Motorized Gantry System

Final Report

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Executive Summary

In the US, millions of people suffer from limb loss, a number which, along with annual limb loss processes, is projected to double in the next few decades. Prosthetics help to alleviate the risk of exclusion and dependence, with benefits in education, the job force, and the economy. The Neurobionics lab at UMich has a gantry system to protect the testee during the prosthetics testing. However, the present gantry system needs the researcher's manual assistance to move the X-direction slide rail. The project intends to incorporate the present manual gantry in the lab with actuation, detection, and control (or called automation) strategies to automatically move the gantry in synchronization as the testee moves forward and backward.

Safety and wellness are driving the efforts of the sponsor. Some primary stakeholders we identified were the patients, testers, and the lab. Secondary stakeholders were the community, university, patient's family, future testers and labs, and prosthetic users while tertiary stakeholders involved manufacturers, orthopedics and disability organizations, government, warehouses, and material providers. User requirements describe the wanted features of the device, while the specifications are written with more technical, quantitative descriptions. There were a total of ten requirements that mostly correspond to the automation and response aspect of the project, along with nine engineering specifications to help meet those requirements.

For design selection, we used various brainstorming methods such as attribute listing to create a mind map of some sub-functions and SCAMPER method to merge, substitute, and replace each of our various design concepts into 20 new designs. We then used gutcheck to further narrow down the options and created a morphological chart to label and list key sub-functions to analyze and optimize using the pugh charts for actuation and automation. After downsizing and optimizing our design options using pugh charts, we then created alpha and beta designs, with the former focusing on overdamped motor, PID, motor encoder, and ropes.

Next, we analyzed the problem domain for this project. We will need to research and learn how to control the system through a microcontroller like a Raspberry Pi or Arduino, and how to integrate components like a microcontroller, sensors, gears, and timing belt. Given that all of us have little experience in designing an actual mechatronic system, we may need time and assistance from our sponsor or textbooks for learning and researching a mechatronic system. Therefore, learning how to build a mechatronic system will be one of our critical tasks to deal with if we are unable to complete the full prototype.

We created CAD models for build and final designs and performed various engineering analyses regarding the electromechanical system and verified how each of our specifications could be tested using a design build and requirements validated eventually. We created a scaled model of the X-direction rail motion of the gantry system to better understand its behavior. This allowed us to run verification for some of our design choices and provide empirical test results to simulate a motor model for the system. We successfully verified the specifications using the scaled down model. Validation process will be conducted by the sponsor. Recommendations with re-design suggestions are made to improve the design. We hope to hand off the scale up task and analogous methods to analyze the real scale gantry to the next group.

ABSTRACT

In the United States alone, 2 million people are suffering from limb loss, with more than 150,000 amputations annually [1]. Prosthetics alleviate the risk of exclusion and dependence, with benefits in education, the job force, and the economy. With the increased demand for prosthetics, more research is needed to expand the knowledge and public use. The Neurobionics lab at the University of Michigan researches leg prosthetics that could benefit disabled individuals worldwide. In the lab, there is a manually operated gantry with a harness attached, which protects the prosthetics testee from falling during the test. The gantry system used at the University of Michigan Neurobionics lab can benefit from motorizing the gantry for promoting the ease of function and safety of the prosthetics testing environment. The current simple gantry system is inconvenient for researchers and does not protect the patients well– our task is to design a motorized gantry system that follows up the patient's movement automatically based on the testee’s movement. The team created a scaled model of the motorized gantry system. The engineering specification of the design is properly verified and the recommended re-design suggestions. The validation plan and user tests will be conducted by the sponsor and the scaled up prototype may be built by the next group.

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INTRODUCTION

The sponsor for the motorized gantry project is Dr. Elliott Rouse of the Neurobionics Lab in Ann Arbor at the University of Michigan, where he works with various leg prosthetics to "answer questions about human locomotion through understanding how limb mechanics are regulated by the nervous system." It becomes possible to develop tools and devices for the disabled by designing robotic systems for neuropathologies and amputations [10]. One important way to keep the lab testees safe during the experimentation of the devices is through the use of a gantry, which is a structure used to help support equipment or objects attached to it. The main benefit of the gantry is to ensure the safety of the patient by supporting their full weight which is crucial in the event the patient falls.

Figure 1 shows the current gantry system in Professor Rouse's lab. The gantry has two parallel, stationary slide rails along the Y-direction which are attached to the ceiling. The gantry also has one mobile slide rail in the x direction, which is attached to the two Y-direction slide rails so that it can also slide along the y direction. One end of the yellow extendable safety belt is attached to the waist and shoulders of the testee, and the other end is attached to a cable that can slide in the X-direction slide rail. Once the patient is properly secured, they can freely move around in the space below the gantry.

The main problem with the current X-Y gantry setup at the lab is that the X-direction slide rail is moved by a testee's strength alone. The yellow safety belt attached to the gantry will be left at an angle from its original vertical position when the X-direction slide rail finally starts moving. This means that the safety protection brought by the yellow belt, which is activated by a sudden jerk, cannot properly function since the gantry will not be directly above the testee [24]. For a project that mainly focuses on the safety and wellness context, the previous system can be troublesome for the testee, exerting loads and unsafety to the testee. The current solution is that when the testee is moving, a researcher is required to manually pull the rope installed at the end of the X-direction slide rail to keep the yellow safety belt in a vertical state. This solution is also inconvenient for the researchers who have to drag the gantry along with another wire parallel to the testee.

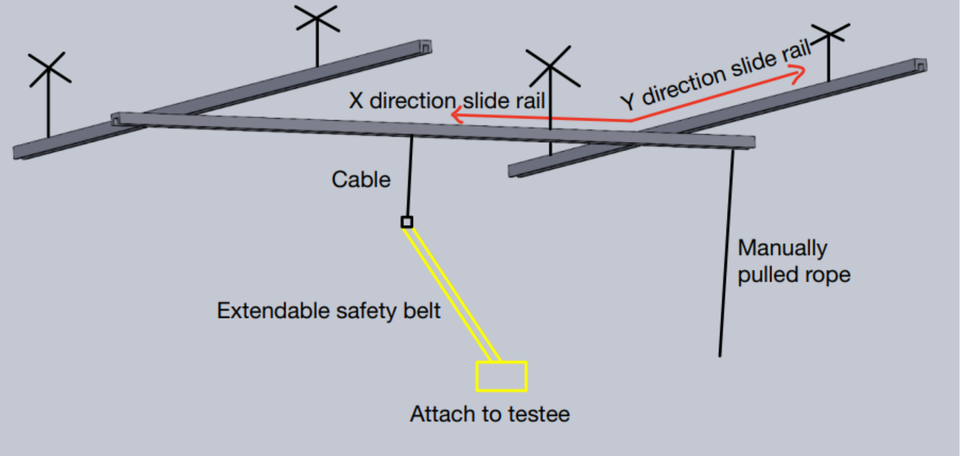


Figure 1. Schematic diagram of the X-Y gantry system in Professor Rouse's laboratory

In order to improve the testing environment, the sponsor verbally communicated that a new motorized gantry would be easier to move in the y direction, since the rollers already make the harness easy to translate in the x direction. More importantly, the sponsor doesn't want to require additional personnel to assist the testee's movement when testing the prosthetics. In other words, the gantry system needs to adjust itself according to the testee's movement, so that the yellow safety belt is always vertically above the tester's head to ensure safety. The main goal of the project is to create a prototype with an automation strategy that allows the X-direction slide rail to automatically move along the Y-axis with the testee. The assisted precise, controlled movement can be achieved by implementing an automation system to help move the gantry and make sure it hovers above the testee.

For our benchmarking, we searched current gantry systems implemented in various fields. For example, ceiling rails have been implemented for therapy and gantries have been used in manufacturing applications, warehouses, and even hospitals [9]. Figure 2 [7] shows a ceiling-mounted track system for physical therapy where customers can choose the shape of the track. The cord is easy to slide into the track and the installation is cheap. However, the patient's movement is restricted by the track and the system needs constant supervision and manual operation from assistants. Applying this design to prosthetic testing results in limited testing space and excessive consumption of human resources. Figure 3 [5] demonstrates a fully motorized X-Y gantry system found in hospitals. The patient can move at constant speeds in the x or y direction through remote control. This remote control can accurately transport the patient to a designated location at a constant speed. However, this system requires a human to operate the remote control, which limits the patient's autonomous movement to a certain extent. Moreover, this system is expensive to install.

Figure 2. Ceiling-mounted track system for physical therapy

Figure 3. One example of a Motorized X-Y gantry system used in hospitals

However, all of these gantry designs require others' assistance and the safety belt can not move with the testee automatically. We are continuing to search relative mechanical system and control system information from scientific journals written previously, as well as Dr. Rouse himself who can provide insight into the robotics and controls aspect of the gantry.

Some engineering standards that may be applied to the project include IEC standards for electric motors [11] and IEEE standards for circuits and power systems [12]. These two standards help select what motor to buy and also make sure the motors meet the energy efficiency according to the national standards. Other standards that can be looked at while researching are AGMA national gear standards [13] as well as ANSI/ASME standards for parts like bearings, screws, and nuts for assembly [14]. These standards ensure that not all gears and parts are different– joining the components together should be consistent throughout according to the standards. Gear standards help with the assembly and inspection of gears as well as make it easier to purchase the right size and ratio. No intellectual property protections are applicable to our project.

DESIGN PROCESS

A design model is a process that guides an engineering design. Steps involved in these models introduced during the lecture include defining the problem, generating concepts to solve the problem, and verifying the solution fits the specified engineering constraints and stakeholder requirements. For our design process, we adopted a linear, problem-oriented, and stage-based method to ensure we would have a diverse approach to the problem. It allows us to follow small steps that we can take to eventually approach a problem, and go back through a feedback loop if necessary to assess any setbacks. In the beginning, we thought about implementing a Dym and Little model [20] as shown below for a linear, solution-based, stage-based model.

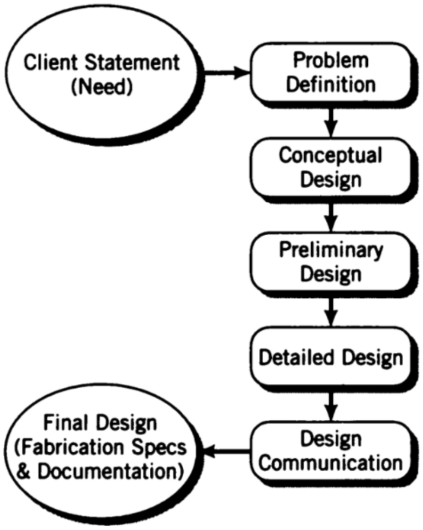


Figure 4. Dym and Little's model of the design process follows a linear and solution-based approach to the design process.

The problem with the model was that it did not take into account various possibilities for a solution– since it is a solution-based approach where a solution is proposed and analyzed in combination with design space and requirements simultaneously [21]. The method focuses more on trying and observing the results rather than analyzing various solutions such as alternatives to PID and types of materials. Hence, it is very straightforward and difficult to adjust to design limitations.

Instead, for our design process, we decided to follow something in line with Cross's model as shown below in figure 5.

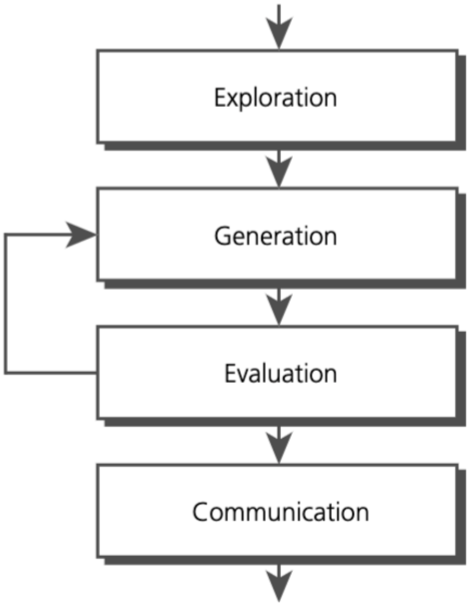


Figure 5. Cross's model of the design process, follows a stage-based, problem-oriented loop design process.

Cross's model of the design process is more open to changes in design than Dym and Little's model due to its loop-based and problem-oriented nature. It stays true to the ME 450 initial design process in that it explores various concepts and generates ideas. After idea generation, we will then evaluate the generated design and go back to generating concepts if necessary via a feedback loop. For example, if we find out that incorporating a velocity sensor is not adequate, a new concept can be created with a distance sensor in mind instead. We will then proceed to communicate the results after evaluation to the sponsor and make sure it meets the requested requirements and specifications. It could also be possible to change the component materials after analysis via Finite Element Analysis or load testing. This procedural model is the most useful in trying out various ideas for each of the parts that we may plan to purchase such as the housing, timing belt, motor, sensors, and more. It also follows a linear model, which can help simplify the design process into smaller steps to help guide through general deadlines and procedures. It is slightly different than the standard process introduced in ME450 because the project does not really have a demand for need identification, which was already provided, or the realization step– Cross's model is more simplified and some processes are worded differently, but the core idea is the same in that it consists of a design space to work in and a loop to generate and validate the choices that we make in our design. When testing our design for functionality, we will make sure to take into consideration input from the prosthetics testees themselves and lab members to make sure it meets the requirements and contains the convenience they want from the project. This means that we may need to iterate on our design choices and specifications as we build on the whole system.

INFORMATION SOURCES

Working with the librarian to find similar ideas and methods regarding a gantry system and how others have approached the problem have helped form our initial ideas. We were able to find various sources starting from simple gantry systems to complex concepts such as how warehouses use some form of motorized machinery to move heavy items from one place to another reliably. Some information gathering techniques that worked well were to search databases for similar projects and patents as well as looking up key words in various controls or engineering textbooks. Some challenges that we faced were that we initially were not familiar with designing a motorized system and had trouble finding those specific keywords that could help start the project.

DESIGN CONTEXT

The implementation of a new motorized gantry system in the Neurobionics lab will have the largest impact on Professor Rouse and the students and researchers who work in the lab. It will also have a large impact on the patients when testing prosthetics in the lab. For these reasons, both the lab, which includes the researchers working in it, and the patients are considered primary stakeholders for this project. This project also has an indirect, but slight impact on the patient's families and community, as well as the University of Michigan, the healthcare industry, and other labs and prosthetics users. These groups will not have to deal with the problem specifically, but may benefit from the successful implementation of a motorized gantry system in the lab. Lastly, the tertiary stakeholders include those who are not involved in the project, but may have some indirect influence on it. This includes groups such as hospitals and gantry manufacturers whose influences may become apparent further into the project as we progress through the design process. All stakeholders for this project are listed in Figure 6. This project will not have any immediate impacts on a global scale, but the new gantry design will likely improve the ability of the lab to conduct research and further develop new technologies in the biomedical field.

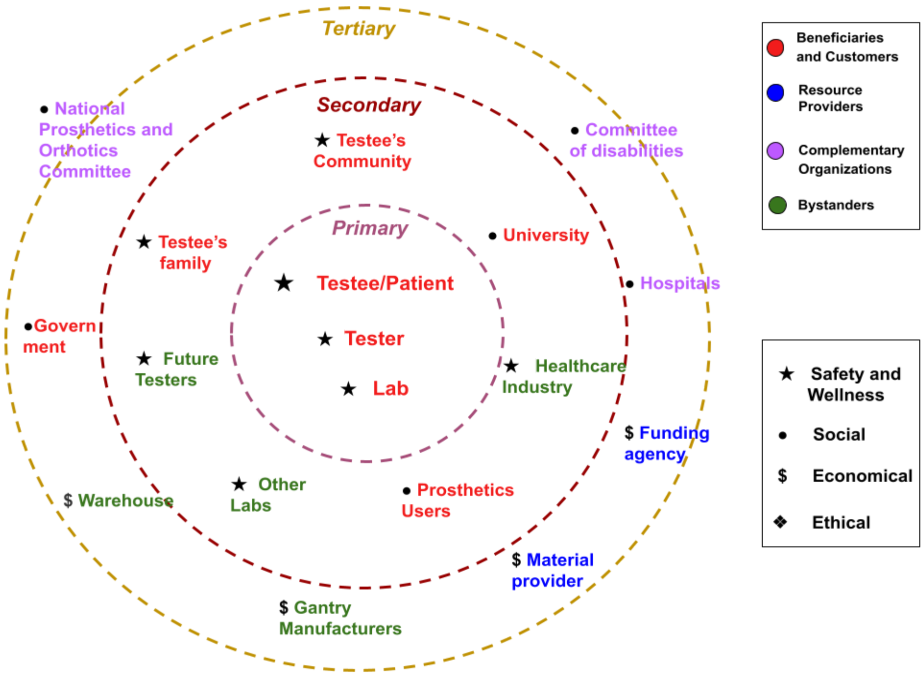


Figure 6. The stakeholder map describes the groups who are involved with, or influenced by this project. The level of involvement is described by the primary, secondary, and tertiary levels. Each stakeholder is also described by what role they play as well the type of design context that is considered.

Stakeholders

The primary stakeholders for this project include Professor Rouse and the researchers who work in the University of Michigan Neurobionics Lab as well as the patients who will use the gantry system when testing prosthetics. With the current gantry design, a member of the lab must follow the movement of the patient around the lab while manually moving the gantry with a rope. By motorizing the gantry, both the lab and patients benefit greatly as less manual effort is required by the researchers to move the gantry which allows them to focus more on the patient and increase research productivity. The patient is also able to move more freely with a motorized gantry while also minimizing the confusion that may result when the patient must communicate their movements to the researcher with a manually operated gantry. Another major advantage to the patient is the increased safety as a result of the motorized gantry automatically following their movements. The main issue with the current system is that when the gantry lags behind the patient's movements, the safety mechanism inside the belt to which the patient is strapped to cannot function properly to catch the patient if they were to fall.

The secondary stakeholders of this project include the University of Michigan, the patient's family and community, as well as other labs and prosthetics users. The patient's families and community, although not directly involved, do benefit from this project as the advancements in prosthetics that may come as a result of this project will allow the patient to interact with their family and community in a positive way. The university also benefits as increased research output allows them to secure more funding and continue to build a reputation as a top public research university. Other prosthetics users who may never use the gantry will likely benefit from the advancements in biomedical technologies that may come as a result of a newly implemented motorized gantry system in the neurobionics research lab.

The tertiary stakeholders include those that we believe may have some influence on the project, even though they will not have any direct involvement with the project itself. These include gantry manufacturers, materials providers, and organizations such as the National Commission on Orthotic & Prosthetic Education (NCOPE) [22] and the Committee on the Rights of Persons with Disabilities (CRPD) [23]. As we explore designs for this project, we will likely come across other systems which are manufactured by companies that will influence how we approach our design. Likewise, because the lab is choosing to develop its gantry system, there is potentially a negative impact (albeit very slight) on companies whose products will not be purchased. The ability of our group to acquire parts from material providers will also have an impact on this project, specifically on the design and timeline, which may need to be reconsidered if we are unable to acquire specific parts at certain points throughout the design process. Lastly, throughout our research for this project, we will likely refer to the information provided by numerous organizations that specialize in disabilities and prosthetic devices for us to better understand the problem we are trying to solve from a broader perspective.

Global Context

Although this project will not have any immediate global impacts, if the successful implementation of this new gantry system allows the lab to increase its research output, there could be new developments in prosthetics technologies which would have a much greater impact.

Ethical and Environmental Considerations

The most crucial ethical consideration that must be addressed throughout this project is the safety of the patient while they are using the gantry. As communicated by the project sponsor, the main reason for moving towards a motorized gantry system is due to the lagging of the current gantry negatively impacting the safety belt's ability to catch a patient if they were to fall. Throughout our design process, we must be careful to not just design a gantry system that can move effectively on its own, but one that will not negatively impact the patient's safety. Our project will have minimal environmental impacts mostly because it is a one-off product that will exclusively be used in the neurobionics lab.

Political and Logistical Factors

The project does not consider political factors that may need to be addressed, although the government can benefit from being able to integrate individuals with physical disabilities into society by increasing the job force. If the gantry helps the prosthetics research and prosthetics research becomes a large topic, the government can also help the research efforts by passing policies or providing funds supporting it.

The project will also not involve logistical factors such as storage, transportation, warehousing, packaging, and handling since the gantry is already present at the lab. While the components that we purchase may have minor impacts such as transportation and storage costs, they are not our primary concern at this stage of the project. We will continue to research more about these contexts.

Socio-cultural Factors

The project does have important socio-cultural factors to take into account. The main purpose of the project is directed towards the amputees, who will be implementing leg prosthetics that are being researched by the Neurobionics Lab– with safe, successful experiments, the prosthetics can be used for the public and it can greatly enhance their quality of life. Improving the mobility and functioning of amputees allows society to be able to integrate individuals with physical impairments, open the door for education and job opportunities, reduce medical costs, and more.

Intellectual Property Considerations

For this project, we were not required to sign any non-disclosure agreements or any other documents relating to intellectual property as the primary purpose of this project is to improve a current tool the lab uses to better conduct research.

Public health, Safety, and Welfare Consideration

As mentioned above, our project aims to build a motorized gantry system that assists in prosthetic research in the Neurobionics lab at the University of Michigan. The new gantry will provide better protection for prosthetics testees and reduce the burden for researchers during the test. As a result, our project takes safety as our priority and will indirectly impact public health and social welfare as the new gantry will assist the prosthetics research.

USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

As mentioned above in the benchmarking, current products of the medical gantry system have to be manually operated or work in a fixed pattern. However, those products more or less have some disadvantages. Particularly, they are unable to detect the testee’s position or speed and follow up with the testee's movement.

Our requirements are from the interview of the sponsor, Professor Rouse. The current gantry system used in the sponsor's lab is manually operated. That is, a researcher will help pull the gantry to follow the testee’s movement during the prosthetics test. The current gantry system is not ideal for safety because the researcher may not be able to pull the gantry to the testee's position in time in the event of a fall. Therefore we collected the requirements from the sponsor during the interview and translated them into quantified specifications as below in Table 1A.

Table 1A. Updated User requirements and specifications with priority

Requirements	Engineering specification	Priority	Source
The gantry should move in walk-like speed	Move with a velocity of about $2m/s$	High	Sponsor [24]
Reach target speed quickly	Max acceleration of $2m/s^2$	High	Sponsor [24]
The gantry should respond with minimum oscillations	The system should respond like a 2nd order system with $\zeta > 0.7$	High	Textbook [5]
Should not get stuck while moving	Gantry sliding bar should tilt <10 deg while moving	High	Sponsor [24]
Enough torque to operate the actuation system	High-performance motor with stall torque around 3 Nm	High	Sponsor [24]
Gantry takes minimum time to go to patient's position	Gantry should take <3 sec to go to the patient's position	High	Sponsor [24]
The gantry should locate the patient's position precisely	Steady state position of the gantry should not be farther than 1m from the patient's position	Medium	Journal [16]
Detect and react to the testee's movement	Able to respond by the time the patient is 2 meters from their original position	Medium	Journal [17]
Motor system does not interfere with gantry movement	1m away from the end of the Y-direction slide rail gantry	Medium	Gantry Spec sheet [25]
The system will be used long term	Last for 10 years before repair and replacement	Low	U.S. DOE Motors [27]

To begin, our gantry should move to the testee's position quickly and the specification is that the gantry needs to move with a max velocity of 2 m/s which is the sponsor's requirement [24]. The velocity of 2 m/s is approximately double that of human walking speed [20]. Under such a velocity, we would expect the gantry to follow up with the testee in a short time as well. We also aim to reach the target speed quickly by keeping a max acceleration of 2 m/s^2 as recommended by our sponsor. It may be difficult to directly verify the linear acceleration and velocity of the gantry, but there are two possible methods we could use to get around this. First, we could analyze the rotational acceleration and velocity of the motor with the use of an encoder. We would then use the parameters from the actuation system such as gear diameters or ratios to determine the linear acceleration and velocity of the gantry. Second, we could estimate the linear acceleration and velocity of the gantry by recording the time it takes it to cross a known distance. We would utilize the equations of motion to calculate acceleration from time and distance traveled. This kinematic relationship is shown in Equations 1 and 2.

$$\Delta x = v_o t + \frac{1}{2}at^2 \tag{1}$$

$$a = \frac{2(\Delta X - v_o t)}{t^2} \tag{2}$$

Where a is the acceleration, Δx is the distance traveled, v_0 is the initial velocity, and t is the time. Equation 1 represents the standard equation used to solve for distance traveled, whereas Equation 2 is rewritten to solve for acceleration. It is important to note that these equations of motion assume constant acceleration, so for the most accurate measurements, we should keep the distance traveled as small as possible. Secondly, we want the gantry to respond with minimum oscillations, similar to how a second-order system with a damping ratio of about 0.7 would behave. The oscillation may cause the gantry bar to fatigue and fail soon [19]. The oscillation will also trigger the lock of the safety belt and interfere with the testee's movement [15]. In DR1, we stated that we wanted the gantry to respond as an overdamped second-order system. Through more discussions within our group and with our sponsor, we determined the original value was too strict to evaluate, thus we changed the description of the requirement to be more tolerant and set a damping ratio target. To verify this requirement and specification, there are two methods we could use. The first, and most simple, method would be to just visually assess the oscillations in the gantry. Our thought is that if the oscillations in the gantry are too small to see, then they are too small to significantly affect the patient's movements. However, if we decide that we need a more quantitative measurement of the oscillations in the system, we could use the equations for the damping ratio to verify this requirement. Equations 3, 4, and 5 show we will calculate the damping ratio of our system.

$$mx''(t) + cx'(t) + kx = F \tag{3}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{4}$$

$$\zeta = \frac{c}{2m\omega_n} \tag{5}$$

Where m, c, and k are system parameters, F is the external force on the gantry, ω_n is the natural frequency of the system, and ζ is the damping ratio. These equations represent the general model for a second-order system which we will have to derive to determine parameters such as the damping ratio. A more detailed derivation of this system and our plans for further analysis are covered in the engineering analysis section of this report. Likewise, the gantry should locate the patient's position precisely, which has the specification that the steady-state position of the gantry should not be farther than 1 meter away from the testee's position. We set the distance of 1 meter which is 1.5 times the average step length of a human[16]. We will be able to easily measure this distance from the ground using a tape measure to verify this requirement and specification. We are using the value of 1.5 as a safety factor. As the gantry moves, another requirement is that the gantry should move in translation. Specifically, the gantry should move with less than 10 degrees of tilt, essentially in linear movement. Knowing that the gantry has two parallel sliding rails and one X-direction bar sliding on them, we don't want the sliding bar to get stuck due to a misalignment. One method of verification would involve using trigonometry and distance measurements between the two sliding rails to estimate the angle. Another simpler method would involve visually observing the tilt in the gantry to ensure it does not get stuck. We want the motorization system to provide enough torque to drive the gantry. Referring to the system the sponsor recommended, AmpFlow E30-150-12 [18], we specify the stall torque of the motor should be around 3 Nm. The gantry should notice whether the testee is moving forward or backward along the Y-direction. We don't consider the movement along the X-direction slide rail since that is not a requirement from the sponsor and the X-direction motion is pretty smooth as is. Lastly, the gantry should move in a short time to go to the testee's position. Thus, we set the specification that the gantry should take less than 3 seconds to go to the testee's position. This requirement can be verified easily by recording the amount of time it takes for the gantry to move. We consider 3 seconds to be an appropriate limit considering the inertia of the gantry and the speed limitation.

The user requirements and specifications above are important because those requirements are related to the safety design context which we are most concerned about. Recall that our project aims to design an automatically controlled gantry system that protects the testee from falling during the prosthetics test; those requirements ensure that the gantry can protect the testee effectively.

