Rock-slide: Developing an Indoor Climbing Volume with a Linearly Actuating Hold

A Technical Report submitted to the Department of Mechanical and Aerospace Engineering

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Background/Introduction

Indoor climbing gyms developed as a way to supplement the ultimate goal of climbing outdoor routes. Since these gyms serve the purpose of being a place to train on a regular basis, there are a number of devices that emerged to improve the training experience. Static training devices such as hangboards and campus boards evolved to help train aspects of grip strength and explosive upper body strength. Hangboards act similarly to a pull-up bar using an array of holds of varying depths to train finger strength by performing dead-hangs, pull-ups, or various other exercises. Campus boards are training devices in the form of a ladder of holds, typically wooden rungs, designed to train vertical moves without using one's feet. Additionally, in recent years small climbing walls have been developed with integrated light emitting diode (LED) systems. Using a smartphone app, LEDs under each hold will light indicating to the climber which holds are in play for a selected route. These walls are standardized, and thus routes that any user sets can be shared across the world.

The goal of this project was to develop a new product that can be in any indoor climbing gym that would bring an aspect to climbing unseen in any other existing device.

Design

Design Criteria

Indoor rock climbing developed as a way to replicate climbing outdoors for training purposes but over time has become a distinct form of the sport. Climbing gyms have become increasingly popular, the number of climbing gyms in the United States has more than doubled in the last decade (Climbing Business Journal, 2021). Outdoor climbing requires a certain measure of skill and may be intimidating to beginners, while indoor gyms offer an accessible entry point to new climbers. Climbing gyms provide a safer experience with padded mats allowing for cushioned falls and a lower barrier of entry by allowing customers to rent shoes and equipment. As indoor climbing continues to grow it has evolved into a separate entity from outdoor rock climbing. Different skill sets are developed climbing on indoor walls than those learned at an outdoor climbing area, and outdoor climbing requires considerably more equipment along with the skill to employ it safely. As indoor climbing further deviates from traditional mountaineering, an opportunity has been identified to develop a novel technology that provides fun, challenging boulder problems within indoor gyms which do not resemble boulders found in nature.

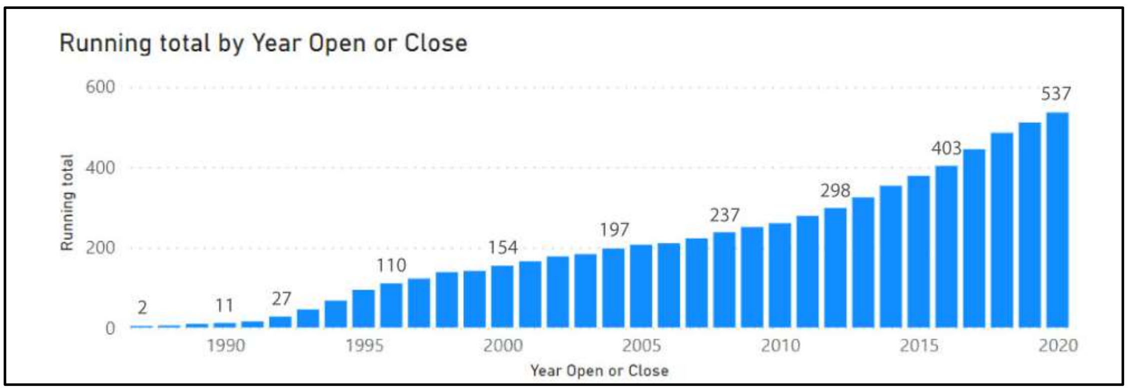

Figure 1: Total Count of Climbing Gyms in the United States (Climbing Business Journal, 2021)

The team felt uniquely positioned to enter this design space. Having members of the climbing community on our design team granted us insight into client needs for the final product. Four of the six team members are avid rock climbers themselves, including one member with extensive experience creating bouldering routes.

The design was to focus on climbers who used the climbing center within Slaughter recreation center at the University of Virginia. The people who use this gym are diverse, ranging from lifelong climbers to curious first timers. In order to guide the design, the following list of customer needs was generated.

Number	Need	Importance (1-5)
1	Offers unique experience	4
2	Integrates into established gym environment	3
3	Product is safe	5
4	Rewarding to engage with	5

Table 1: Customer Needs

Due to the existence of already established training boards such as the tension board, the team prioritized novelty as a key requirement for the final design. The final product would need to set itself apart from any previously existing technology and offer an experience which climbers had not experienced before. Ideally, this design would provide a novel experience for both long time climbers while also being accessible to newer and less skilled beginners. Other identified customer needs included the product integrating well into an established gym environment and the product being rewarding to engage with. If the product was out of place in the climbing gym it would be less likely to be used by the community. Additionally, the product needed to be rewarding to use either by providing an enjoyable experience or by providing a training experience that helps climbers improve.

