Portable Stair Lift System

A Major Qualifying Project
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Abstract

Nowadays, multi-level condominiums have become many adults' choice of home. However, moving large and heavy objects such as a grand piano through the narrow stairwells requires the labor and effort of multiple people, and could potentially be dangerous. Our project developed a prototype for carrying a large and heavy object up and through narrow stairwells for homeowners and moving companies. To accomplish this, we researched and studied the specifications of standard stairs, contingent products in the market and iterated our designs to improve. We developed the Portable Stair Lift System that helps people move faster and easier by running the cart on the rail, and eliminates the potential injuries.

Executive Summary

In modern society, more and more people are pursuing an urban lifestyle instead of living in rural areas. According to the data the United Nation has collected, between 80-85% of Americans live in urban areas, and we are expecting this number to continue increasing[1]. This urbanization caused the popularity of condominiums, the multi-level residential complexes, and created a problem while moving in or out without the existence of elevators.

In order to solve this problem, our team has designed a Portable Stair Lift System in order to aid people while moving large and heavy objects. The Portable Stair Lift System consists of a rail and a robotic cart. Our first iteration of the design happened in the academic year of 2019-2020, and we finished our second iteration of the design in the academic year of 2020-2021. The first design focused on a pulley system that is attached to the cart, and the second design emphasizes a robotic cart that powers itself through the rail. The new design allows more flexibility of the system movement, and is easier to put the whole system together.

Throughout the design process, the design team values the safety factor, efficiency, and practicality of this project. The robotic cart features the safety gear that grabs on the rail to lock the cart on the rail in case of emergency, and it minimizes the need of human labor during the lifting process, keeping people away from potential injuries while moving large and heavy objects. Two linear actuators are built on the robotic cart, which keep the load balanced during embarkation and disembarkation.

Upon completion of the prototype, there are some recommendations to be made for future advancement of this project. In some cases, the stairwells do not go straight up and down, but have a 90-180º turn. Our prototypes are only designed for direct stairwells, and we hope the future iterations would be able to solve this problem.

Acknowledgements

We would like to express our special thanks to the following people and groups. This project would not have been at all possible without their help and support.

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Introduction

This project is a continuation of Portable Stair Lift System MQP completed in the academic year 2019 - 2020. The purpose of this project is to continue developing a robotic prototype that can help move large and heavy appliances or objects through narrow stairwells. The team has done inclusive research on specifications of standard staircases and analyzed the forces with free body diagrams for the design of the machine. Currently, there are no products that would serve the same purpose as we hoped. The prototype includes a set of adjustable rails, and a robotic cart that carries the object.

Background

It is dangerous and tiring to move large and heavy objects such as appliances and bulky instruments through narrow stairwells in a condominium. Because of the lack of space and accessible grips, the object can potentially fall, and cause serious injury, death, or damage. To keep people safe and relaxed during situations like this, our design of the Portable Stair Lift System keeps people away from the large objects while carrying them upstairs by itself. In order to achieve this goal with a better understanding of the situation and the potential barricades, we have done extensive research relating to this project, such as, specifications of standard stairs in the United States and similar products. Since this is a continuing project from last year, we will also discuss the academic years previous work.

Continuation of Last Year's Project

In order to create a better design and understand the desired capabilities of our Stair Lift Device, we first looked at the design iteration we began in the spring semester of 2020. Since the team was a mix of third and fourth year students, the three people out of five from the previous team were able to continue making this system better, with an additional member from the Robotics Department. By looking at the previous ideation (Figure 1), we were able to see where the system required the most improvements to not only make it more effective but also safer. This primitive design we began with, utilized a pulley and steel cable system to move the plywood cart. We felt this steel cable and pulley system would be ineffective because of the challenges that would come with adjusting the length of the cable, depending on how many stairs needed to be ascended. We also found difficulties in properly attaching the cable to the cart without greatly increasing the profile of the cart, but also without losing strength and integrity in the system. Additionally, we found some issues with the rail system, which used acrylic panels to hold the wheels inside the channels. If the cart is to lift heavy loads, the acrylic would likely crack and break, which may lead to the channel being unable to hold the cart in place. Further, we found that the mounting and dismounting of the object being lifted would be challenging given this cart's design. We also felt the pulley system would require a more elaborate system of pulleys in order to make the system efficient and not require too large a motor. The issue with this was if the cart and rail system had to be assembled on site, the person charged with assembly would have to know how to set up the proper gear ratio given the load being lifted and would also have to know where to put the cables so they would not be interfering with the cart or track. Another issue we saw with this rail system design was that all the weight of the object being lifted was directed into the base of the rail system and not distributed evenly along the stairs, which made the possibility of slippage of the system very plausible and dangerous.

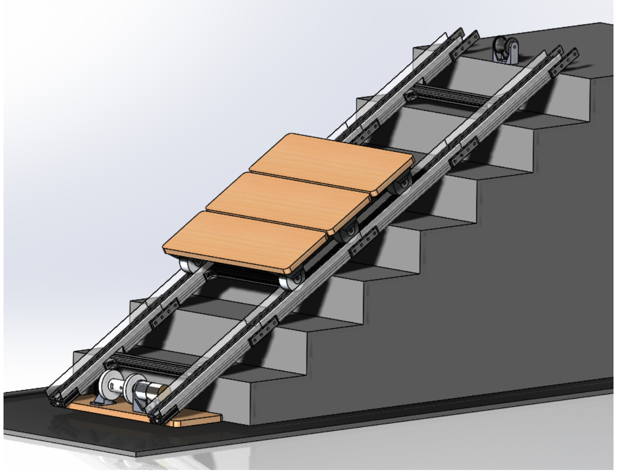


Figure 1: Stair Lifting System Design from Previous Year

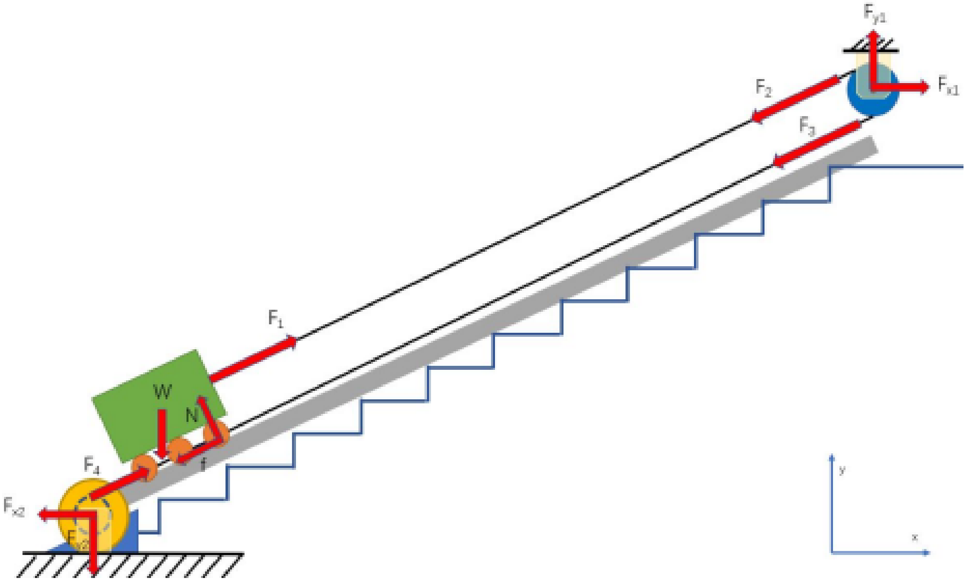


Figure 2: Free body Diagram of Previous Project that Shows the Pulley System

Specifications of Standard Stairs

We have done extensive research on the standards of stairs in the United States. Even though there can be variations in angles and elevation, in Figure 3, we can see the stairway rise and tread dimensions in various degrees from 30 to 50, and the data presented are in an empirical system. Figure 4 shows the basic structure of stairs, and we learned that most stairways in the United States have nosing, beside tread and riser[2]. According to the United States Department of Labor. The nosings will make the fixture of rails more challenging since there can't be any stabilizer design to utilize the 90 degree angles on the edge of a stair.

After all this information, we found out that the most common stair angle is 40 deg. 08'. Therefore, we will focus on our project with this specification for the design, and hoping to make our design compatible with different specifications of stairways.

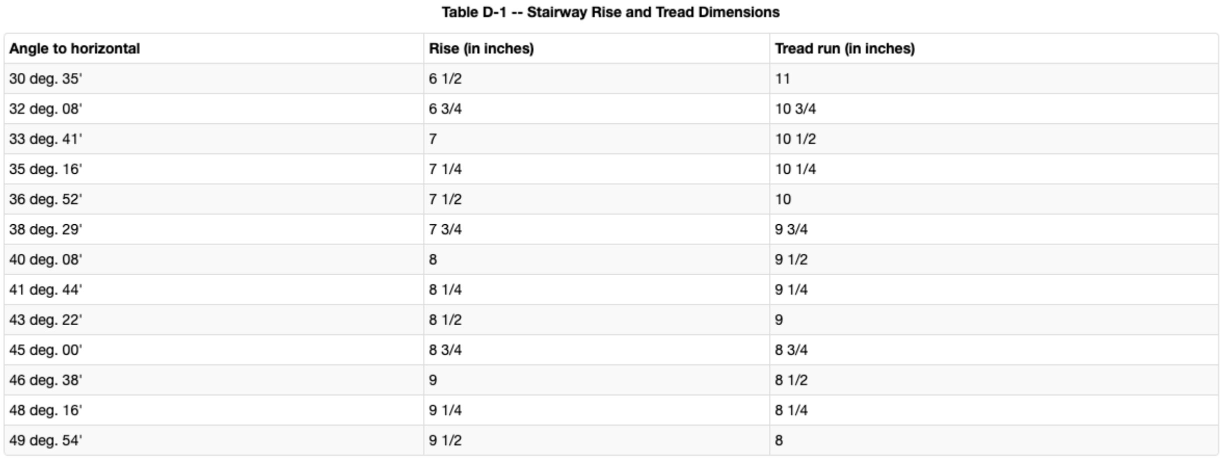
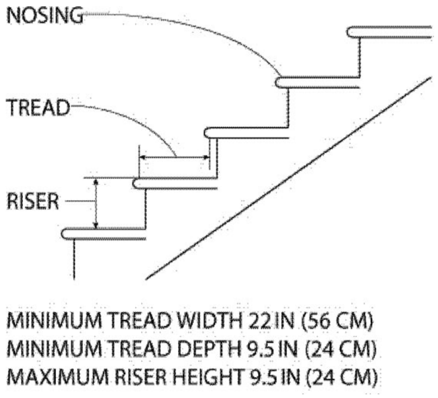


Table D-1 -- Stairway Rise and Tread Dimensions

Angle to horizontal	Rise (in inches)	Tread run (in inches)
30 deg. 35'	6 1/2	11
32 deg. 08'	6 3/4	10 3/4
33 deg. 41'	7	10 1/2
35 deg. 16'	7 1/4	10 1/4
36 deg. 52'	7 1/2	10
38 deg. 29'	7 3/4	9 3/4
40 deg. 08'	8	9 1/2
41 deg. 44'	8 1/4	9 1/4
43 deg. 22'	8 1/2	9
45 deg. 00'	8 3/4	8 3/4
46 deg. 38'	9	8 1/2
48 deg. 16'	9 1/4	8 1/4
49 deg. 54'	9 1/2	8

Figure 3: Stairway Rise and Tread Dimensions



MINIMUM TREAD WIDTH 22 IN (56 CM)
MINIMUM TREAD DEPTH 9.5 IN (24 CM)
MAXIMUM RISER HEIGHT 9.5 IN (24 CM)

Figure 4: Cross-Section View of the Stairs

Existing Similar Projects

We have been researching for products in the industry that serve similar purposes. One product is especially interesting, the Stairrobot as shown in Figure 5. It was described as a high tech stair climbing robot Developed by AATA International BV[3]. What is special about this product is that it utilises the single conveyor belt to make the lifting up or down much easier and efficient. However, a person is required to hold the Stairrobot during the whole lifting process. Therefore, it could be potentially dangerous if there's any human errors, such as mishandling could result in accidents.

Figure 5: Design of Stair Robot

Potential Constraints

As we learned from last year's project, there could be some constraints for this whole system. We prioritized safety, and we make changes if it will not decrease the safety factor. Our goal is to develop an automatic lifting system that does not require human labors beside putting the object on or taking it off the cart. In addition, it could be potentially hard to fix the rail to the stairs, since the floor materials could be different such as wooden floor, carpeted floor, or tile floor. This particular design can also be limited when the startwalls have turns.

Methodology

In this Methodology section, we will discuss the process from developing ideas to realization of this project, which includes design objective determination, brainstorming, design analysis, and the realization of the final design.

Determining Design Objective

We had a clear goal when we first started this project - to create a stairwell lifting system to help people move large and heavy appliances. For our design prototype, we have determined that our lift load is 500 lbs, and our calculations for the analysis is also based on this number. This system should be designed so that it is suitable for different types of potential loads, such as a baby piano, a washing machine, or a grand piano. The design should be able to securely fix objects in various shapes, sizes, and loads. In addition, this system should be portable and easy to assemble, in order to make the "delivery" fast and efficient without being laborious. Most importantly, our design system has to ensure people's safety, because our original goal is to keep people safe while moving heavy and dangerous objects, and without ensuring safety, this project would be meaningless. Therefore, we have to ensure that our design is absolutely safe to use.

Brainstorming

Ideation helps our group to come up with various ideas through brainstorming together, and we will compare our options to find the best one for us. Beside the pulley system design from the previous year's MQP, we have also come up with two new ideas for this year's new design. The first idea was the same rail system, but with a robotic cart (Figure 6). In this design, the movable rubber buckles will be able to secure the rail on the stairwells with various materials, and the self-powered cart will carry the load upstairs on its own while ensuring the load is balanced.