The following requirements are useful to have but not necessary. Firstly, we want the system that drives the gantry to not interfere with gantry movement. That is, we want to install the system 1 meter away from the end of the Y-direction slide rail. The 1 meter we specified comes from two-thirds of the average adult arm span [17] which ensures a proper distance for installation and adjustment without interfering with the gantry. This requirement and specification can also be verified by directly measuring the distance between the gantry rail and the automation devices. In addition, we hope the motorized gantry system we built will last till the end of the lab program. Therefore we set the specification that the gantry system will not be replaced or repaired for 10 years after when the prosthetic project may come to an end. The duration of the devices can be verified through the specification of the motor, gears, and other components. The following table summarizes our methodology of how to evaluate our specification:

Table 1B. Updated User requirements and specifications with measure methodology

Requirements	Engineering specification	Measurement Methodology
The gantry should move at walk-like speed	Move with a velocity of about $2m/s$	Use decoder signal and first derivative to monitor velocity
Reach target speed quickly	Max acceleration of $2m/s^2$	Record time and distance to derive acceleration
The gantry should respond with minimum oscillations	The system should respond like a 2nd order system with $\zeta > 0.7$	Use 2nd order system equation to estimate damping ratio and use MATLAB to simulate response behavior
Should not get stuck while moving	Gantry sliding bar should tilt <10 deg while moving	Visually see whether it has obvious tilt
Enough torque to operate the actuation system	High-performance motor with stall torque around 3 Nm	Check motor spec and test whether the motor can provide wanted torque
Gantry takes minimum time to go to patient's position	Gantry should take <3 sec to go to the patient's position	Record using timer
The gantry should locate the patient's position precisely	Steady state position of the gantry should not be farther than 1m from the patient's position	Measured using tape measure
Detect and react to the testee's movement	Able to respond by the time the patient is 2 meters from their original position	Using tape measure
Motor system does not interfere with gantry movement	1m away from the end of the Y-direction slide rail gantry	Using tape measure
The system will be used long term	Last for 10 years before repair and replacement	Check motor spec and estimate the gear lifespan

Our requirement and specification has High, Medium and Low priorities in which High priority requirements are directly from the sponsor that we must meet; the Medium priority requirements came from our own thoughts that are important but don't need to meet strictly; the Low priority requirements are helpful to meet but not necessary. These priorities were chosen based on safety and wellness of the testees.

That's all the requirements that our sponsor and we are concerned about. All related standards are mentioned in the Introduction section above. As for now, we don't have further standards to meet.

CONCEPT GENERATION

We created a divergent/convergent concept generation by first brainstorming and focusing on certain sub-functions of the project instead of looking at the project as a whole. We first utilized attribute listing to decompose the project into different sub-functions, or “attributes.” [28] This allowed us to zone in on each of the different sub-functions separately instead of having to figure out the entire system design at once. A sub-functions map we created using attribute listing is shown in Figure 7 below:

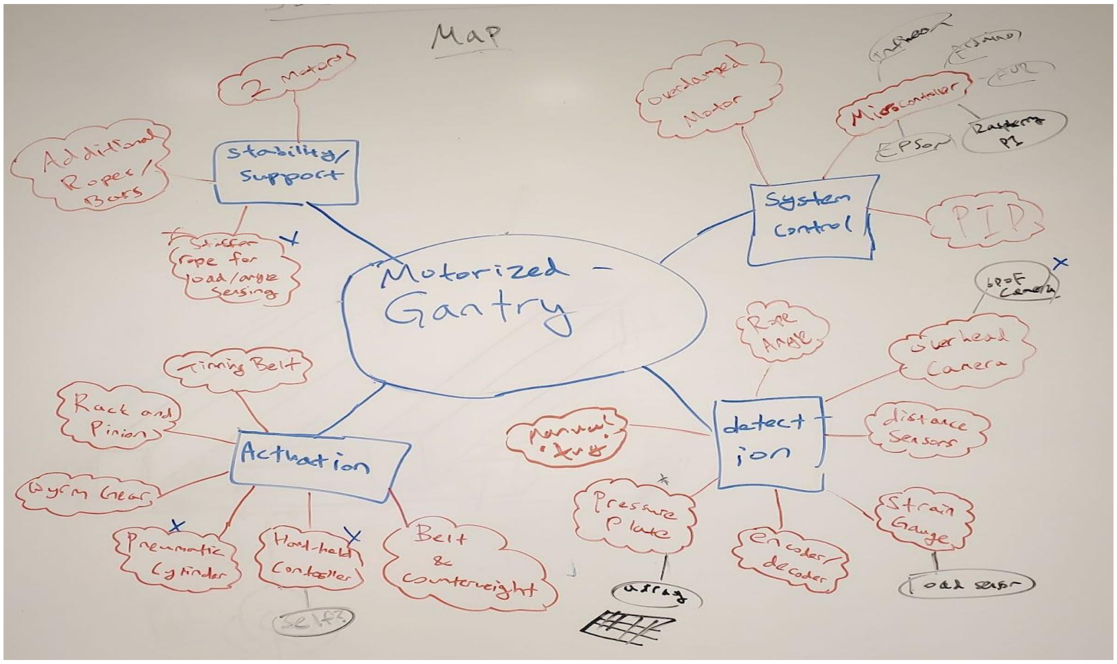


Figure 7: Map of attribute listing consisting of 4 different subfunctions: systems, detection, controls (or called automation), and actuation.

The blue bubbles represent the four sub-functions that we devised for the project, and we further broke down those attributes into more specific components that could fulfill the tasks provided. The black bubbles show more specific companies that we can purchase those items from. After creating the sub-functions map, we each created 40 designs that could either perform the sub-functions or unique designs that could be useful for our final designs. Some examples of these drawings can be seen below in Figures 8 and 9:

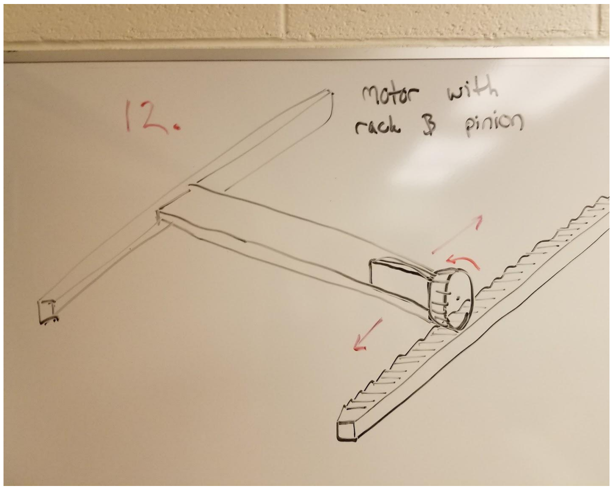


Figure 8: Actuation using rack and pinion

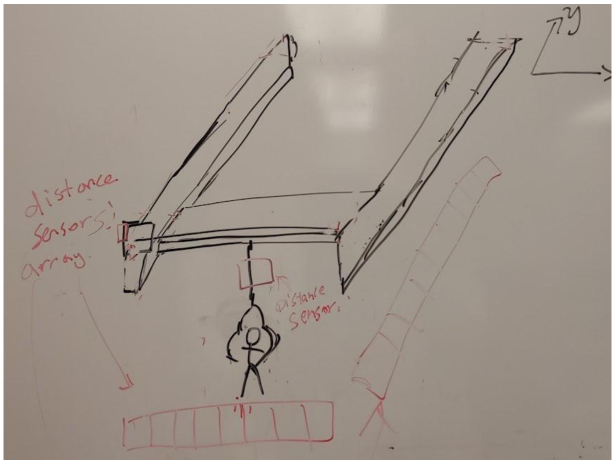


Figure 9: An array of distance sensors for pinpointing position

We then utilized the SCAMPER method [29], which stands for Substitute, Combine, Adapt, Modify, Put to other use, Eliminate, and Reverse. The process works similarly to design heuristics in that it attempts to take an idea or a concept and change it so that it fulfills other functions or gives new insights into a difficult problem. Through this method, we combined, analyzed, and condensed the aforementioned concepts and generated 20 new design concepts. While some of the designs were more innovative and had unique ideas, many of the ideas shared a motor, actuation method, and automation method. The concepts can be classified based on which sub-function each design focuses more on– for example, designs like the Treadmill focus more on actuation rather than detection since it relies on the testee's speed rather than where the testee is standing. One example of a newly generated concept can be found in Figure 10 below:

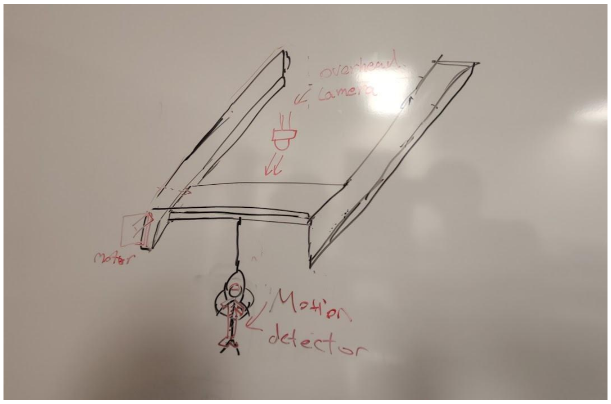


Figure 10: SCAMPER method to combine multiple sensors into one overhead camera, as well as substituting distance sensing to motion sensing.

We then narrowed down our design selection by first performing a gut check for feasibility. This was the step where we removed any impractical design choices that were difficult to implement within a semester or were very costly. One example is shown below in Figure 11:

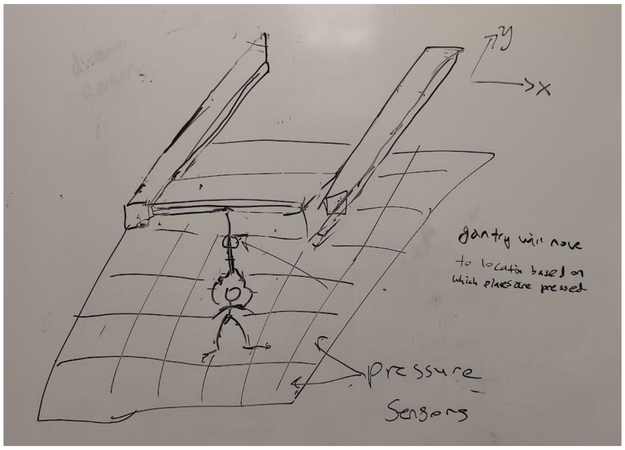


Figure 11: Utilizing pressure sensor floor mats instead of cameras or distance sensors. The position of the patient is measured by which plate they are standing on.

The design with pressure sensors is impractical because the mats will have to be placed throughout the lab, which will be costly, technically difficult, and inefficient. Also, it interferes with other tests in the lab such as the stair test where they go up and down a set of stairs.

CONCEPT SELECTION

After deleting some impractical design ideas, we created a morphological chart to organize and list the sub-functions for systems control (or called automation), detection, actuation, and additional support. The chart shown below in Table 2 provides feasible solutions to how we would approach each of the sub-functions.

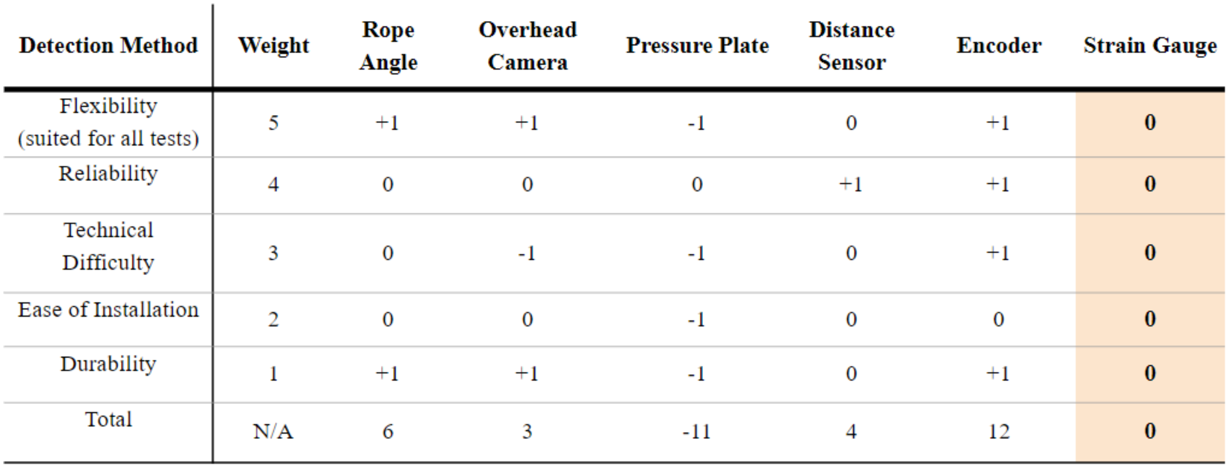
Table 2: Morphological chart of sub-functions and possible solutions

Sub functions	Solutions					
Systems Control	High-Performance overdamped Motor	Microcontroller	PID Control			
Detect “Movement”	Rope angle sensing	Overhead camera	Distance sensor	Strain gauge	Encoder	Pressure plates
Actuate Gantry Movement	Timing belt	Rack and pinion	Worm gear	Pneumatic cylinder	Hand-held controller	Belt and counterweight
Additional Support	Use of 2 motors	Additional rope				

The table allowed us to visually represent necessary functional requirements and see various alternate combinations to achieve each of the sub-functions.

To find out the appropriate design for the Detect sub-function and Actuation sub-function, each of the concepts was compared with a Pugh chart. We used a pugh chart for each sub-function to help us assess and determine the best sub-design for each category. The pugh chart for the Detection sub-function is shown in **Table 3**.

Table 3: Pugh chart showing the criterion for Detection design made by each design. Each criterion has a graded weight that is given based on the importance of the criterion to the design.



Detection Method	Weight	Rope Angle	Overhead Camera	Pressure Plate	Distance Sensor	Encoder	Strain Gauge
Flexibility (suited for all tests)	5	+1	+1	-1	0	+1	**0**
Reliability	4	0	0	0	+1	+1	**0**
Technical Difficulty	3	0	-1	-1	0	+1	**0**
Ease of Installation	2	0	0	-1	0	0	**0**
Durability	1	+1	+1	-1	0	+1	**0**
Total	N/A	6	3	-11	4	12	**0**

In this pugh chart, we compared seven different designs and ranked them on how they fulfilled a list of criteria. These criteria were ranked based on their priority. For example, we determined that the flexibility of the design was the most important as the lab in which the patients will be walking is an open space that can change in-between tests. For example, there are walking tests, staircase tests, and ramp tests. When changing from walking tests to staircase tests, the patient will step to a high platform and the safety belt will shorten. This will cause some detection mechanisms, like strain gauge and distance sensor, to fail. As patients step on the staircase, they go high and away from the X-direction sliding rail. This change may send an inappropriate signal to certain detection devices, like strain gauge and distance sensor, that the patient is moving away slowly compared to walking on flat ground. Thus, the gantry may not protect the patient in time.

Similar situations would happen as patients change to ramp tests. One possible solution would be using a state machine to switch the detection strategy corresponding to different prosthetics tests. However, implementing a state machine is much more difficult. Instead, we set the highest weight of 5 for this criterion to show that we want a strategy that can deal with all the prosthetics tests. The second important criterion is reliability. This criterion relates to whether the detection method directly reflects the distance between the patient and the X-direction rail. Some indirect detection methods may have unexpected behavior as the patient moves freely. For example, if the patient crouches or ducks down accidentally, the strain gauge and the distance sensor may incorrectly recognize that the patient is far away from the X-direction sliding rail which may trigger the gantry to move. As a result, we set the weight of the reliability to be 4.

Similarly, the Technical Difficulty has a weight of 3, as we consider this criterion is just below the priority of reliability – it is important to be able to troubleshoot as fast as we can and to be able to design a system without too many parts that can break. In addition, we intend to ensure our design provides the least amount of inconvenience for both the researchers and patients if the system had to be reinstalled and we hope that our design may last long enough to assist our sponsor to finish their research. Thus, we set the Ease of Installation and durability weight as 2 and 1 respectively. The weight ranged from 5 to 1 ranked the different criteria by their relative importance. To complete the Pugh chart, we then chose a reference design, that being the strain gauge method, which was given all zeros to compare with other designs. Each design was given a +1 or -1 based on whether it fulfilled each requirement better or worse compared to the strain gauge design.

Ultimately, we decided that the encoder method would provide the most flexibility and reliability, while also reducing the technical complexity of implementation. Likewise, we determined that the pressure plate design was the least practical of the seven mostly because it would be very difficult to implement and changes to the lab layout would be required with this design.

For the Actuation sub-function, we also used the Pugh chart to help us assess and select the find design, shown in **Table 4** below

Table 4: Pugh chart showing the criterion for **Actuation design** made by each design. Each criterion has a graded weight that is given based on the importance of the criterion to the design.

Actuation Method	**Weight**	**Timing Belt**	**Rack and Pinion**	**Worm Gear**	**Pneumatic Cylinder**	**Hand-Held Controller**	**Belt and Counterweight**
Durability	3	+1	+1	-1	+1	0	**0**
Maintenance	3	0	-1	-1	-1	0	**0**
Simplicity	2	0	0	0	0	1	**0**
Configurability	1	+1	0	-1	0	1	**0**
Total	N/A	4	0	-7	0	3	**0**

Similarly, we chose Durability, how long the mechanism could operate, and Maintenance, how expensive to maintain the device, as primary criteria with a weight of 3. Since the Actuation sub-function will bear the force from the motor and will be very heavy due to its required length, we want it to be able to hold its weight and to be available for use in the long term. Knowing that the actuation system will be installed on the ceiling as our sponsor required, the falling dust will more or less affect the operation of the actuation system. Therefore, we want the design to be easy to maintain, which is why it was viewed as important as durability. Also, we want to design the system to be simple and configurable. It will be a big actuation system, so we want the structure to be simple to reduce the installation difficulty. In addition, knowing that our determination of gear ratio or size is purely theoretical, there may be a chance that we need to modify the configuration of the actuation system. Therefore, we also set the criteria of how easily we could configure the system to our needs. These two criteria were decided as less important than Durability and Maintenance, so we assigned a weight of 2 and 1, respectively. We then utilized the same procedure as we mentioned above and decided to select the Timing Belt actuation . A simple visual model of the timing belt can be found in the Alpha Design section below.

For the Control (or called Automation) system, we decided to incorporate all the design ideas — the overdamped motor, the microcontroller, and the PID controller — together. Based on our previous research on motor parameters, we found little information on the response behavior of motors. We firstly want to find a desired overdamped motor. However, to avoid devoting too much time to searching motors, we may need to implement a PID controller, which was also requested by the sponsor. This would allow us to tune the motor to respond in the way that we want. What's more, based on our knowledge from ME 350, we may need a microcontroller to operate the encoder and decoder.

ALPHA DESIGN

The two pugh charts contain concepts suggested by the sponsor and concepts generated by our research. Based on the scores in the Pugh charts, we have selected the best solutions to fulfill each subfunction. For the actuation, we chose to connect the X-direction slide rail to two timing belts driven by two motors. For detecting the movement of the testee, we choose to use the motor encoder to sense the pull of the X-direction slide rail and timing belts when the subject moves. By selecting a motor with an appropriate damping coefficient, the second-order system may behave in an overdamped manner. So far, we haven't found the desired motor. What's more, to avoid spending much time on searching for the desired motor and to ensure our system response in less rise time, we plan to implement a PID controller to finely tune system parameters.

The detailed drawing of our alpha design is shown in **Figure 12**. The motor, gearbox, and microcontroller will be mounted on one end of each Y-direction slide rail. Since the safety belt will extend and it may not have enough strength to perform the initial pulling on the X-direction slide rail and activate the motor encoder, we plan to implement an additional elastic rope between the testee and the slide rail to help pull the X-direction slide rail.

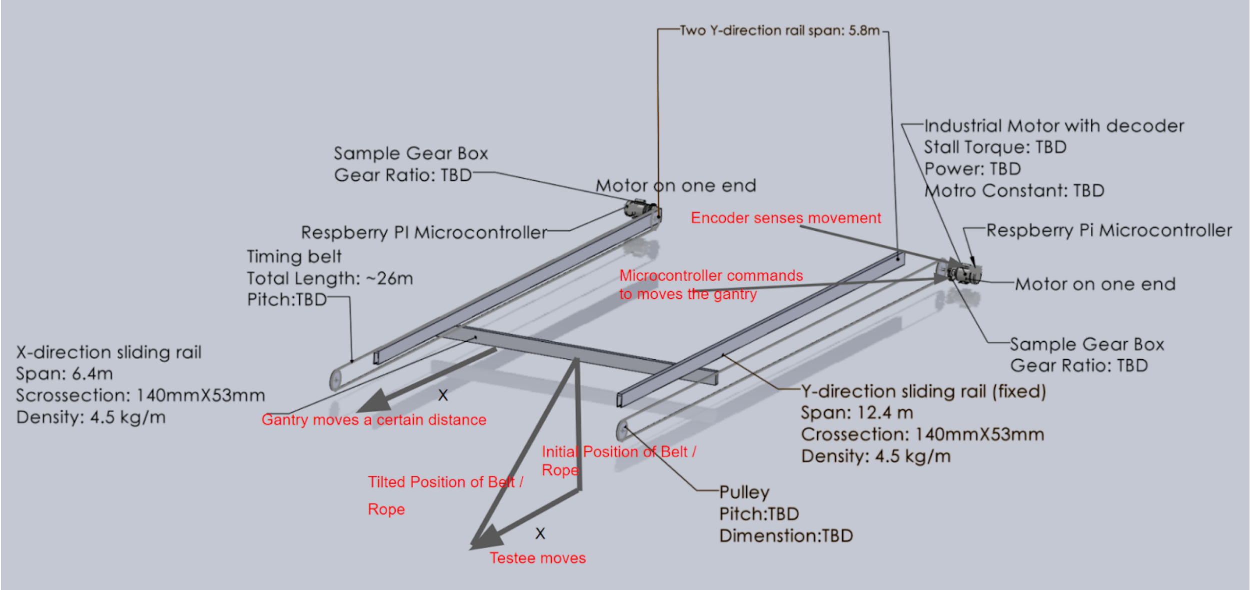
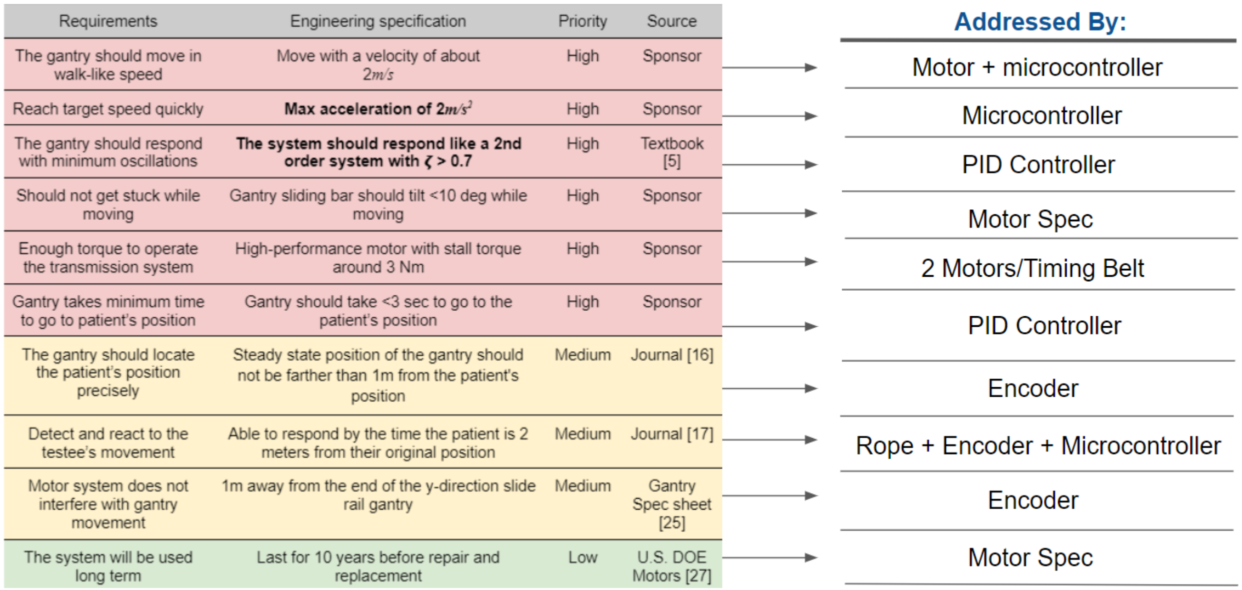


Figure 12: The picture of the detailed alpha design taken from the CAD file.

Initially, the safety belt and the additional rope are vertical. When the testee moves a certain distance X, the safety belt tilts in a certain angle, and the additional elastic rope will have enough elastic force to drag the X-direction slide rail a little bit. The value of the distance X is fixed and measurable, which essentially corresponds to the scenario when the elastic force of the rope exceeds the system's static friction. Once the X-direction slide rail has been dragged, the motion will be transferred to the timing belts since they are rigidly connected. Then the two motors will rotate due to the motion of two timing belts, which will be finally perceived by the motor encoders. After receiving the signal from motor encoders, the microcontroller will command the motor to drive the timing belt for the exact displacement X. Eventually, the slide rail will follow up the testee and the safety belt will become vertical again. We will further add a retraction device to the elastic rope, which will behave similarly to the retractable backpack shoulder strap so that we can easily adjust the length of the additional rope when performing the staircase test and ramp test.

More detailed description and installation methods of the alpha design can be found in the Final Design Description below. It will include how the timing belt connects with the gantry rail, how we fix the motor and pulley and how the motor wire connects with the microcontroller, and more.

Our alpha design with the encoder triggering detection method can meet each of these engineering specifications and user requirements. For example, by selecting the motor and programming the microcontroller, we can meet requirements regarding the specified velocity and acceleration. By tuning the PID controller, we make our system behave as a second-order system with a damping ratio greater than 0.7. An overdamped motor may meet the damping ratio requirement but for now, we didn't find the desired motor and to not spend much time searching for the motor, we will prepare a PID controller to tune the system. We can set the travel distance to activate the motor by selecting the appropriate elastic rope. This design concept is not difficult to achieve within the constraints of ME450. The following Figure 13 shows how our alpha design meets the requirements:



Requirements	Engineering specification	Priority	Source	Addressed By:
The gantry should move in walk-like speed	Move with a velocity of about $2m/s$	High	Sponsor	Motor + microcontroller
Reach target speed quickly	**Max acceleration of $2m/s^2$**	High	Sponsor	Microcontroller
The gantry should respond with minimum oscillations	**The system should respond like a 2nd order system with $\zeta > 0.7$**	High	Textbook [5]	PID Controller
Should not get stuck while moving	Gantry sliding bar should tilt <10 deg while moving	High	Sponsor	Motor Spec
Enough torque to operate the transmission system	High-performance motor with stall torque around 3 Nm	High	Sponsor	2 Motors/Timing Belt
Gantry takes minimum time to go to patient's position	Gantry should take <3 sec to go to the patient's position	High	Sponsor	PID Controller
The gantry should locate the patient's position precisely	Steady state position of the gantry should not be farther than 1m from the patient's position	Medium	Journal [16]	Encoder
Detect and react to the testee's movement	Able to respond by the time the patient is 2 meters from their original position	Medium	Journal [17]	Rope + Encoder + Microcontroller
Motor system does not interfere with gantry movement	1m away from the end of the y-direction slide rail gantry	Medium	Gantry Spec sheet [25]	Encoder
The system will be used long term	Last for 10 years before repair and replacement	Low	U.S. DOE Motors [27]	Motor Spec

Figure 13. Initial assessment to see how the specifications are addressed by the alpha design.

Based on the alpha design, we estimated the materials we may use and the price of those materials. **Table 5** below shows our initial bill of materials.

Table 5: Estimated bill of materials for gantry prototype

Part No.	Part Title	Dimensions	Supplier	Quantity	Price (based on initial research)
1	Timing belt	TBD	GPR industry	2	$1500
2	Timing belt pulleys	TBD	SDP SI	4	$110
3	Permanent magnet DC motor with rotary encoder	TBD	Kollmorgen	2	$350
4	Microcontroller	Raspberry Pi 3 Model B+	Raspberry Pi	2	$200
5	Gear	TBD	SDP SI	TBD	$50 - 100

BETA DESIGN

We also selected two beta designs of testee's movement detection, which achieves the second and the third highest scores from the movement detection pugh chart. The first beta design as shown in **Figure 13** is to use an overhead camera mounted on the X-direction slide rail that can move with the safety belt. The camera can record the planar position of the testee and the gantry rail and calculate the position difference between them in a vector form. The difference will serve as a signal to activate the motor. However, this method is less reliable than our alpha design since mounting the camera is at high technical difficulties and the camera itself is expensive.

