a baseline design for the group to build off as they work towards finishing the project. To create the final design as shown in *Figure 10*, the group will be using several miscellaneous resources, such as 3D Printed parts, already manufactured parts, the NAU machine shop, and any knowledge we can get from NAU professors or other engineers. Our client would like the team to design custom pulleys for the robot which will help keep the cable being used attached to pulleys and in a closed loop. The team will also need to custom make their own motor mounts as there are no L-brackets on the market that are long enough to attach the motors to the design of the robot. The links for the robot will be purchased and will be made of aluminum. There will be plenty of other hardware that is going to be purchased for the robot primarily from McMaster-Carr, all of which can be found in the bill of materials in *Appendix C*. The team would like to continue to work closely with the client to help finish this project therefore we will continue to ask questions where we feel we need to. Using all the resources listed above, the group is in great shape to create a functional design that meets all the customer requirements on time.

The team has set deadlines for themselves which can be viewed in *Table 3*. This schedule is a full sixteen-week overview of the Fall 2023 Semester that shows several different design, testing, and website deadlines that were set by the group. The group aims to have a Final Design built by the end of the eighth week of the semester in order to proceed with a number of different tests for the robot. After the initial tests begin, the team will work through the remaining eight weeks to continue to test the design of the robot and make any necessary changes. By the end of the fourteenth week, the team will have all the testing of the robot complete and a design that has met all of the customer and engineering requirements for the project.

Table 3: Fall 2023 Team Schedule

Week 1	Member	Completion	Start	End
Client Meeting	All	0%	8/28/23	8/28/23
CAD Redesign	Josh	0%	8/28/23	9/1/23
Simulink Progress	Rakan	0%	9/1/23	9/3/23
Team Meeting	All	0%	9/2/23	9/2/23
Week 2	Member	Completion	Start	End
Client Meeting	All	0%	9/4/23	9/4/23
Code Programming	All	0%	9/4/23	9/7/23
Simulink Testing	Rakan	0%	9/8/23	9/9/23
Website Update	Tommy	0%	9/8/23	9/10/23
Team Meeting	All	0%	9/8/23	9/8/23
Week 3	Member	Completion	Start	End
Client Meeting	All	0%	9/11/23	9/11/23
33% Completion	All	0%	9/13/23	9/13/23
Simulink Update	Rakan	0%	9/13/23	9/15/23
Website Update	Tommy	0%	9/13/23	9/13/23
Team Meeting	All	0%	9/15/23	9/15/23
Week 4	Member	Completion	Start	End
Client Meeting	All	0%	9/18/23	9/18/23
CAD Update	Josh	0%	9/18/23	9/21/23
Final Simulink	Rakan	0%	9/21/23	9/23/23
Team Meeting	All	0%	9/22/23	9/22/23
Week 5	Member	Completion	Start	End
Client Meeting	All	0%	9/25/23	9/25/23
All Parts Ordered	Logan	0%	9/25/23	9/25/23
Website Update	Tommy	0%	9/25/23	9/29/23
Robot semiassembly	All	0%	9/28/23	9/30/23
67% Complete	All	0%	10/1/23	10/1/23
Week 6	Member	Completion	Start	End
Client Meeting	All	0%	10/2/23	10/2/23
3D Print Designs	Chris	0%	10/2/23	10/8/23
Assemble custom parts	Logan	0%	10/2/23	10/8/23
Team Meeting	All	0%	10/6/23	10/6/23
Week 7	Member	Completion	Start	End
Client Meeting	All	0%	10/9/23	10/9/23
3D Print Designs	Chris	0%	10/9/23	10/12/23
Assemble custom parts	Logan	0%	10/9/23	10/12/23
Team Meeting	All	0%	10/13/23	10/13/23
Begin Assembly	All	0%	10/13/23	10/22/23
Week 8	Member	Completion	Start	End
Client Meeting	All	0%	10/16/23	10/16/23
Robot assembly	All	0%	10/19/23	10/19/23
Team Meeting	All	0%	10/20/23	10/20/23
Final Test Plan	Chris	0%	10/20/23	10/21/23