Design constraints also played a major role in guiding the design. Three major constraints were identified: Budget, time, and manufacturability. The project had an overall budget of $900. This was a clear limitation on the resources that could be used to construct the final design as the team would need to be purposeful in its purchases. Additionally, the project had an overall timeline of ten weeks, which limits the amount of testing and iteration which could be performed. Manufacturing was the last major constraint. Any proposed design would need to be able to be manufactured by the team. Rapid prototyping techniques such as 3D printing and acrylic laser cutting were the main manufacturing processes available to the team. Metal fabrication techniques were limited to water jetting, basic machining, and welding.

Ideation

Many ideas were explored at the beginning of the design process. In an effort to promote creativity, no design requirements were initially specified. Instead, free flowing group discussions were held in which team members were encouraged to share any and all ideas that could lead to a novel innovation for indoor bouldering.

In this discussion the team focused on design innovations for a climbing wall that could be used for training. In order to distinguish a potential new training wall from existing competitors such as the Tension Board, features such as rotation holds, moving holds, and the ability to retract holds were proposed. Novel uses for these features were also discussed including enabling the board to replicate outdoor routes, the ability to use the wall to aid route setters, and creating different games which would utilize hold movement to present fun challenges for the user. At the end of the initial brainstorming session three core design ideas with different target clientele were identified: a board which would aid serious climbers in training, a tool which would support and aid route setters, and an entertainment focused board which would provide novel fun for casual climbers.

As the team began to consider design ideas within the context of the prescribed design constraints, the scope of the project was changed. Instead of focusing on building an entire climbing wall which incorporated novel systems the team decided to pursue the creation of a smaller system which could be mounted to an existing bouldering wall. This system would better satisfy the budget constraints of the project and would allow more time to be dedicated to the mechanical systems and their integration rather than the fabrication of the wall itself.

Volumes are large hollow features used in climbing gyms to alter the shape of the wall and are often shared by many routes in bouldering gyms. Volumes used present a unique design opportunity as they alter the features of existing walls and would allow ample room for internal mechanisms. Volumes are also used on the wall in nearly every climbing gym meaning the design would easily integrate into the gym environment. After careful consideration the initial prototype was decided to be a single moveable hold mounted on a constructed volume. Instead of providing an enhanced training avenue for climbers, the volume would instead focus on providing enjoyment to those using it. The design would satisfy the novelty requirement by being able to change a route while a climber is on it, something which is unlike anything offered in a gym currently.

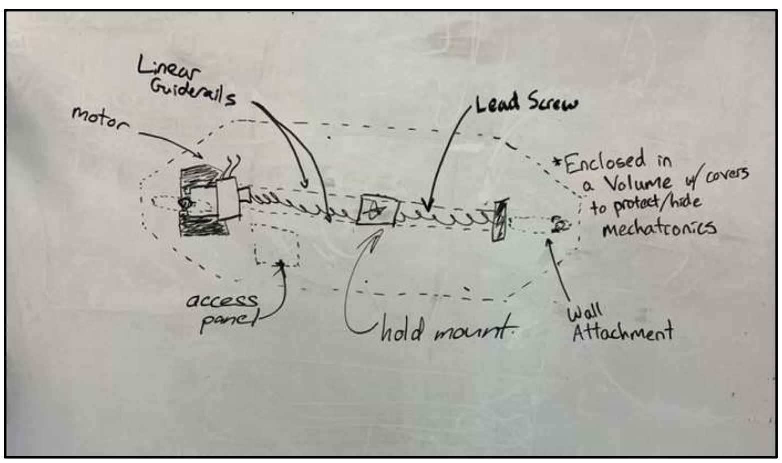

Figure 2: Rough Sketch Depicting Initial Design Concept for Volume System

Initial Prototyping

After the design concept solidified, the team moved on to the prototyping phase. The goal of the first prototype was to provide a proof of concept for the overall design. In order to move the climbing hold, an external leadscrew system was chosen. Connecting a motor to a leadscrew with a carriage allows for linear motion to be achieved. The initial design used a stepper motor-leadscrew assembly acquired from Amazon, which can be seen in Figure 3.

The stepper motor would allow for reliable precision without the need for positional feedback. A linear guide rail ensures smooth movement of the external carriage. Using SolidWorks, a 3D model was created of the entire assembly with the leadscrew system contained within a volume like structure. The final model can be seen in Figure 4. A shaft was designed to connect the climbing hold on the outside of the device, which is able to be screwed into the leadscrew's carriage.

Figures 3 & 4: Prefabricated Leadscrew Assembly (Zeberoxyz); 3D Model of the Initial Design

During the development of the initial prototype concern arose about the possibility of climbers placing their hands in the slot along the front of the design. While climbing, climbers will use anything available to them to make the climb easier, sometimes even placing their fingers in the bolt holes which line the wall in a climbing gym. Because of this, the team was concerned about deliberate placement of climbers' hands in the front slot. The motor was planned to be strong enough to move while supporting the weight of a person so the risk of injury would be high. To address this problem, the team designed a rudimentary belt system that would adjust with the hold to cover the slot on the front of the design. This belt system prevented the user from inserting their hands into the front slot which could result in crushing injuries as the hold moved towards the end of the slot.