The second beta design is to use four distant sensors as shown in Figure 14, where sensor 1 and sensor 2 will perceive the signal from sensor 4 and output the testee's movement direction along the Y-axis. Sensor 3 and sensor 4 will measure the elongation of the belt, which is a positive correlation with the distance the testee travels. However, this design is so inflexible that we need to consistently change the threshold distance between sensor 3 and sensor 4 when performing the staircase test and ramp test, since during these two tests the distance between sensor 3 and sensor 4 will change. These approaches have been proven to have some drawbacks based on our pugh chart, so we chose them to serve as our backup designs.

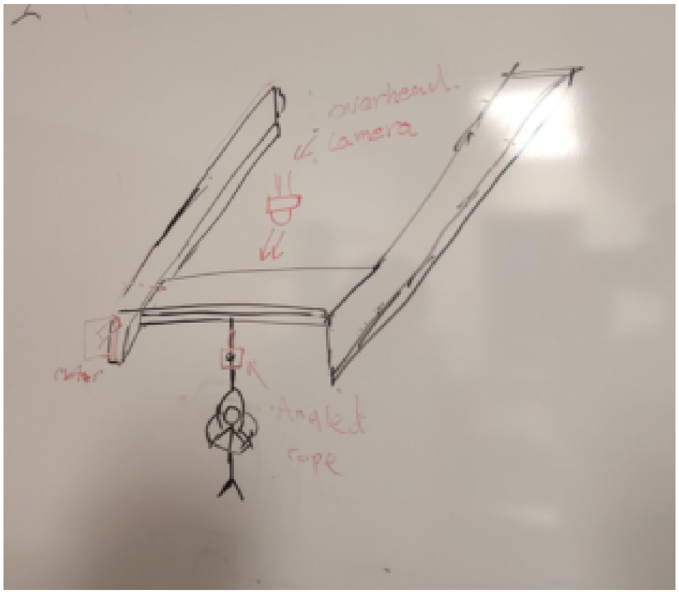


Figure 14. Overhead camera detection method.

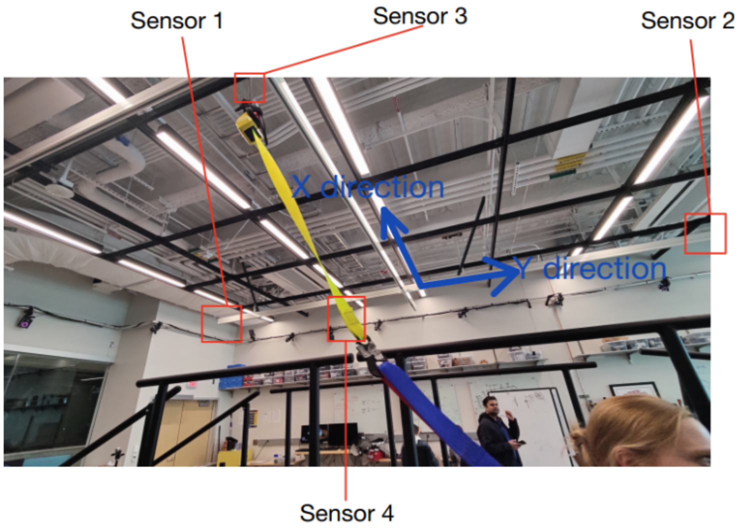


Figure 15. Four distance sensors detection method

ENGINEERING ANALYSIS

First we need to determine the friction forces that exist in the current gantry system since we need to ensure our selected motors have enough torque to meet engineering requirements regarding velocity and acceleration. For static friction, we pulled on the gantry rail using a rope at different angles and measured the minimum force required to accelerate the gantry from rest. The measurement was recorded using a digital force gauge. For each angle, we determined the horizontal force component to determine the static force acting on the gantry, this is shown in **Figure 16**.

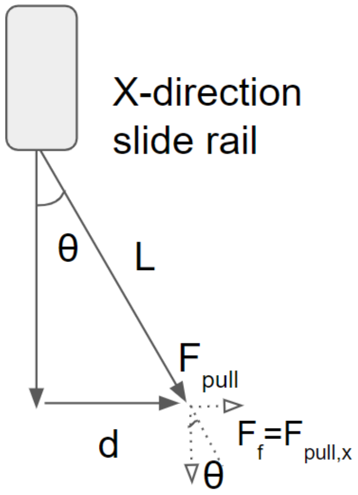


Figure 16. Tensile force decomposition to calculate the static friction force needs to be overcome. The distance *L* represents the length of the rope to which the force gauge was attached. At a given angle *θ*, the distance *d* was measured along the floor using a tape measure. The X-direction slide rail in the figure spans into the page.

We calculated the static friction force using similar triangles, and values of the distance *d* and the pull force *F* to calculate the static friction force $F_{f,static}$ as shown in Equation 6 below.

$$F_{f,static} = \frac{F_{pull}}{L} \times d \tag{6}$$

where $F_{f,static}$ represents the static force, F_{pull} represents the threshold pull force, *L* represents the length of rope attached between the X-direction gantry and the force gantry, and *d* represents the horizontal distance between the original vertical position and the current position. By averaging static friction forces calculated with different tilting angles *θ*, we determined the static friction force to be around 3.5 *N*. Considering the additional friction force brought by the timing belts and pulleys, we set a factor of safety to be 1.5. Hence, the total friction force in our system is $3.5\ N \times 1.5 = 5.25\ N$.

We conducted another test to determine the dynamic friction acting on the gantry while it is in motion. We used a long rod to accelerate the gantry at various speeds and then released it at an exact location. Once released, the gantry was then allowed to coast to a complete stop. The distance traveled and time to decelerate to zero were recorded for each test. Using the equations of motion with known parameters of time, distance traveled, and final velocity, we could determine the deceleration of the gantry and thus the dynamic friction force acting on it. Initial velocity was also calculated for each test so we could ensure we collected a somewhat even distribution of speeds ranging from >0 m/s to <2 m/s. Equations 7 and 8 were used to calculate initial velocity and deceleration, respectively.

$$v_0 = \frac{2d}{t} - v_f \tag{7}$$

$$a = 2\frac{v_f t - d}{t^2} \tag{8}$$

Where v_0 is the initial velocity in m/sec, d is the distance traveled in m, t is the time to decelerate in seconds, v_f is the final velocity in m/sec (equal to zero in our case), and a is the acceleration of the gantry in m/sec, which will be negative since the gantry is decelerating. After determining the deceleration of the gantry for each test, we multiplied it by the mass of the gantry and belt (~30.5 kg) to determine the dynamic friction force acting on the gantry for each speed. The value was relatively constant regardless of the initial velocity, averaging around 1.5 N for each test.

Given that the linear density of the X-direction slide rail is 4.5 kg/m and the length of the rail is 6.4 m, we calculate the mass of the X-direction slide rail in Equation 9.

$$m_{rail} = \rho \times L = 6.4\,kg/m \times 4.5\,m = 28.8\,kg \tag{9}$$

where m_{rail} is the mass of X-direction slide rail, ρ is the linear density of X-direction slide rail and L is the length of the rail. To make the X-direction slide rail reach an acceleration greater than 2 m/s^2, the minimum torque that each motor should provide is shown in Equation 10.

$$T_m = \frac{1}{2} r \times (f + m_{rail} \times \alpha) = \frac{1}{2} \times 0.1\,m \times (5.25\,N + 28.8\,kg \times 2\,m/s^2) = 3.1425\,N{\cdot}m \tag{10}$$

where T_m is the minimum torque that each motor should provide, and r is the radius of the pulleys. Based on the sponsor's requirement for a brushed DC motor, we selected the two DPP728T-570 brushed motors to drive timing belts implemented in the real X-Y gantry system. When the translational speed of timing belts reaches 2 m/s, the corresponding angular velocity of the motor is calculated in Equation 11.

$$\omega = \frac{v}{2\times\pi\times r} = \frac{2\,m/s\times 60\,s/min}{2\times\pi\times 0.1m} = 191\,rpm \tag{11}$$

where v is the translational speed of timing belts, ω is the angular velocity of the motor to drive the timing belts. From the DPP728T-570 brushed motor spec sheet shown in **Figure 17**, we can confirm our motors can still make timing belts have an acceleration greater than 2 m/s^2.

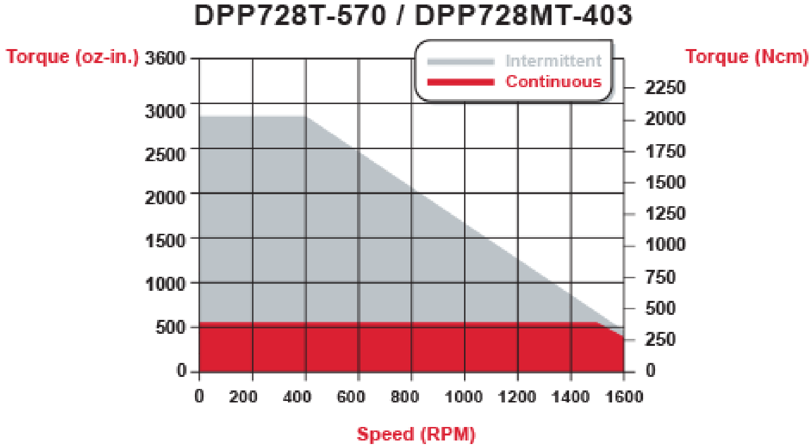
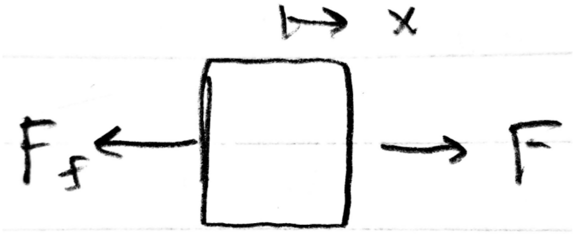


Figure 17. The speed vs. torque curve of the DPP728T-570 brushed motor. When the motor angular velocity reaches 191 rpm, the motor output torque is 500 $oz \times in = 3.53N/m$. Hence the two DPP728T-570 brushed motors can make timing belts accelerate at 2 m/s^2 at a speed of 2m/s, which fulfills our engineering specifications.

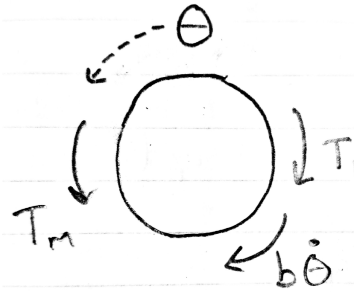
Because we are attempting to control the motion of the gantry through the use of a motor, or potentially, a controller, we know that we will be dealing with an electromechanical system. In order to precisely control the motion of the gantry, we must derive the equations of an electromechanical system in relation to our gantry system. Most of the equations for this analysis were sourced from *System Dynamics [3rd Edition]* [30]. For starters, we can look at the mechanical system of the gantry and the forces acting on it. Figure 18 shows the free body diagram of the gantry. Equation 12 shows the relationship between the forces from this FBD.



$$F_{acc} = mx''(t) + F_f \qquad (12)$$

Figure 18: Free Body Diagram (FBD) of the system with the resultant force, $mx''(t)$, the input force, F_{acc}, and the frictional force, F_f. Equation 6 is derived from this FBD.

Next, we will look at the electrical side of this system, which includes the motor. Figure 19 shows the FBD for the torques on the motor shaft. Equation 13 is derived from the FBD below.



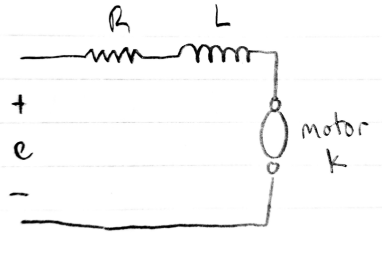
$$T_o = J\theta''(t) = T_m - b\theta'(t) - T_L \tag{13}$$

Figure 19: Free Body Diagram (FBD) of the motor shaft which includes the resultant torque, $T_o = J\theta''(t)$ where J is the total moment of inertia, the motor torque, T_m, the damping forces from any bearings which may be present in the final design, $b\theta'(t)$, and the load torque, T_L which balanced the friction force of the load.

In addition, the $\theta''$and θ' are related to x'' and x' through the radius of the output gear/pulley, r. The detail conversion is that $\theta'' = rx''$ and $\theta' = rx'$.

To further describe this system, we must determine the inputs to the motor which cause the motor torque, T_m. Equation 14 relates the motor torque to the applied current, i, and motor constant, K. Furthermore, we must determine the equations from the circuit that powers the motor. Figure 20 shows the schematic of the armature circuit present in the motor. Equation 14 represents the voltages present in the armature, it is derived from the schematic.

$$T_m = Ki \tag{14}$$



$$e = Ri + Li''(t) + K\theta'(t) \tag{15}$$

Figure 20: Schematic for the motor armature. e is the source voltage, Ri represents the voltage across the resistor, $Li''(t)$ represents the voltage across the inductor, and $K\theta'(t)$ represents the back-EMF (also known as the counter-electromotive force) voltage. It is important to note that these equations apply only to a DC motor.

In order to combine these equations, we must relate the output motor torque, T_o, to the input force of the gantry, F_{acc}, which just provides acceleration of the gantry. This can easily be done with Equation 16.

$$NrF_{acc} = T_{o} \tag{16}$$

Where r is the radius of the output gear/pulley of the motor, and N is the transmission ratio of the actuation system. If the torque of the motor alone is sufficient to move the gantry, this value will be equal to 1. Lastly, we must combine these equations into one to fully represent our electromechanical system. Equation 17 combines Equations 12, 13, 14, and 16 to relate the output forces from the motor to the input forces acting on the gantry.

$$mx''(t)Nr = [Ki - b\theta'(t) - T_{L}] \tag{17}$$

In order to derive the transfer function of our system, which relates the system outputs to its inputs, we need to combine equations 13, 15 and 17. It is important to derive the transfer function, which we will represent as *T(s)*, in order for us to design a control method for our system. Equation 18 shows how the transfer function relates the system's outputs to its inputs.

$$T(s) = \frac{\Theta'(s)}{E(s)} \tag{18}$$

Where the output is the rotational velocity, $\Theta'(s)$, of the motor which will be further translated to linear velocity and *E(s)* is the input voltage to the motor. For the transfer function, both these parameters become functions of the frequency domain (or s-domain). This transformation from the time domain, which is accomplished via the Laplace Transform, simplifies our system by replacing derivatives and integrals with much simpler algebraic expressions. This analysis is preliminary, thus any errors present here will need to be corrected for the next. The transfer function can be applied in Simulink to simulate the gantry movement and then verify the velocity, acceleration and oscillation specifications without conducting multiple experiments on the real-size gantry system.

It is also worth noting that although we are deriving a system, we may not necessarily need to design a controller for our system if it is determined that the motor output successfully meets our engineering requirements and specifications. In order to get numerical values for the parameters of this system, we will need to conduct some empirical testing of the current gantry system. For example, we could utilize a force sensor to measure the static friction of the gantry. We will also need to explore further methods of empirical testing in order to derive a model for this system.

FINAL DESIGN DESCRIPTION

The final design does not have too many changes from the alpha design CAD model– due to the constraint and magnitude of the project, we will mainly be focusing on the build design as our deliverable for the semester. To summarize, the X-direction slide rail will have two timing belts driven by two motors. For movement detection, a motor encoder will sense the count change of the encoder due to the pull of the X-direction rail. With the help of a microcontroller and PID tuning to control the system behavior, we will be able to amplify the signal and cause the rotation of the motor to the desired position. For more specific information about how it works, please refer to the alpha design section above. The detailed drawing of our final design is shown below in **Figure 21**.

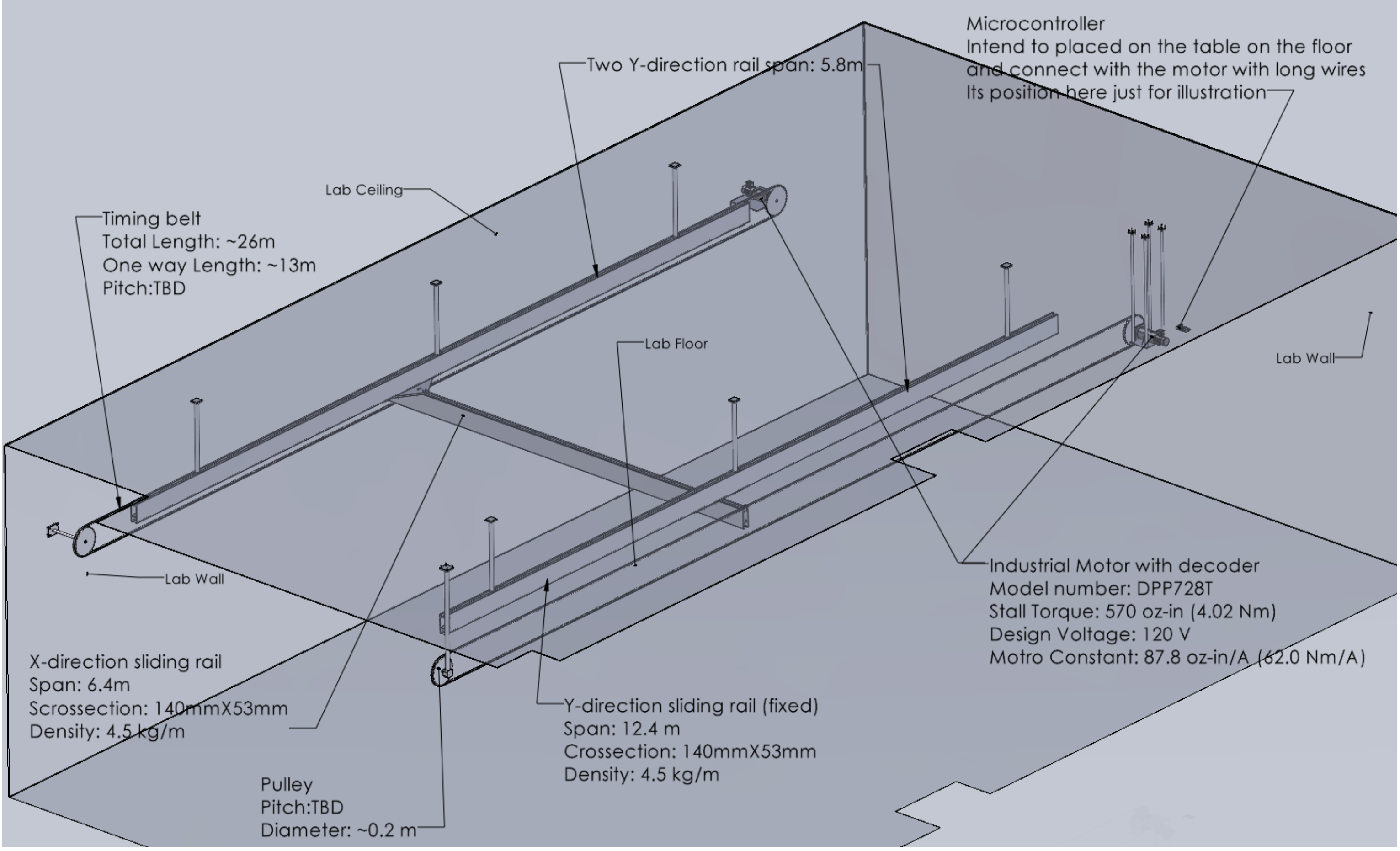


Figure 21: The picture of the detailed final design taken from CAD Solidworks showing various dimensions of different parts.

Several important installations and connections should be addressed to better understand the gantry system and our final design. All of the current installation methods serve only as a rough design. More discussion on the installation approaches should be conducted by the following teams who may take over the project.

Firstly, the X-direction sliding rail is connected to the Y-direction rail by a triangular-shaped mount with a roller which allows the X-direction rail to slide along the Y-direction. The mount is designed by *Hillrom co.* and is part of the simple gantry system the company sells. The mount model is shown in **Figure 22** below:

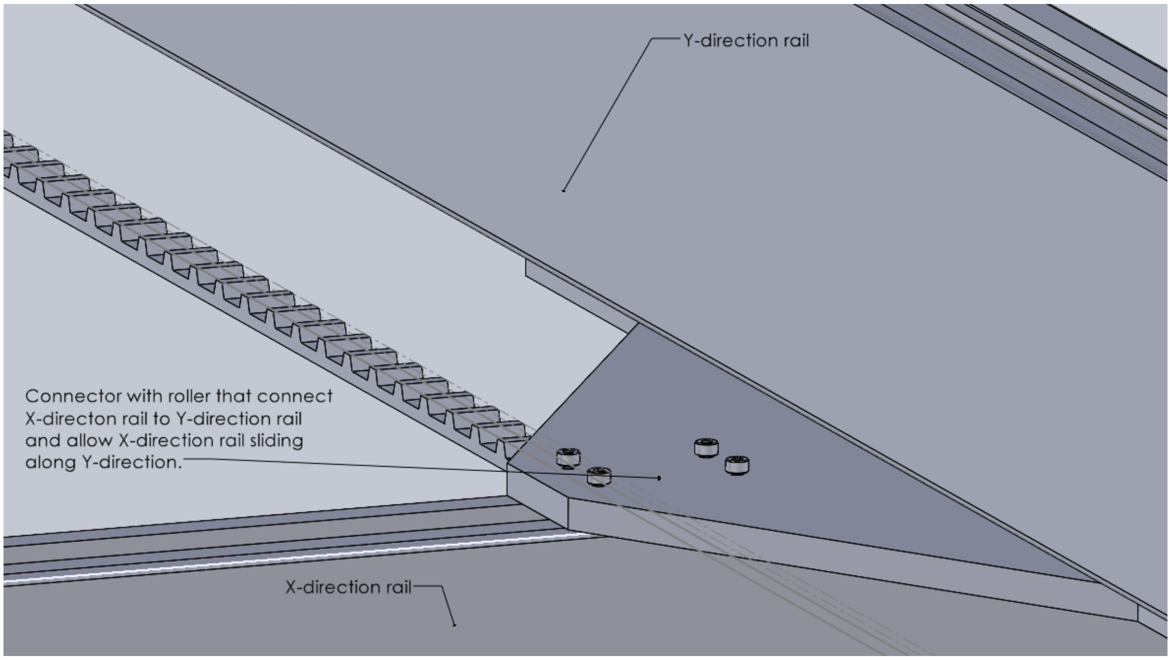


Figure 22. The connection of the X-direction rail and Y-direction rail.

Secondly, there are six rods that hang the gantry rails to the ceiling. These rods are part of the gantry product invented by the *Hillrom co.* as well. Like the triangular-shaped mount, the detail dimension and shape of the rods are not accessible. **Figure 23** below conceptually shows the rods and the gantry rails.

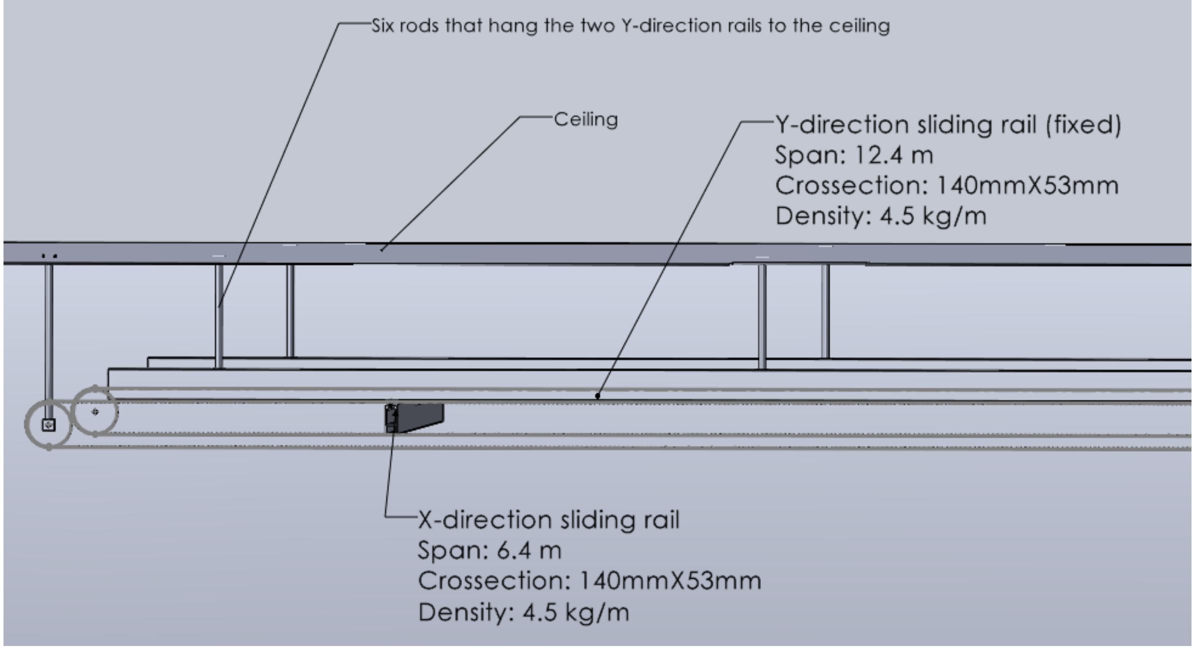


Figure 23. The six rods connect the gantry rail to the ceiling for support.

Thirdly, the motor is mounted to the wall through a designed L-shaped metal plate. The L-shape can be manufactured by casting and the holes on the plate can be drilled. The plate is mounted to the wall through bolts. The motor can be either fixed on the plate by a zip tie or thin iron wire. The encoder of the motor works as a sensor that detects the testee's movement and sends a signal to the microcontroller. The microcontroller is installed on the table on the floor while the motor is installed near the ceiling. For the electrical power supply of the motor, a plug board with a long wire could be used and the board can be glued on the wall at the same height as the motor. **Figure 24** below shows the installation of the motor. The microcontroller position in the figure is for illustration convenience. The plug board is hard to model thus it's not shown in the figure.

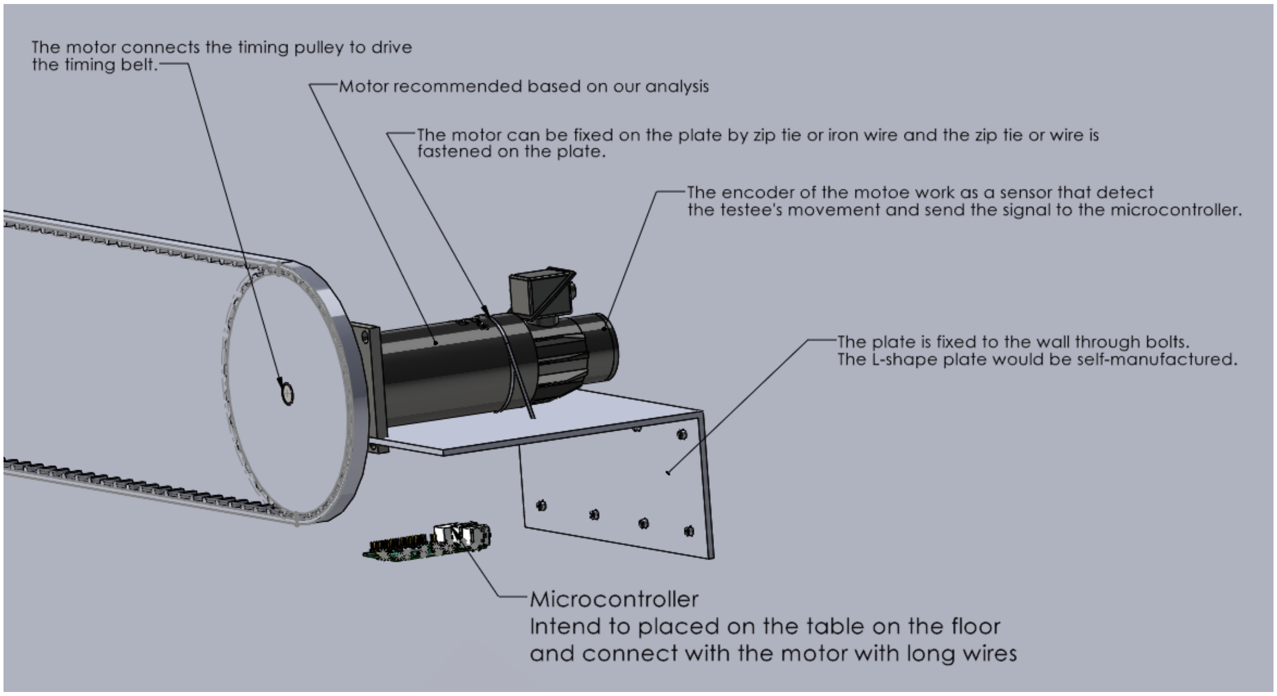


Figure 24. Motor mounting methods and how the motor connects to the microcontroller. Microcontroller will be placed lower near the ground level with wires, while plates fixed to the wall will support the motor and the gearbox.