Week 9	Member	Completion	Start	End
Client Meeting	All	0%	10/23/23	10/23/23
Testing	Chris	0%	10/23/23	10/27/23
Evaluation	All	0%	10/27/23	10/27/23
Team Meeting	All	0%	10/27/23	10/27/23
Repairs/Updates	Logan	0%	10/27/23	10/29/23
Week 10	Member	Completion	Start	End
Client Meeting	All	0%	10/30/23	10/30/23
Testing	Chris	0%	10/30/23	11/1/23
Evaluation	All	0%	11/1/23	11/1/23
Website Update	Tommy	0%	10/30/23	11/3/23
Repairs/Updates	Logan	0%	11/1/23	11/4/23
Team Meeting	All	0%	11/3/23	11/3/23
Week 11	Member	Completion	Start	End
Client Meeting	All	0%	11/6/23	11/6/23
Testing	Chris	0%	11/6/23	11/8/23
Evaluation	All	0%	11/8/23	11/8/23
Repairs/Updates	Logan	0%	11/8/23	11/11/23
Team Meeting	All	0%	11/10/23	11/10/23
Week 12	Member	Completion	Start	End
Client Meeting	All	0%	11/13/23	11/13/23
Testing	Chris	0%	11/13/23	11/15/23
Evaluation	All	0%	11/15/23	11/15/23
Repairs/Updates	Logan	0%	11/15/23	11/17/23
Team Meeting	All	0%	11/17/23	11/17/23
Week 13	Member	Completion	Start	End
Client Meeting	All	0%	11/20/23	11/20/23
Thanksgiving Break	All	0%	11/22/23	11/26/23
Week 14	Member	Completion	Start	End
Client Meeting	All	0%	11/27/23	11/27/23
Final Testing	Chris	0%	11/27/23	11/29/23
Final Evaluation	All	0%	11/30/23	11/30/23
Final Repairs/Updates	Logan	0%	11/30/23	12/3/23
Team Meeting	All	0%	12/1/23	12/1/23
Week 15	Member	Completion	Start	End
Client Meeting	All	0%	12/4/23	12/4/23
Final Deliverables	All	0%	12/4/23	12/11/23
Final Website	Tommy	0%	12/4/23	12/8/23
Final Physical Model	All	0%	12/4/23	12/9/23
Team Meeting	All	0%	12/8/23	12/8/23
Week 16	Member	Completion	Start	End
Final Presentations	All	0%	12/16/23	12/16/23
Final Model Due	All	0%	12/16/23	12/16/23
End Project	All	0%	12/17/23	12/17/23

The total budget for the project was initially projected at roughly $2,150. The team has made two purchases thus far for the project which were filament for a 3D printer and parts for the prototype of the design. This filament will be used for printing the pulleys and any other parts the group is able to fabricate on their own. *Figure 16* shows the overall budget of the project, expenses to date, and any future expenses for the project. *Figure 17* shows a condensed version of the bill of materials for the project, while *Appendix C* shows the entire BOM for the project. In *Figure 16* you will see the future expenses for the project are roughly $551.03 and the money left over from the budget is just shy of $1400. In *Figure 17* you will see the team is going to purchase a little more than $300 for the parts needed for the final design of the robot. That leaves roughly $235 for further prototyping of the design. The motors of the robot are supplied by the client leaving the total cost for purchases made by the group relatively low. By keeping the cost low, the group will not run into budget constraints and will be able to provide the client with a quality product that meets all the requirements.