Testing and Implementation of Initial Prototype

After finalizing the initial design, it was fabricated using 3D printed ABS plastic and laser cut acrylic parts. Acrylic was used to make the front and back plates of the volume while everything else was made using 3D printed parts. The initial prototype can be seen in Figure 5 below. Testing was performed on the prototype design in order to gain insight into how the final design may work and what changes may need to be made.

Figure 5: Initial Prototype

When testing the initial prototype, it quickly became apparent that the hold mount took a long amount of time to travel the relatively short 200mm distance. This was likely due to the fact that the device was being powered by a relatively small stepper motor. Stepper motors are extremely accurate but are not able to move quickly. As a consequence, the team decided the final prototype needed a different motor in order to generate the speed of linear motion desired.

DC motors are able to provide more torque and speed than a stepper motor using gear systems though they are harder to control precisely. It was decided that this was a necessary tradeoff and a DC brush motor would be used in the final prototype. Additionally, the leadscrew used had a relatively small travel distance per turn due to only having one thread start and having a small pitch. This informed the final prototype design by creating the need for a leadscrew with a large pitch and multiple thread starts. These changes would result in a much larger travel distance per turn and a faster rate of linear travel for the hold mount.

While the initial prototype was an overall success, there were many essential components needed in the final prototype that were not implemented due to size and material constraints. Due to the fact that the final prototype needs to be able to withstand the weight of a human traveling vertically or a climber stepping on one of the edges of the volume, the final prototype needed to have a strong frame. As the initial prototype frame was made of brittle acrylic, our final prototype design needed to have a strong metal frame made out of aluminum.

Furthermore, creation of a SolidWorks model allowed the team to simulate the types of loads that would be expected during climbing. From these simulations it became apparent that the central shaft would bend under load. Two stress concentrations were observed during testing. The first concentration occurred where the shaft presses against the front face slot, and the second concentration occurred where the shaft attaches to the bottom carriage. To address these problems in the final prototype design, linear guide rails were attached to support the shaft where it exits the front face of the volume. These should prevent some of the bending and support some of the areas where the stress was found to be concentrated.

Overall, the initial prototype was a successful proof of concept for the overall mechanism our device would use, and it also informed the final design. Noting the takeaways from testing of the design, the prototype allowed the team to be confident that the concept of the design was solid and such a product could be constructed.

Final Prototype Development

Design Overview

Using what was learned during the initial prototyping phase, the final prototype design was developed using SolidWorks modeling. After initial design, Finite Element Analysis (FEA) was applied to ensure stability throughout the process. The volume is a rectangular pyramid made of an aluminum welded frame covered with plywood sides. Inside the volume, the mechatronic system is mounted to the aluminum framing. A high-torque motor powers the system connected to a leadscrew using a flexible shaft coupling. The leadscrew is supported by two pillow block bearings that are mounted on the aluminum frame. As the motor turns the screw, a carriage is driven along its length. Attached to the carriage is an aluminum shaft which supports the climbing hold on the outside of the volume. Three linear guide rails support the movement of this carriage with one being attached below the leadscrew to facilitate smooth movement and two being attached at the front of the volume to counteract any bending in the shaft when the climber is applying their weight to the hold. At the top of the shaft, the hold is bolted into a tapped hole in the aluminum. The motor will be powered using an 18-volt Milwaukee battery back and is controlled using a programmed Arduino Nano microcontroller. Renderings of the prototype can be seen below in Figures 6, 7, 8, and 9.