For another motor, since it is far from another wall, we used four rods and a plate to hang it up. **Figure 25** below shows the installation of another motor:

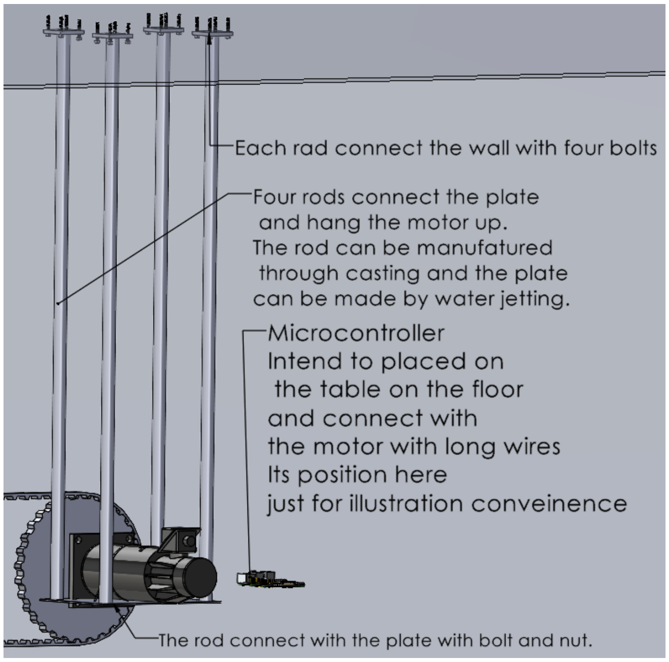


Figure 25. Hang up the motor on the other side of the gantry with four rods.
The four rods are connected to the wall with four bolts for each rod. Each rod is connected to the plate by one bolt and nut. The rods can be made by casting and the plate can be made by water jetting.

What's more, we made a design to connect the timing belt with the X-direction sliding rail. By looking into the cross-section of the gantry rail, we thought using clamps and a bolt could connect the timing belt and the gantry rail. The detailed design of the connection mechanism is shown in **Figure 26** below.

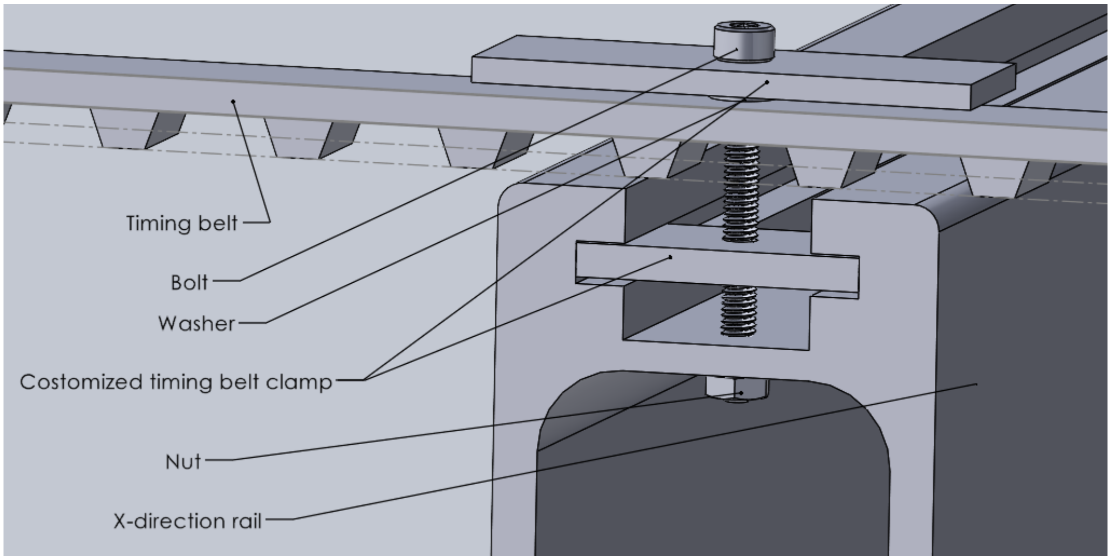


Figure 26. Connecting mechanism between the timing belt and X-direction rail

We want to use two clamps, one on top of the timing belt and the other one on the X-direction rail, to further stabilize the connection. The washers aim to distribute the load of the bolt.

Similar to the motor that is fixed on the wall, we design to fix one of the pulleys on the wall through a rod. The rod connects the wall with four bolts connecting the pulley with a bearing to let the pulley rotate freely. All the pulleys have diameters of 0.2m which are estimated by the height of the cross-section of the X-direction gantry rail. The rod part also can be made by casting. **Figure 27** below shows the installation of the pulley:

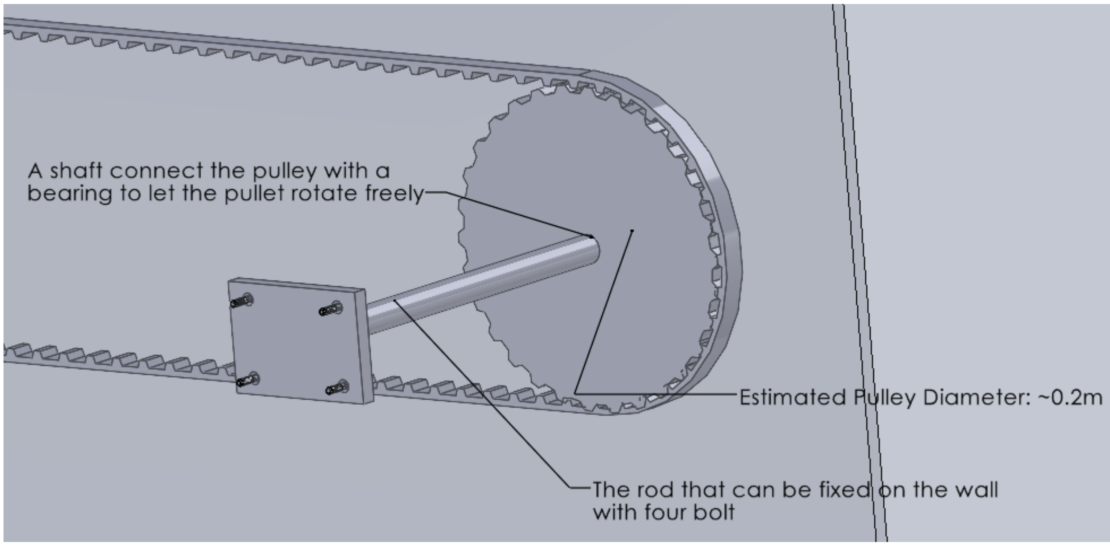


Figure 27. Shaft connection with the timing belt pulley using bolts to fix the wall.

For another pulley, which is far from the wall on the other side, we designed a similar rod connection component to hang it up just like the motor before. A small rod connects the pulley with a bearing to let the pulley rotate freely. The thicker rod connects the wall with four bolts and hangs up the pulley. **Figure 28** below shows the installation.

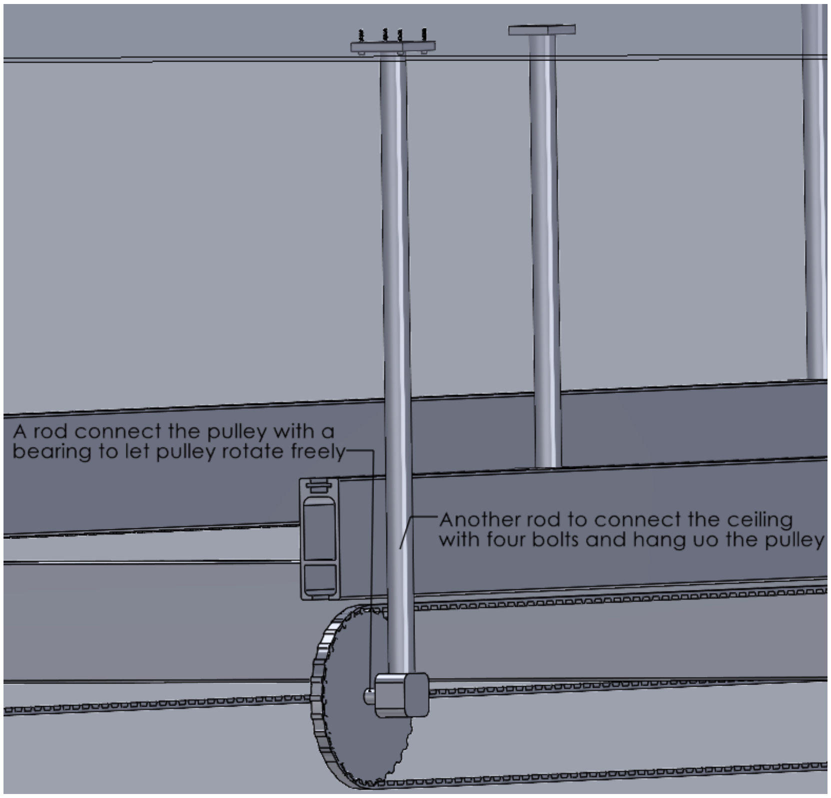


Figure 28. Rod mechanism that hangs up the pulley.

What's more, the motor vibration is worth discussing since the vibration of the motor may be too fierce to make the gantry oscillate dramatically. Based on our specification of the gantry max velocity and acceleration, the selected motor will have about 200 RPM angular velocity and the runtime is less than 3 seconds. The max angular velocity of the motor is relatively slow compared to other applications and the operation time is short. Since the gantry system has a huge mass, the vibration of the motor may not have a great impact on the gantry oscillation.

As mentioned above, due to the constraint and magnitude of the project, we will mainly be focusing on the build design as our deliverable for the semester. As a result, the installation and mounting approach provided are not carefully justified. But we have checked the theoretical feasibility of those methods by searching for similar components online. The following team who will take over the project and continuously work on the installation of the real-size prototypes may refer to and further improve our installation methods.

Risk Assessment

Our final design has several weak parts that would probably fail when running for some time. We will apply the Design FMEA (Failure model Estimation Analysis) to demonstrate the potential risks of the design in the **Discussion** part below.

BUILD DESIGN FOR A SCALED MODEL

Since incorporating our control strategy directly into the full-size gantry would be difficult, we opted to simplify the X-Y direction gantry to a single slide rail and a carriage block. We assumed this to be reasonable as the control strategy for the full-size gantry is only required in one direction. In order to ensure that our design choices for the final design meet the requirements and specifications, we chose to create a scaled-down model of the system. The system serves as a simplified way to illustrate the sliding of the gantry in the Y-direction. We scaled down the length of the X-direction to $\frac{1}{38}$ of the original length, so the scaled-down length of the linear rail guide is 325 mm. The total length of the guide rail is 400 mm, while the functional length suited for the carriage block is 325 mm. The scaled-down model is shown below in **Figure 29**:

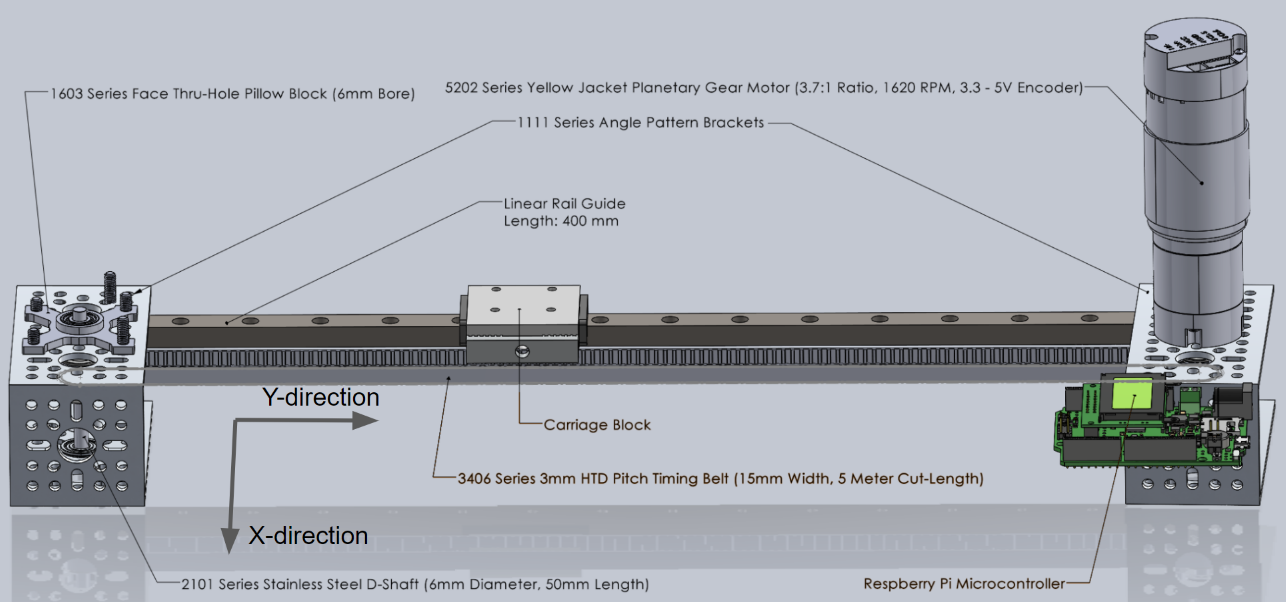


Figure 29: Final CAD design for the scaled model of the project. It incorporates a linear rail guide supported by two angle pattern brackets. The rail carriage block will be attached to a timing belt clamp. The timing belt will be driven by a motor with a microcontroller.

Corresponding to the change in dimensions, other parameters such as the mass of the rail carriage are likely to be scaled down to $\frac{1}{38}$ of the mass of the original X-direction slide rail. Some engineering specifications can also be scaled down accordingly. However, these are hard to achieve and not necessary, since the scaled-down model mainly focuses on validating that our design strategy is feasible and can meet the general user requirements. If our movement detection strategy and actuation strategy can function well in the scaled-down model, and by tuning the parameters, the carriage block can move to a certain position with a minimum settling time and steady-state error, then we are confident the same strategy can be implemented in the real gantry system. The scaled-down model will be controlled the same way as the prototype with an Arduino UNO microcontroller and a brushed DC motor. We changed the previous option of Raspberry Pi to Arduino UNO as the Arduino UNO board has a better function in reading the encoder output. The mechanism of the whole system will be similar, first we pull the carriage block a little bit, the motor encoder will perceive the little displacement, and then the microcontroller will command the motor to rotate a certain amount and drive the rail carriage for a certain distance, which represents the X-direction slide rail catches up with the testee.

The scaled model will have different materials requirements than the final design, and the bill of materials for the above scaled-down model can be found below in **Table 6**:

Table 6: Bill of Materials for the scaled-down model of the linear rail gantry. The link to the Bill of Material can be found in Appendix A.

Item	Link	Price	Quantity	Subtotal	Net Total
Linear Rail Guide 400 mm	https://www.ama	$25.99	1	$25.99	$152.74
1603 Series Face Thru-Hole Pillow Block (6mm Bore)	https://www.gobi	$6.99	1	$6.99	
1111 series angle pattern brackets	https://www.gobi	$5.99	2	$11.98	
1611 Series Flanged Ball Bearing (6mm ID x 14mm OD, 5mm Thickness) - 2 Pack	https://www.gobi	$3.99	1	$3.99	
2101 Series Stainless Steel D-Shaft (6mm Diameter, 50mm Length)	https://www.gobi	$1.79	1	$1.79	
2800 Series Zinc-Plated Steel Socket Head Screw (M4 x 0.7mm, 12mm Length) - 25 Pack	https://www.gobi	$3.59	1	$3.59	
3406 Series 3mm HTD Pitch Timing Belt (15mm Width, 5 Meter Cut-Length)	https://www.gobi	$29.99	1	$29.99	
3mm HTD Pitch Set-Screw Pinion Timing Belt Pulley (6mm D-Bore, 18 Tooth)	https://www.gobi	$6.99	2	$13.98	
2811 Series Zinc-Plated Steel Hex Nut (M4 x 0.7mm, 7mm Hex) - 25 Pack	https://www.gobi	$2.49	1	$2.49	
30:1 Metal Gearmotor 37Dx68L mm 12V with 64 CPR Encoder (Helical Pinion)	https://www.polo	$51.95	1	$51.95	

Most of the parts will be purchased, and we are looking to 3D print the connector that will be used to attach the timing belt to the carriage block, and 3D print the timing belt clamps. The scaled model is useful because it provides a simplified version of the project with a similar circuit board connection as well as the movement detection and actuation strategy. It can also help demonstrate that the analogous system can behave with minimum oscillation, settling time, steady-state error, and other parameters along with the help of PID tuning. The main purpose of the model we are working on this semester is to validate the design and extract methods for implementation with the approval of the sponsor.

Our scaled-down model will have different values for mass, length and friction, and will have different motor selections and PID parameter tunings to meet engineering specifications. As a result, we will also need to conduct similar tests on the real-size gantry in order to develop a control strategy. We hopefully will be able to work on the actual prototype for the real-size gantry but this will most likely not be the case due to time constraints. In a word, the scaled-down model is a good embodiment of the final design and can be used to justify the verification method of specifications.

SYSTEM IDENTIFICATION

Before we fully describe the verification and validation, conducting the system identification process would be helpful in verifying damping ratio specifications.

One method of empirically deriving a model of our system to estimate the damping ratio which we could, but may not use for the scaled model, is to construct a bode plot. In the case of a linear system, any sinusoidal input will produce a sinusoidal output of the same frequency with the addition of a phase shift. This is shown in **Figure 30**. Because our system is likely nonlinear, we will need to linearize it using techniques learned in our control courses. We may use dynamic friction value to linearize. Once this is done, we can then conduct our system identification.

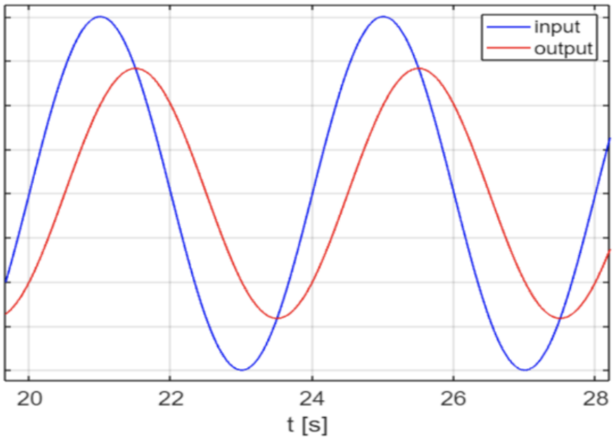


Figure 30. Example of a sinusoidal input and output for a linear system where time is on the X-axis. The output will have the same frequency as the input but it may differ in amplitude. The peak-to-peak difference in the X-axis between the input and output is known as the phase shift. The equation for the output can be written as $B \times sin(\omega t + \phi)$, where B is the output amplitude and ϕ is the phase shift.

Using this knowledge, we can input a range of sinusoidal inputs to our system and record the output response of the gantry. In our case, we will likely use voltage to the motor as our input and will either use the rotational position of the motor or the linear position of the carriage on the gantry as the output. We can then construct a Bode plot with both Magnitude (in dB) and Phase (in degrees) over the range of inputted voltage frequencies. An example of these plots is shown below in **Figure 31**.

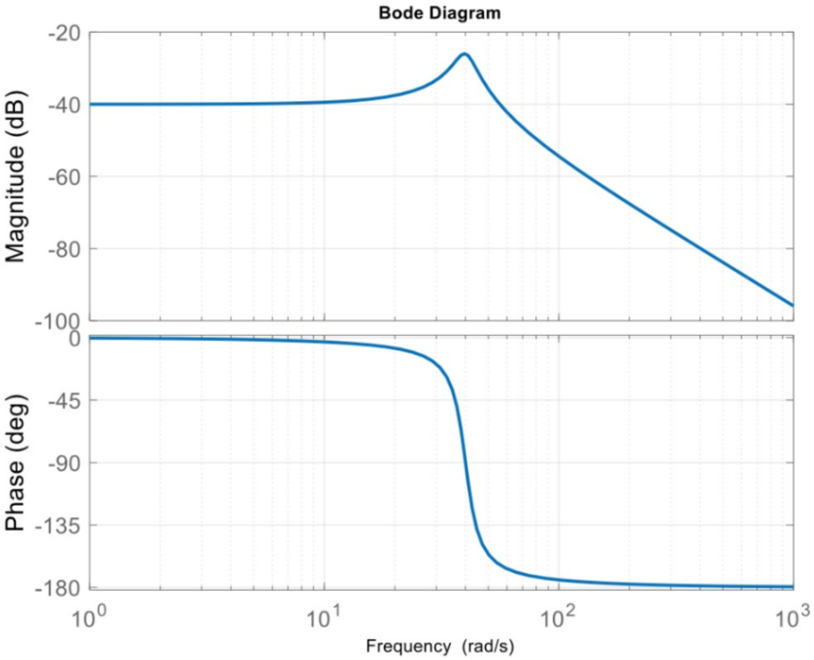


Figure 31. Example of a bode plot showing the magnitude and phase over a range of sinusoidal inputs. The magnitude is calculated as $|G| = 20\times log_{10}\left(\frac{B}{A}\right)$ where *B/A* is the ratio of the output amplitude over the input amplitude. In this example, as will likely be the case with our model, this bode plot represents the response of a second-order system. This can be observed given the phase varies from 0 to -180 degrees. If the system was the first order, the phase would hit a horizontal asymptote at -90 degrees.

Once we construct the Bode plot, if it is a second-order system, we can then derive the second-order transfer function of the system based on a few key parameters. We can determine the natural frequency, ω_n, by looking at the resonant frequency where the peak response magnitude, M_P, occurs. We can determine the damping ratio by looking at the overshoot (i.e. M_P) in magnitude using Equation 19.

$$M_P = 20\times log_{10}\left(\frac{1}{2\zeta\sqrt{1-\zeta^2}}\right) \tag{19}$$

Where ζ is the damping ratio and M_P is the peak response magnitude in the frequency domain. Importing the damping ratio and natural frequency into Simulink, we can build up the corresponding simulation model.

If the system is a first-order system, then there is no damping ratio but there is no oscillation in the first-order system. The next section will discuss more the verification and the validation plan.

Our system will behave like a second-order system as we implement a PID controller to it.

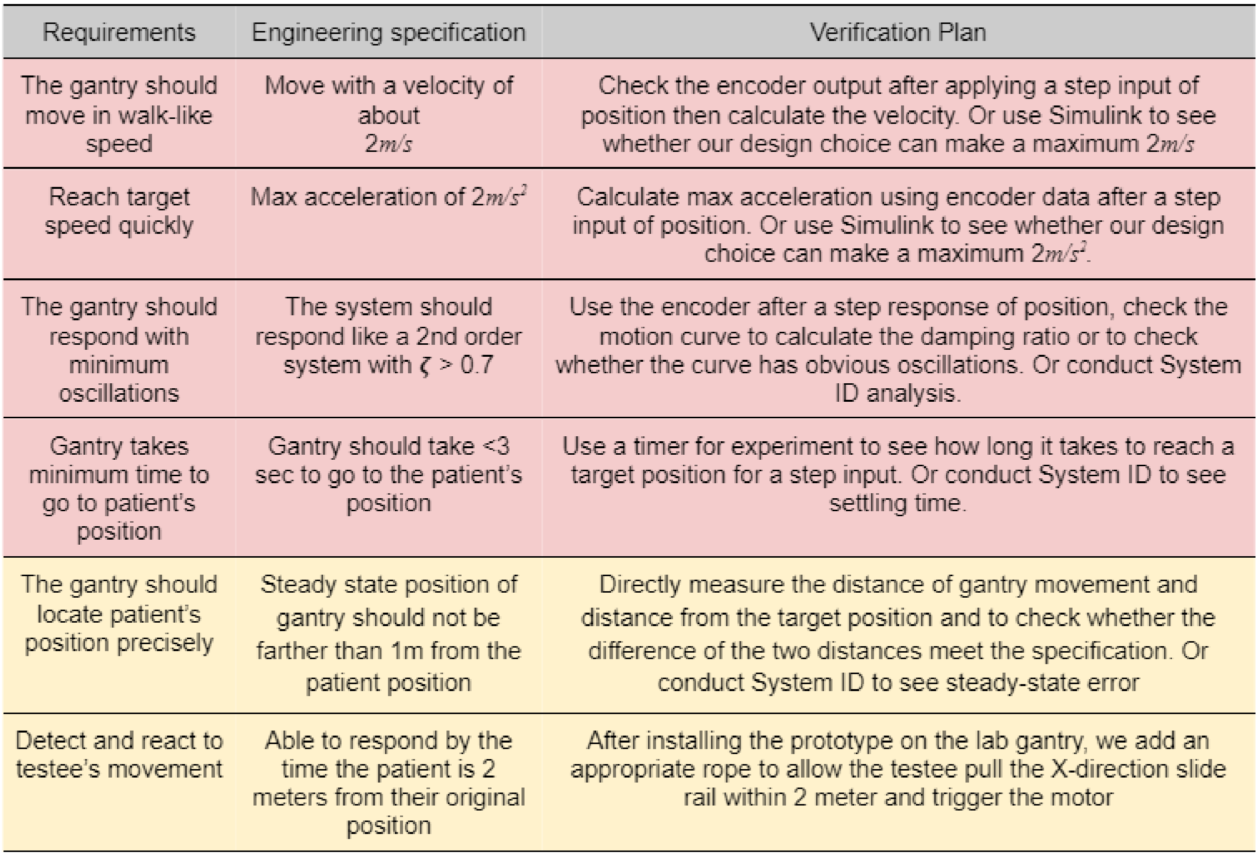
VERIFICATION AND VALIDATION

For the verification part, the build-up model is a good example to justify our verification plan and whether it can apply to the real-size gantry system. We will need further experimental testing using the build design to verify whether our final design can meet each of these engineering specifications and user requirements. The final design will work because if we can make sure that the controller can adeptly control the behavior of the scaled-down model system, we can translate the same strategies used in the scaled model to the real gantry as well. While some aspects of the design choices will need to be adjusted, such as the motor selection, gear ratio, and the damping effect, the final design will run like the build design with the said accommodations. We tried to run a predicted Simulink simulation for the real gantry system and predicted behavior as mentioned in the engineering analysis, but we learned that we had no real parameters to work with. Using the scaled model to see the system behavior will help us better achieve the design solution and verification outcomes.

Due to the inherent complexity of the gantry system, even in the scaled-down system, we will need to conduct some verification tests to determine the accuracy of our model which is used to control the gantry. We will focus on the scaled-down model to verify our method and experiments and check whether the same methods can be used to analyze the real gantry system. Noteworthy, our scaled-down model and real gantry system may have different linearity, orders, and parameters, so our scaled-down model is just used to demonstrate the feasibility of our methods.

Shown below in **Table 7** are verification plans for engineering specifications of the real-size gantry that we plan to perform.

Table 7: Verification Plans for critical engineering specifications.