Budget			
Current Budget	Expenses to Date	Future Expenses	Leftover
$2,150	$210.85	$551.03	$1,388.12

Figure 16: Overall Budget of Project

Bill of Materials							
Item #	Item	Item Description	Vendor	Part Number	Quantity	Costs ($)	Total Cost Per Pair of Units ($)
1	Shaft Joint	Metal Universal Joint, Coupling Shaft	Walmart	N/A	2	$31.22	$15.61
2	Motors	EC Maxon Brushless Motor	Maxon	283873	3	$1,963.50	$654.50
3	Angle Iron	Low-Carbon Steel 90 Degree Angle, 3/8" Wall Thickness, 6" x 4"	McMaster-Carr	9017K34	1	$34.83	$34.83
4	3/4" Bearing	Base Bearing	McMaster-Carr	60355K297	1	$12.25	$12.25
5	6mm Bearings	Link Bearings	McMaster-Carr	6661K11	6	$120.36	$20.06
6	Shaft Clamp	Aluminum Low-Profile T-Shaped, for 3/4" Shaft Diameter	McMaster-Carr	1865K5	2	$54.72	$27.36
7	Hex Screw	Medium-Strength, 1/4"-28 Thread Size, 1-9/32" Long	McMaster-Carr	94622A415	18	$15.00	$7.50
8	Hex Nut	Grade 5, 1/4"-28 Thread Size, MS51968-2	McMaster-Carr	94575A120	18	$10.73	$10.73
9	3ft Aluminum Rod	Polished Multipurpose 6061 Aluminum, Brushed, 3/4" Diameter	McMaster-Carr	2655N19	1	$36.30	$36.30
		Total				$315.41	

Figure 17: Condensed Bill of Materials

6 CONCLUSIONS

In summary, the team updated the customer and engineering requirements based on client needs and technical solutions to the final design. The above CAD design is set to be the final outline of the team's model. The memo included the appropriate codes of ethics that apply to the project as well as two testing procedures, critical failures, BOM and budget tables being discussed in detail. The prototype provided in this memo shows a general proof of concept in terms of design outline, range of motion, and a three degree of freedom motion. The design has gone through many changes throughout this summer semester, but each has been necessary to help satisfy all the engineering and customer requirements. The physical prototype of the model will start in the fall semester after the digital testing procedures have been completed as well as the parts needed based on the BOM are purchased.