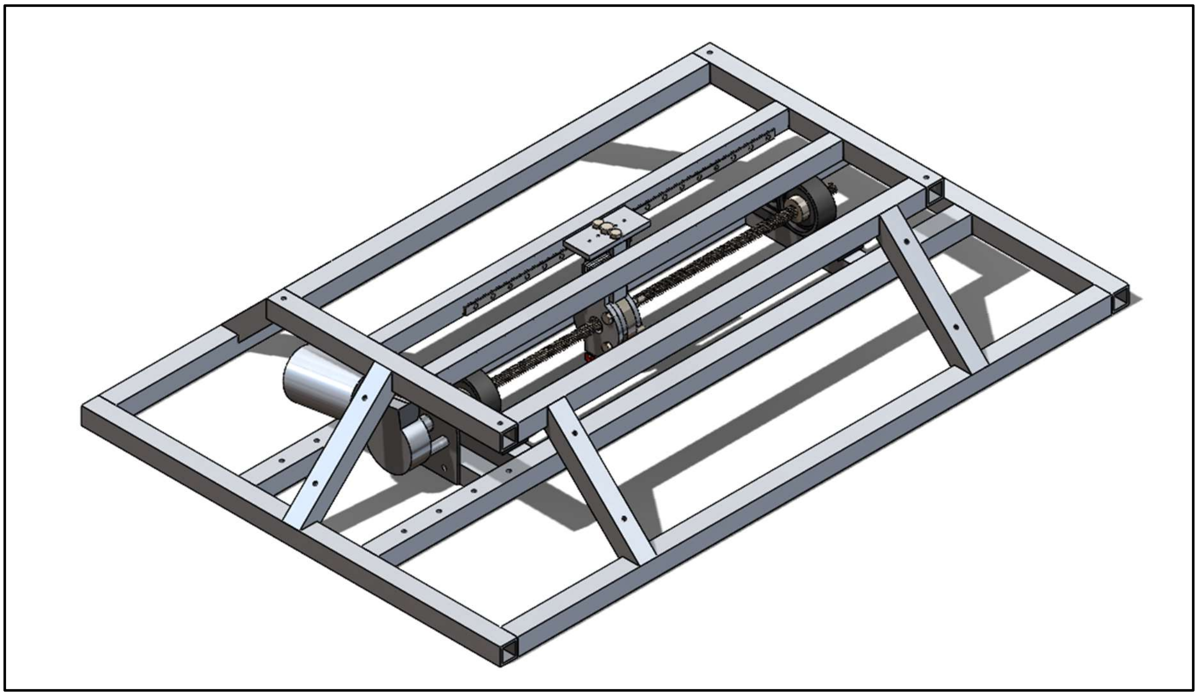

Figure 6: Final Prototype Isometric

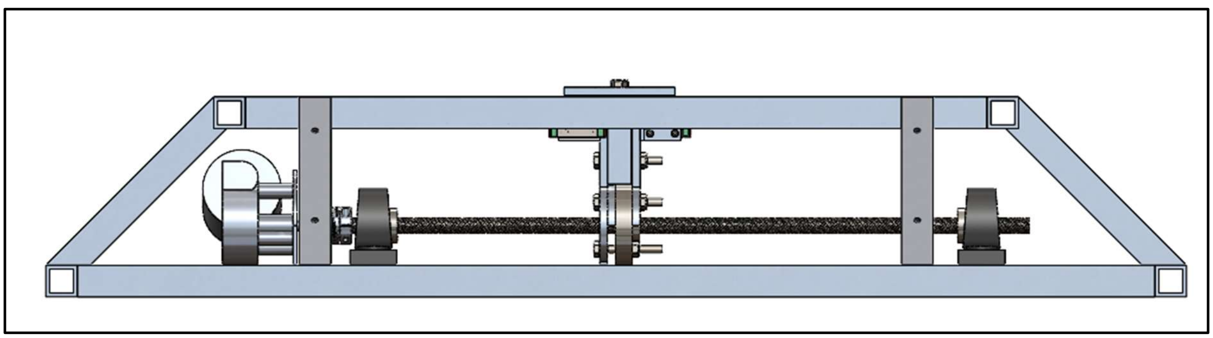

Figure 7: Final Prototype Side View

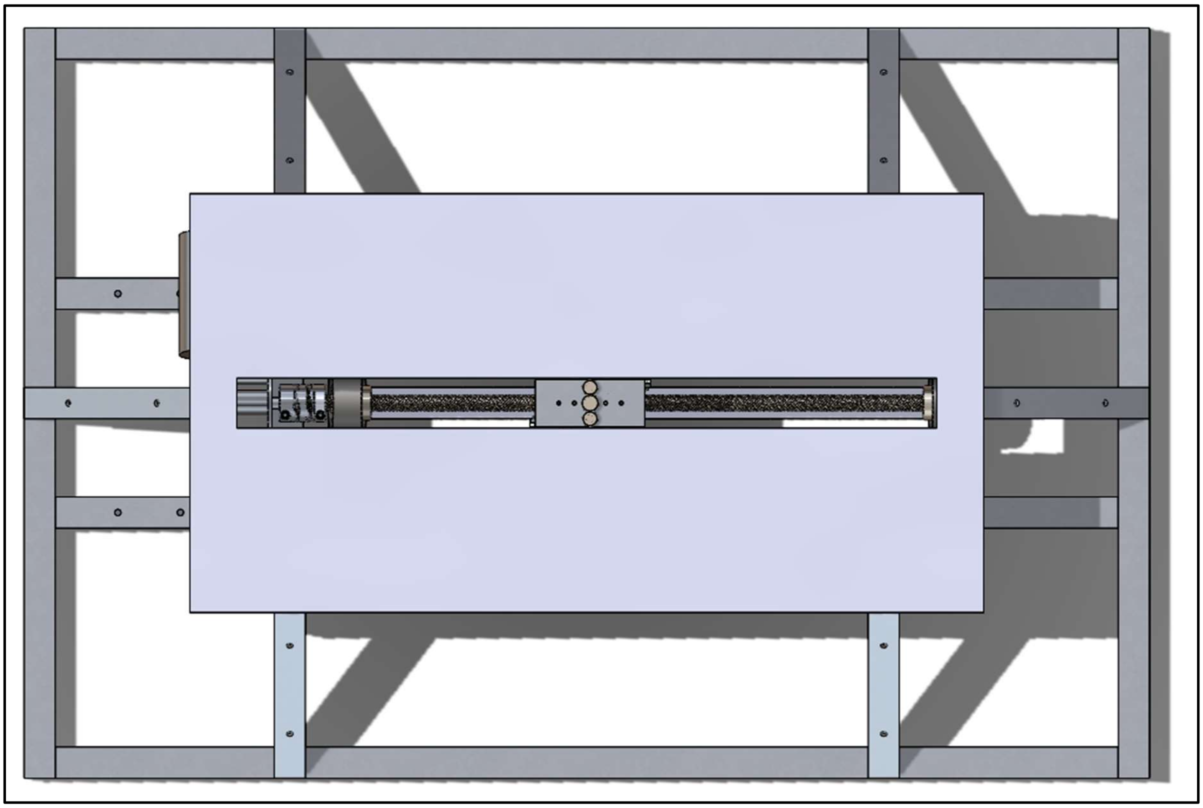

Figure 8: Final Prototype - Top View with Front Plate

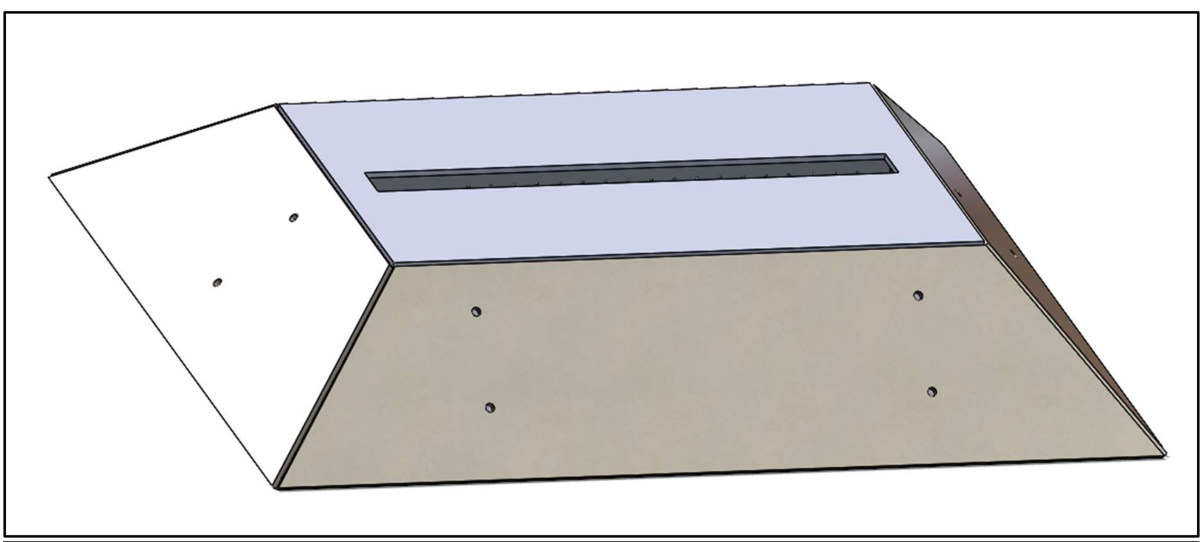

Figure 9: Final Prototype with Side Plates Attached

Design Choices

This project was complex due to the sheer number of mechanical and electrical elements. In order to achieve a realistic design, compromises had to be made. The team determined it was very important that the hold was able to move with a climber hanging from the hold. This meant that a high-torque motor had to be selected. The team also wanted the hold to be able to move quickly across the volume. Torque and speed are inversely related, and it was very difficult to find a motor that could provide everything required. Eventually, a high-torque DC brush motor was selected off Amazon which can be found in Appendix A. This motor uses internal worm gearing to provide a large amount of torque and has enough power to still provide a reasonably high rpm. The worm gearing also prevented the system from being back driven.

A leadscrew was chosen over a ball screw as this setup resulted in the optimal distance traveled per turn by selecting a screw with a large pitch and multiple thread starts. Using this combination it was determined that the system should be able to move a 250 lb person two feet vertically in ten seconds with a factor of safety of 1.5.

One component of the Rock-slide went through many iterations after the original SolidWorks design was finalized due to a number of oversights involving the manufacturing process. This was the central shaft connecting the leadscrew flange to the hold as well as the hold mount. In the original design, the guide rail carriages were designed to hug the central shaft. All of the components of the assembly are connected with a ¼-20 through bolt and locknut. The SolidWorks model of this design can be seen in the figure below (top through bolt not shown).