Requirements	Engineering specification	Verification Plan
The gantry should move in walk-like speed	Move with a velocity of about $2m/s$	Check the encoder output after applying a step input of position then calculate the velocity. Or use Simulink to see whether our design choice can make a maximum $2m/s$
Reach target speed quickly	Max acceleration of $2m/s^2$	Calculate max acceleration using encoder data after a step input of position. Or use Simulink to see whether our design choice can make a maximum $2m/s^2$.
The gantry should respond with minimum oscillations	The system should respond like a 2nd order system with $\zeta > 0.7$	Use the encoder after a step response of position, check the motion curve to calculate the damping ratio or to check whether the curve has obvious oscillations. Or conduct System ID analysis.
Gantry takes minimum time to go to patient's position	Gantry should take <3 sec to go to the patient's position	Use a timer for experiment to see how long it takes to reach a target position for a step input. Or conduct System ID to see settling time.
The gantry should locate patient's position precisely	Steady state position of gantry should not be farther than 1m from the patient position	Directly measure the distance of gantry movement and distance from the target position and to check whether the difference of the two distances meet the specification. Or conduct System ID to see steady-state error
Detect and react to testee's movement	Able to respond by the time the patient is 2 meters from their original position	After installing the prototype on the lab gantry, we add an appropriate rope to allow the testee pull the X-direction slide rail within 2 meter and trigger the motor

For velocity, we plan to first use Simulink to see if our motor can handle a maximum velocity of 2 meters per second. Then, during the experiment, we can check the encoder output after applying a step response of position to calculate the velocity. For maximum acceleration, we will do the same with Simulink and then calculate max acceleration using encoder data after a step input. We can take derivatives of the encoder output to have velocity and acceleration data.

For the time limitation to go to the patient's position, we can experimentally use a timer to see how long the real-size gantry takes to reach a target position for a step input and make sure it is less than 3 seconds. Another way to approach this is to conduct the system identification analysis using our scaled model, checking the settling time to see how long it took the gantry to reach a certain position. We decided to use the timer to record the runtime directly and check whether it meets the specification since it's a simple and effective way.

For a steady-state position less than one meter away from the testee, we could directly measure the final position of the gantry rail and compare it with the target position we want the gantry to reach. We then compare the two position values to see whether the distance is less than 1 meter.

Another way to check the steady-state error is to use the simulation. We could analyze the steady-state error using a response curve near the target position to verify that it stays within a certain range. While it will not be 1 meter on the scaled model, we want to make sure that the oscillations near the end of the response stay below a certain threshold.

Figure 32 below shows how to verify the damping ratio, steady-state error, and runtime specifications based on the system response curve.

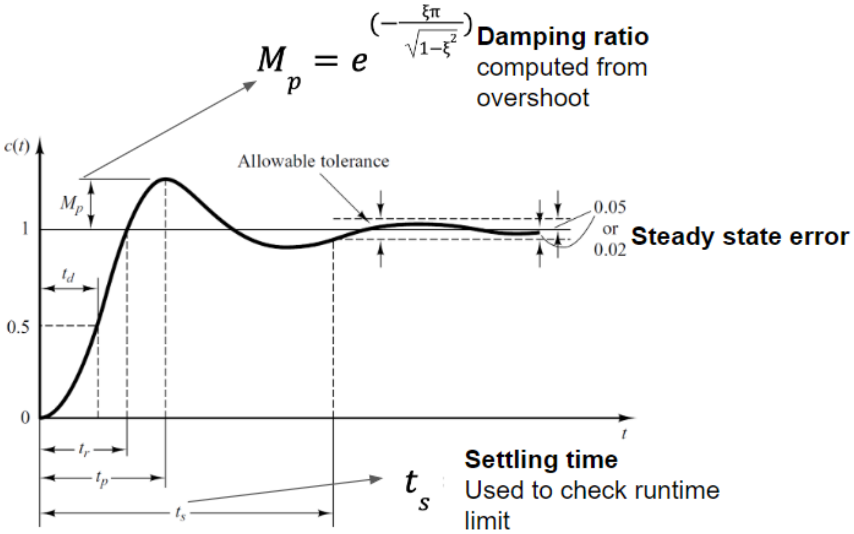
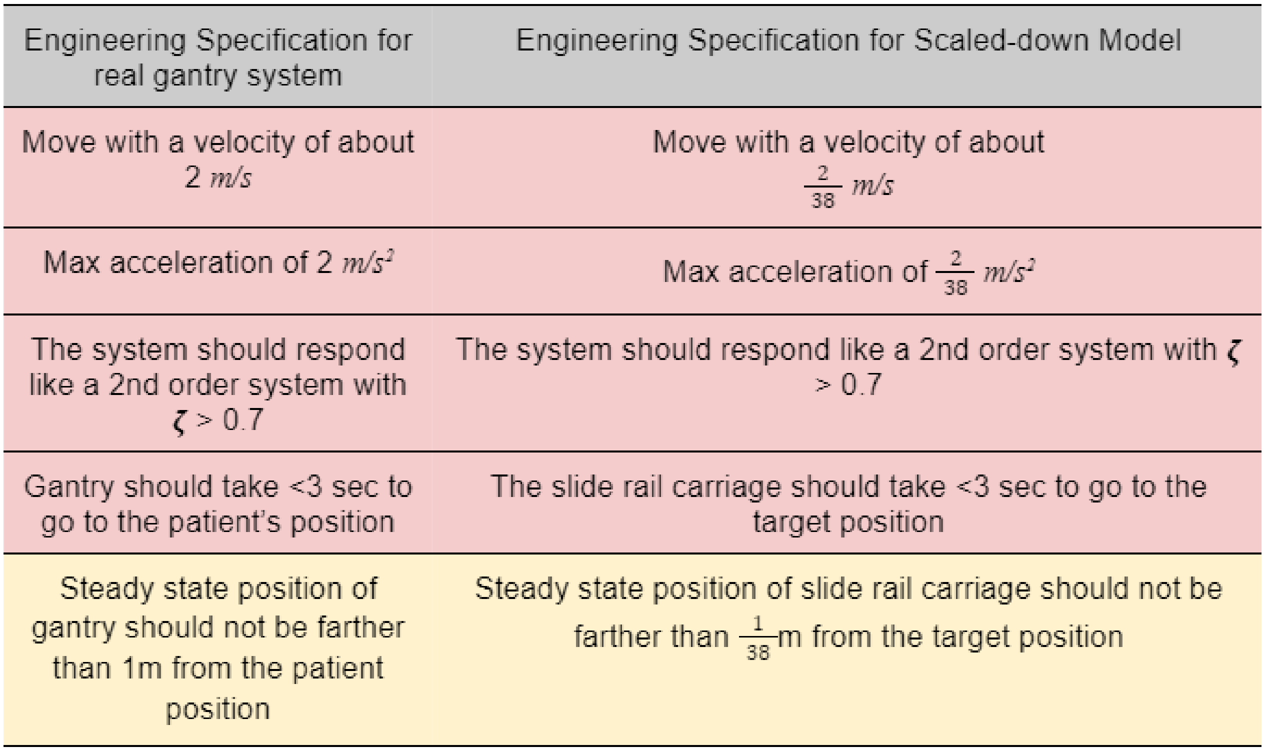


Figure 32. The system identification process on the response curve. The M_P is the overshoot in the time domain.

For the specification of being able to respond by the time a patient is a certain distance away, we can easily select an appropriate rope that can stretch and trigger the encoder reading to change. We set a certain value of encoder reading changes as a threshold value to activate the motor. Then we experimentally test whether the testee with the selected rope can activate the motor when the testee moves 2 meters.

These verification plans can also be done in our scaled-down physical model. We plan to ensure that our scaled-down model methods for verification can translate into a real gantry system and that if we were to run the same tests on a real system, the same methods can be applied. Since we scaled down the original gantry system to a prototype with a linear rail guide, which is $\frac{1}{38}$ the length of the original Y-direction slide rail, we will correspondingly scale down the engineering specifications regarding the distance, velocity, and acceleration. The other engineering specifications like time and damping ratio will remain the same. Noteworthy, the scaled-down model here is mainly used to prove the verification methods are feasible and the design strategy can meet the user requirements. Hence, we will not justify how the original engineering specifications for a real gantry system can convert well to the engineering specifications for the scaled-down model. As long as the engineering specifications for the scaled-down model have been met, then it's promising that the engineering specifications for the real-gantry system can be satisfied by tuning the PID controller. Below in **Table 8** are updated engineering specifications for the scaled-down model compared with the original engineering specifications for the real gantry system.

Table 8: Critical engineering specifications for real gantry system and the scaled-down model



Engineering Specification for real gantry system	Engineering Specification for Scaled-down Model
Move with a velocity of about 2 m/s	Move with a velocity of about $\frac{2}{38}$ m/s
Max acceleration of 2 m/s^2	Max acceleration of $\frac{2}{38}$ m/s^2
The system should respond like a 2nd order system with $\zeta > 0.7$	The system should respond like a 2nd order system with $\zeta > 0.7$
Gantry should take <3 sec to go to the patient's position	The slide rail carriage should take <3 sec to go to the target position
Steady state position of gantry should not be farther than 1m from the patient position	Steady state position of slide rail carriage should not be farther than $\frac{1}{38}$m from the target position

We decided to measure values directly by running experiments on the scaled-down model instead of using system identification methods to justify these engineering specifications. The verification process is conducted on the scaled-down model. We recorded the encoder output and converted the encoder reading into the distance with a unit of a centimeter to check the kinematic behavior of our scaled-down model and justify the specification of the scaled-down model. One centimeter is equivalent to 362 encoder counts by measurement. For the walking simulation, we set the "testee" to walk at a constant speed of 2.6 cm/s and move back and forth between two fixed positions. The distance between the two positions is 32.5 cm. In the gantry moving simulation, we set the gantry to follow up with the testee after 2s when the testee moves, which represents the time when the rope is stretched and activates the motor. The Arduino can't record the encoder reading when the gantry stops. The following **Figure 33a** and **Figure 33b** show the distance output of the testee walking simulation and gantry moving simulation.

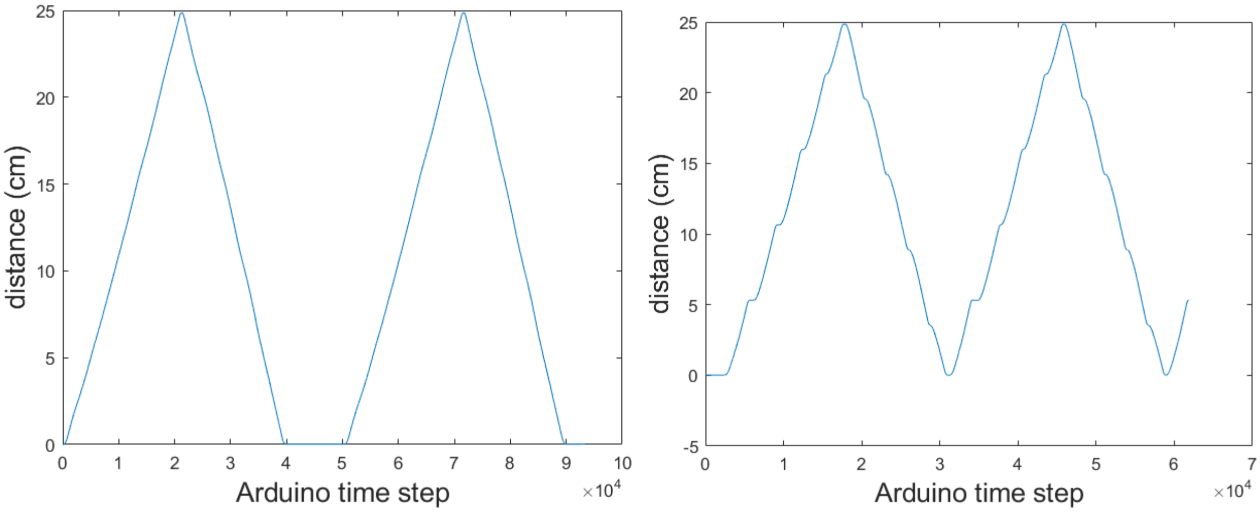


Figure 33a and 33b: The left figure (33a) shows the testee walking simulation and the right figure (33b) shows the gantry moving simulation.

As shown in **Figure 33a** and **Figure 33b** above, the gantry moved in the same manner of our strategy. When the test moves far away from the gantry, the gantry will move to follow up with the testee and wait for the next triggering. We set the simulation of the gantry moving with one second stop after moving for a while to simulate the triggering mechanism. The one-second stall can't be recorded by Arduino. Therefore on **Figure 33b** the stop is not obvious. In a word, the scaled-down model embodies the final design well. What's more, from **Figure 33b**, the gantry model moved without oscillation which possibly indicates that the system has a damping ratio greater than 0.7, meaning the damping ratio specification is justified. In addition, the simulation takes less than 3s to get to the target position which satisfies the runtime specification. Besides, the simulation has a steady-state error of 5 encoder counts(0.014 cm) which is smaller than the specification value of 2.6cm ($\frac{1}{38}$ m).

The following **Figure 34a** and **Figure 34b** show the velocity of the testee walking simulation and gantry moving simulation from the scaled-down model.

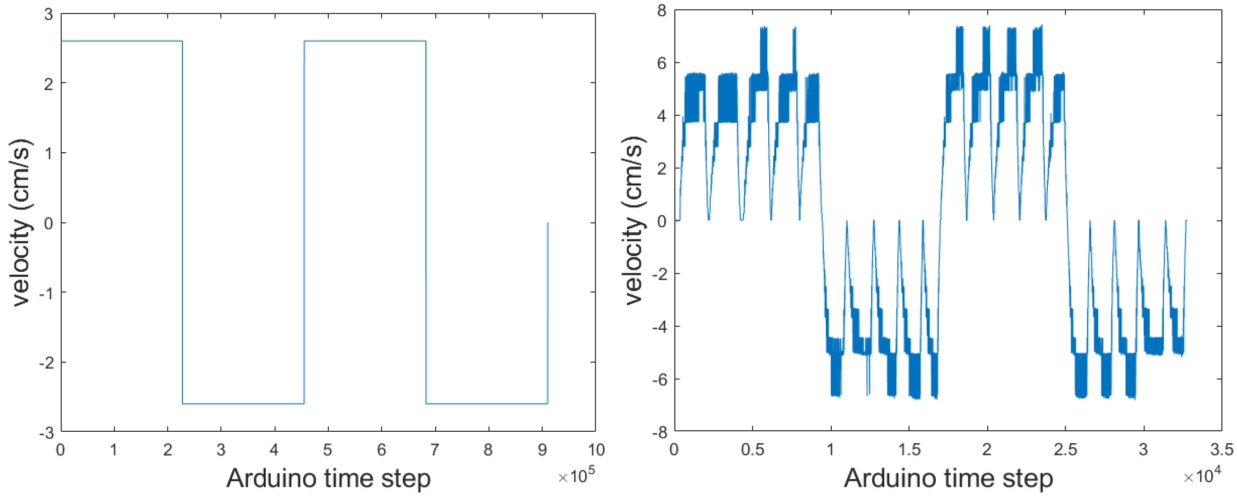


Figure 34a and 34b: The left figure (34a) shows the testee walking simulation of velocity and the right figure (34b) shows the gantry moving simulation of velocity.

The velocity is calculated through the difference in the encoder reading divided by the time changes. The scaled walking velocity is about 2.6 cm/s as shown in **Figure 34a** and the gantry maximum velocity is about 5.5 cm/s, after eliminating the noise data, which is close to the specification of 5.3 cm/s ($\frac{2}{38}$ m/s). The gantry velocity is shown in **Figure 34b**. The velocity plot contains noisy data due to encoder reading. A complicated filtering algorithm is needed in the future to calculate the velocity better, but the algorithm is time-consuming for us to develop. For now, the noisy output is enough to justify the specification. As a result, we could assert that the velocity justification method can be applied to the real-size design with fairly good accuracy and our scaled-down model meets the velocity specification well.

Figure 35 below shows the acceleration of the gantry moving simulation from the scaled-down model.

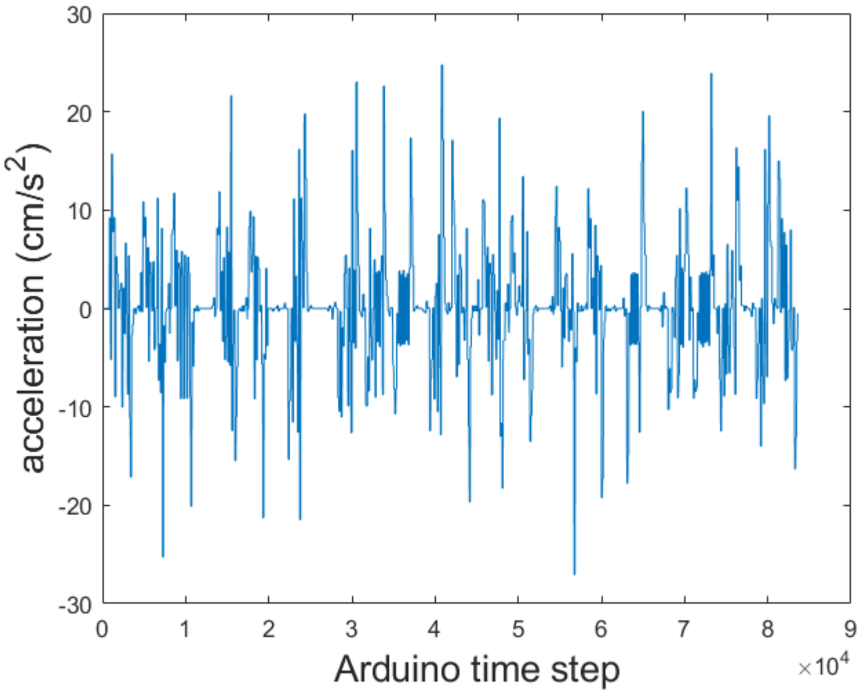


Figure 35. The gantry moving simulation of acceleration.

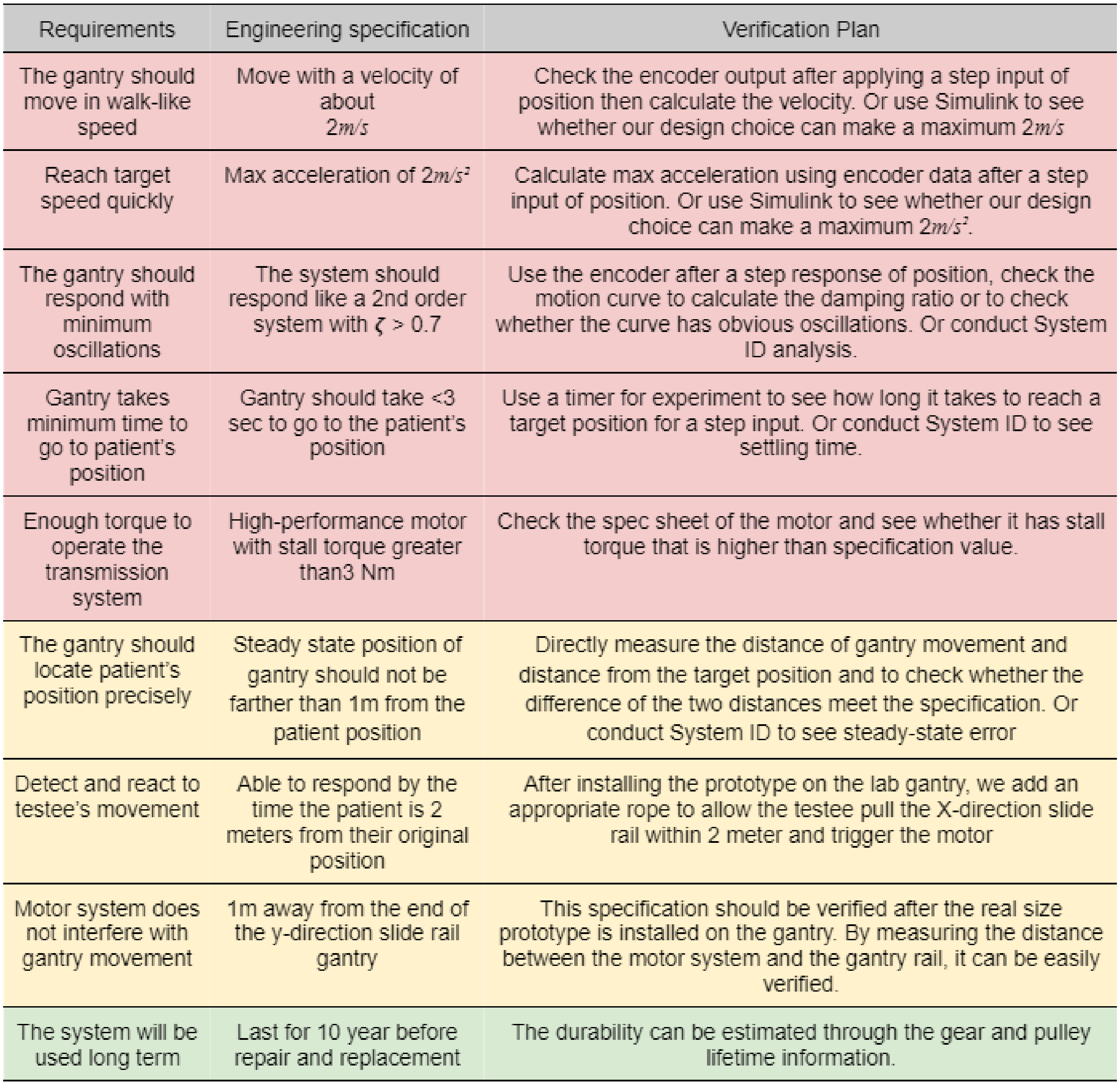
The acceleration data is derived from velocity differences divided by time changes. After eliminating the noise data, the maximum acceleration is about 5.7 cm/s^2 where the data density is relatively high. The simulation acceleration is a little bit higher than the target specification value of 5.3 cm/s^2 ($\frac{2}{38}$ m/s^2). The acceleration can be further tuned by reducing proportional and derivative gain and increasing the integration gain. The simulation acceleration satisfied the specification with acceptable error.

We didn’t justify the trigger specification using scaled-down mode, but the trigger specification can be easily achieved by selecting an appropriate rope connecting the testee and the gantry sliding rail. As the testee moves 2m away from the X-direction sliding rail, the selected rope will pull the sliding rail and trigger the motor to move.

In conclusion, the scaled-down model embodies our final design strategy well with acceptable error. What’s more, the scaled-down model met the scaled specification and was properly justified. The same justification method can be applied to the real-size design.

The following **Table 9** shows all the verification plans. Some of them are not explained in the report in detail like other verification plans. This is because they are easily verified by direct measurement or checking spec sheets.

Table 9: Verification Plans for all engineering specifications.



Requirements	Engineering specification	Verification Plan
The gantry should move in walk-like speed	Move with a velocity of about $2m/s$	Check the encoder output after applying a step input of position then calculate the velocity. Or use Simulink to see whether our design choice can make a maximum $2m/s$
Reach target speed quickly	Max acceleration of $2m/s^2$	Calculate max acceleration using encoder data after a step input of position. Or use Simulink to see whether our design choice can make a maximum $2m/s^2$.
The gantry should respond with minimum oscillations	The system should respond like a 2nd order system with $\zeta > 0.7$	Use the encoder after a step response of position, check the motion curve to calculate the damping ratio or to check whether the curve has obvious oscillations. Or conduct System ID analysis.
Gantry takes minimum time to go to patient's position	Gantry should take <3 sec to go to the patient's position	Use a timer for experiment to see how long it takes to reach a target position for a step input. Or conduct System ID to see settling time.
Enough torque to operate the transmission system	High-performance motor with stall torque greater than3 Nm	Check the spec sheet of the motor and see whether it has stall torque that is higher than specification value.
The gantry should locate patient's position precisely	Steady state position of gantry should not be farther than 1m from the patient position	Directly measure the distance of gantry movement and distance from the target position and to check whether the difference of the two distances meet the specification. Or conduct System ID to see steady-state error
Detect and react to testee's movement	Able to respond by the time the patient is 2 meters from their original position	After installing the prototype on the lab gantry, we add an appropriate rope to allow the testee pull the X-direction slide rail within 2 meter and trigger the motor
Motor system does not interfere with gantry movement	1m away from the end of the y-direction slide rail gantry	This specification should be verified after the real size prototype is installed on the gantry. By measuring the distance between the motor system and the gantry rail, it can be easily verified.
The system will be used long term	Last for 10 year before repair and replacement	The durability can be estimated through the gear and pulley lifetime information.

The stall torque of the motor can be easily verified by checking the spec sheet. The one-meter installation specification can be directly measured when installing the real-size prototype. The durability of the system can be verified by components, like gear and pulley, and lifetime.

For the real gantry design, we could also apply the same experimental justification method. However, the gantry is too giant that conducting such a justification experiment may be inconvenient. Therefore, we could use system identification and the MATLAB simulation method mentioned above to simulate the kinematic behavior of the real-size gantry. Due to the tool restriction, we can't apply the similar method of simulation on the scaled-down model since the motor parameters, like moment inertia, resistance, inductance, motor constant, viscous friction force coefficient, and electromotive force constant of the motor are not provided by the manufacturer and we don't have enough time and appropriate equipment to conduct experiments to determine those motor parameters. To compute the motor parameters, the AC voltage generator with different frequencies, voltmeter, and ammeter are needed. In the future, we would suggest conducting such a simulation to justify the specification. **Figure 36** below shows the conceptual Simulink model of the real-size gantry yet without parameter values.

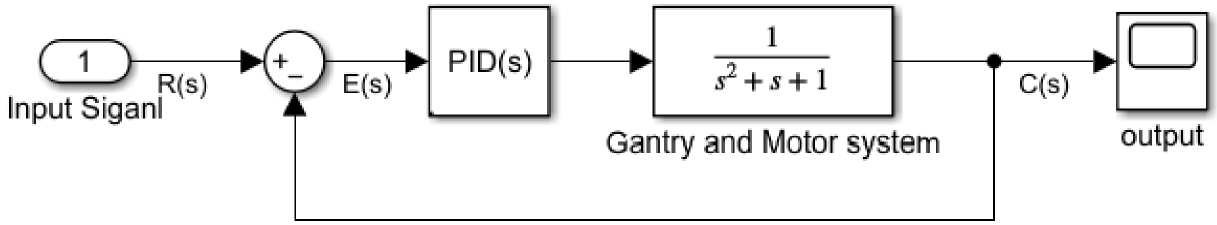


Figure 36. Conceptual Simulink code without real parameters used to simulate the real-size gantry behavior

The purpose of validation is to see if the design solution addresses the design problem that we established in the beginning and to make sure our design meets the requirements. The scaled model that we plan to create provides a good insight into some of the design choices for the problems. While it will not be able to directly validate our final design, running tests analogous to the scaled model on the real gantry will help validate our design. For example, using system identification and analyzing system behavior for requirements such as accuracy of location and oscillations can help validate the control aspect of our design choices. We hope to eventually run tests on the real gantry to check if the prototype addressed all of the design problems, and we will conduct user testing and sponsor inspection afterward for further validation.

As a result, our design is successful while could be further improved. Our design solved all the design problems and met all the modified specifications though the validation is not conducted for now. The detection method could be improved by real-time monitoring the tilt angle of the rope to make the detection more sensitive and accurate. With the new detecting method, the safety requirements will be further addressed.

DISCUSSION

Problem Definition

Due to the limited time of the ME450 course in the semester, our project and design solution is not fully developed. If more time is available, we would like to explore more different motion detection methods and improve the control algorithm to further reduce jerky motion and motor oscillations.

Design Critiques

The encoder triggering method to detect the testee's movement is simple and cheap. We successfully use our scaled-down model to verify the scaled-down engineering specifications, and we are confident that the engineering specifications for the real gantry system can also be verified and met by tuning the PID controller. However, this method still has two potential security issues. For the real-size gantry system, even though the motor will be activated when the testee is only within 2 meters from his/her original position, the safety belt cannot function perfectly since the safety belt already has a little tilt angle. Moreover, if the testee continues moving, since the X-direction slide rail will be driven to move a certain distance each time and then the actuation is triggered again, the discrete displacement along the Y-direction provides a "jerky" motion. The "jerky" motion may interfere with the testee's motion and possess some security risks. Lastly, by adjusting the length of the additional rope attached to the testee, we can decrease the encoder triggering distance to avoid a large tilt angle of the safety belt, while this will generate more discrete displacements to reach the testee's final position and hence induce more vibrations in the gantry system. The increase of vibration has already been observed in our scaled-down model, and the vibration in the real-gantry system may shorten the life of the system and pose a safety risk.

An alternative method that we provide in the "Beta Design" section is to use an overhead camera to detect the testee's real-time movement and output that signal to actuate the motor. This method may be able to eliminate the time delay in motion detection, but it was deemed too costly and time-consuming.