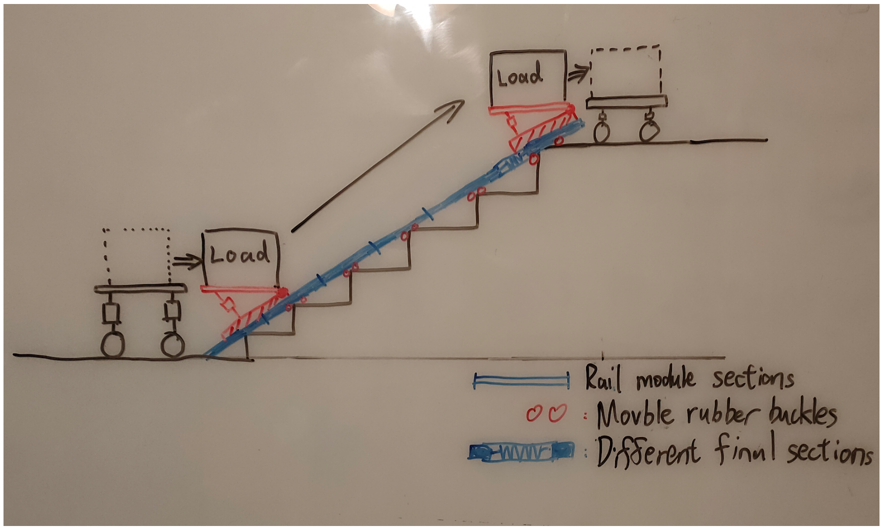


Figure 6: Ideation for Same Rail System but Different Cart

Our second idea was to design a remote controlled conveyor belt robot (Figure 7)that could direct the load to the destination while gripping the stairs with conveyor belts while keeping the load balanced.

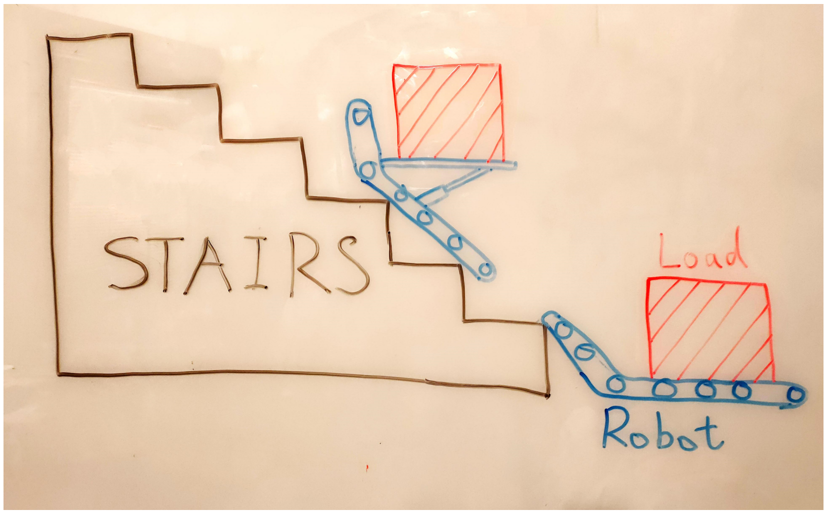
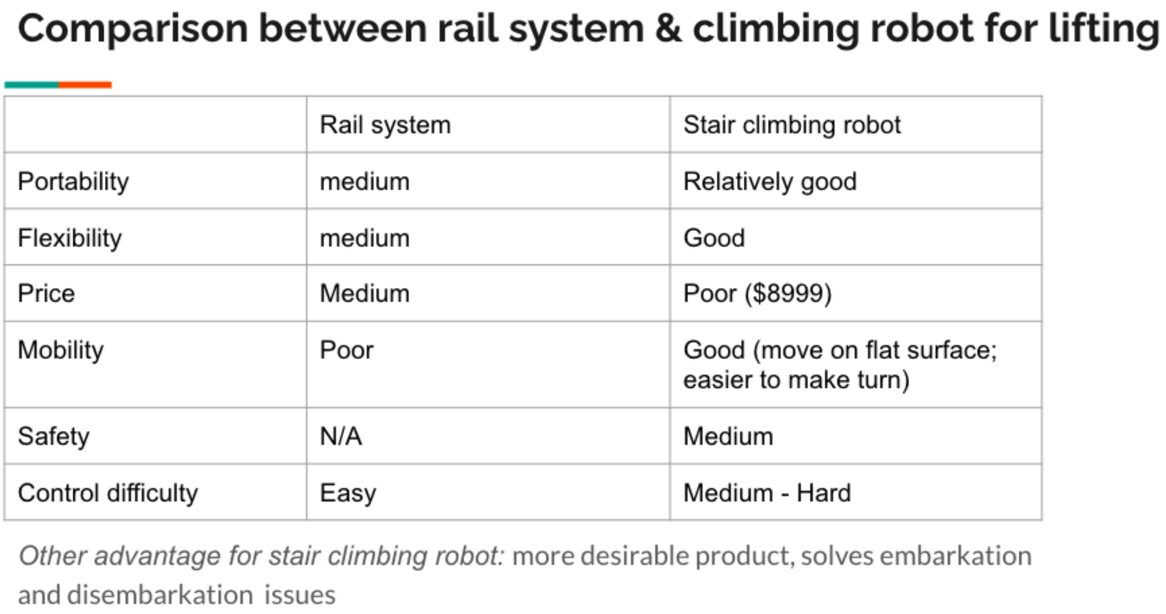


Figure 7: Ideation for Remote Controlled Conveyor Belt Robot

In order to compare these two robots, we have made a table to compare them in various factors; as shown in table 1.



Comparison between rail system & climbing robot for lifting

	Rail system	Stair climbing robot
Portability	medium	Relatively good
Flexibility	medium	Good
Price	Medium	Poor ($8999)
Mobility	Poor	Good (move on flat surface; easier to make turn)
Safety	N/A	Medium
Control difficulty	Easy	Medium - Hard

Other advantage for stair climbing robot: more desirable product, solves embarkation and disembarkation issues

Table 1: Comparison between Rail System and Climbing Robot

In the end of ideation, we decided to continue with the rail system, with self-driven cart and linear actuators balancing the load, because it is a lot more cost-effective, easier in terms of control, and makes embarkation and disembarkation easier during the delivery while ensuring safety.

Design Analysis

We have conducted different kinds of design analysis in order to better understand our goal and project. We have first conducted a static analysis to calculate all the forces involved in the system and created a free-body diagram. We have also conducted dynamic analysis to simulate when the cart is running on the rail, and make sure that the material we have chosen is capable of handling the forces during the movement. Moreover, we have also conducted bond graph and stress analysis for the motor, and the linear actuator. In the end, with all the results of the calculations and analysis, we have determined the specifications for a ½ scale of our design prototype, which we will be manufacturing. The analysis will be discussed more specifically in “Technical Details” next chapter.

Final Design and Realization

After all the analysis, we have completed our final design on SolidWorks, and created a Bill of Material (Appendix A). Having the design specifications, we began ordering all the components and manufacturing. We have first manufactured the rails. Since we have bought most materials from McMaster-Carr, we only need to assemble the rail components together. When fabricating the cart, we had to machine some components for the gearbox and tapping holes on the frame of the cart before we started the cart assembly. We will be discussing our final design and manufacturing in the next chapter.

Mechanical Design

System Static Analysis

To have an initial idea of how much force F is required to drive the vehicle, we started with a system sketch for static analysis. We assumed that the total weight of the vehicle W is 25kg (Load 15kg, mass of vehicle 10kg), and the angle of the stairs is 40 degrees (designated maximum degree). The friction coefficient between the rail and vehicle is assumed to be 0.2 including rolling friction of wheels and friction of the gears. The FBD (Free-Body Diagram) of system static analysis is shown as Figure 8 below.

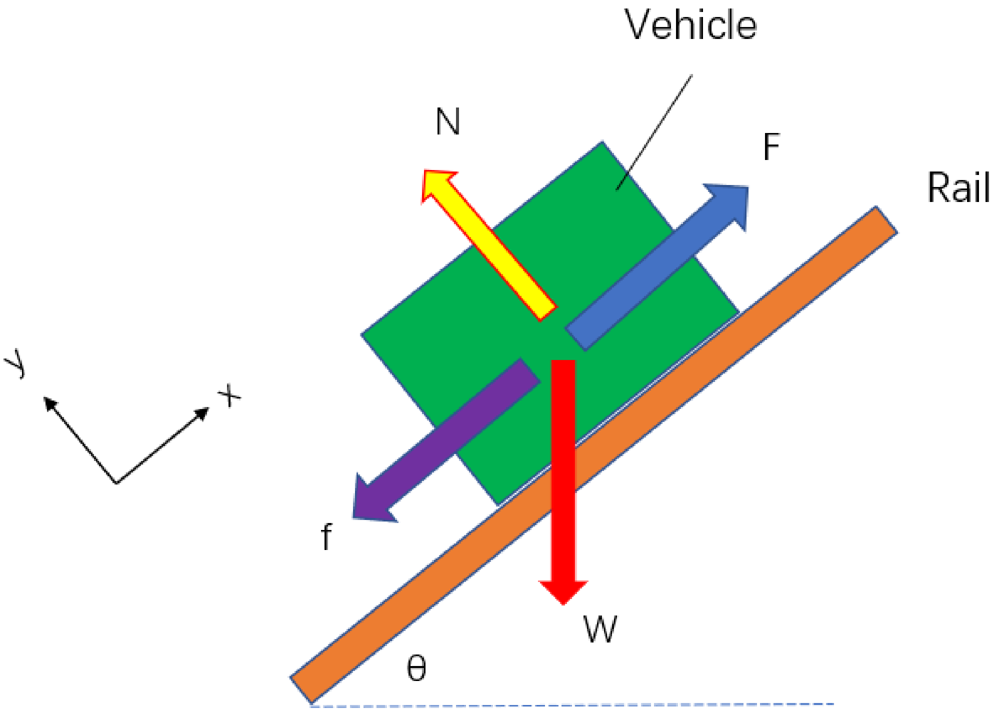


Figure 8: FBD of system static analysis

$f = \mu N$

$\Sigma Fx \ = F - f - mg \cdot cos(\theta) = \ 0$

$\Sigma Fy \ = \ N - W \cdot sin(\theta) \ = 0$

$\Sigma Fx \ = F - 0.2N - 25kg \cdot 9.8 \cdot cos(40) = \ 0$

$$\Sigma Fy = N - 25 \cdot 9.8 \cdot sin(40) = 0$$

From the equations above, we can get:

N = 157.5N

f = 31.5N

F = 219.2N

A safety factor of 2 is assumed in our circumstances, so through static analysis, if the vehicle is assumed to be operated in a static or constant linear motion, the force produced by our selected motor should not be less than 438.4 N(Newtons).

System Dynamic Analysis

Besides static analysis, we also considered acceleration when the vehicle starts moving upward. The designed moving speed of our vehicle is 20 cm/s, and we assumed that it takes 1 second for the vehicle to reach that speed and then move at a constant velocity. In that case, the average acceleration within the first second is $20cm/s^2$. Since the initial velocity is zero, then we can estimate that the max acceleration during that period is $0.4m/s^2$. The FBD of system dynamic analysis is shown in Figure 9 below.

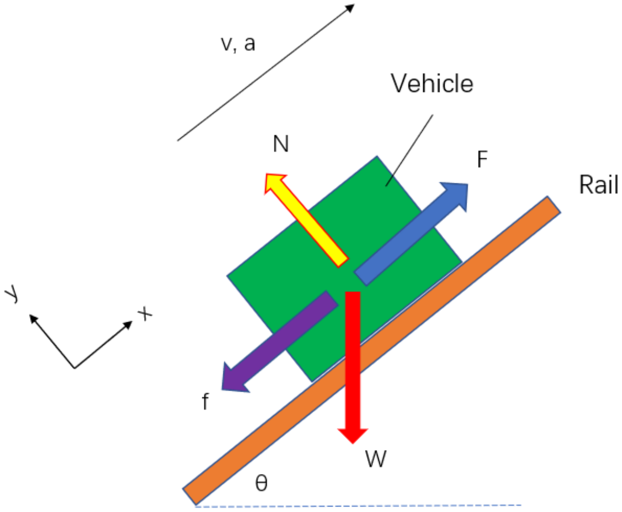


Figure 9: FBD of system dynamic analysis

$f = \mu N$

$\Sigma Fx = F - f - mg \cdot cos(\theta) = ma$

$\Sigma Fy = N - W \cdot sin(\theta) = 0$

$\Sigma Fx = F - 0.2N - 25kg \cdot 9.8 \cdot cos(40) = 25 \cdot 0.4m/s^2$

$\Sigma Fy = N - 25 \cdot 9.8 \cdot sin(40) = 0$

From the equations above, we can get:

N = 157.5N

f = 31.5N

F = 229.2N

A safety factor of 2 is assumed in our circumstances, so through static analysis, if the vehicle is assumed to be operated in a static or constant linear motion, the force produced by our selected motor should not be less than 458.4N.

Power System Components Selection and Torque Calculation

Through the previous static and dynamic calculation, we found that the required force to power the vehicle is $458.4N$. The next step of the design process is to select the power transmission components, which mainly includes motor selection and gearbox selection. We need to ensure that both designated speed and force requirements can be satisfied. We decided to use a rack and pinion to transmit the power from our power source to move the vehicle. Due to the constraints of size of rack, the way to install the rail, and the mounting method of the pinion gear, we firstly selected the rack and pinion gear as shown in the Figure 10 below.

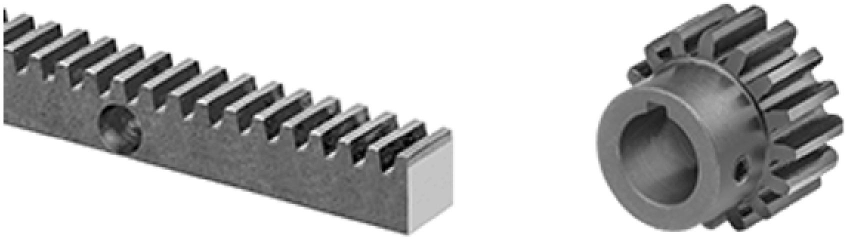


Figure 10: Selected rack and pinion gear

The rack can be mounted through horizontal set screws into the groove of our rail extrusion, and the pinion gear would be mounted with keyed bore and set screw. The pitch of the rack and pinion is 16 with a pitch diameter of 0.875inch (22.2mm). In that case, we can calculate the minimum output torque is $T_a = F \cdot r = 458.4N \times 1.1cm = 51.9kg \cdot cm$.