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8 APPENDICES

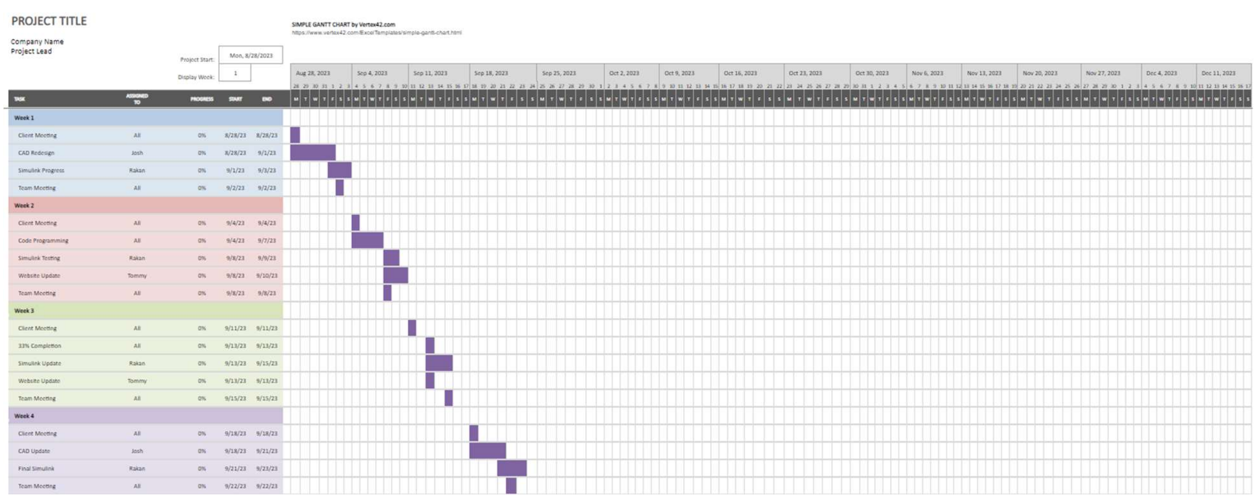
8.1 Appendix A: Full FMEA

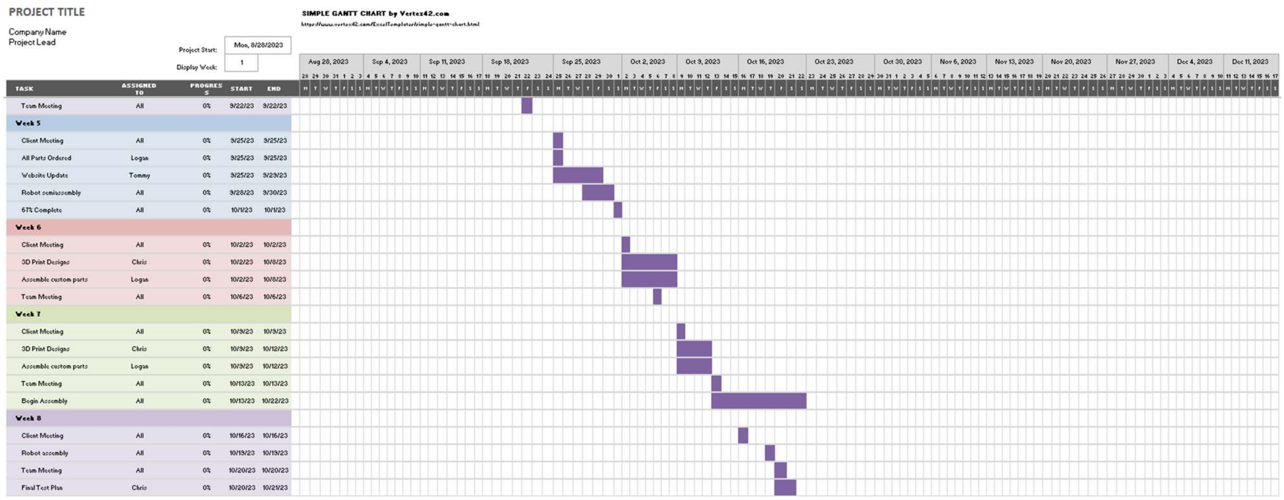
1	Product Name: Haptic Robot		Development Team				Page No 1 of 1			
2	System Name						FMEA Number			
3	Subsystem Name						Date: 7/29/23			
4	Component Name									
5	Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
6	Sub Assembly: Motor Assembly									
7	Motor Shaft	Mechanical	Shaft Strain	9	Pinion pulley not supported	3	Solidworks/Simulink	8	216	Add a bearing to the pinion pulley to prevent strain
8	Motor Failure in Maxon Motor	Mechanical	No power production	8	Overheating and overall motor damage	4	Solidworks/Simulink	5	160	Mount motors in open space
9	Motor Positioning	Mechanical	High torque constraint	6	Mounting motor high from the base	7	Solidworks/Simulink	7	294	Place motors as close as possible to the base
10	Loose Fittings in Pinion Gear	Mechanical	Misalignment, inaccurate motion, and collapsing	6	Wrong sized fittings used, not enough tightening	5	Solidworks/Simulink	4	120	Ensure fitting tightness and use appropriate tight fastners
11	Low Torque	Mechanical	Not enough power transmission	2	Weak power production by pulley and motors	3	Solidworks/Simulink	5	30	Increase gear ration and/or motor power
12	Motor overheating in Maxon Motor	Thermal	Motor is damaged permanently	3	Too much rpm	4	Solidworks/Simulink	2	24	Mount motors in open space and/or attach a fan
13	Pinched wires on Maxon Motor	Mechanical/ electrical	Wires damaged permenently, electricity not transmitted	2	Wire material used	2	Design Analysis	1	4	Use high strength material
14	Binded wires on Maxon	Mechanical/ electrical	Wires damaged permenently, electricity not transmitted	2	Motor placement effecting range of motion	4	Design Analysis	1	8	Place motors with space tolerance away from wires
15	Motor bearing strain in Maxon Motor	Mechanical	Bearing wears into its mount	1	Collapsing of motor	2	Solidworks/Simulink	7	14	Use strong bearings with appropriate rubbers
16	Weak mount for Maxon Motor	Mechanical	Mounting failure	2	Pulley system misalignment	1	Solidworks/Simulink	8	16	Use screws and bolts to ensure stability of motors mount
17	Sub Assembly: Pulley Assembly									
18	Pulley	Mechanical	No power transmission from motor	7	Cable coming off pulley recieving no power	7	Hand Calculation	5	245	Make sure cables are tensioned and alligned properly using accurate sized cables and material
19	Cable Failure	Mechanical	Violent motion, loss of power transmission	9	Cable overtightening producing high tension on other parts	10	Hand Calculation	3	270	Use a stronger cable with high life cycle and design to easily replace the cables
20	Binding of Cable	Mechanical	No electric transmission	5	Cable damage and loss of power	5	Solidworks	8	200	Correct placement of motors
21	Backlash	Mechanical	Delayed motion and inaccurate force feedback	9	Unneccesary space between pinion and driven gear	8	Design Analysis	7	504	Use a cable-driven system
22	Friction	Mechanical	Material deflection and strain	7	Parts malfunction and inaccurate motion	2	Solidworks/Simulink	7	98	Implement bearings as much as possible and avoid metal to metal interactions
23	Pulley Ratio	Mechanical	Not enough torque production	6	Slow to no movement in system	2	Design Analysis	1	12	Increase pulley ratio
24	Cable Material	Mechanical	Damaged pulley system and other parts	4	Overall system malfunction, weak cable choice	4	Design Analysis	3	48	Use strong cable material to withstand stress and strain
25	Pulley Positioning	Mechanical	Increase of distance on shafts increases shear	5	Bearing and connection joints wear	1	Design Analysis	2	10	Decrease shaft connection distance
26	Slip on Shaft	Mechanical	Pulleys become useless if they slip with motion	9	Set screws not tightened	2	Design Analysis	1	18	Ensure screws are tight enough to avoid slip