To achieve real-time detection and hence eliminate the potential security risks, we come up with a redesign for the testee's motion detection. We plan to implement three presence sensors in the real-gantry system, where two of them will be mounted on the left edge and right edge of the safety belt box. The last one will be mounted at the end of the safety belt which is attached to the testee as shown in **Figure 37**.

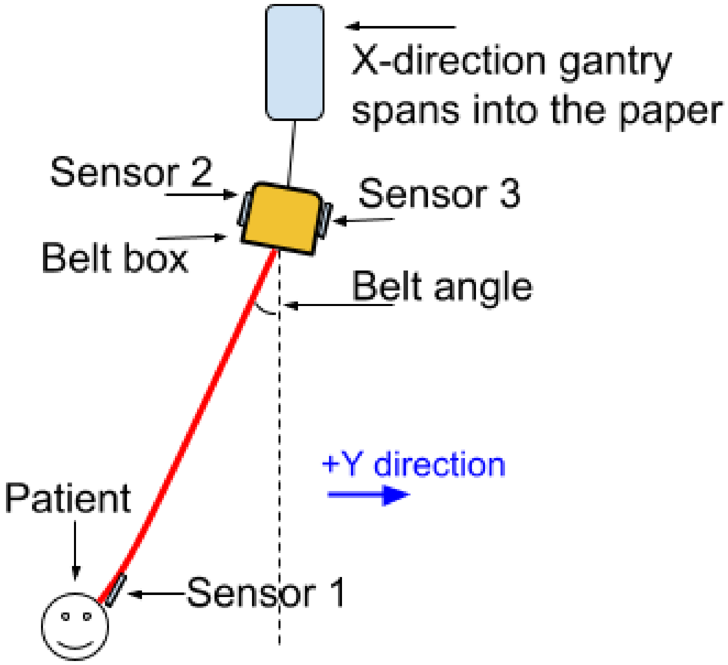


Figure 37. The design of presence sensors to detect the testee's movement.

The presence sensor attached to the end of the safety belt will output a signal to the two presence sensors mounted on the left and right edges of the safety belt box. When the testee moves in the X-direction, a signal S will be generated, which is defined as the distance between sensor 1 and sensor 2 minus the distance between sensor 1 and sensor 3. The signal has positive and negative values so that it can indicate the direction of the testee's movement.

After receiving the signal, the control and actuation process is shown in Figure 38.

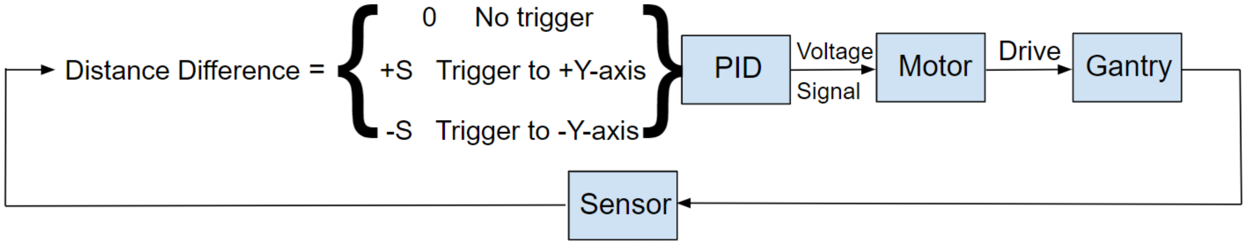


Figure 38. The design of the control and actuation process.

The input of the distance difference signal has three states: 0 means no trigger and the gantry will not move, +s is to move the gantry in +Y direction, and -s does the opposite. These signals will output different voltages to drive the gantry, and stronger signals produce higher velocity. The PID controller will help us reduce oscillations and steady-state errors. The updated tilt angle signal will be fed back and the process is repeated in a loop.

Then we process the similar verification process to verify the feasibility of the design and some important engineering specifications. **Figure 39** below shows the relationship between the input signal and output position. From the 0 position, the +s signal moves the gantry in the +y direction, and -s does the opposite. The position graph showing the movement of the gantry can help us analyze and meet specifications of velocity, acceleration, and oscillation.

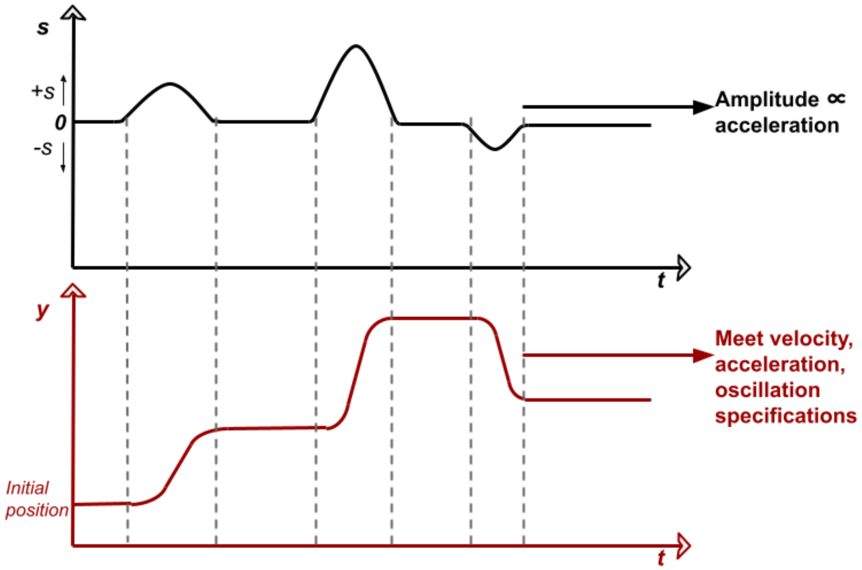


Figure 39. The conceptual graph shows the relationship between signal and motor movement behavior.

The following **Figure 40a** and **Figure 40b** shows the simulation of the signal and motor movement behavior in our scaled-down model. Since we haven't implemented the motion detection system, we artificially input the target position signal.

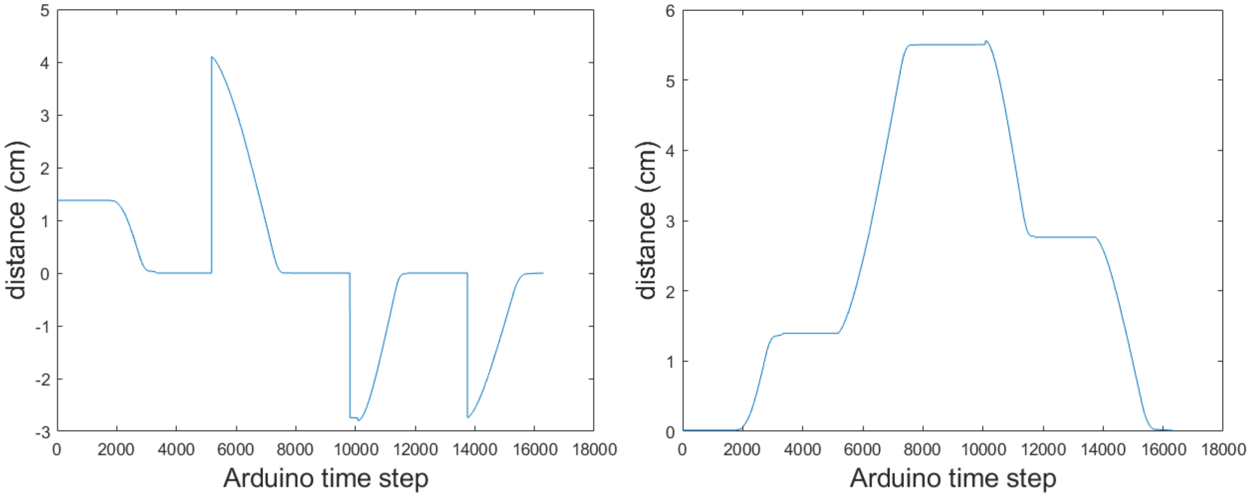


Figure 40a and Figure 40b. The left plot shows the signal of the distance between the target position and the current position. The right plot shows the motor (gantry) movement.

The simulation is conducted on the scaled-down model with fixed target position inputs thus the plot contains a sudden change of signal. However, we can observe that the signal magnitude is proportional to the moving velocity and the positive/negative signal corresponds to the moving direction. Since the strategy functions well in our prototype, then we are confident the same strategy can be implemented in the real gantry system.

Risk Assessment

Our final design has several weak parts that would probably fail when running for some time. We will apply the Design FMEA (Failure Model Estimation Analysis) method to demonstrate the potential risks of the design. First, the clamp that connects the timing belt and X-direction sliding rail is fragile. As shown in **Figure 27** above, there is a long bolt getting through the timing belt which makes the timing belt experience high stress as the gantry moves. The failure of the timing belt will make the actuation mechanism fail and the timing belt itself will drop down to the floor which may cause safety issues. Ways to avoid the timing belt failing is to replace the timing belt periodically or use a better clamp and connector to reduce the stress on the belt. What’s more, due to the oscillation of the motor when accelerating and decelerating, the rod connecting to the ceiling and wall that supports the motor experiences cyclic load that would harm the durability of the bolt connecting the motor and the ceiling or wall (**Figure 25** and **Figure 26**). The methods to avoid such problems include adding clean dampers on the motor to reduce motor oscillation and to reinforce the connection between motor supports and the ceiling or wall. Besides, as mentioned in the Design Critiques above, the encoder triggering strategy has risks that could interfere with the experiment and the testee. **Table 10** below summarizes the risk assessment.

Table 10. Design FMEA table summarizes the risks assessment.

Item / Function	Potential Failure Mode	Potential Causes/ Mechanism of Failure	Current Design Control	Recommendations
Clamp connecting sliding and timing belt	Fracture and fatigue	High stress with low-frequency cycles	Additional clamps to share the stress	Use another type of clamp that not needed to make a hole on the timing belt
Motor support and the	Fatigue	Low stress with high-frequency cycles	More bolts or rods to support the motor	Reduce motor oscillation when operating
Encoder triggering mechanism	Can’t follow up in time and jerky motion	The motor is triggered after testee moves a distance	Add additional rope to reduce the distance between testee and the sliding rail when triggering	Try another trigger method like using presence sensor to monitor the tilt angle of the safety belt

Lesson Learned

In the development of the project, we learned how to propose and design a new product. What's more, we understood the importance of having a design plan and strictly following the plan. Besides, we learned how to extract the main part of the final design and built a scaled-down model to embody the design idea. During the modeling process, we also learned how to use the microcontroller to activate the motor. We understood that simple design ideas could also meet requirements well. The system identification is another tool we learned to find out the parameters of the system and help establish the simulation.

REFLECTION

Looking back at the entirety of the project and considering all the impacts of our project, the design contexts addressed previously were utilized. In a global context, the successful implementation of a motorized gantry system can help new advancements in prosthetics technologies. The environmental context will have minimal impacts mostly because it is a one-off product that will exclusively be used in the neurobionics lab. The government can benefit from integrating individuals with physical disabilities into society and can also help the research by funding prosthetics projects. The project will not consider logistical factors such as storage– while the components that we purchase may have minor impacts such as transportation and storage costs, they are not our primary concern at this stage of the project. The project has important socio-cultural factors to take into account.With successful implementation, the widespread use of prosthetics can improve the mobility of amputees and allows society to be able to open the door for education and job opportunities, reduce medical costs, and help them regain their sense of normalcy. For economical context, the medical gantry manufacturers could improve their product by referring to our design. In terms of welfare and health considerations, which is our main focus, the new gantry motor system will ensure a safer testing environment. The stakeholder map that we utilized to identify potential impacts of the design can be found mentioned previously on page 11.

In the team, we identified various cultural, privilege, identity, and stylistic similarities and differences between each member that influenced some of our approaches. First, being college students with limited knowledge about certain engineering topics that could be more suitable for the project, we chose design choices based on topics we learned from years prior. Some topics we chose to utilize included controls, identifying system behaviors, motor control, and circuits. Some of us are also from different project teams and U of M labs, so we brought a diverse culture of testing methods and a hard-working mindset to approaching various problems. There were also considerations of power differences with the sponsor. Our sponsor had significant knowledge and experience in working with controls and the gantry itself, so he had great recommendations. While the advice was extremely helpful, it did limit our design choices from using cameras to using encoders instead. Our sponsor and we both shared an engineering background, which helped facilitate the design creation and selection processes due to our shared jargon and understanding of engineering ideas. Lastly, it was great that Professor Rouse was also part of the University of Michigan and allowed us to take a more learning-focus, student-centered approach to tackle the various challenges.

Inclusion and equity are important when working in a team environment and with stakeholders as well. In terms of dynamics between team members, we combined our own experiences with the gantry such as its movement and discomfort as well as input from the sponsor and lab members in order to shape our design choices. We have not been able to receive input from end users, or testees, which would have been great to have to ensure that the design is suitable for the users themselves. One way we could include diverse viewpoints of stakeholders and the team simultaneously is to have interviews with the testees or other stakeholders that are closely involved with the project and have them test the initial prototype. Afterward, the team would be able to reiterate the design process and address any discomfort or complaints with the new design.

There were no ethical dilemmas that we had to deal with for the project since the main focus of the project is the safety and wellness of the testees. The project also has no real deadline since it takes place at the University of Michigan and it is not of major focus. There are issues that could have arisen if the project had a strict deadline– it would have been hard to make sure safety is accounted for in every aspect. If someone were to get hurt because we rushed to meet the deadline, the team would be accountable for it.

RECOMMENDATION

Overall, the alpha design provided above meets all the specifications and successfully finished the design tasks through the scaled-down model, which is also likely successful on the real-size gantry system. For the system level, two out of three functions of our final design, actuation, and automation functions, work well. The detection function is not ideal and we recommend improving it. The ideal detection function is to monitor the tilt angle of the safety belt directly as discussed above. To achieve the ideal detection, more complex sensor circuits and signal-processing algorithms need to be developed. For example, the detection strategy could be re-designed with presence sensors. We would recommend using presence sensors to monitor the tilt angle. For detail-level recommendations that can reduce the risks identified in the **Discussion** section, we advise reinforcing the motor supporter or reducing the motor oscillations for better durability. What’s more, the clamps and connectors that connect the timing belt and the X-direction sliding rail could be replaced with the ones that do not need to drill a hole on the timing belt, or add more clamps to share the stress on the timing belt.

CONCLUSION

The current problem with the gantry at the U of M Neurobionics lab is that it is manual– when the person moves, the gantry will be left behind and will create an angle, which is unreliable for the safety mechanism to trigger. Combined with the research on the current gantry system in the lab and benchmarking on other medical gantry products, the ME450 team has established an overview of the requirements and problems the team needs to solve. We conducted initial experiments on the current gantry system to attempt to analyze the friction force. We utilized Cross's design process for its flexibility and procedural approach to the design process. We also figured out our stakeholder map with the primary stakeholder of the researcher, testee, and sponsor's lab and determined the main design context for the stakeholder map as being safety and wellness. Also, we arranged and updated the user requirements and defined reasonable specifications. After concept generation and design selection, we were able to create an alpha design containing a motor with an encoder, a gearbox, a microcontroller, a PID controller, as well as a timing belt, and pulleys and later updated it to the final design with dimensions using CAD. Besides, with sponsor recommendations, we chose our data input to be the encoder count of the motor. In order to check the feasibility of the motorized gantry, We created a scaled model for the X-direction rail. We wrote Arduino codes to simulate the walking testee and ran tests to verify specifications using the assembled scaled model. This helped us understand the behavior of the system and how we can apply the same methods of verification to the real gantry. The results for the encoder triggering method were fairly accurate with acceptable error, but there needs to be more work with PID or code to reduce noise found in the experiments, as well as expanding on or finding alternative ways to receive data to trigger the gantry movement. We hope that using similar methods on the real gantry as the scaled model along with running real gantry simulations for motor parameters can get a better understanding of the problem and how to implement the motorized system. What's more, we would recommend trying presence sensors to detect the testee's movement instead of using the encoder count. The presence sensor could monitor the testee's movement continuously. The continuous signal input may avoid the jerky motion problem caused by encoder count signal input.

ACKNOWLEDGEMENT

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APPENDIX

Appendix A: BUILD DESIGN BILL OF MATERIALS

Item Quantity Source Catalog Number Cost Contact Notes
3/8”Rod end 12_ McMaster-Carr 60645K14 $4.12@ mcmaster.com _left hand

Item	Quantity	Source	Catalog Number	Cost	Contact
Linear Rail Guide 400 mm	1	Amazon	B07ZVFTZVP	$25.99	Amazon.com
1603 Series Face Thru-Hole Pillow Block	1	goBILDA	1603-0032-0005	$6.99	gobilda.com
1111 Series Angle Pattern Bracket	2	goBILDA	1111-0004-0001	$5.99	gobilda.com
1611 Series Flanged Ball Bearing (6mm ID x 14mm OD, 5mm Thickness)	1	goBILDA	1611-0514-0006	$3.99	gobilda.com
2101 Series Stainless Steel D-Shaft (6mm Diameter, 50mm Length)	1	goBILDA	2101-0006-0050	$1.79	gobilda.com
2800 Series Zinc-Plated Steel Socket Head Screw (M4 x 0.7mm, 12mm Length)	1	goBILDA	2800-0004-0012	$3.59	gobilda.com
3406 Series 3mm HTD Pitch Timing Belt (15mm Width, 5 Meter Cut-Length)	1	goBILDA	3406-0015-0005	$29.99	gobilda.com
3mm HTD Pitch Set-Screw Pinion Timing Belt Pulley (6mm D-Bore, 18 Tooth)	2	goBILDA	3419-1006-0018	$6.99	gobilda.com
2811 Series Zinc-Plated Steel Hex Nut (M4 x 0.7mm, 7mm Hex)	1	goBILDA	2811-0004-0007	$2.49	gobilda.com
2800 Series Zinc-Plated Steel Socket Head Screw (M4 x 0.7mm, 12mm Length) - 25 Pack	1	goBILDA	2800-0004-0012	$3.59	gobilda.com

2811 Series Zinc-Plated Steel Hex Nut (M4 x 0.7mm, 7mm Hex)-25 Pack	1	goBILDA	2811-0004-0007	$2.49	gobilda.com
30:1 Metal Gearmotor 37Dx68L mm 12V with 64 CPR Encoder	1	Pololu	4752	$51.95	polulu.com
3mm Pitch HTD Timing Belt Clamp	2	3D Printed			
Fillet Connector between Rail Carriage and Timing Belt	1	3D Printed			

(https://docs.google.com/spreadsheets/d/1oILicHgJPeALrHmAa5Le6_K219MJOMNGfHAqgAUNr1o/edit?usp=sharing)

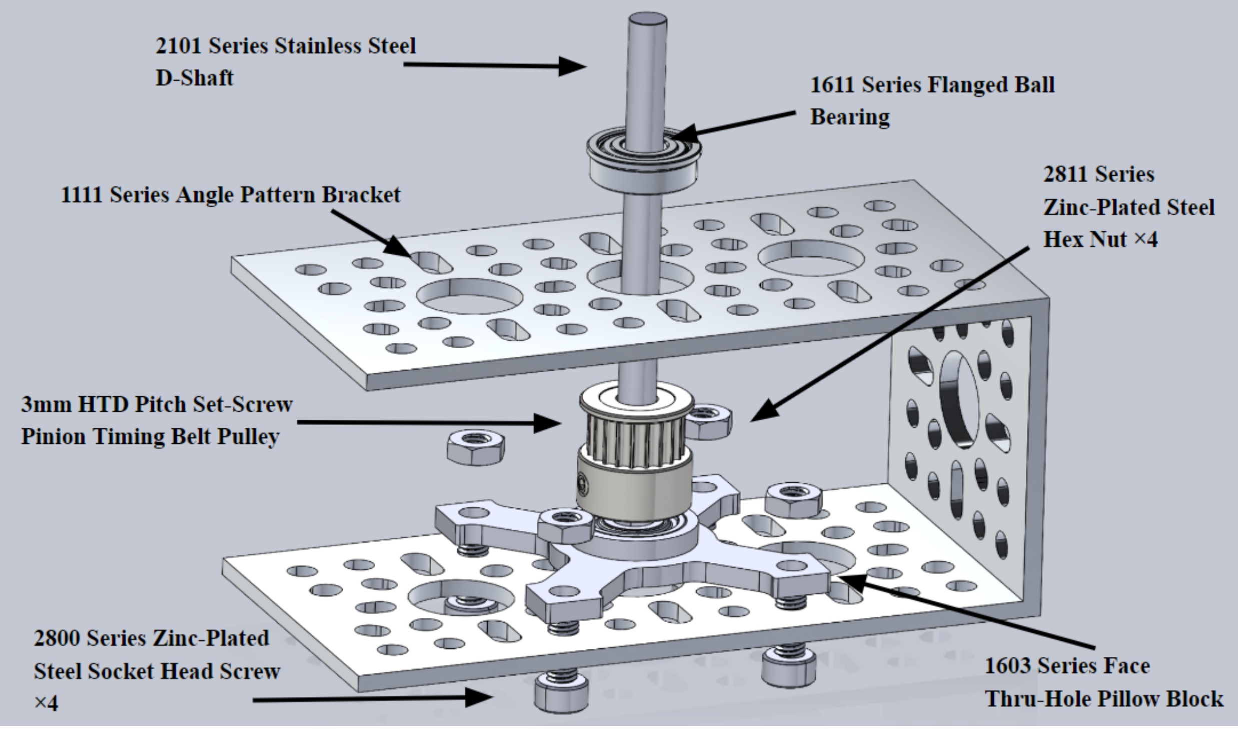
Appendix B: MANUFACTURING PLAN

Fabrication Plan:

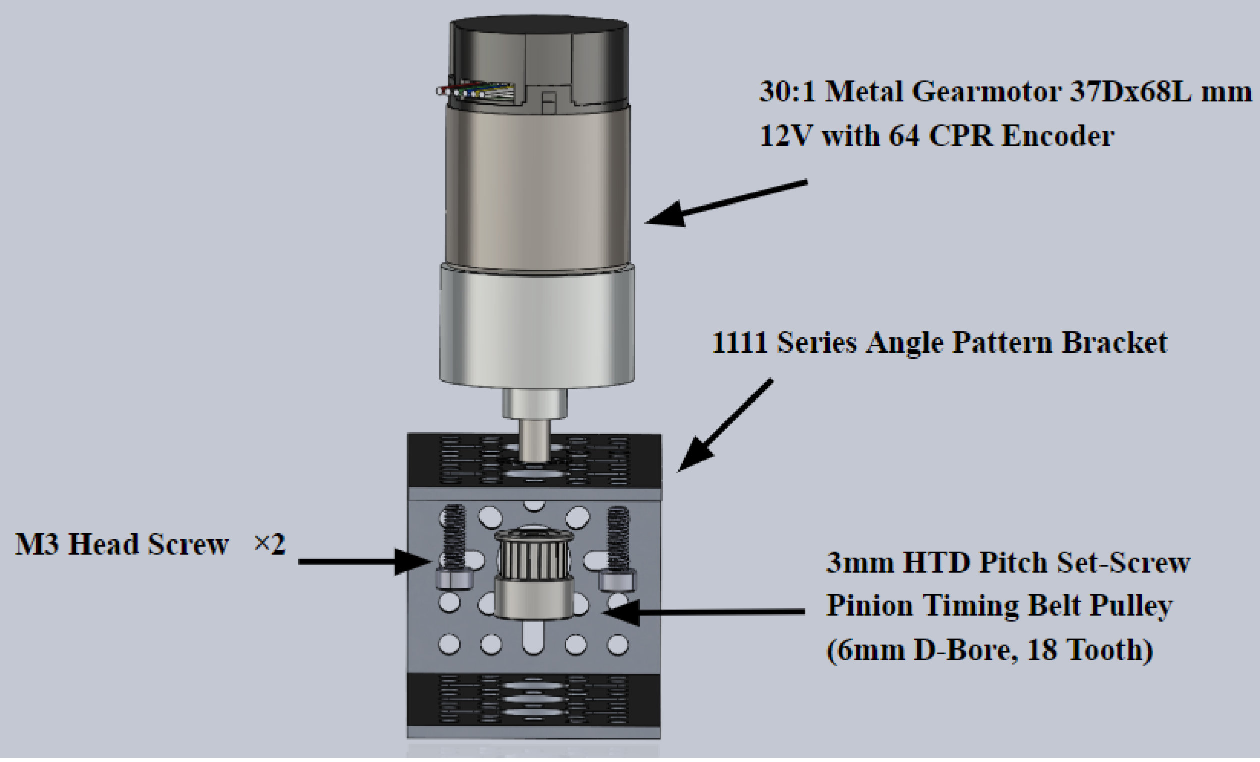
The only two types of components need to be fabricated are the “3mm Pitch HTD Timing Belt Clamp” and the “Fillet Connecter between Rail Carriage and Timing Belt.” They are 3D printed by the 3D Systems SLA machine.

Assembly Plan:

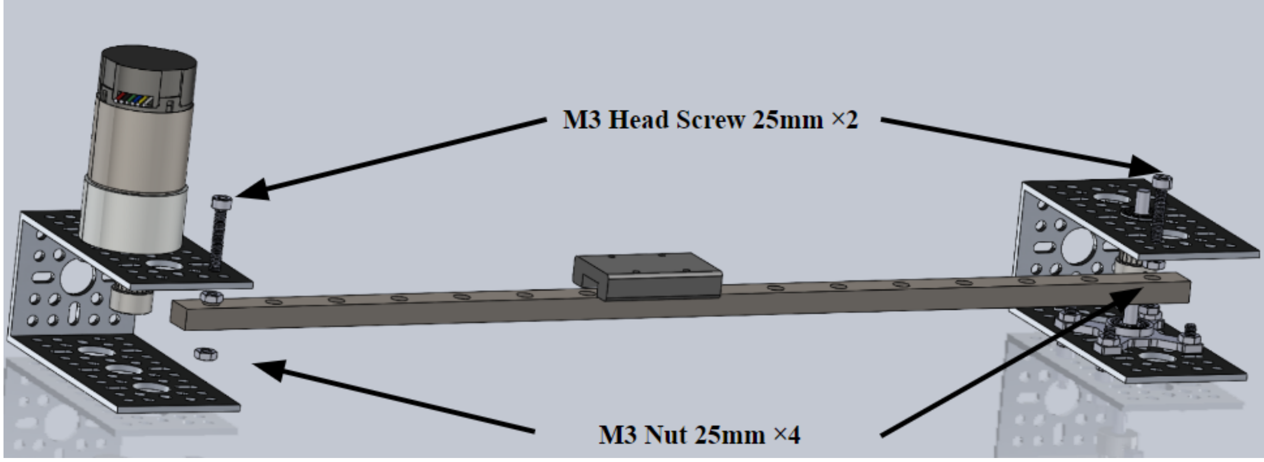
1. Put 1603 Series Face Thru-Hole Pillow Block on the bottom of the 1111 Series Angle Pattern Bracket and fix it with four screws and nuts. Then put the 1611 Series Flanged Ball Bearing (6mm ID x 14mm OD, 5mm Thickness) on the top and insert the 2101 Series Stainless Steel D-Shaft (6mm Diameter, 50mm Length) through the bearing and the 3mm HTD Pitch Set-Screw Pinion Timing Belt Pulley (6mm D-Bore, 18 Tooth) till the pillow block. Fix the timing belt pulley on the shaft with setscrew.