We selected a 37Dx68L (Figure 11) motor manufactured by Pololu with a no-load speed of 330 RPM and stall torque of 14 $kg \cdot cm$. With the motor performance figure provided by Pololu (Figure 12), we assumed that the motor is operated at its max power 12W with 7.2$kg \cdot cm$ torque and 160 RPM.

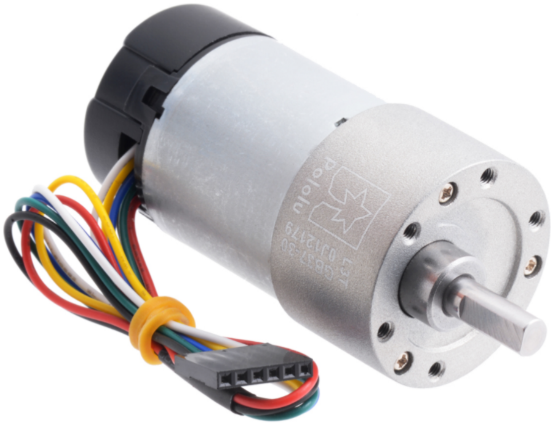


Figure 11: Pololu 37Dx68L motor

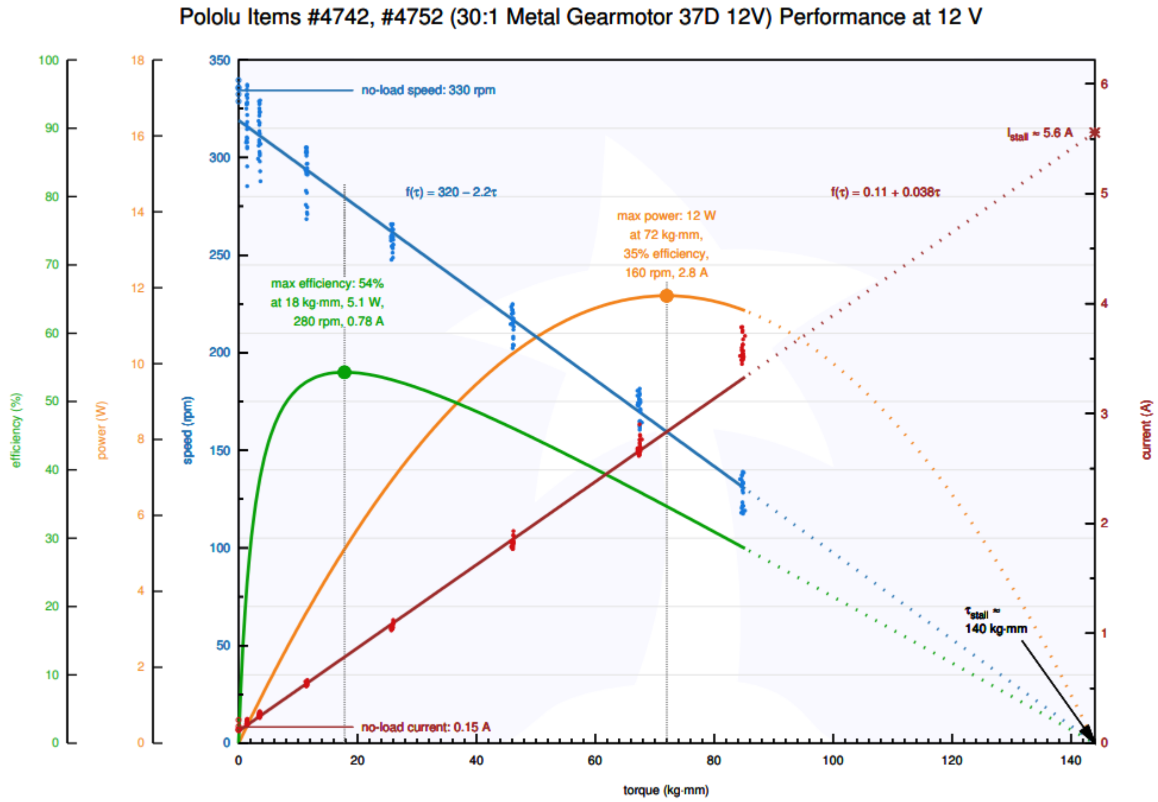


Figure 12: Motor performance diagram of motor 37Dx68L

We also selected worm gear sets (Figure 13) from SERVOCITY. This gear set has a ratio of 27:1. The main reason we selected worm gear instead of spur gears is because of the self-locking property. With that property, the transmission system can ensure that the vehicle would not slip back if the power is suddenly cut off.

Figure 13: SERVOCITY worm gear set

With that said, if we assume the transmission efficiency is 75% between worm gears, and the dynamic efficiency loss due to the velocity difference between the two motors is 90%, our actual output torque would be $T_{actual} = 27 \cdot 7.2kg \cdot cm \cdot 2 \cdot 75\% \cdot 90\% = 233kg \cdot cm$, which satisfies our torque requirement.

Linear Actuator Selection and Calculation

Since our prototype is mainly a proof of concept, we selected the linear motor first and then calculated the weight we could lift and change. Dynamic analysis was performed to calculate the weight of load. Due to the structure constraints, the angle range of our current design is 19.5 degree to 40 degree. Since at the smallest angle, the linear actuator would bear the largest force, we perform the analysis at the smallest stair angle. The wood plate is assumed to be a rigid body, and the weight of the wood plate is neglected. $F_p \cdot sin(19.5) = mg$, $F_p = 440N$

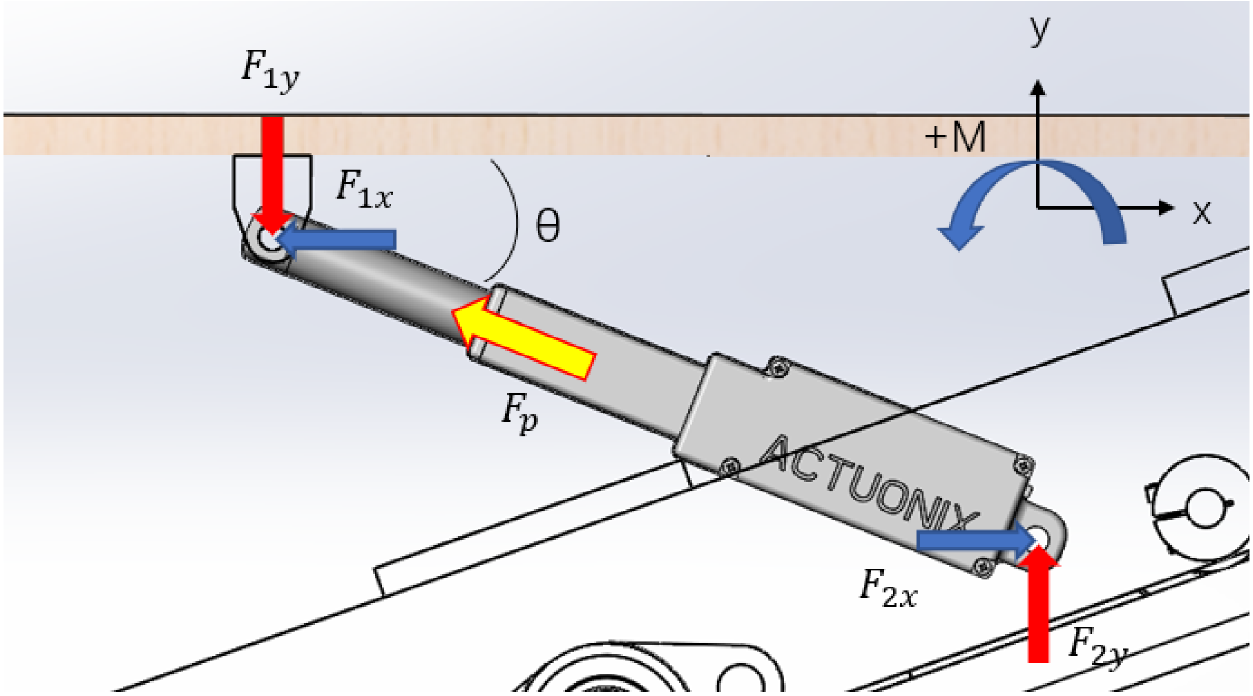


Figure 14: Dynamic Analysis of linear actuator

We selected L12-P Linear Actuator from Actuonix Motion Devices, which can operate at peak power point with a speed of 7mm/s and 310N lift force. We designed to have two linear actuators, one on each side so that our total lift force would be about 620N, which satisfied the minimum force requirement. The linear actuator is shown in Figure 15 below.

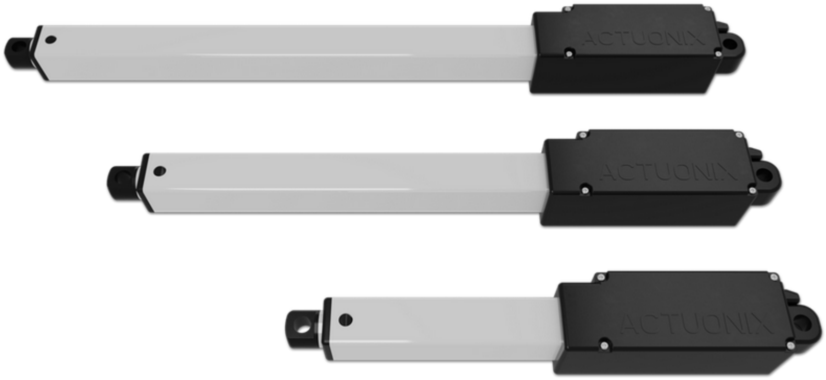


Figure 15: L12-P Linear Actuator

Detailed Static Analysis

After the initial design analysis, we finished our design iteration 1 and made a detailed static analysis of the vehicle. Previously we assumed the load weight to be 15kg to calculate and select the power system, and now we would like to know how much weight the cart could bear in real design. The position of center of mass for both load and vehicle and wheels are estimated as the Figure 16 shown below. The FBD of the detailed design is shown in Figure 17 below.

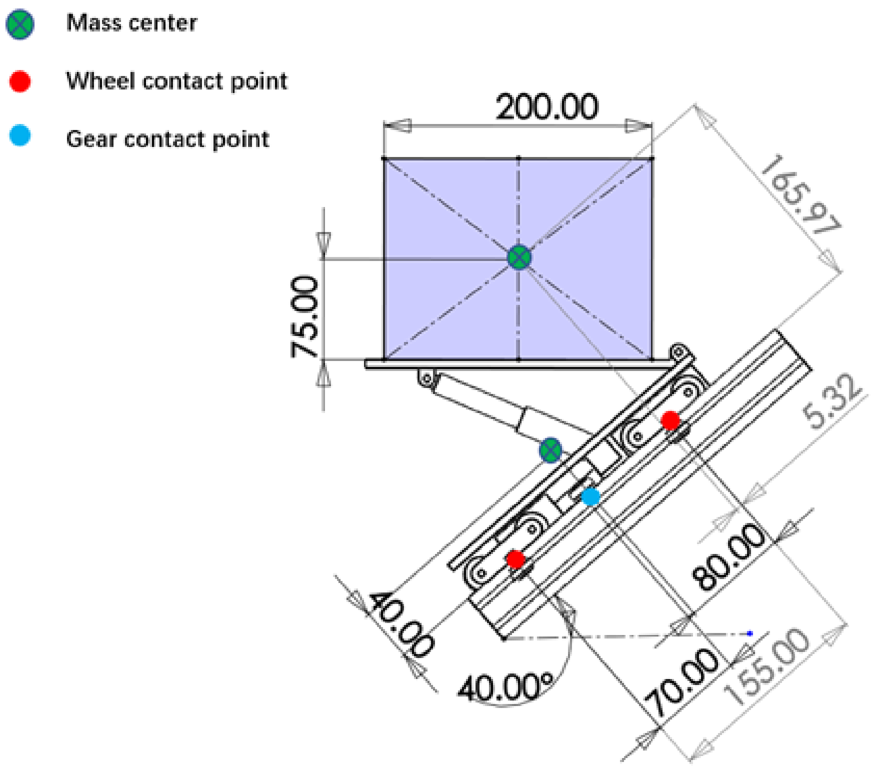


Figure 16: Specifications for the Cart

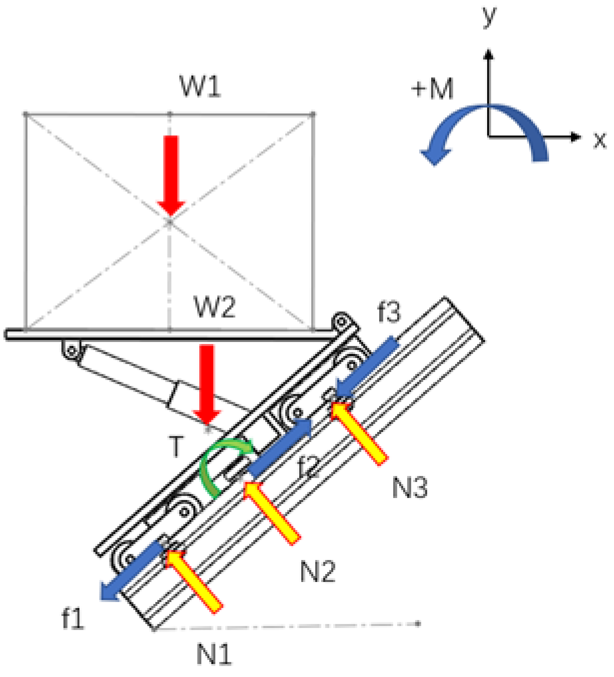


Figure 17: FBD of the Detailed Design

Equations:

$$\Sigma Fx = -N1 \cdot sin(40) - N2 \cdot sin(40) - N3 \cdot sin(40) - f3 \cdot sin(40) - f1 \cdot sin(40) + f2 \cdot sin$$

$$\Sigma Fy = N1 \cdot cos(40) + N2 \cdot cos(40) + N3 \cdot cos(40) + f2 \cdot cos(40) - f3 \cdot cos(40) - f1 \cdot cos(4$$

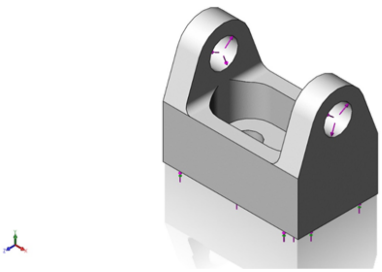
$$\Sigma M_T = W1 * 32.2cm + W2 * 17.3 - T = 0$$

We assume that $N_1 = N_3$, $f_1 = f_3$ to solve the equation above, $T = 233kg \cdot cm$. $W_2 = 10kg$. After plugging these values in the equilibrium equations, we could solve that $W_1 = 46.8kg$, which indicated that our cart could carry about 100lbs load without lifting it.