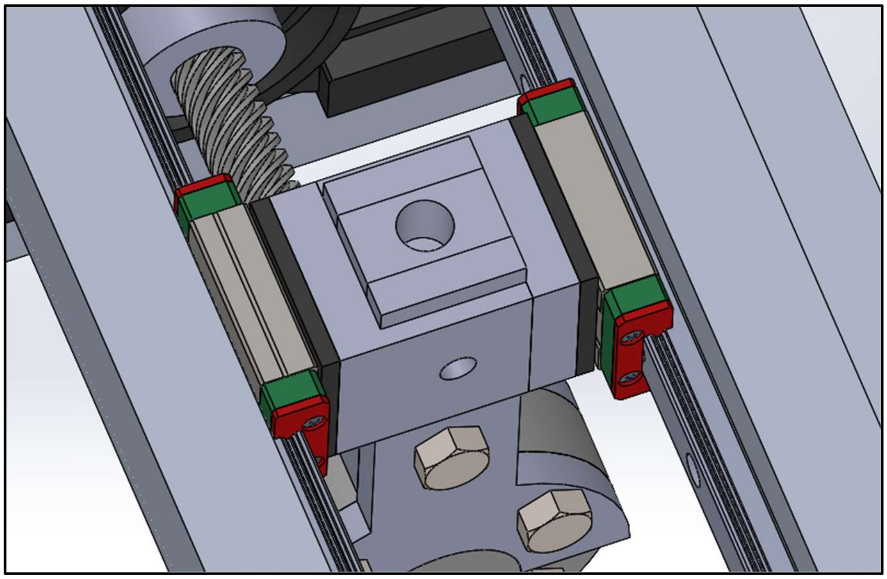

Figure 10: Original Central Shaft Assembly Design

The heads of the screws attaching the L brackets that hug the central shaft to the guide rail carriages were meant to be countersunk into the base of the L brackets. When it came time to manufacture the L brackets, scrap ⅛” thick L brackets were chosen for the part, saving the expense of water jetting the original design with a thicker bottom from expensive thick aluminum. The space gap created by using a thinner L bracket was to be filled with an additional rubber gasket. This decision was proven to be an oversight as it eliminated the possibility of countersinking the heads of the screws. Additionally, it was realized that this design does not provide a way to prevent the wooded hold mounting block from rotating when an unbalanced load is applied to it. The wooden hold mount is pictured below and is attached to the central shaft using a single ⅜ inch bolt.

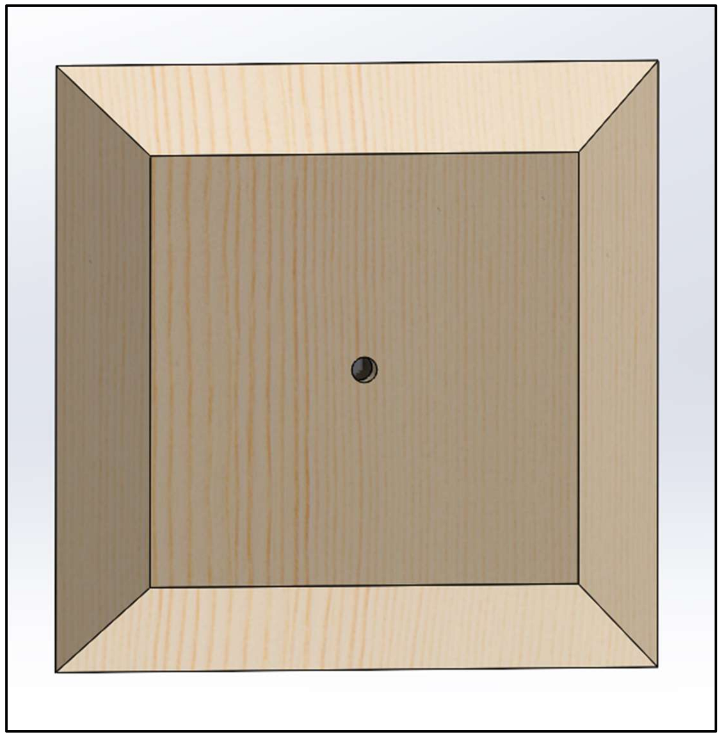

Figure 11: Wooden Hold Mount Version 1

To prevent the rotation of the hold mount, additional L brackets were added to the underside of the wood block. These brackets fix to the central shaft by running the ¼-20 bolt through the holes along the lower arm of the brackets. Additionally, space for a T-nut to be attached on the back was made. This allows the hold to attach to the hold mount with a ⅜ bolt and the hold mount to attach to the central shaft by running the top through bolt through the hold mount L brackets. This eliminates the need to tighten the hold to the central shaft and potentially pull the hold block down to the surface of the front plate, creating friction when translating the hold side to side.