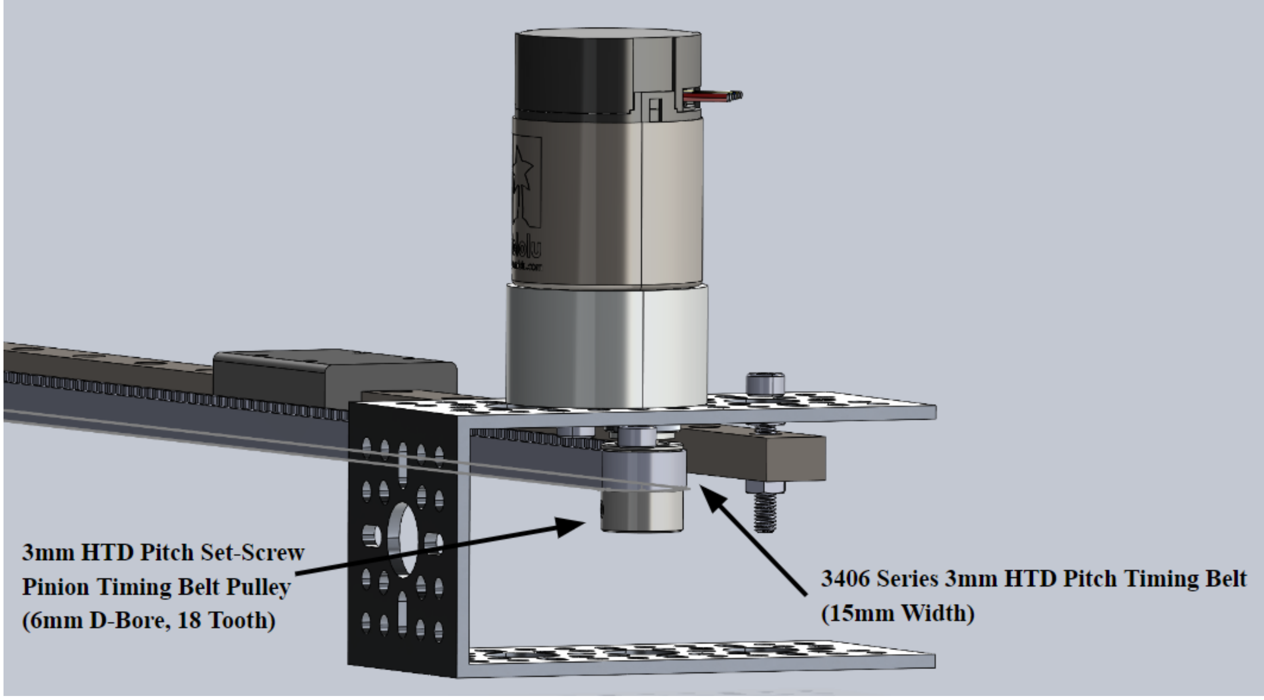
2. Put the 30:1 Metal Gearmotor 37Dx68L mm 12V with 64 CPR Encoder on the top of the 1111 Series Angle Pattern Bracket and used two screws to fix it. Then fix the timing belt pulley on the shaft of the motor. Adjust the height of the pulley to be at the same height of the pulley on the D-shaft.



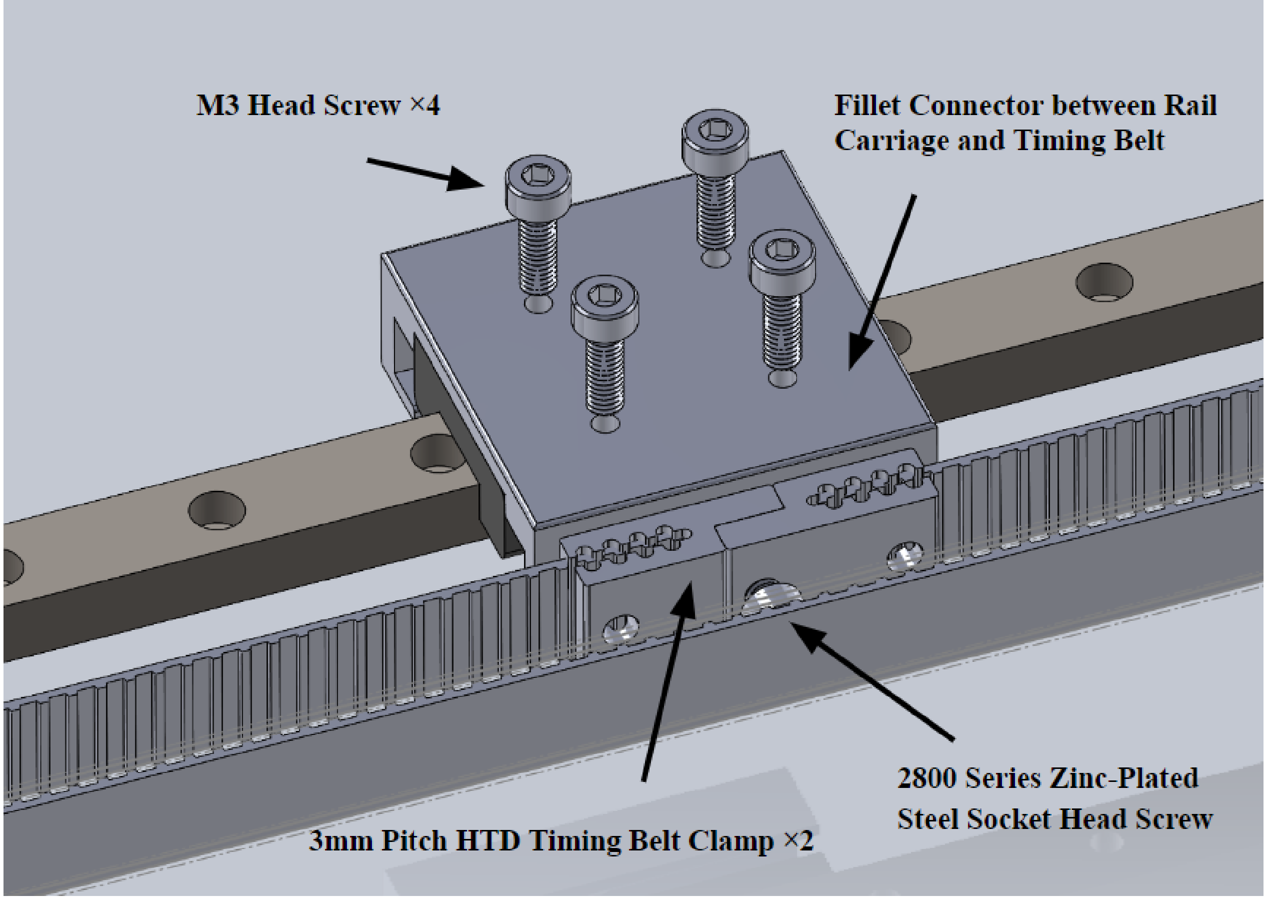
3. The Guide Rail is connected to the two Angled Bracket with two M3 screws and four nuts



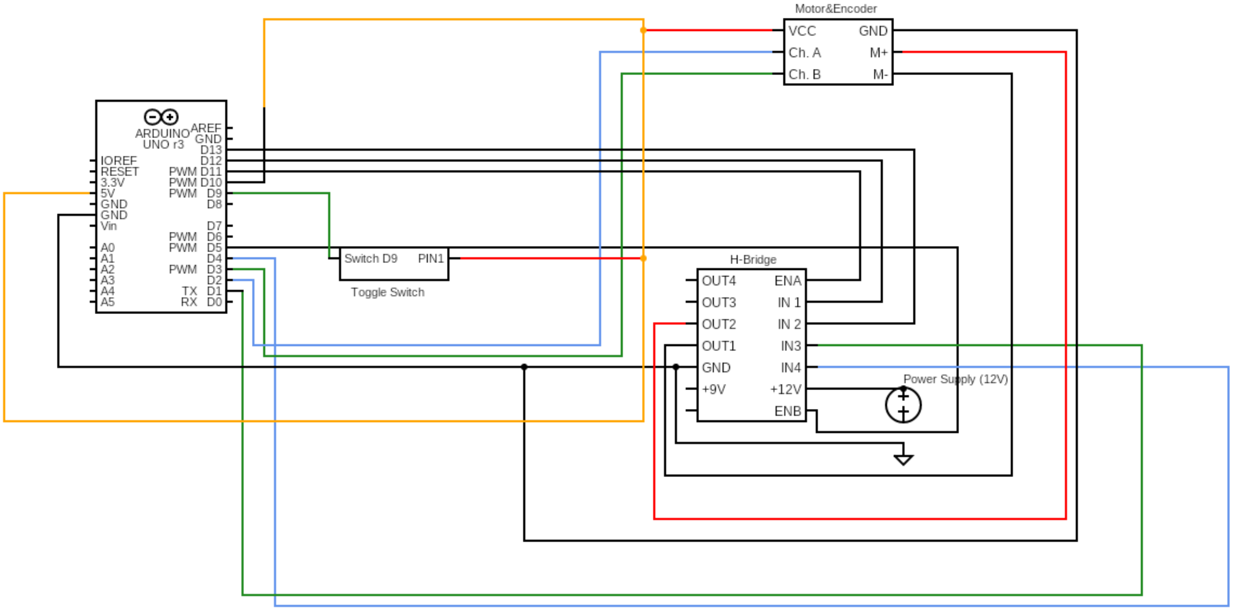
4. The timing belt fits the two timing belt pulleys.



5. The Fillet Connector between Rail Carriage and Timing Belt is fixed on top of the carriage block on the Linear Rail Guide with four screws. The two 3mm Pitch HTD Timing Belt Clamp is fixed on the connector by a screw. The 3406 Series 3mm HTD Pitch Timing Belt (15mm Width) is installed at last. The two ends of the timing belt are inserted into the clamp. Then the timing belt will form a closed loop

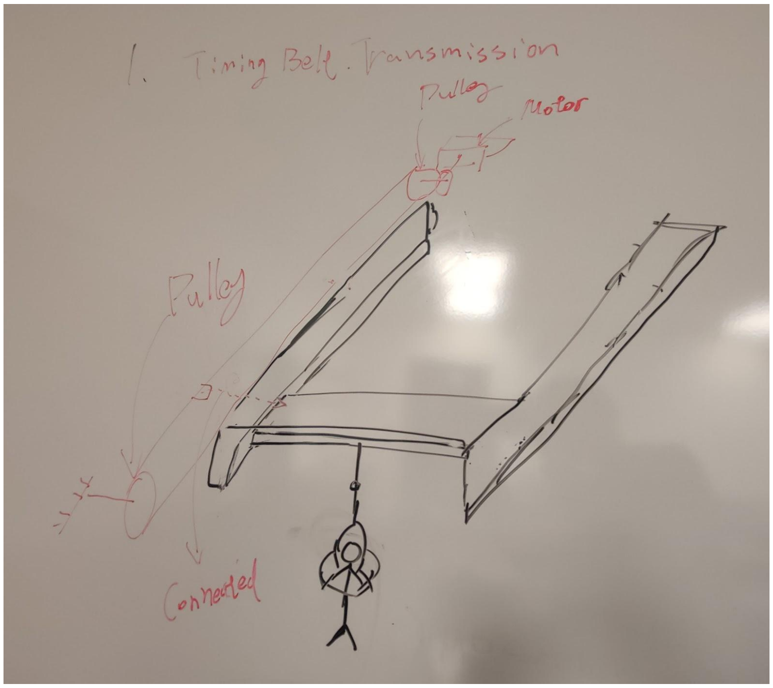


6. Finally, the Arduino board, H-bridge and motor are connected as shown in the circuit graph. (https://www.circuit-diagram.org/editor/)

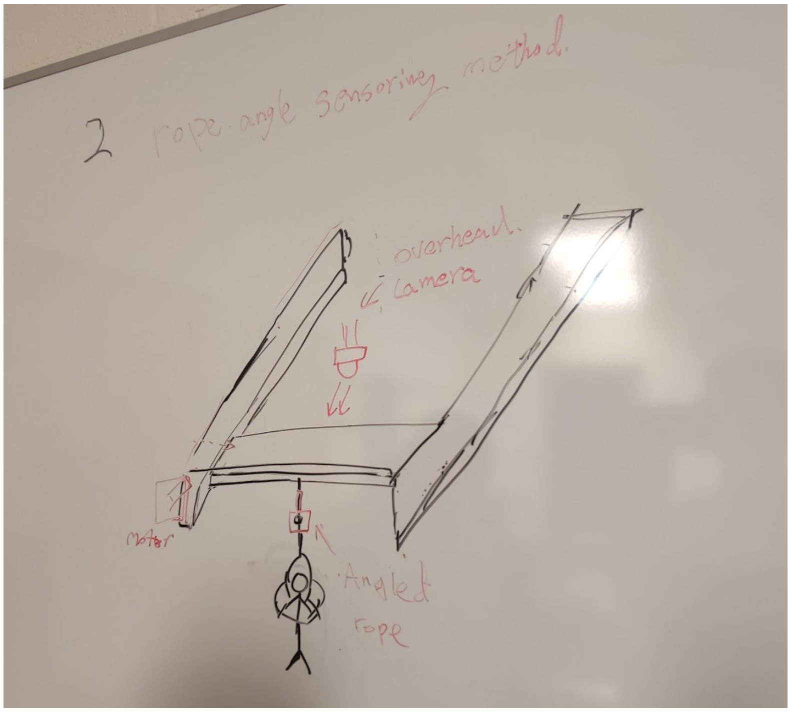


Appendix C: All design ideas are listed below

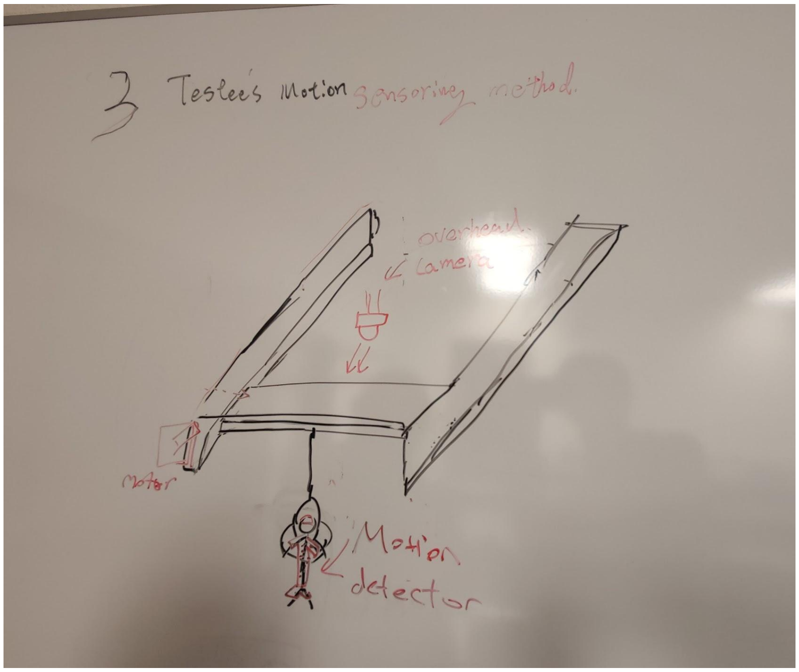
1. Timing belt actuation: Implement two timing belts on the two ends of the X-direction slide, and each timing belt will be driven by a motor.



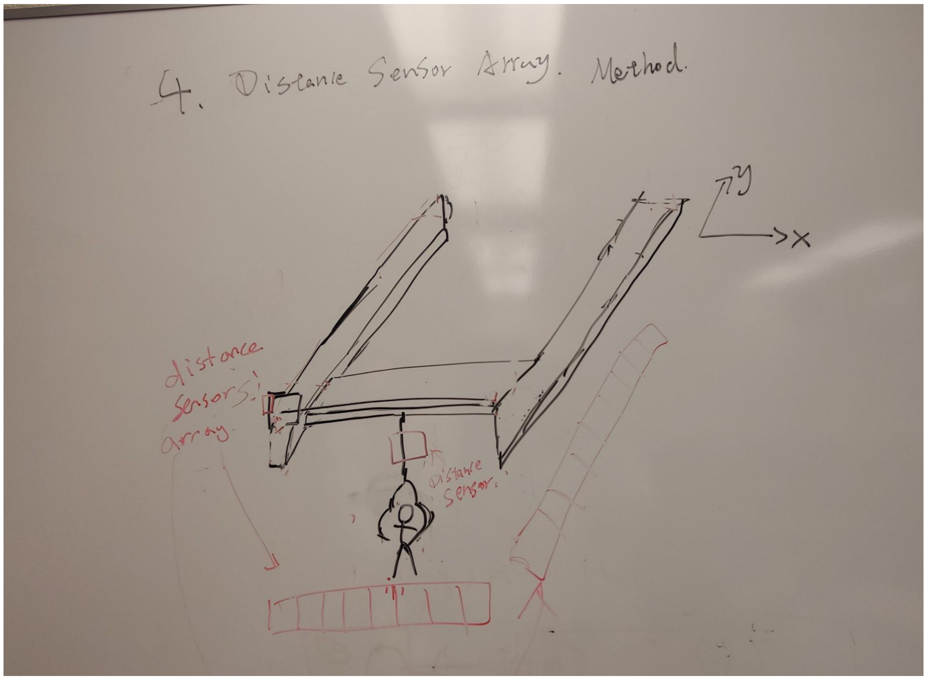
2. Rope angle censoring method: Use an overhead camera to monitor the tilting angle of the rope, which represents the movement of a testee along the y axis.



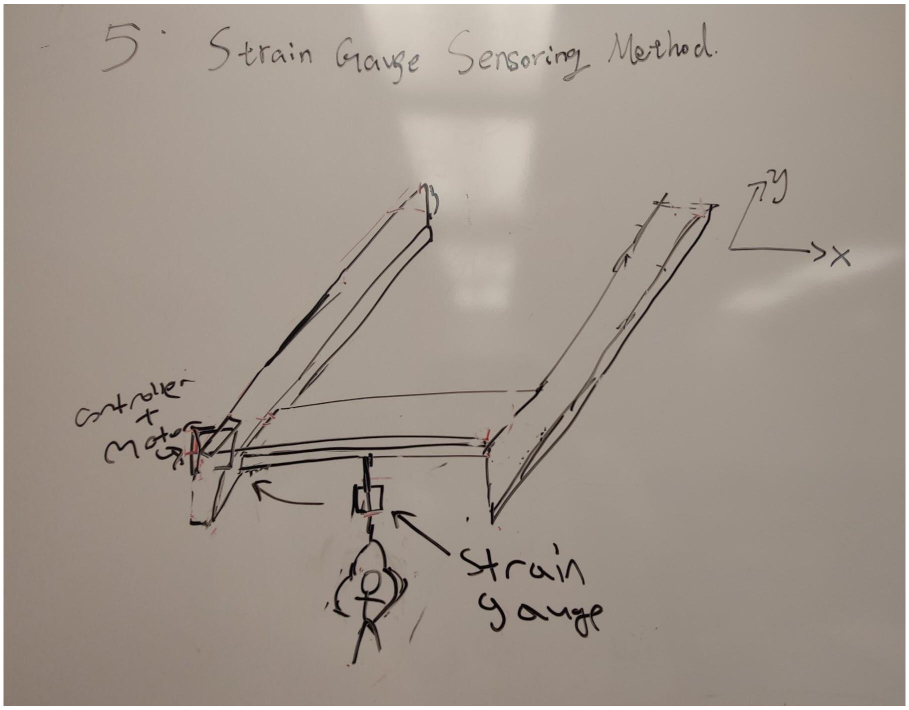
3. Testee motion censoring method: Use an overhead camera to monitor a testee's movement along y axis directly.



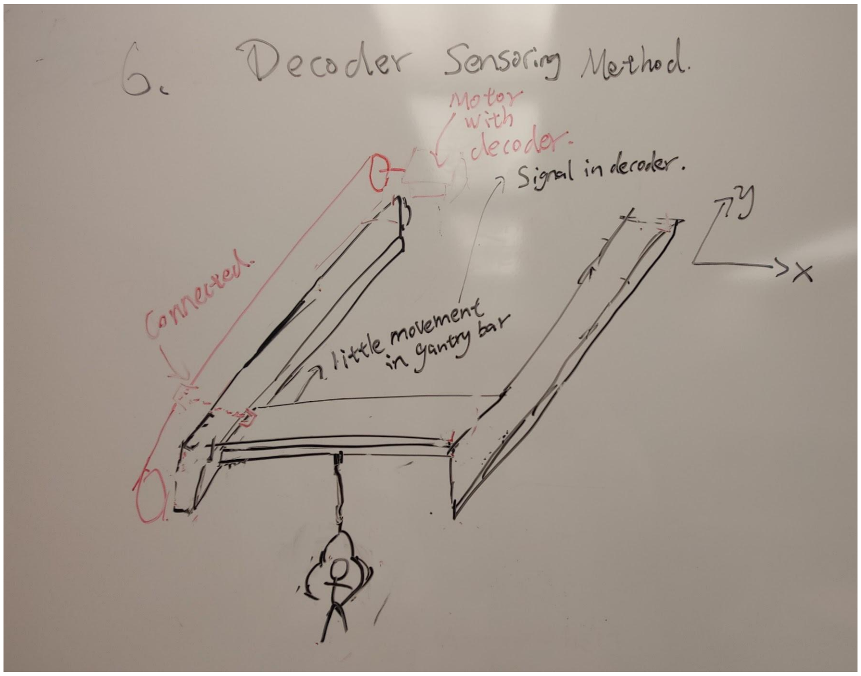
4. Distance sensor array method: Implement two arrays of distance sensors on the ground to detect the position of the testee.



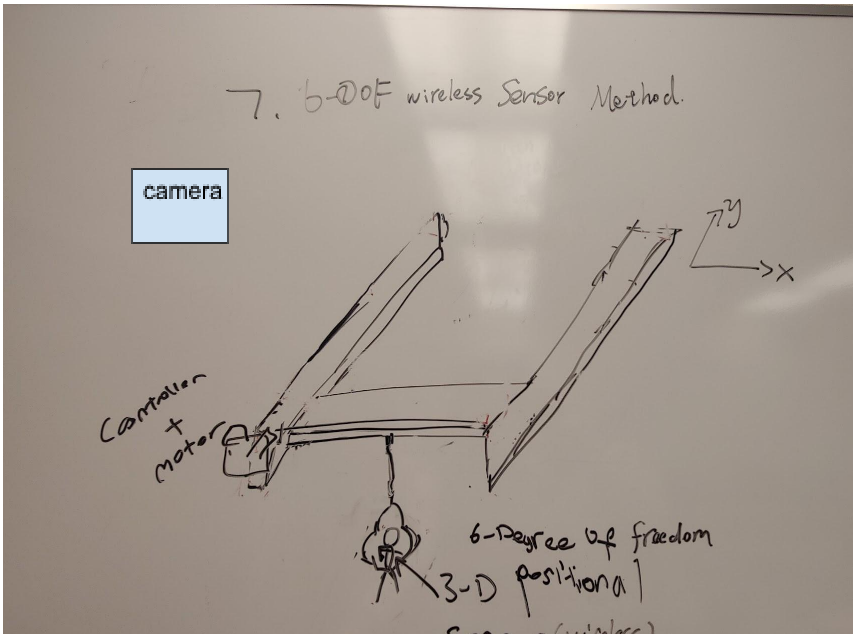
5. Strain gauge censoring method: The strain gauge is attached to the extendable belt, and the elongation of the belt represents the movement of the testee in the y direction.



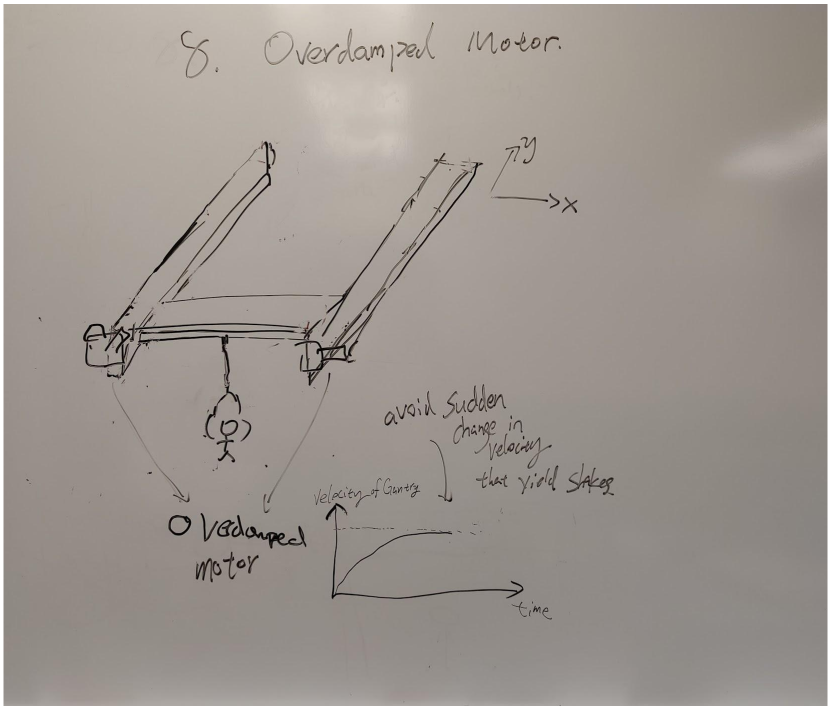
6. Decoder censoring method: When the small displacement of a testee causes the little movement of the X-direction slide rail, the motor decoder will perceive the movement and amplify it.



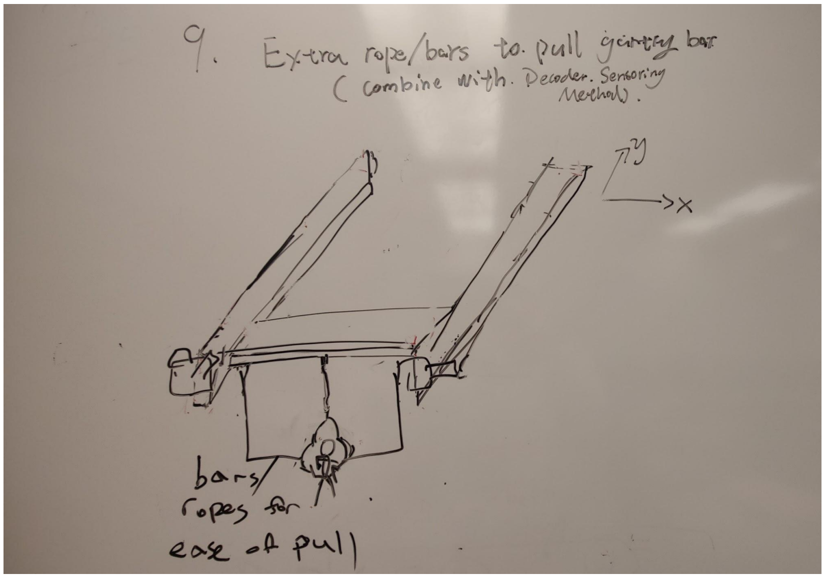
7. 6-DOF wireless sensor method: Use a camera to capture the movement of a testee in 6 degrees of freedom.



8. Overdamped motor: Implement two motors capable of achieving overdamped responses.

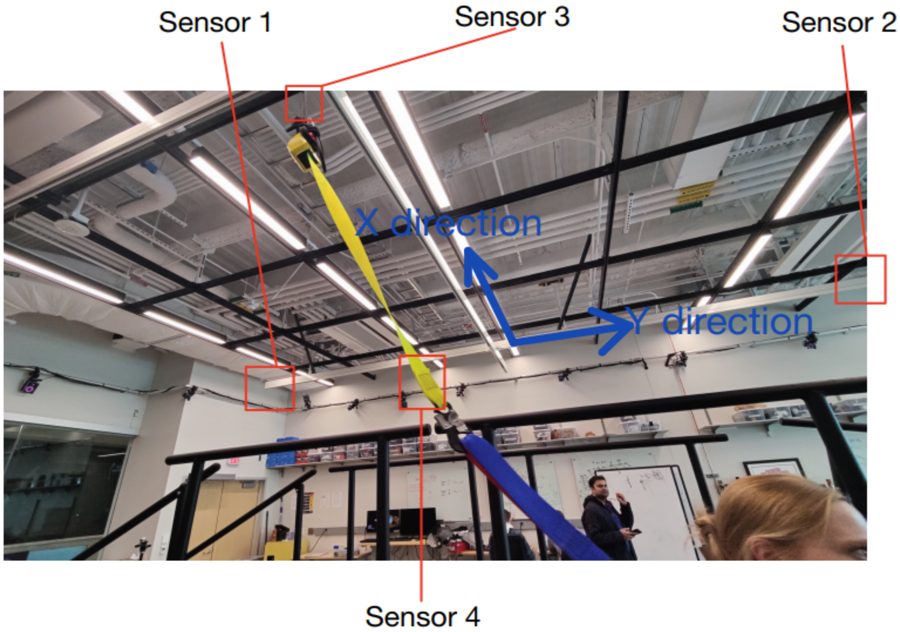


9. Extra rope/bars to pull X-direction slide rail (Improved based on concept 6): Attach another elastic rope between a testee and the X-direction slide rail to help the motor encoder perceive the movement of the X-direction slide rail.