Stress Analysis

Most parts in our design are either commercial products or metal parts. Those parts are reasonably reliable with a long life cycle. Due to limited processing technology, some parts can only be 3D-printed such as the hinge of the linear actuator support, different types of washers, etc. Some 3D-printed parts could also bear large force. In these cases, stress analysis is necessary while designing these pieces. The properties of the stress analysis of the linear actuator support is shown below.

Table 2. Material Properties of Linear Actuator Support

Model Reference	Properties
	Name: ABS Mass density: $1020kg/m^3$ Tensile Strength: $3 \cdot 10^7 N/m^2$ Elastic modulus: $2 \cdot 10^9 N/m^2$ Poisson's ratio: 0.394 Shear modulus: $3.189 \cdot 10^8 N/m^2$

We assumed that the load was 500N, which is a little over the maximum load we could bear from our calculation, and the same load is applied on the bore face of the connection holes. The bottom flat surface was assumed to be fixed during stress analysis. After these definition, a stress analysis simulation was run in Solidworks, and the simulation results are shown below:

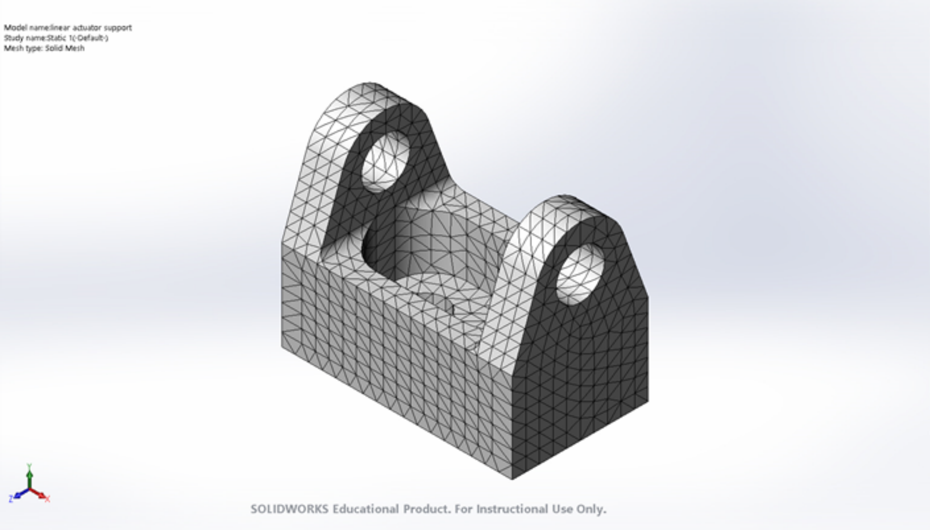


Figure 18: Mesh result of the object

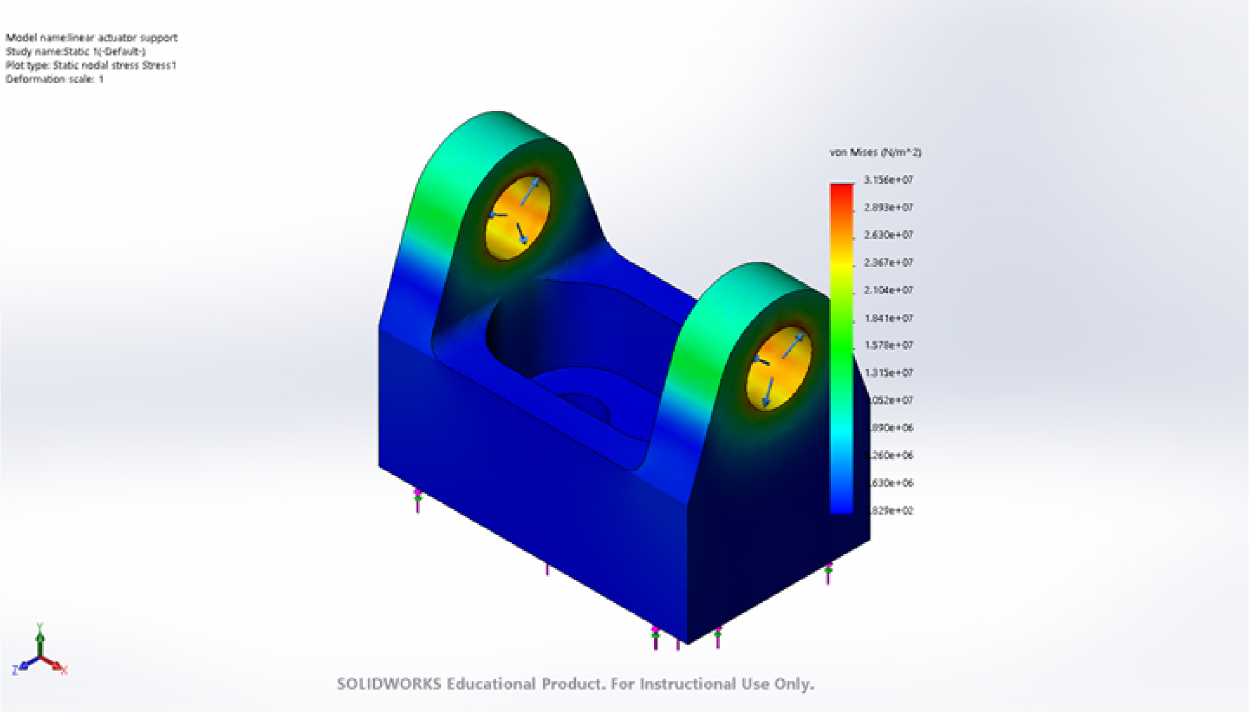


Figure 19: Von Mises result of the test object

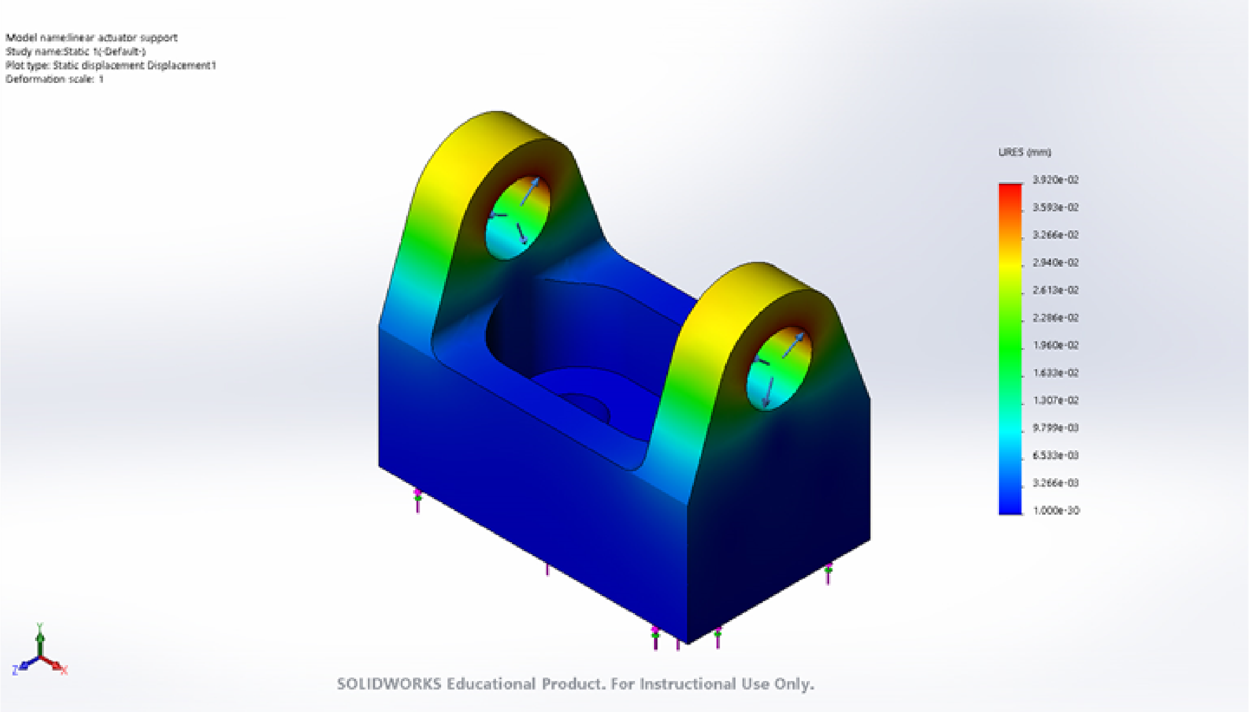


Figure 20: Displacement result of the test object

As we can see from Figure 19 and Figure 20, the maximum von Mises Stress is about $3.156 \cdot 10^{7} N/m^{2}$, and the maximum displacement is about 0.0392 mm, which are both within the safety range.

Rail Design

To satisfy the requirement of easy-to-assemble and portable system, we selected 2020 and 2040 aluminum extrusions profile to form h-shape rail modules (Figure 21 and Figure 22). 2020 aluminum extrusion profiles are mainly used to connect with the lower layer of 2040 profiles at two sides. Two racks are vertically mounted on the upper layer of 2040 profiles. This design mainly considers separating the rail support in the middle and the power transmission system to ensure that they would not conflict with each other.