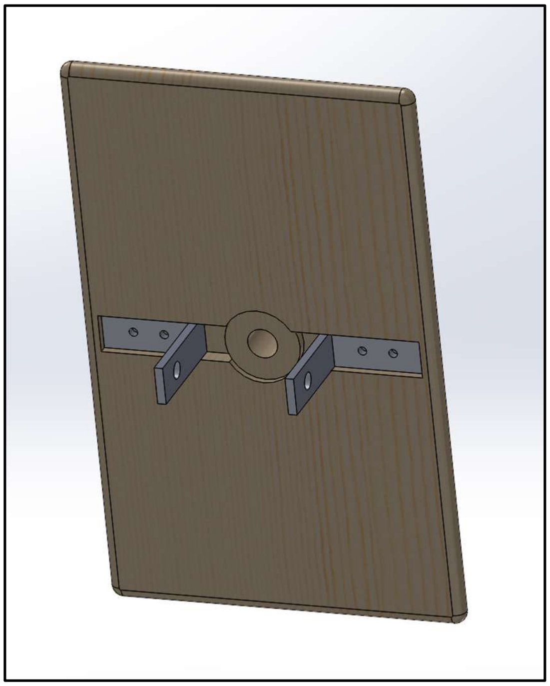

Figure 12: Wooden Hold Mount Version 2

Structural problems were discovered with this solution. When the rock-slide is mounted horizontally on the wall, loading in this condition would result in the two small hold mount L brackets enduring the entirety of the load. Because of this and in addition to the other flaws that had become apparent with the original design, this design had to be revised. The redesign was intended to fix the problems inherent in the first design, namely an easier way to assemble the shaft and a robust way to prevent the hold mount from spinning. This was achieved by offsetting the guide rail carriages which allowed for easier assembly and eliminated the need to countersink the bolt heads, which was impossible to do in the new thinner L brackets. To fix the issue of high stress at the hold mount L brackets, the wooden hold mounting block was eliminated altogether. In its place, the top flat plate was machined to have holes for the climbing hold to screw into. Because the carriages were now offset from each other, this allowed for a much wider central shaft. On top of the central shaft, the flat plate is bolted. Because the central shaft was widened, this allowed for three bolts fixing the top plate to the central shaft, eliminating the possibility of rotation.

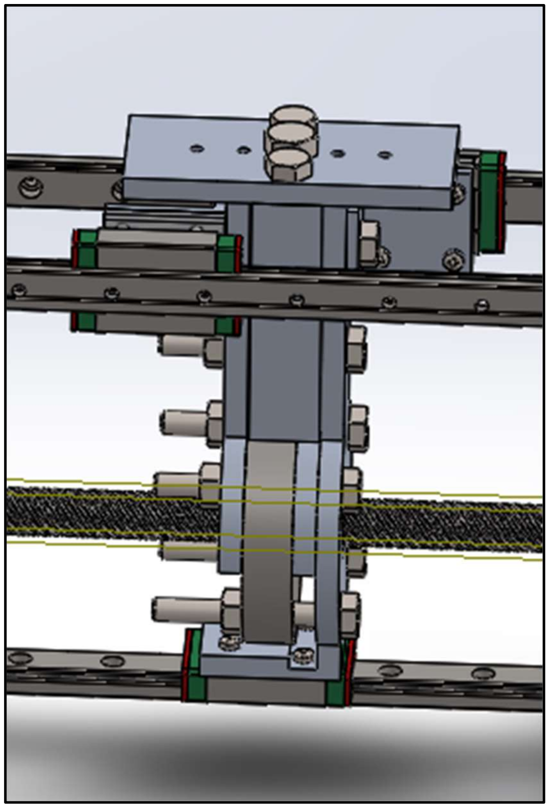

Figure 13: Central Shaft Assembly Final Design

FEA simulating the weight of the climber hanging on the hold, 200lb, was run on this design and high stress concentrations were found at the top inside corner of the L brackets and on the inside wall of the through-bolt hole. The stress at the upper corner of the L bracket is ~22.8MPa. Using the yield strength of 1060 Aluminum, 62MPa, the safety factor for yielding under this loading condition is calculated to be 2.7 (MatWeb Material Property Data, n.d.). The high safety factor proved that the L brackets were not a source of concern for the structural integrity of the assembly.