27	Conflicts of motion	Mechanical	Pulleys and motor assemblies touch if pulleys are large	9	Large pulleys and cable positioning	1	Design Analysis	1	9	Place pullies in appropriate space from motors
28	Sub Assembly: Joint Assembly									
28	Sub Assembly: Joint Assembly									
29	U-Joint overall failure	Mechanical	Lack of ability to transmit torque to move the robot	10	Weak material properties and friction within the joint	5	Solidworks/Simulink	2	100	Using strong material to withstand high stress and friction and process joints through a stress analysis
30	Extra degree of freedom in U-joint	Mechanical	Robot loses stability	5	Material deforms, incorrect joint type	1	Design Analysis	1	5	Bigger joint assembly in high strain areas
31	Pin failure in U-joint	Mechanical	Total failure of joint assembly	8	High shear force on asembly when in use	2	Solidworks/Simulink	2	32	Properly manage shear force and upgrade pin size
32	Slip U-joint	Mechanical	Lack of strength in force feedback	3	Loose set screws in joint connectors	3	Design Analysis	1	9	Drill complete hole through arm link for no slippage
33	Torque in U-Joint assembly	Mechanical	Internal parts now have torque	3	Parts such as shafts are too thick in the housing	2	Solidworks/Simulink	8	48	Make sure movement is in correct oritation
34	Thick U-Joint	Mechanical	limits motion of rod and touches other parts	6	Joint is too thick	2	Design Analysis	1	12	Pick a less thick joint with the same strength to hold arms
35	Internal friction in U-Joint	Mechanical/ thermal	Increase in friction and damage to parts	6	Individual parts touch without proper lubricant	2	Solidworks/Simulink	4	48	Apply lubercant or bearnings
36	Stiff hinge in U-Joint	Mechanical	Limits motion and shear can occur	2	Lack of lubricant	1	Design Analysis	2	4	Add lubricant for smooth motion
37	Long U-Joint	Mechanical	Increase moment of inertia due to increase in length	2	Choice in length of the joint	3	Solidworks/Simulink	1	6	Choose a shorter joint to decrease moment of inertia
38	Limited U-Joint	Mechanical	Limited motion decreases range of robot arm	1	Choice of style joint	2	Solidworks/Simulink	1	2	Make sure clearance is made
39	Sub Assembly: Arm Assembly									
40	Pinching User With Aluminium Link	Mechanical	User injury	10	The rotation of arms and the use of certain joints	4	Solidworks/Simulink	3	120	Create shell around components
41	Flex in Aluminium Link	Mechanical	Lack of stiffness to provide correct feedback	3	Weak material can't handle torque output	4	Solidworks/Simulink	3	36	Make sure material meets required strength
42	Length of Aluminium Arm	Mechanical	Increase moment of inertia	5	Longer arm lengths	1	Solidworks/Simulink	1	5	Choose shorter arms for a decreased amount of moment of inertia
43	Lack of Range In Aluminium Arms	Mechanical	Decrease of useability	8	Shorter arm lengths	2	Solidworks/Simulink	1	16	Adjust the choice of the different arm links to decrease moment of inertia and meet the required range of motio
44	Bending of rod	Mechanical	Permanent deformation and decrease slack in cable	10	Overpowering force on rod	2	Solidworks/Simulink	2	40	Attach support covers on rods to increase strength
45	Fatigue in Rods	Mechanical	Weak linkage with joints and deformation	8	Aluminum material type	1	Solidworks/Simulink	9	72	Choose a strong aluminum material type
46	Weak Arm-Joint Connection	Mechanical	Inaccurate motion and backlash	9	Not tightened enough	2	Solidworks/Simulink	4	72	Ensure connection tighteness and stability
47	Ends of Arm Stress	Mechanical	Link deformation and joint damage	7	Friction with joint connection	3	Solidworks/Simulink	4	84	Attach arms to joints where it won't physically touch to decrease stress on ends
48	U-Joint Connection Holes	Mechanical	Weakened arm	3	Holes drilled for U-Joint security/ connection	2	Solidworks/Simulink	5	30	Optimize the amount of holes drilled
49	Arm Fracture	Mechanical	System malfunction	10	External physcial forces on the arm	1	Solidworks/Simulink	1	10	Cover arms with shells to avoid arm fracture