Figure 21: Front View of the Rail Design

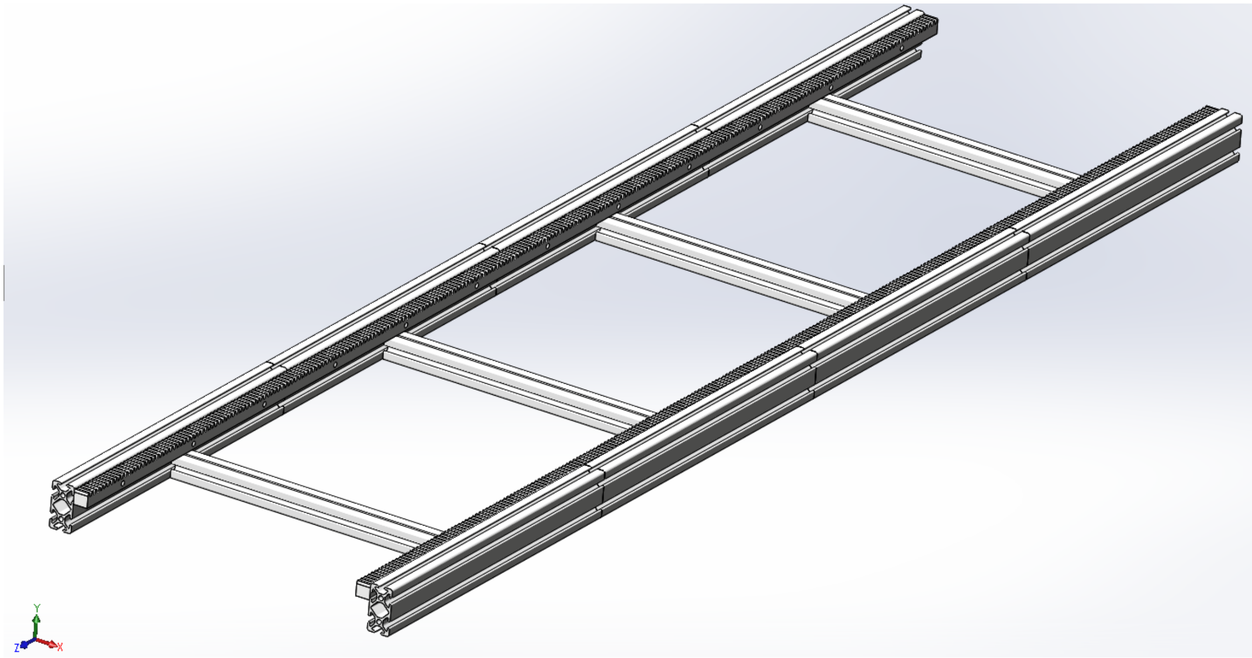


Figure 22: Isometric View of the Rail Design

Electrical Design

Control System Design

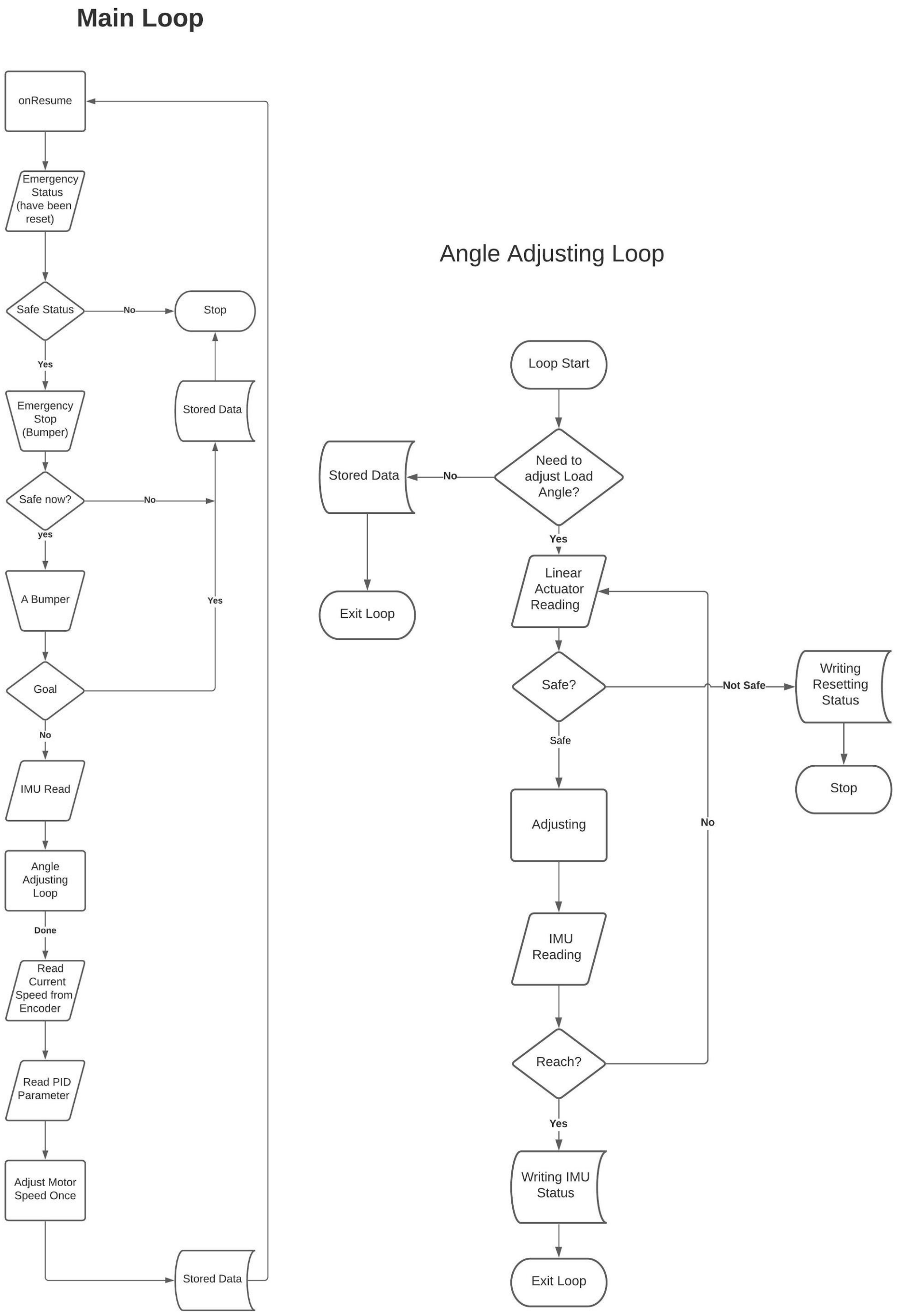


Figure 23: Main Loop and Adjusting Loop of Control System

Based on the lifting system's functionalities and expected user behaviors, the autonomous control cycle was designed. There are two control loops included in this system, which are shown in the pictures above.

The first one is the main loop. In the main loop, the autonomous program checks the safety of the current machine's running status, including whether the emergency status is still activated or the motors get stuck. Then the program will check if the lifting system reaches its goal to determine if the system is going to launch. Next, the program will check the platform status (angle) to see if it needs to be adjusted angle. If so, the program will run into the angle adjusting loop. When the program gets out of the angle adjusting loop, it will read the motor status (velocity, distance run) to modify the motor output based on the preset PID parameters.

The second control loop is the angle adjusting cycle. When the program runs it, the current platform incline status will be read and the linear actuator will continuously level up or down the platform until the platform reaches an angle to keep balance in a safety tolerance.

Electrical Components Selection

Motor Controller

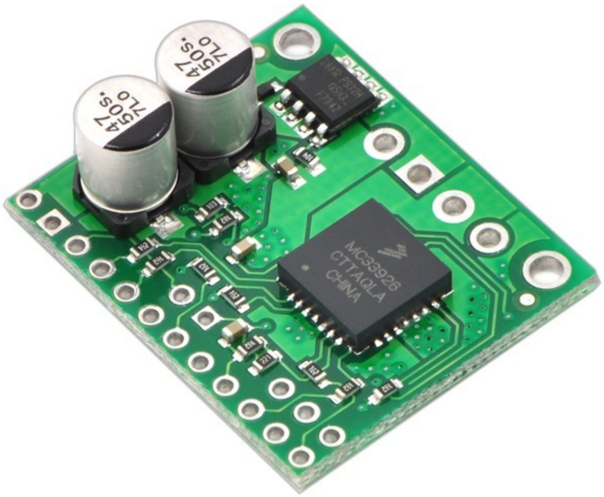


Figure 24: Pololu MC33926 H-Bridge Motor Driver Carrier

From the model calculated in mechanical analysis, two motors (pololu 37D gear motors with 1:27 gear ratio) were determined to be used based on the output requirements for the whole system. This motor provides a 6 pins plug for connection, which allows us to use a motor controller to precisely control the motor revolution. For the motor controller, we selected Pololu MC33926 as the H-Bridge motor drive carrier. This controller allows us to separate the power source and control signal inputs, giving us more options when building the system.

Linear Actuator Controller

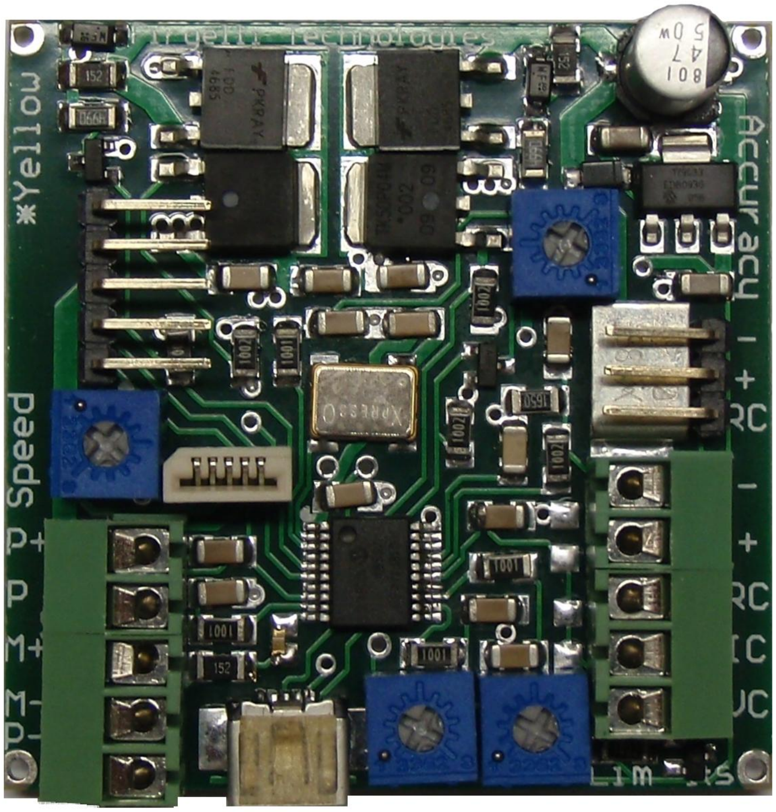


Figure 25: Actuonix LAC

For the linear actuator, actuonix L-12P linear actuator was selected as the support of the load platform. This linear actuator satisfied our output requirements calculated in the mechanical model analysis. It also comes with a controller board which allows us to control the actuator with analog signals.

System controller board

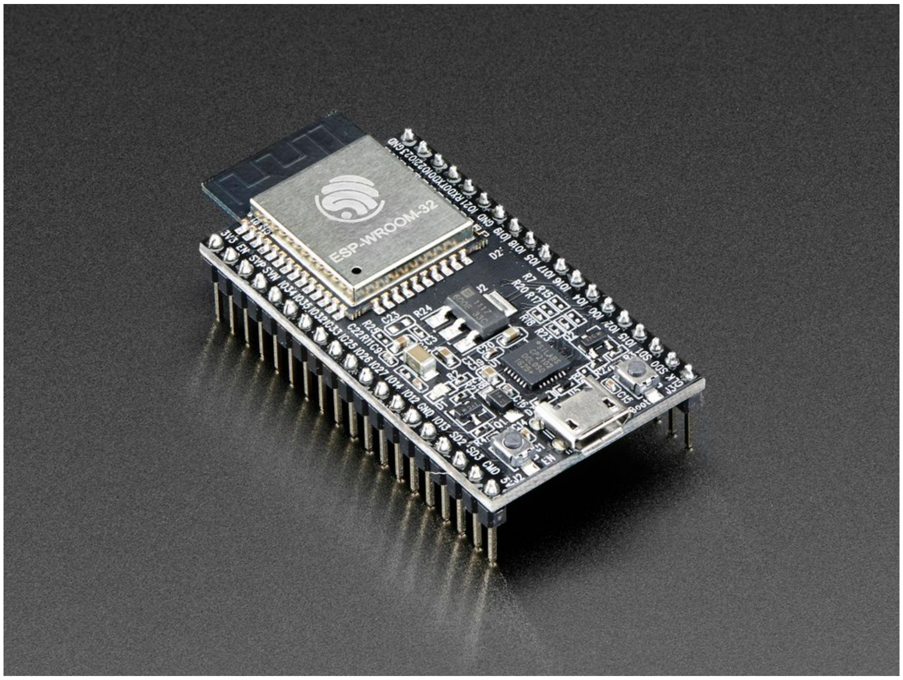


Figure 26: ESP32 Development Board

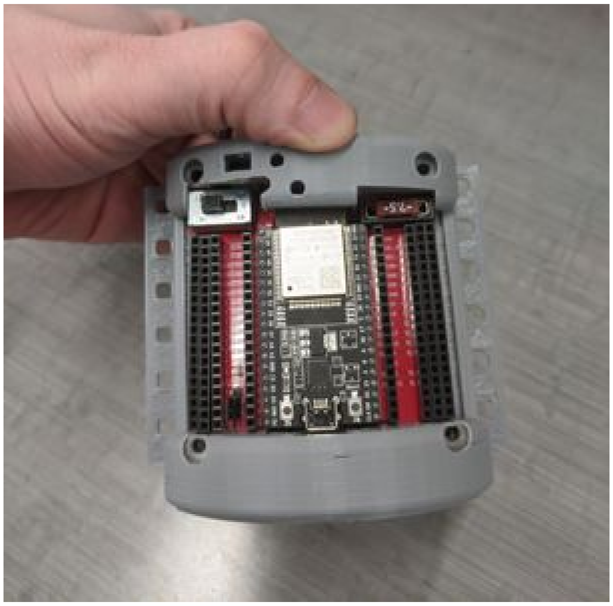


Figure 27: Robot Interface Board from WPI Robotics Lab

For the system controller, ESP32 development board was chosen. Compared to the previous version of electrical design, which is based on the Arduino development board, esp32 is more integrated with more ports and advanced functions. With the interface board developed in WPI Robotics Lab, the controller board can also be assembled with a power system, which is more convenient when adjusting the circuit connections. Also, WPI's RBE200X courses provide a full code library for this controller. This code library was continuously updated in two years (starting from 2019) and has been developed to provide hundreds of functions that could be used to control two-motor cars, which could provide this project an stable and easily deployed code environment.

Other parts

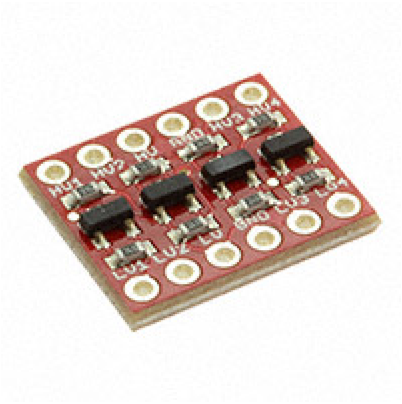
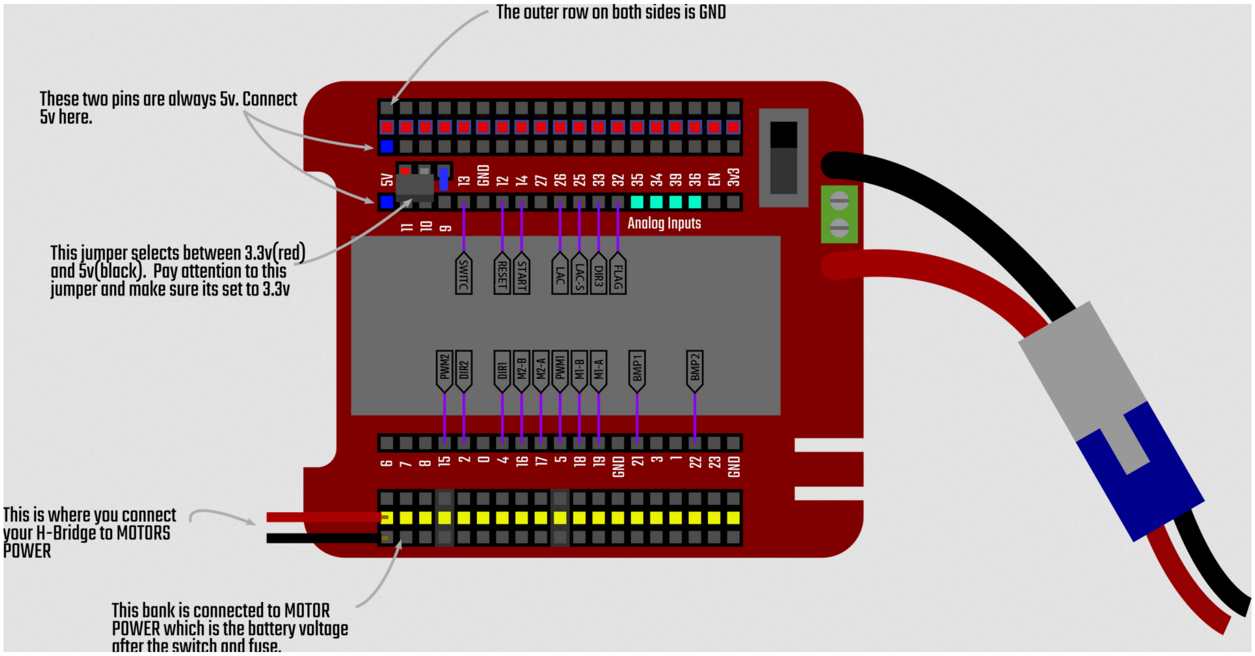


Figure 28: Logic Level Converter - Bi-Direct

Since there is a voltage IO difference between controller board (esp32) and the H-bridge motor controller, a level shifter was also required for circuit connection.