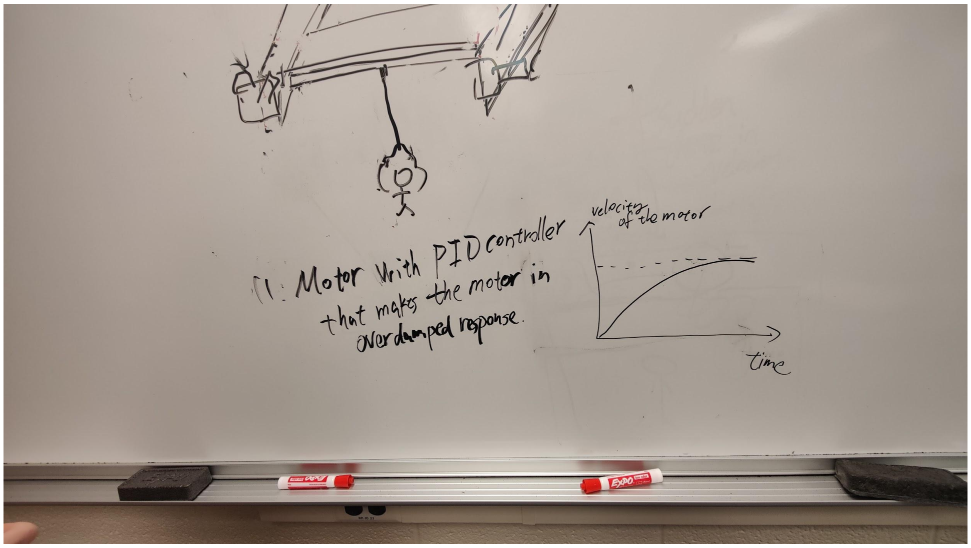


9. Extra rope/bars to pull gantry bar (combine with. Decoder. Sensoring Method).

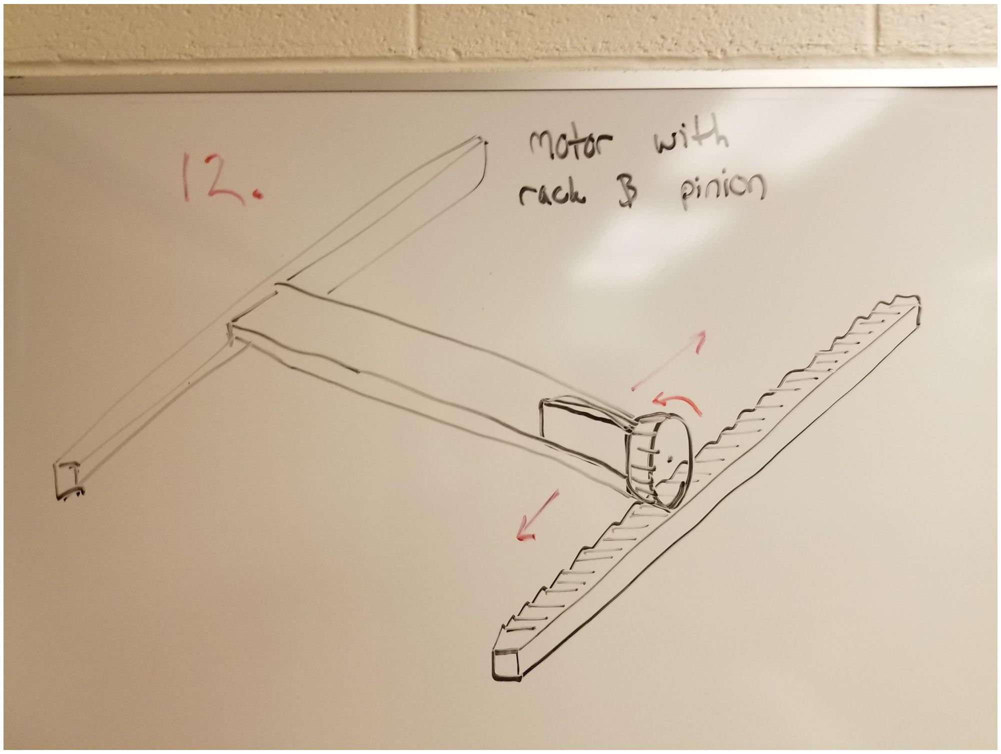
10. Four distance sensors to detect testee’s movement in y direction: Sensor 1 and sensor 2 will perceive the direction of movement in y axis. Sensor 3 and sensor 4 will measure the elongation of the safety belt.



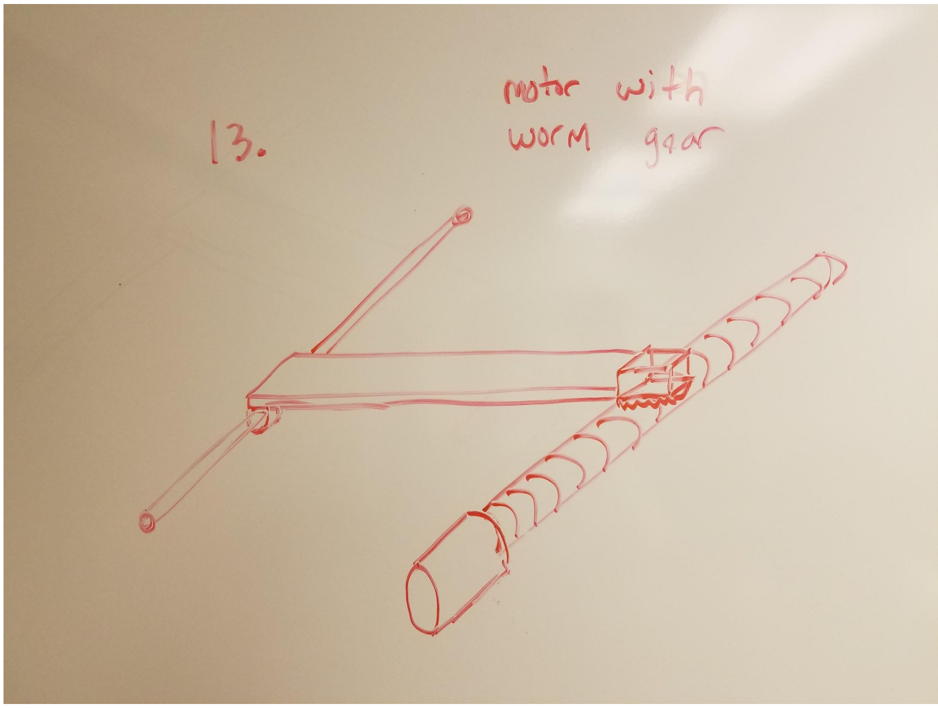
11. PID controller: Implement PID controller to help achieve the overdamped scenario.



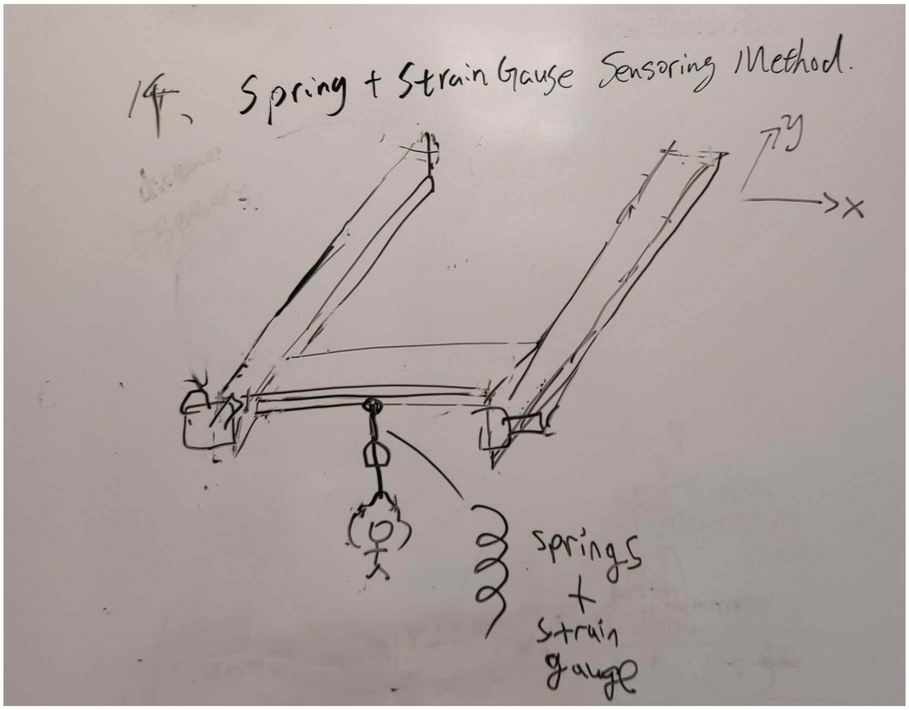
12. Motor with rack and pinion to actuate gantry movement. This design would include the motor on the gantry which would increase gantry mass but could be easier to implement.



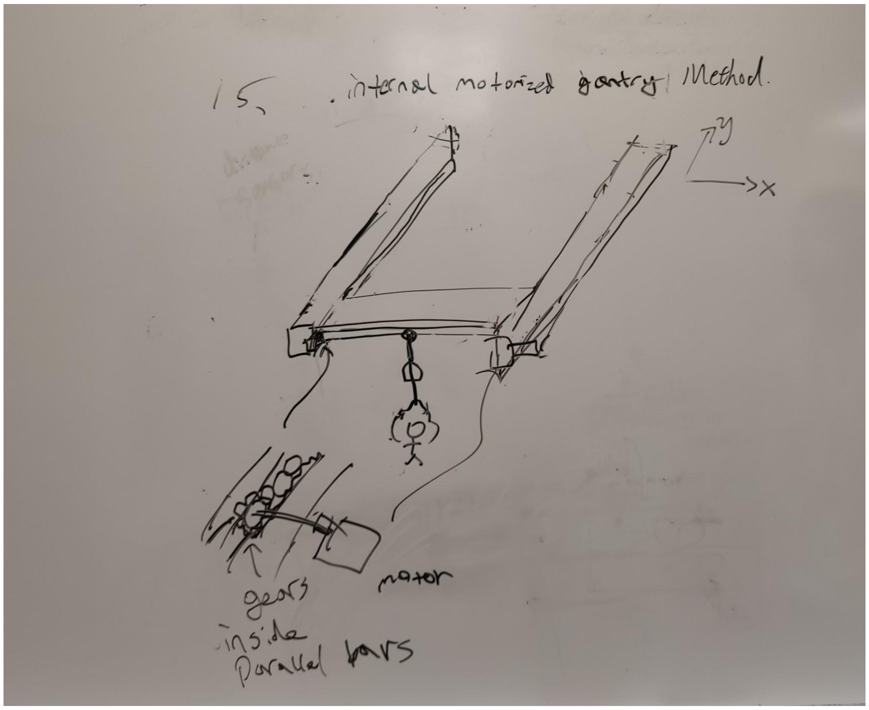
13. Motor with worm gear / power screw to actuate gantry movement. This design reduces the mass of the gantry but the worm gear could be difficult to source. The worm gear would also allow for a large gear ratio.



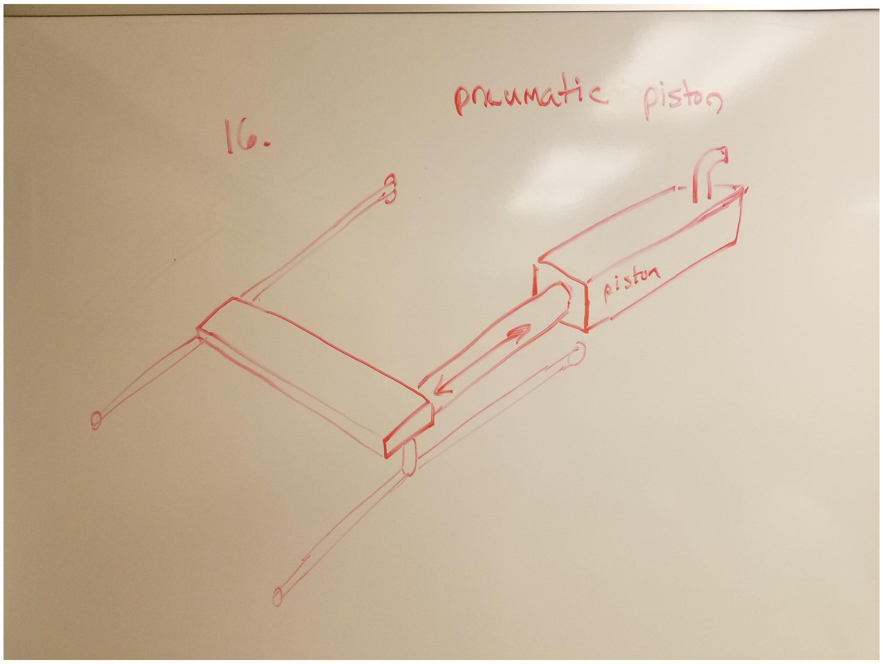
14. Spring + strain gauge censoring method: Replace the extra rope in design 9 to be a elastic spring to help trigger the motor encoder perception



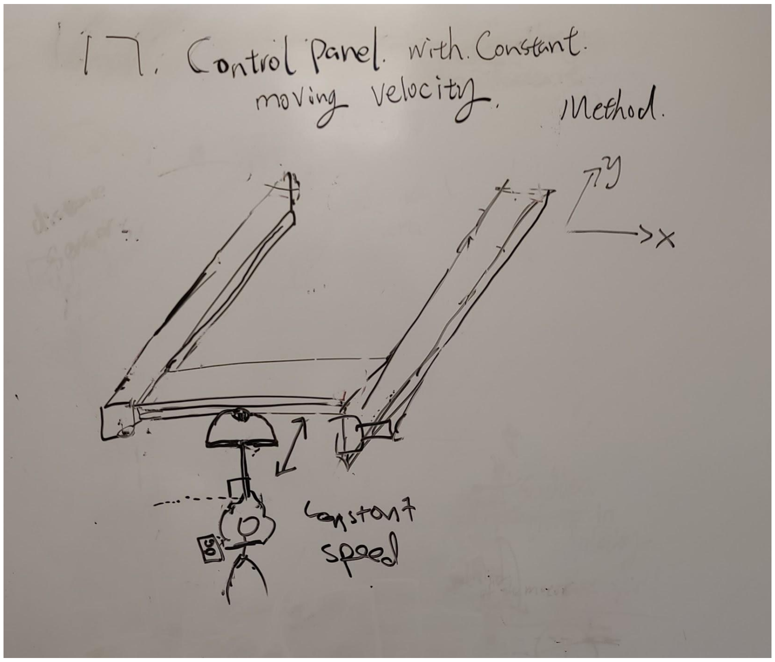
15. Gantry with internal motors on X-direction bar and roller on Y-direction bar to let X-direction bar to driving by the motor



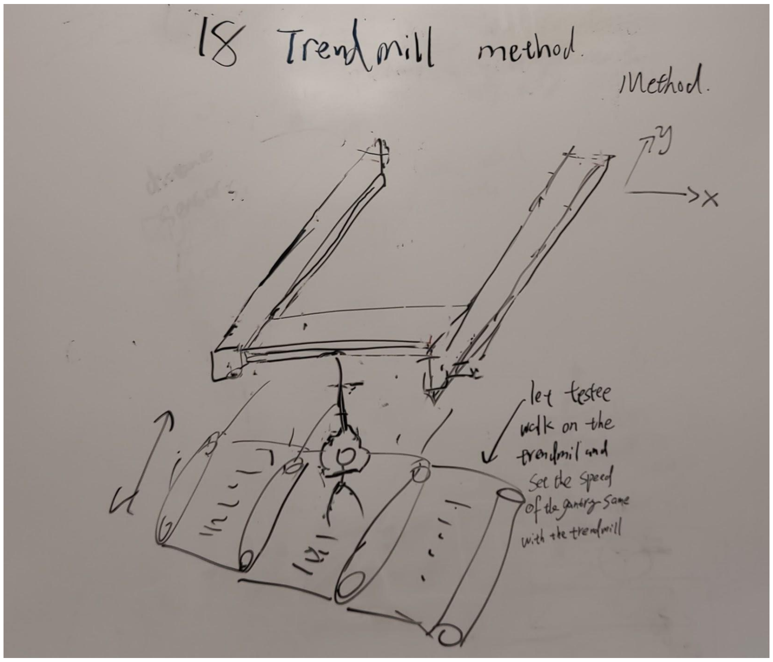
16. Pneumatic cylinder to actuate gantry motion. It could provide very fast linear motion but would likely be complex and hard to control



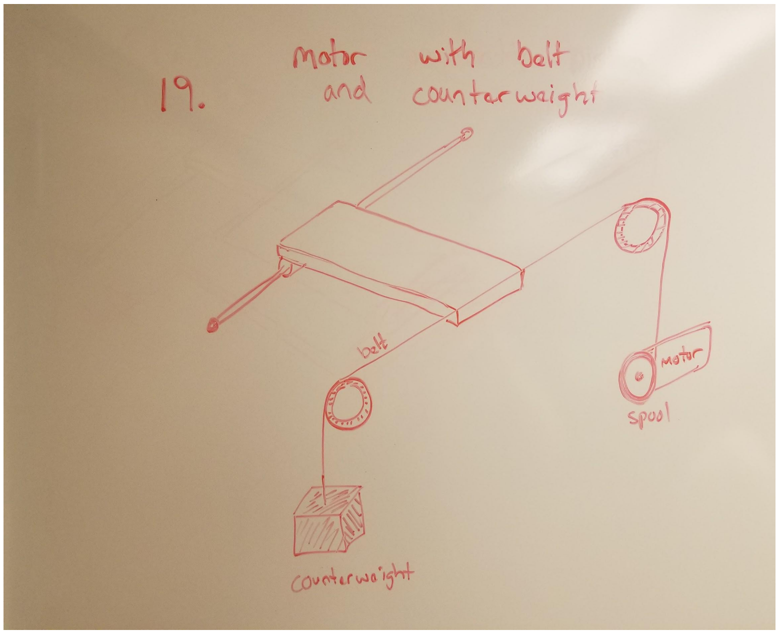
17. Hand held control panel which allows the patient / researcher to move the controller at constant velocity.



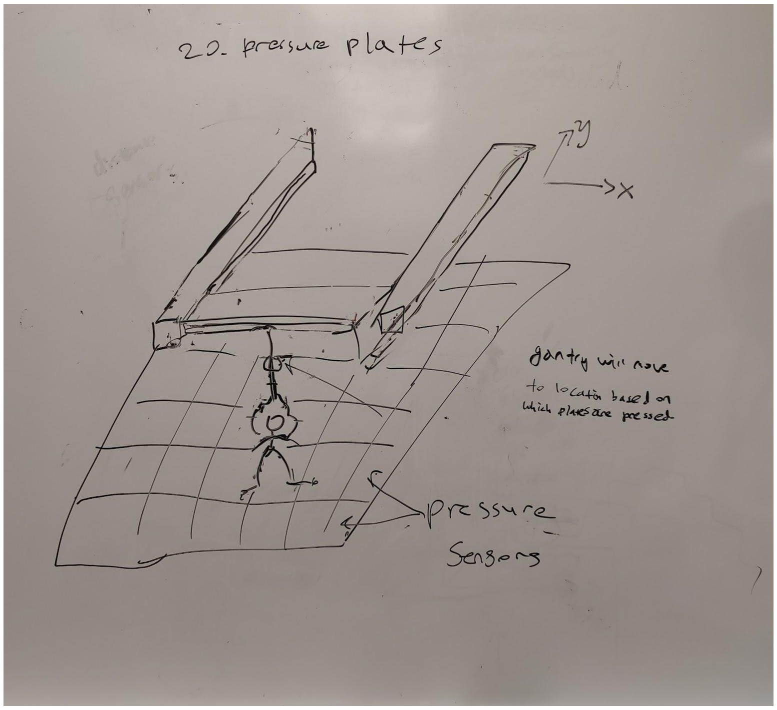
18. Treadmill design. The speed of the treadmill will be the same as the gantry's speed, so it will always be above the testee for the safety to function properly.



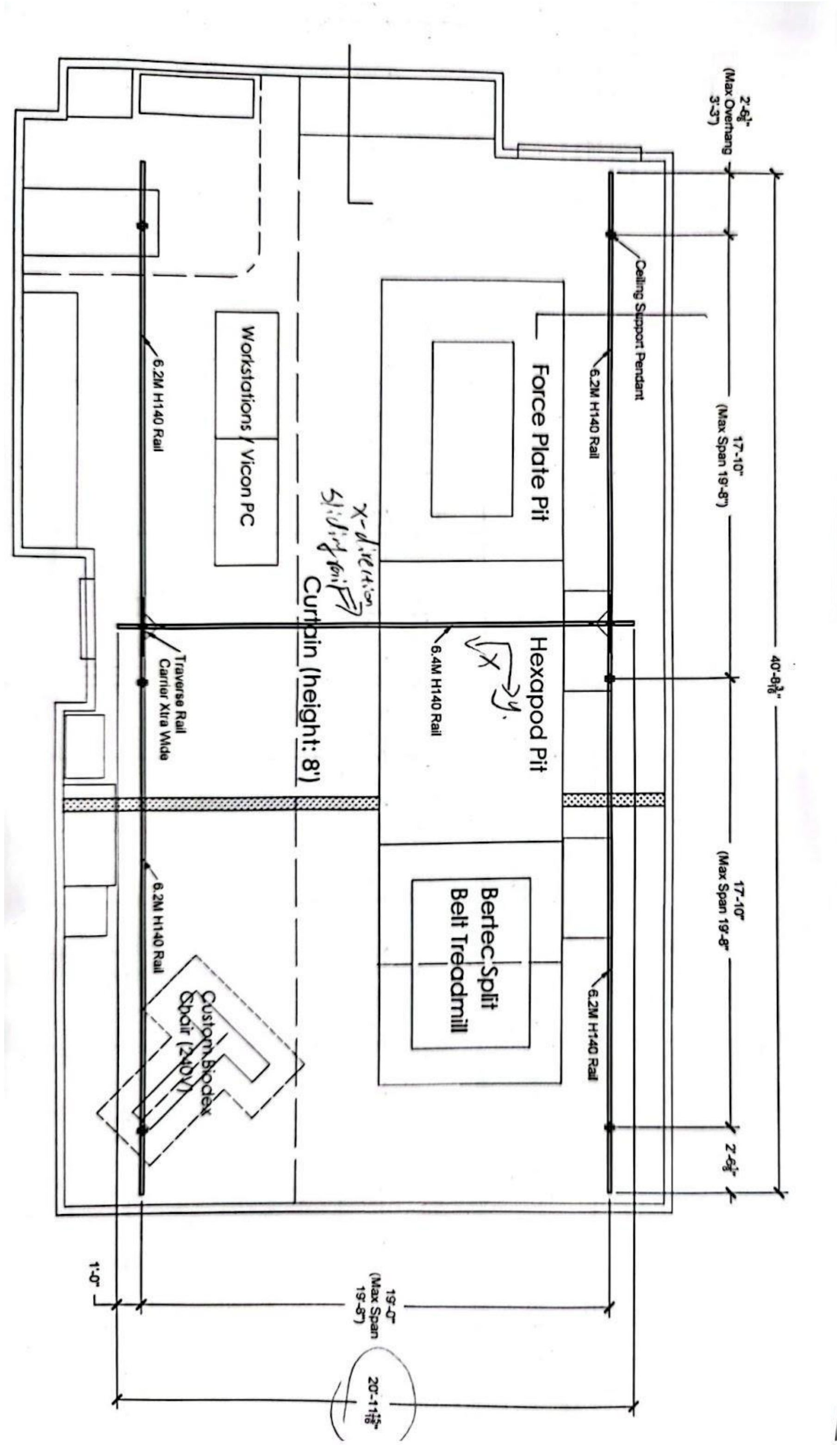
19. Motor with belt and counterweight. The counterweight could help with gantry motion in one direction which could help to reduce the load on the motor in that direction and increase motor life. But this extra weight could also be slow to control.



20. Pressure sensors on the floor across the room. For example 1 x 1 meter square pads across the floor that, when stepped on, would notify the gantry system of the patient's location in the room and communicate with the controller to move the gantry to them.



Appendix C: Layout of the Neurobionics lab. The picture shows the dimensions of the gantry to take into consideration when implementing the design.

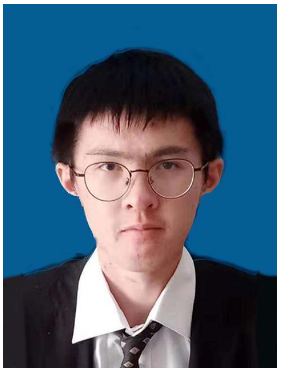


BIOS

Brandon Phee

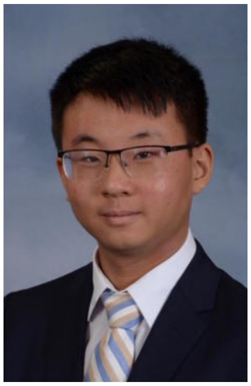
Brandon Phee is a senior in mechanical engineering currently attending the University of Michigan at Ann Arbor. He was born in Seoul, South Korea and moved to New Jersey, United States when he was 12 years old. Growing up, he was exposed to engineering from his father, who studied metallurgical engineering and his brother, who loved learning about and researching different cars in magazines and articles. Upon choosing to attend the University of Michigan as a mechanical engineer, he got to experience working with other team members at clubs such as Michigan Rover and Michigan STARX to expand on his interests. He also worked at the Boehman lab to study and produce algae-based biofuels using both hydrothermal liquefaction and lipid extraction. Mechanical engineering is a field that can make a huge impact on many people's lives, and it will be incredible to be able to work on various high-impact projects in the future. He would like to work in the automotive industry or in manufacturing, and may choose to pursue a business MBA in the future. Some interesting facts about Brandon are that growing up as a Manchester United fan, he loves playing and watching soccer. He also likes researching new cars, reading science fiction, and playing video games.

Chenhao Zhu:



Chenhao Zhu is a junior student majoring in Mechanical engineering in the University of Michigan, Ann Arbor. He transferred from Sichuan University in Chengdu, China. Both of his parents are not engineers so he is the first engineering student in his generation. Mechanical engineering is a highly developed major. Right now mechanical engineering cooperates with other majors exploring new technology and physical products. In the future, he will continue his academic career in graduate school with a multi-subject research direction. Currently, he is working with Prof. Eric Johnsen's lab in parallel computing with openMP GPU offloading. In ME 450 Capstone project, he wants to experience a full project related to control and mechatronics stuff to diversify his undergraduate Mechanical Engineering life.

Hang Yin:



Hang Yin is a transfer student from Sichuan University in Chengdu, China. Now he is a senior student majoring in Mechanical Engineering at UMich, Ann Arbor. Both of his parents majored in Mechanical Engineering, with his father specializing in Fluid Machinery and Engineering and his mother specializing in Process Equipment and Control Engineering. Hang developed his interest in Mechanical Engineering so he chose this major for his undergraduate and future graduate study area. Mechanical Engineering is highly multi-subject disciplinary, which enables students to solve various engineering problems. Now he is working in Prof. Wei Lu’s labs, developing piezoelectric battery separators to prevent the growth of battery dendrite. As for the ME 450 Capstone Project, he wants to experience more electromechanics and control, to fulfill his diversity of Mechanical Engineering experience. He is an avid soccer fan, and he likes to listen to music and play video games in his spare time.

Chris Symonds:

Chris Symonds is a senior in Mechanical Engineering at the University of Michigan. His interest in engineering stemmed from his involvement in high school robotics as well as working in his father’s CNC machining business, where he learned critical skills in manufacturing which he still uses to this day. Outside of coursework, Chris is involved in the University's Formula SAE team, MRacing, where he plays a key role in the design of suspension hardware as well as the machining of numerous components. Nearly all of his free time and social activities involve MRacing, but due to the crucial skills, experiences, and connections he’s made along the way, he cannot think of a better way to spend his time while in university. After graduation, Chris is looking to start his engineering career in the aerospace industry as he has a passion for astronomy and space exploration.