8.2 *Appendix B: Bill of Materials*

ITEM NO.	PART NUMBER	DESCRIPTION	QTY
1	Hex Nut	Steel Hex Nut	18
2	Aluminium Rod	1st and 2nd Arm	2
3	U-Joint	U-Joint Rod Connector	4
4	U-Joint Pulley Shaft	Pulley Shaft	2
5	U-Joint Cube	U-Joint Cube	2
6	Driven Pulley	1st and 2nd Pulley	2
7	U-Joint Screw	U-Joint Screw	22
8	Hex Head Screw	Steel Hex Head Screw	6
9	L Bracket	Motor Mount	3
10	Pillow Block	Bearing Mounts	2
11	Haptic Motor	Maxon Motor	3
12	Pinion Pulley	Small Pulley	3
13	Coupler Shaft	Shaft for Coupler	3
14	Coupler	Coupler	3
15	Coupler Set Screw	Coupler Screw	12
16	Aluminium Rod Short	Second Arm	1
17	Link Mount	L-Bracket Mount	2
18	Bolts	Steel Hex Head Screw	18
19	Bottom Driven Pulley	First Pulley	1
20	Golden Knob	Handle	1
21	1/4' Ball Bearing	Ball Bearing in Base	1
22	Real Base	Wooden Base	1
23	U-Joint Shaft	U-Joint Shaft	4
24	Rod Support	Rod Support	2