Final circuit design

Colors are used to indicate the type of signal. Purple signals are not voltage rails - their outputs from encoders or inputs to other modules. The colors BLACK, RED, BLUE, and YELLOW are used to indicate VOLTAGE RAILS.



The outer row on both sides is GND

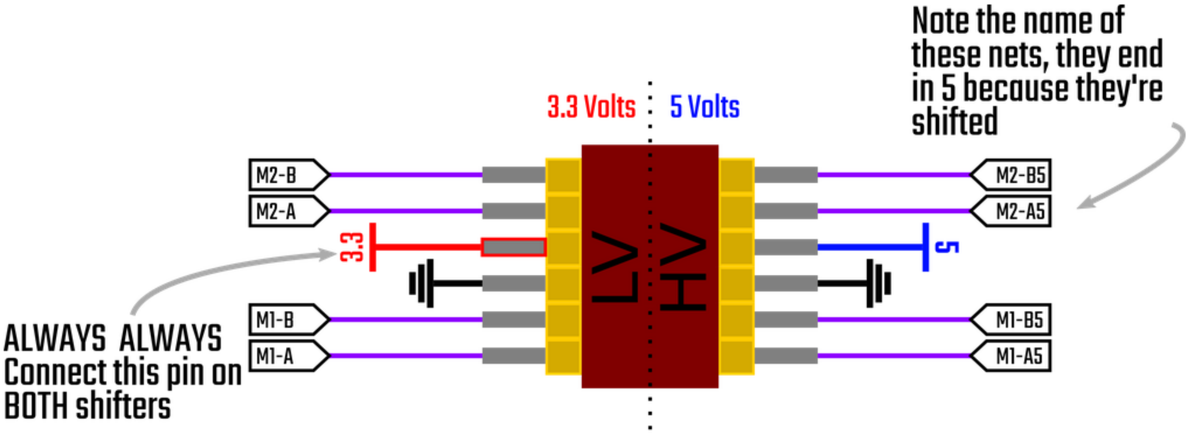
These two pins are always 5v. Connect 5v here.

This jumper selects between 3.3v(red) and 5v(black). Pay attention to this jumper and make sure its set to 3.3v

This is where you connect your H-Bridge to MOTORS POWER

This bank is connected to MOTOR POWER which is the battery voltage after the switch and fuse.

Figure 29: Mainboard Connection



Note the name of these nets, they end in 5 because they're shifted

ALWAYS ALWAYS Connect this pin on BOTH shifters

Figure 30: Level Shifter

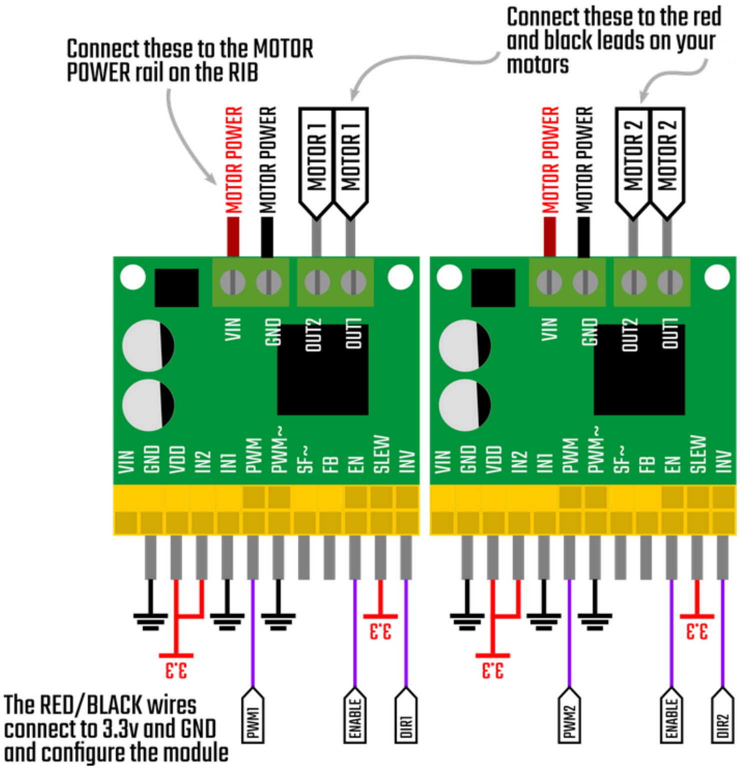


Figure 31: H-bridge Module

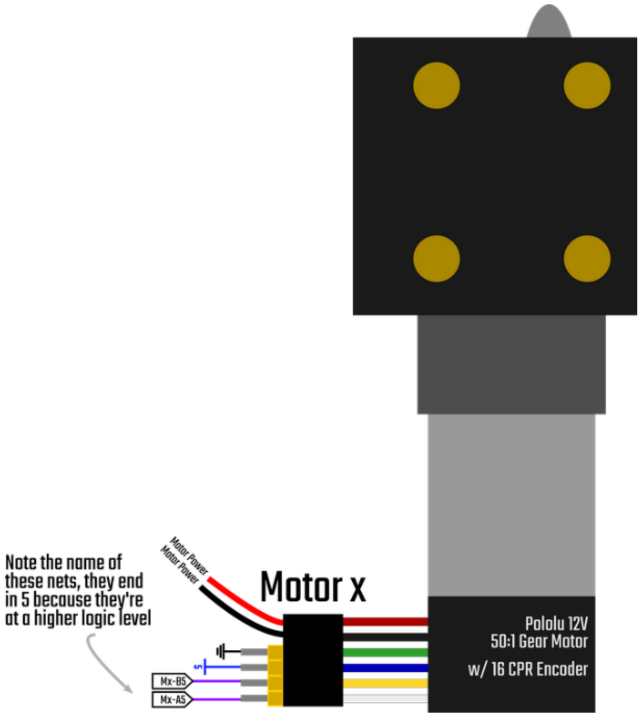


Figure 32: Motor Connection

Final Design Specifications

Here is the technical specifications of our final design:

Net weight: $\approx 9.6kg$
Maximum Load: $\approx 46kg$
Working angle: 19.5 degree to 40 degree
Operating Speed: $\approx 25cm/s$