8.3 *Appendix C: Full Fall 2023 Semester Schedule*





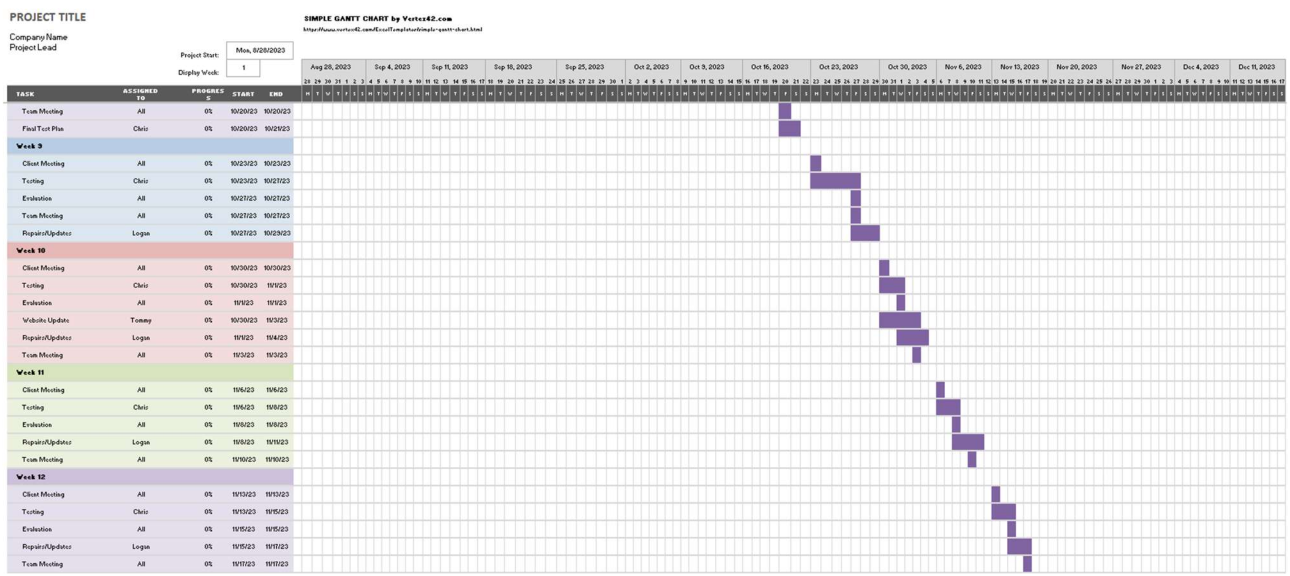
PROJECT TITLE

Company Name
Project Lead

Project Start: Mon, 8/28/2023
Display Week: 1

SIMPLE GANTT CHART by Vertex42.com

TASK	ASSIGNED TO	PROGRESS	START	END
Team Meeting	All	0%	9/22/23	9/22/23
Week 5				
Client Meeting	All	0%	9/25/23	9/25/23
All Parts Ordered	Logan	0%	9/25/23	9/25/23
Website Update	Tommy	0%	9/25/23	9/29/23
Robot semiassembly	All	0%	9/28/23	9/30/23
67% Complete	All	0%	10/1/23	10/1/23
Week 6				
Client Meeting	All	0%	10/2/23	10/2/23
3D Print Designs	Chris	0%	10/2/23	10/8/23
Assemble custom parts	Logan	0%	10/2/23	10/8/23
Team Meeting	All	0%	10/6/23	10/6/23
Week 7				
Client Meeting	All	0%	10/9/23	10/9/23
3D Print Designs	Chris	0%	10/9/23	10/12/23
Assemble custom parts	Logan	0%	10/9/23	10/12/23
Team Meeting	All	0%	10/13/23	10/13/23
Begin Assembly	All	0%	10/13/23	10/22/23
Week 8				
Client Meeting	All	0%	10/16/23	10/16/23
Robot assembly	All	0%	10/19/23	10/19/23
Team Meeting	All	0%	10/20/23	10/20/23
Final Test Plan	Chris	0%	10/20/23	10/21/23



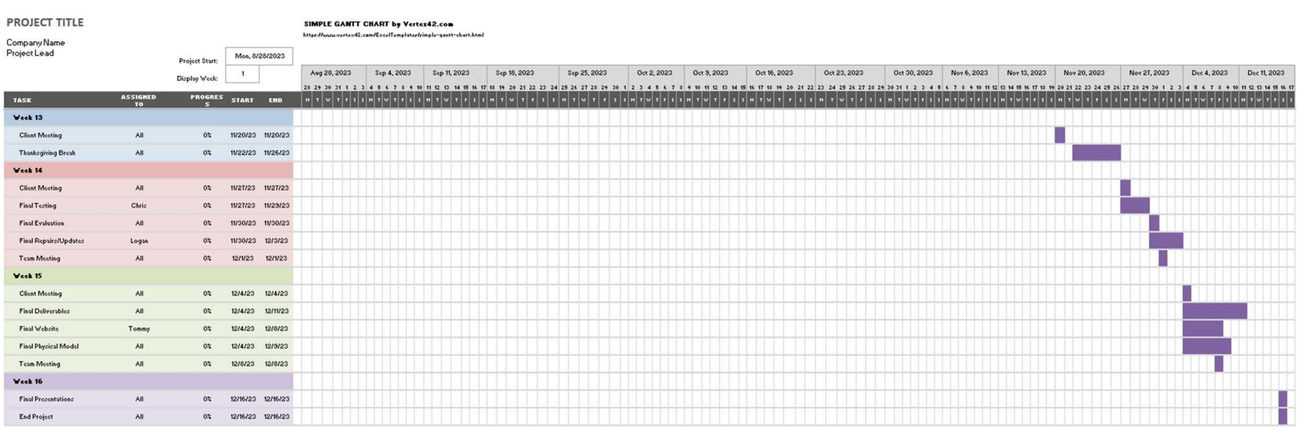
PROJECT TITLE

Company Name
Project Lead

Project Start: Mon, 8/28/2023
Display Week: 1

SIMPLE GANTT CHART by Vertex42.com

TASK	ASSIGNED TO	PROGRESS	START	END
Team Meeting	All	0%	10/20/23	10/20/23
Final Test Plan	Chris	0%	10/20/23	10/21/23
Week 9				
Client Meeting	All	0%	10/23/23	10/23/23
Testing	Chris	0%	10/23/23	10/27/23
Evaluation	All	0%	10/27/23	10/27/23
Team Meeting	All	0%	10/27/23	10/27/23
Repairs/Updates	Logan	0%	10/27/23	10/29/23
Week 10				
Client Meeting	All	0%	10/30/23	10/30/23
Testing	Chris	0%	10/30/23	11/1/23
Evaluation	All	0%	11/1/23	11/1/23
Website Update	Tommy	0%	10/30/23	11/3/23
Repairs/Updates	Logan	0%	11/1/23	11/4/23
Team Meeting	All	0%	11/3/23	11/3/23
Week 11				
Client Meeting	All	0%	11/6/23	11/6/23
Testing	Chris	0%	11/6/23	11/8/23
Evaluation	All	0%	11/8/23	11/8/23
Repairs/Updates	Logan	0%	11/8/23	11/11/23
Team Meeting	All	0%	11/10/23	11/10/23
Week 12				
Client Meeting	All	0%	11/13/23	11/13/23
Testing	Chris	0%	11/13/23	11/15/23
Evaluation	All	0%	11/15/23	11/15/23
Repairs/Updates	Logan	0%	11/15/23	11/17/23
Team Meeting	All	0%	11/17/23	11/17/23



PROJECT TITLE

Company Name
Project Lead

Project Start: Mon, 8/28/2023
Display Week: 1

SIMPLE GANTT CHART by Vertex42.com

TASK	ASSIGNED TO	PROGRESS	START	END
Week 13				
Client Meeting	All	0%	11/20/23	11/20/23
Thanksgiving Break	All	0%	11/22/23	11/26/23
Week 14				
Client Meeting	All	0%	11/27/23	11/27/23
Final Testing	Chris	0%	11/27/23	11/29/23
Final Evaluation	All	0%	11/30/23	11/30/23
Final Repairs/Updates	Logan	0%	11/30/23	12/3/23
Team Meeting	All	0%	12/1/23	12/1/23
Week 15				
Client Meeting	All	0%	12/4/23	12/4/23
Final Deliverables	All	0%	12/4/23	12/11/23
Final Website	Tommy	0%	12/4/23	12/8/23
Final Physical Model	All	0%	12/4/23	12/9/23
Team Meeting	All	0%	12/8/23	12/8/23
Week 16				
Final Presentations	All	0%	12/16/23	12/16/23
End Project	All	0%	12/16/23	12/16/23