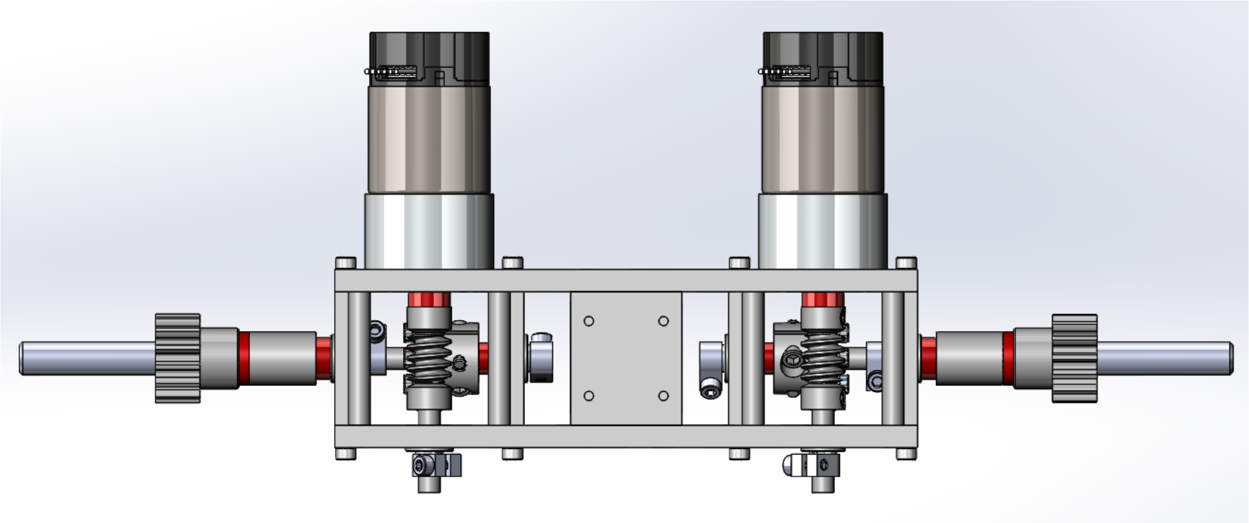


Figure 33: Top view of the motor and power transmission system

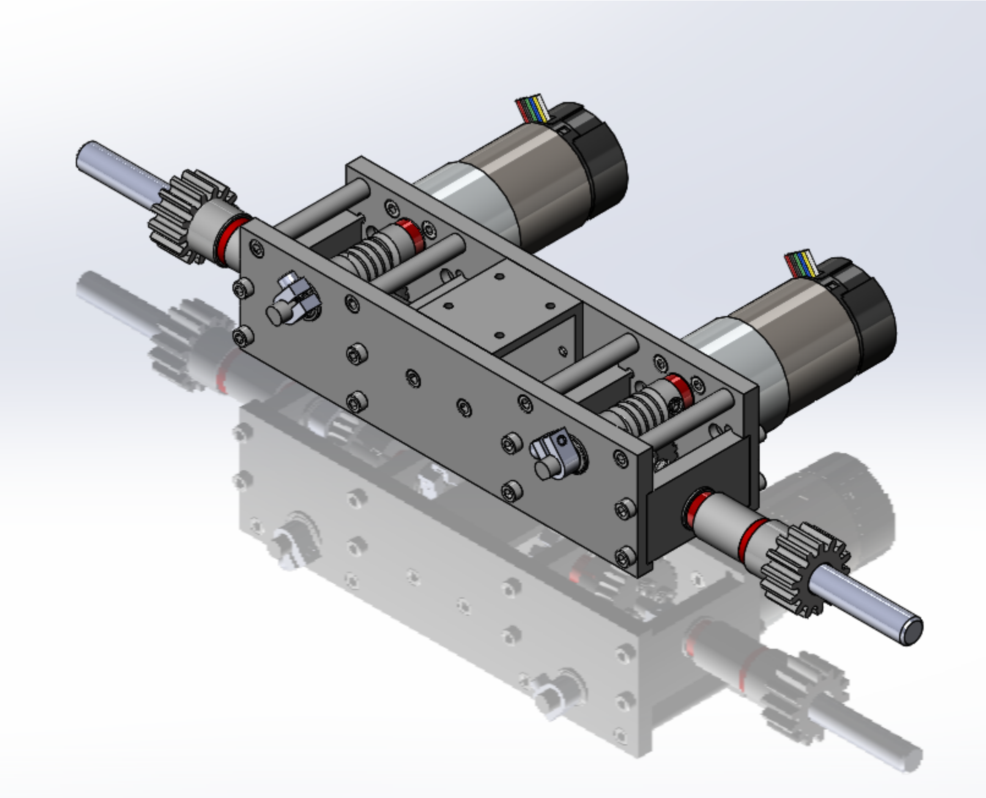


Figure 34: Isometric view of the motor and power transmission system

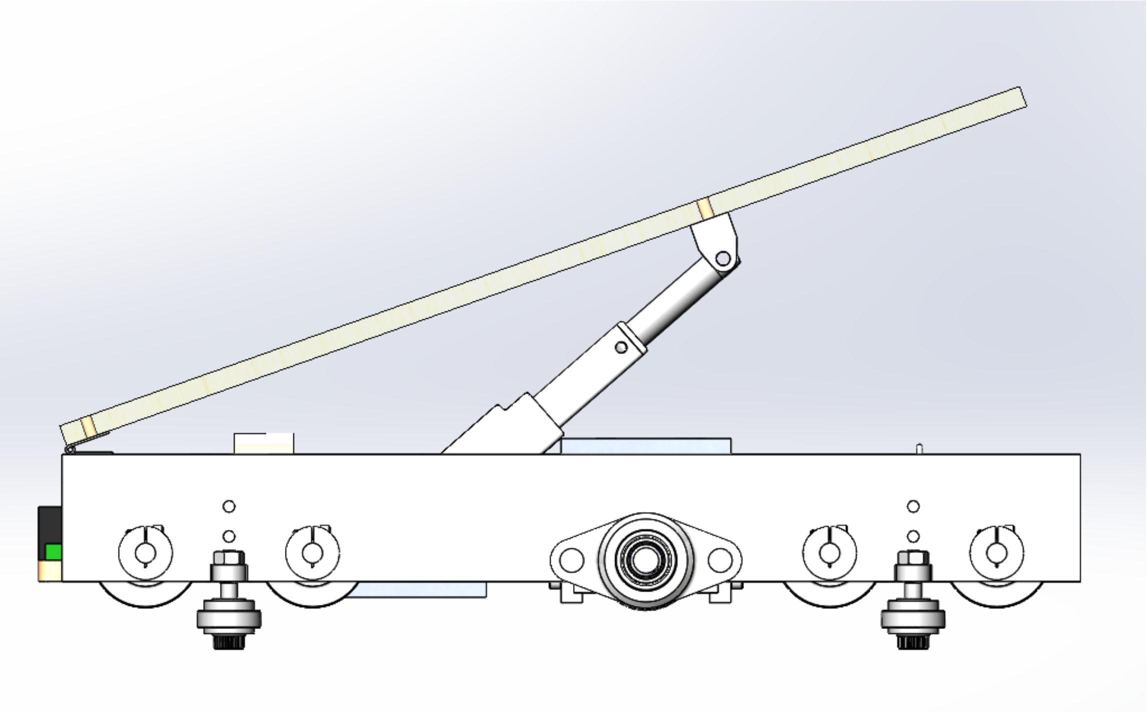


Figure 35: Side view of the vehicle

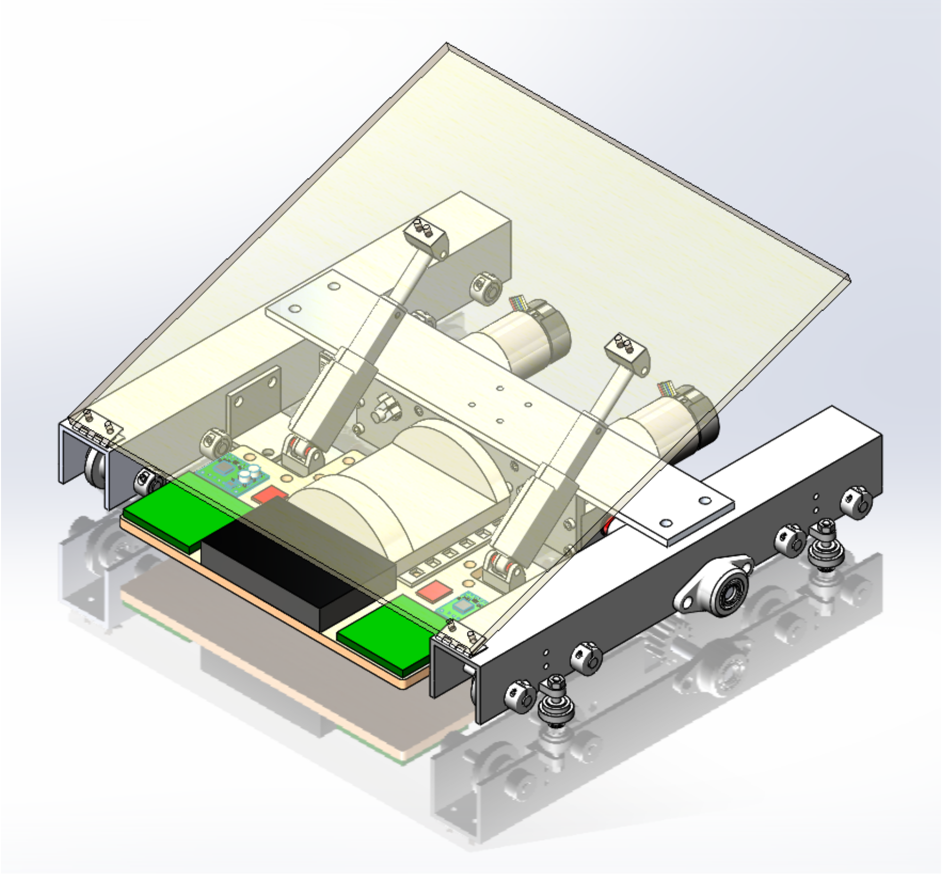


Figure 36: Isometric view of the vehicle

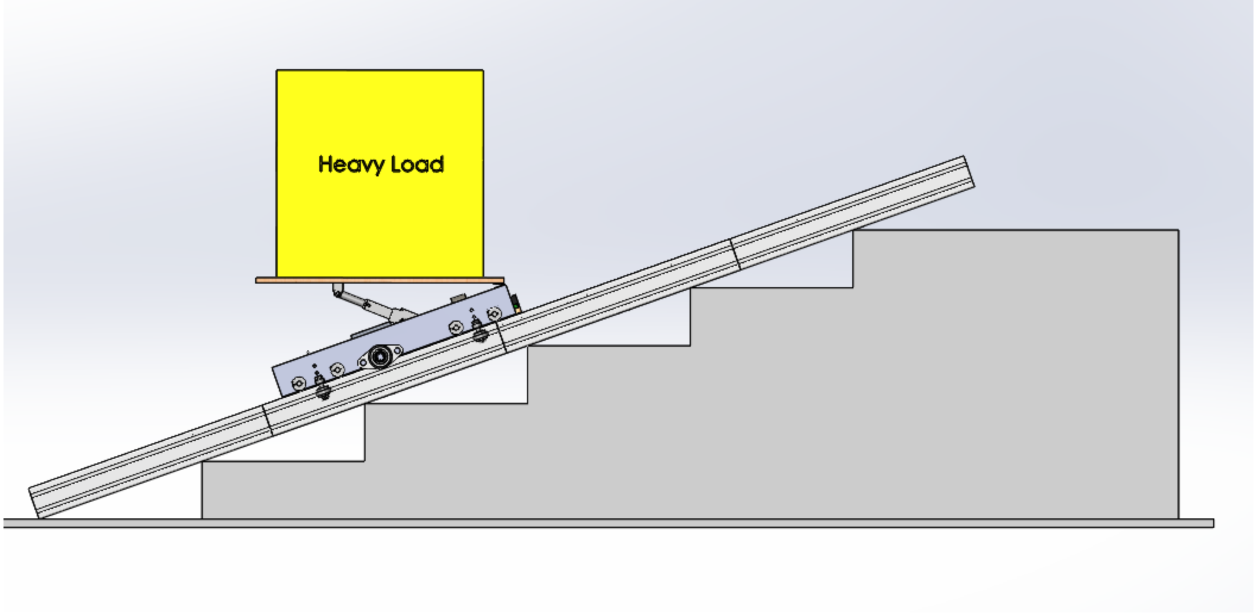


Figure 37: Side view of the working simulation of Portable Stair Lift System

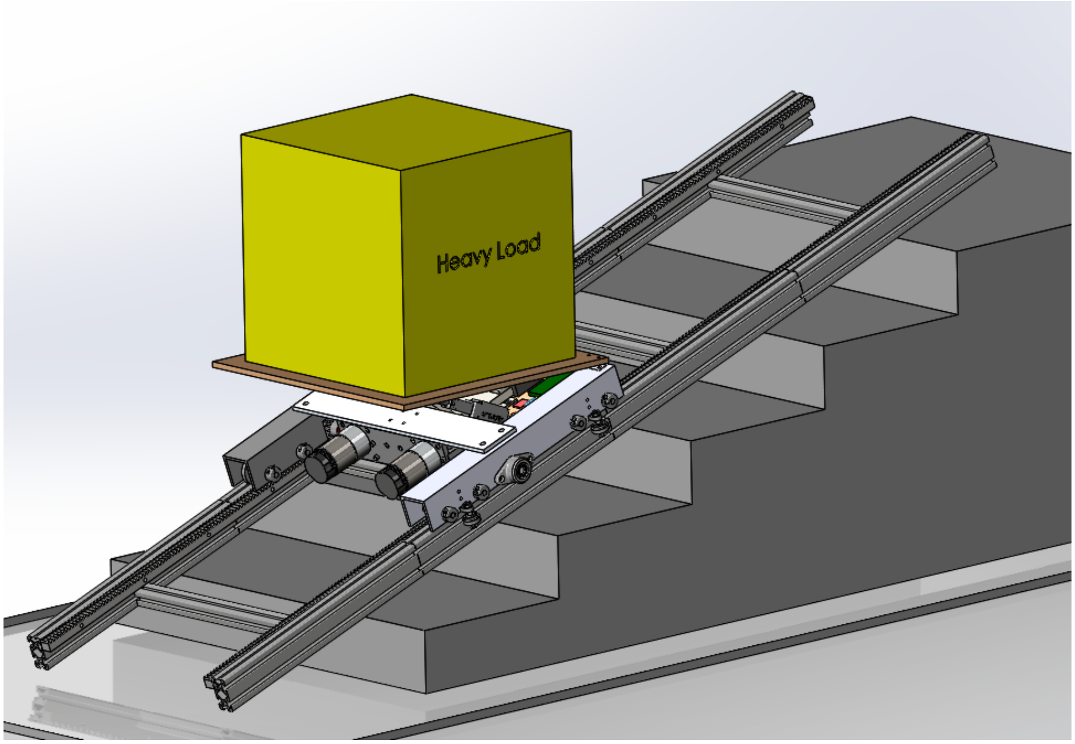


Figure 38: Isometric view of the working simulation of Portable Stair Lift System

Manufacturing and Assembly Process

Rail Manufacturing

We will begin by discussing the manufacturing process of the rail system, seen in Figure 39 below. Later in this section, we will go more in depth about building the primitive cart, as can be seen in Figure 40. To begin the manufacturing process, we have already come up with multiple designs using both CAD software and hand-drawn pictures as mentioned in the previous sections. From these multiple designs, we met as a team throughout C term and narrowed our rail design, down to what is seen in Figure 39.

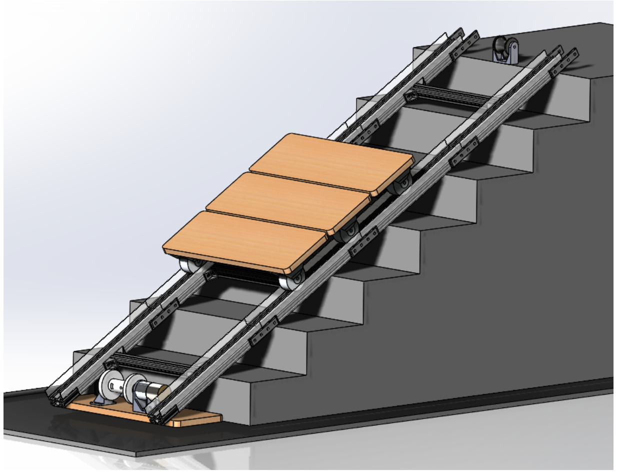


Figure 39: Original Cart and Rail Design from C-term 2020

The primary idea behind this design was multiple individual sections that could be easily linked together in order to form a rail system that met the demands of the stairs that the cart was trying to ascend. To manufacture this rail system, we utilized McMaster-Carr as well as Grainger, both well-known industrial supply companies, to gather the materials, which included sheets of acrylic, small four screw holed brackets, screws, anchors, and extruded aluminum shelf material. To begin, we knew that our cart would need to stay on some sort of track in order to ensure that it would travel in a straight line for the duration of its ascent and not need to be steered or placed back on the track in the event that it fell off. To do this, we laser cut acrylic panels, as seen in Figure 39, which attached at the four holed bracket locations. The idea in this first iteration with the acrylic was that its rigidness would keep the wheels moving completely straightforward. As we later learned, the acrylic proved far too brittle, would easily crack, and often rubbed against the rubber wheels. For this reason in future iterations, we did not continue with this aspect of the design. To cut the acrylic panels to shape, we utilized the Washburn laser cutter to gain precise dimensions and allow us to laser cut holes in the acrylic where it would attach to the rail system in order to avoid drilling through the acrylic, which would have led to cracking and splitting of the delicate material. Once we were able to cut the acrylic panels to the desired dimensions, we moved on to making the aluminum rail modular so the length of it could be adjusted, depending on the number of steps. To do this, we took an 8-foot long piece of extruded aluminum that had our desired cross section, and we cut it down into 1-foot long sections to simulate the modular aspect of the rail if it were to be scaled up to larger dimensions and utilized on a greater number of stairs. Once our 8-foot section was cut to the 1-foot desired length and we had acrylic segments, we took our four holed brackets and anchors and slid the anchors into the channel of the extruded aluminum. Then, we tightened the screws and sandwiched the acrylic panels as well as the four holed brackets on either side, where the 1-foot aluminum rail sections met to form an almost gapless interface between the 1-foot sections of the rail. This can be seen in greater detail in the upper right hand corner of Figure 39, which shows what each side of the rail looks like. Our next concern was securing each side of the rail to the opposite in order to form a sturdy, ladder-like structure that kept its shape and would prevent the two rails from becoming unparallel to one another. In order to do this, we added crossbars on the inside of the rails that used screws and anchors and ninety-degree brackets that fit into the channels of the extruded aluminum and were tightened to prevent slipping of the crossbars. After all these steps, we had a rail system that roughly resembled a 4-foot long aluminum ladder. From here, we mounted the top pulley, as can be seen in the top right of Figure 39, to the end of our rail system. We also mounted our motor and cable reel to the end of the rail system that sat at the bottom of the stairs. With everything tightened and secured, we felt we had a sufficient rail design for the first iteration of our project. From here, we moved on to the manufacturing of our primitive plywood cart design as is seen in Figure 40.

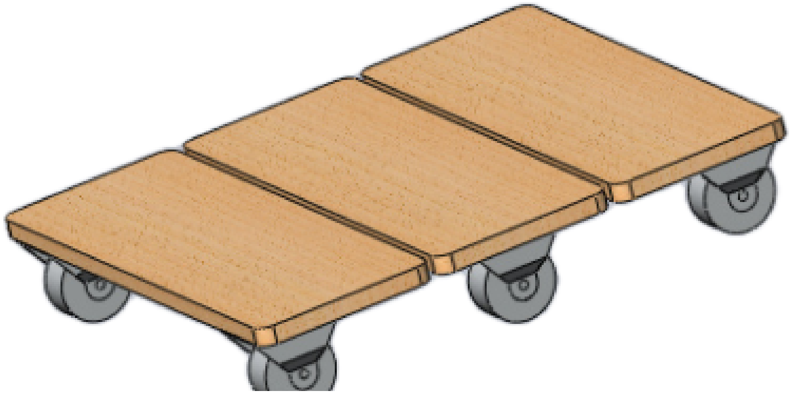


Figure 40: Initial cart system from C term 2020 built from plywood and rubber-coated caster wheels

To manufacture the cart that would sit on our rail, we purchased half-inch birch plywood, quarter-inch screws, and rubber wheeled casters. We knew that our cart would need to be flexible, somewhat like a caterpillar, in order to both mount the inclined stairs as long as dismount them. Because of this, we came up with the idea to cut the plywood into three sections and attach them to one another using hinges. This would allow the cart to flex at the hinges to mount and dismount with more ease. We also chose to use birch plywood because it was somewhat malleable and a very smooth wood that is cheap and readily available. After cutting the three sections seen in Figure 40, we went about mounting the rubber-wheeled casters with screws and pre-drilled holes. We attached one caster to each side of each of the three pieces of wood, as can be seen in Figure 40. Once the casters were mounted and all collinear to one another on each side, we tested the ease by which the casters were able to move within the channel of the aluminum rail system. While by the end of C term 2020 we were able to have the cart sliding inside the channel of the rail system, we found that it did not move with as great an ease as we had hoped and many of the acrylic-dyed rail panels have broken. Due to COVID-19 canceling D term 2020, we were unable to see our first iteration have power to the motor or any working electrical components on our Stair Lift Device. Over the summer, the team worked on the second iteration of our cart and rail system in hopes of improving some of the previous design faults. Despite not being able to see a fully functioning iteration 1, we hope that A term will bring full manufacturing capabilities as well as a greater understanding of how to make our Stair Lift Device more effective and easier to use. In the next academic year we hoped to add professional manufacturing standards to our design and create a prototype more representative of a desired end product. Fall 2020 and Spring 2021 design and manufacturing will be covered in more depth in the following section.

Cart Manufacturing

Throughout A and B terms 2020, our team has been working on a detailed CAD model of the second iteration of the Stair Lift Device. In this iteration, we were able to execute a more robust design that we felt would not only hold a larger testing load but also have a safer and more efficient system for lifting the payload up a set of stairs. However, this more robust design translated into more robust manufacturing requirements and the manufacturing of stronger components in order to make both the cart and rail systems more effective at their task. Many of the components and all manufactured components were made from 6061 aluminum alloy, which was malleable to machine with while still providing sufficient rigidity and strength to support our desired load. Some of the components that were manufactured entirely from scratch included a solid aluminum gearbox for the motors that connected to the powered wheels on the cart, the wheels that supported the load on the cart while staying within their channels, components of the frame, as well as many other parts throughout the cart. In order to do much of this manufacturing, we used machines such as a horizontal bandsaw, vertical bandsaw, drill press, HAAS minimill (Figure 47), HAAS st-10 lathe (Figure 42), and many other power and hand tools. All tools and machines used in manufacturing will be explained in greater detail later in this section. Much of the manufacturing done utilized Washburn Shops on WPI's campus. While COVID restrictions made manufacturing a much greater challenge, our team was able to persist and make substantial progress in enabling our design to come to fruition. Through our experience with last year's Stair Lift Device design, we were able to require less iterations, which enabled us to come up with a final design much faster as well as narrow the scope of the project and consider the hindrances caused by the pandemic. By looking at some of the manufacturing faults in competing devices as well as their design flaws, we had an easier time creating a device that avoided known complications.

Briefly mentioning some of the machines used in our manufacturing process is important in understanding the complexity of manufacturing particular components as well as to illustrate the importance of Washburn Shops to our MQP project. The powered machines such as the vertical bandsaw and drill press were important in putting holes in some of the frame components of the cart, including the U-shaped bracket seen in Figure 41. Using this U-shaped bracket, which was a prefabricated shape, enabled us to not have to create a computer-aided machining operation (CAM). Instead, we cut existing material to length and drilled precise holes in it using the vertical bandsaw and drill press, respectively. On this U-shaped bracket, as well as other components that made up the frame of the cart, using these powerful machines, we were able to produce quality parts that did not require the lengthy CAM process. In order to operate the bandsaw and drill press, one member of the team became a lab monitor to access the Washburn Shops after hours. In this process, he received training on how to properly feed material into these powered machines, as well as set proper speeds for cutting different materials at different thicknesses. Many of these hand-formed components can be seen in more color in the CAD photos from the earlier section.

Figure 41: 6061 aluminum alloy U-shaped cart frame

Once these parts were made, our team moved on to creating parts such as the wheel that supported the weight on the load on the cart, as well as the solid aluminum gearbox. To manufacture the wheels, an st-10 HAAS lathe (Figure 42 & 44) and Esprit CAM software was utilized. The wheel was first designed using SolidWorks and then transferred into the Esprit software, where simulated 2-inch-diameter rod-shaped stock was used to represent the stock material that would be physically in the lathe. A program was then written that used a drill bit to drill the center of the wheel, then a 35-degree cutting insert to create the outer profile of the wheel. The wheel simulation (in Esprit CAM) can be seen in the cutoff step in Figure 43. Lastly, a micro-boring bar was used to widen the dimension of the inner diameter of the wheel to allow for a proper press fit of bearings of the inside of the wheel. The micro-boring bar operation can be seen in greater detail in Figure 43. After many iterations, the wheel was properly toleranced for a precision fit with an accuracy within 0.0005 of an inch. When the team was finally satisfied with the dimension of the wheel, eight wheels were manufactured with bearings press-fitted into either side, as can be seen in Figure 43.


Figure 42: HAAS st-10 Lathe used to manufacture wheel

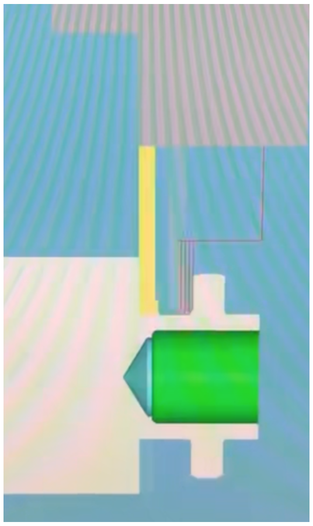


Figure 43: CAM simulation of wheel

Figure 44: Wheel manufacturing in st-10 Lathe

The next parts manufactured were the six components that made up the gearbox for the two motors powering two drive wheels, one on each side of the cart. Once a manufacturable design was created in SolidWorks, the CAD file was transferred over to Esprit, where many operations including facing, contouring, pocketing, and drilling were used to create the holes seen in Figure 45 as well as the shape of the gearbox piece. In order to countersink screw heads that were of a relatively small dimension, 3/16th endmills were used to create small pockets surrounding the larger motor drive shaft hole. Slots were also cut into the aluminum using a 3/8th endmill to allow the walls of the gearbox to sit perfectly perpendicular to the components of the gearbox that held the motors. The tools used to make the gearbox can be seen in greater detail in Figure 9. The stock used to make the gearbox was 2.5 inches in width and 0.75 inches in depth. In making a quarter-inch gearbox, a substantial amount of material had to be removed, which was done using special features such as stock automation from the CAM software. In order to make sure the drill holes lined up perfectly, a 3/8th chamfer mill was used to dent the surface of the stock, which ensured that the drill holes would be in the exact correct location. The remaining pieces of the gearbox assembly were manufactured in a similar fashion with hand-tapped holes making up the wall components of the gearbox. The fully assembled gearbox can be seen in later sections.

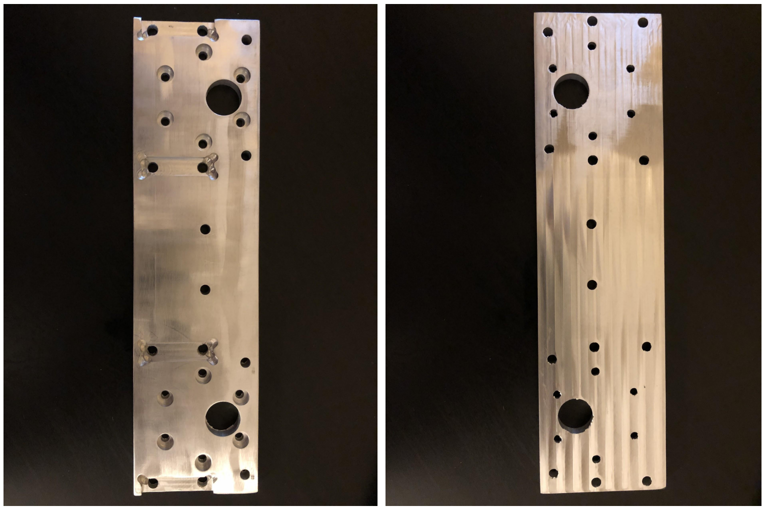


Figure 45: Front and back of main gearbox component

Figure 46: Tools used in minimill (3” Facemill & 3/8th Endmill)

With proper tolerancing and heavy consideration to the precision of the manufactured pieces, we were able to create a final design that had the desired rigidity as well as desired functionality. While some of the pieces could have been manufactured in bulk more precisely and with less waste, the team was somewhat pleased with the quality of the manufactured pieces. In retrospect, the U-shaped brackets manufactured using the vertical bandsaw and drill press could have been made with more precision if done using CAM software. This was not possible, however, because our team was not familiar with manufacturing on the HAAS VM2, which has a larger working area so larger parts can be manufactured. Using proper feeds and speeds for both the minimill and lathe, the team was able to avoid crashing, breaking, or damaging any of the machines in Washburn Shops. While the manufacturing done for the team's Stair Lift System was crude and somewhat wasteful, the potential for this device to be manufactured on a larger scale was proven to be a possibility. Since many components were made in house, the manufacturing capabilities of the team were strongly represented.

Figure 47: HAAS minimill used to manufacturer gearbox components

Conclusion & Recommendation

Due to the urbanization in the US, there is a mass immigration from rural to urban areas. A condominium has become increasingly popular especially among the newer generations, and more people start to consider these small, multi-storey buildings to be their permanent home. Therefore, the demand for moving large and heavy objects through these narrow stairwells has been gradually increasing.

Our Design Project especially serves moving companies and individual families that are moving in or out of a multi-level home, and to ensure that they accomplish this goal safely and efficiently. After two iterations of design, our later prototype became a combination of a robotic cart and a rail, ensuring everyone's safety and efficiency during the process of moving.

As the prototype is being completed, we would like to make a recommendation for potential future iterations of this project. In some cases, the stairwells do not go straight up and down, but have a 90-180º turn. Our prototypes are only designed for direct stairwells, and we hope the future iterations would be able to solve this problem. There can be many different ways to solve this problem, and we look forward to seeing more advancement of the Portable Stair Lift System.

References

[1]Department of Labor logo United Statesdepartment of labor. (n.d.). Retrieved March 17, 2021, from https://www.osha.gov/laws-regs/regulations/standardnumber/1917/1917.120#:~:text=Riser%20height%20shall%20be%20from,shall%20be%20straight%20leading%20edges.&text=Stair%20landings%20shall%20be%20at,(50.8%20cm)%20in%20depth.

[2] Department of Labor logo United Statesdepartment of labor. (n.d.). Retrieved March 17, 2021, from https://www.osha.gov/laws-regs/regulations/standardnumber/1917/1917.120#:~:text=Riser%20height%20shall%20be%20from,shall%20be%20straight%20leading%20edges.&text=Stair%20landings%20shall%20be%20at,(50.8%20cm)%20in%20depth.

[3]What is a Stair Robot ® ?stair climber machines. (2019, February 25). Retrieved March 17, 2021, from https://stairrobot.com/en/

Appendixes

Appendix 1 Bill of Materials of Self-powered Vehicle

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Wheel Design_5537T705.STEP	driven wheels	8
2	grainger-49de49.STEP	mounted screw of shaft collars	16
3	U Channel updated 121.STEP	U-shape Aluminum extrusion of the main chassis	1
4	wheel shaft.STEP	shaft of driven wheels	4
5	SHAFT COLLAR_9506T3.STEP	shaft collars of driven wheels	16
6	ALUMINUM T-SLOTTED FRAMING EXTRUSION_5537T353.STEP	T-slotted framing extrusion	4
7	STEEL HEX NUT_90592A095.STEP	Nuts to fix side wheels	4
8	SHOULDER SCREW_91273A796.STEP	Shoulder screw of side wheels	4
9	sidewheel connector 121	3D-printed structure	4
10	2820T35	mounted sleeve bearing	2
11	L shape fixture	connection parts of main chassis	2
12	1603A23	hinge	2
13	side chassis	/	1
14	wheel single shaft	shaft of driving wheels	4
15	center bar 2	center bar of chassis (short)	1

16	center bar	center bar of chassis (long)	1
17	37d-gearmotor-19-30-encoder	gearmotor	2
18	test motor mount plate	left side wall of gearbox	1
19	0.25in shaft 1in length	short shaft in gearbox	2
20	0.25in shaft 2in length	long shaft in gearbox	2
21	test motor mount plate 2	right side wall of gearbox	4
22	633140	Round aluminum standoff of gearbox	4
23	test motor mount plate 3	support plate of gearbox	1
24	625102 assembly	Flanged Aluminum Clamp Collar	6
25	535198	Flanged ball bearing	8
26	91290A111	Socket head screws	8
27	90128A144	Alloy socket head screws	28
28	motor collar	/	4
29	motor collar 2	/	2
30	625114 assembly	Set screw shaft coupler	2
31	8632T133	D-profile shaft	2
32	pinion collar	/	2
33	6867K39	pionion gear	2
34	aluminum tube	aluminum tube of main chassis	1
35	545694.STEP	barrel hub for worm gear	2

36	545694 screw_91864A024.STEP	screws for barrel bubs	4
37	632108_90128A121.STEP	Scoket head Machine Screw	8
38	615464	27 Tooth Brass Hub Mount Worm Gear	2
39	controller plate	ESP32 Development Board	1
40	electric plate	Wood plate for mounting elelctric components	1
41	mc33926-motor-driver-carrier	linear motor driver controller	2
42	logic level	Bi-direct logic level converter	2
43	linear actuator controller board	/	2
44	battery pack	battery	1
45	linear actuator support	3D-printed structure	4
46	linear actuator coupler	3D-printed structure	4
47	1603A23	hinge	2
48	wood plate	wood plate to hold load	1
49	linear actuator coupler2	3D-printed structure	4
50	EXTENSION_10403_30MM.stp	/	2
51	CLAMSHELL_BOT_10417.stp	/	2
52	CLAMSHELL_TOP_10416.stp	/	2
53	FASTENER_10427.stp	/	16
54	CLAMSHELL_BOT_10654.stp	/	2

55	CLAMSHELL_TOP_10653.stp	/	2
56	GUIDE_10429.stp	/	2
57	NUT_10419.stp	/	2
58	SHAFT_10408_30MM.stp	/	2
59	PLUG_10428.stp	/	2
60	GROMMET_3_HOLE.stp	/	4
Notes: 1. Not all type of screws are included in this table 2. Add-on structures are not included in this table			