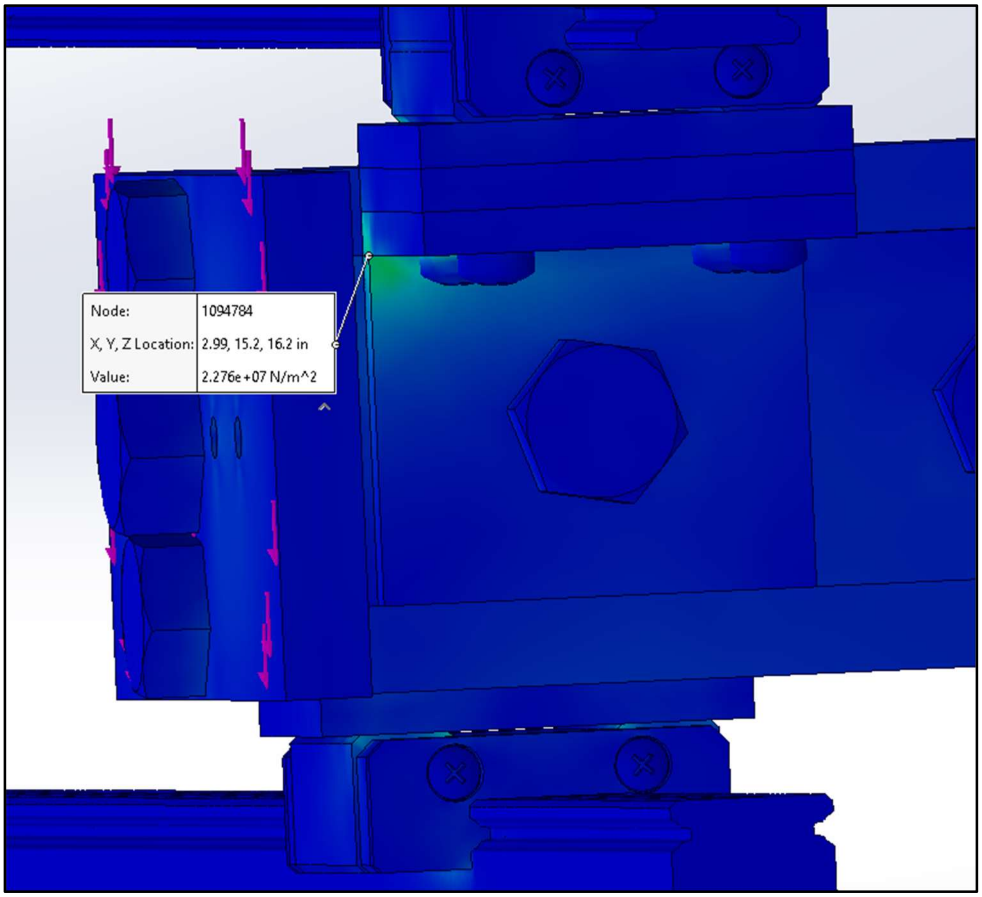

Figure 14: Stress Concentration in Corner of Guide Rail L Bracket

The maximum stress of 59.2MPa occurred on the surface of the top through bolt. Using the minimum proof strength of Grade 2 Steel, 379MPa, the safety factor for yielding under this loading condition is calculated to be 6.4 (Engineering ToolBox, n.d.). However, the SolidWorks model does not match reality. The gap in the model is a product of tolerancing to ensure all the shaft components have a free fit. In reality, this gap is not existent as the bolts are tightened to ensure no gaps are present. This fact should result in a real life stress concentration that is much less than the simulated one. To mitigate these stress concentrations, the L brackets were extended to be fastened by both bolt holes rather than just the top one.

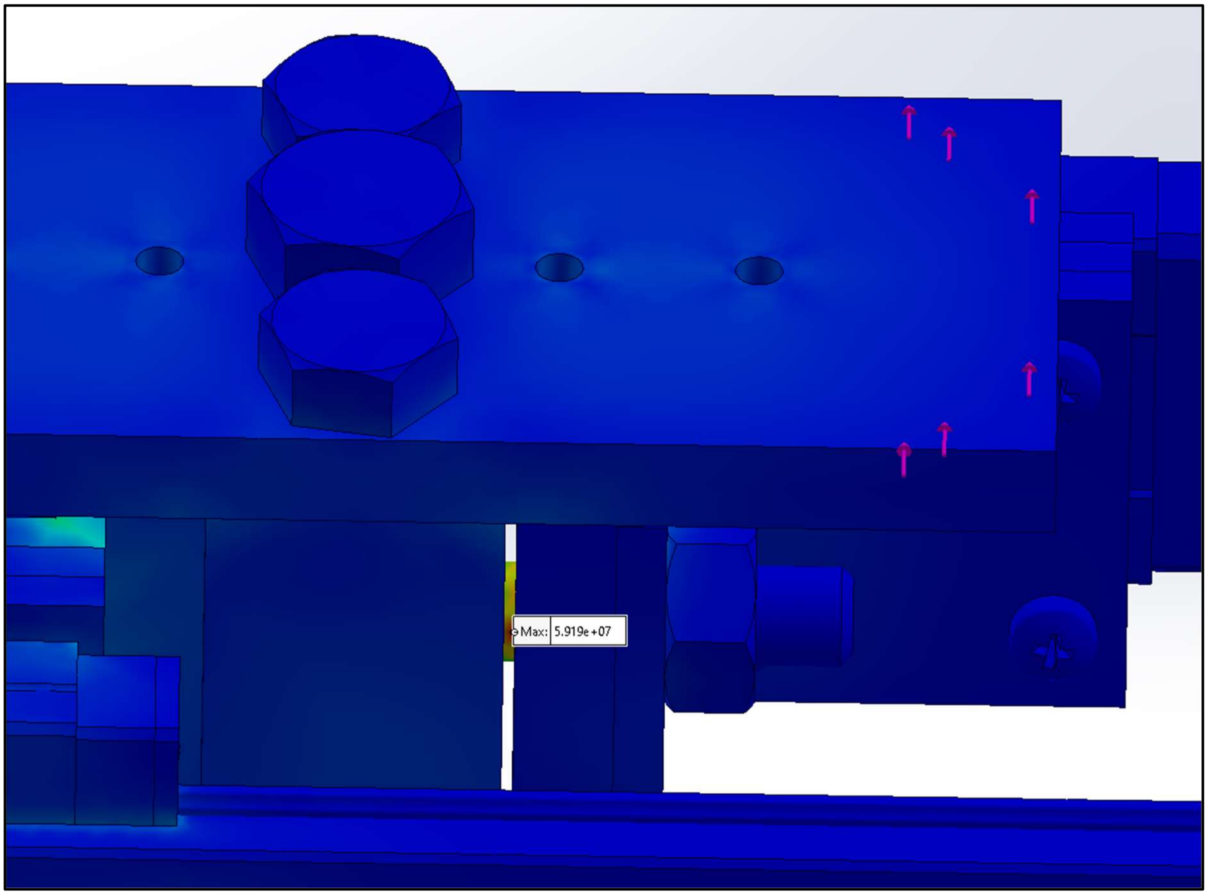

Figure 15: Maximum Stress in Singular Shaft Bolt

The addition of the second bolt hole mitigated the first stress concentration to 18.3MPa and the resulting safety factor was 3.4.

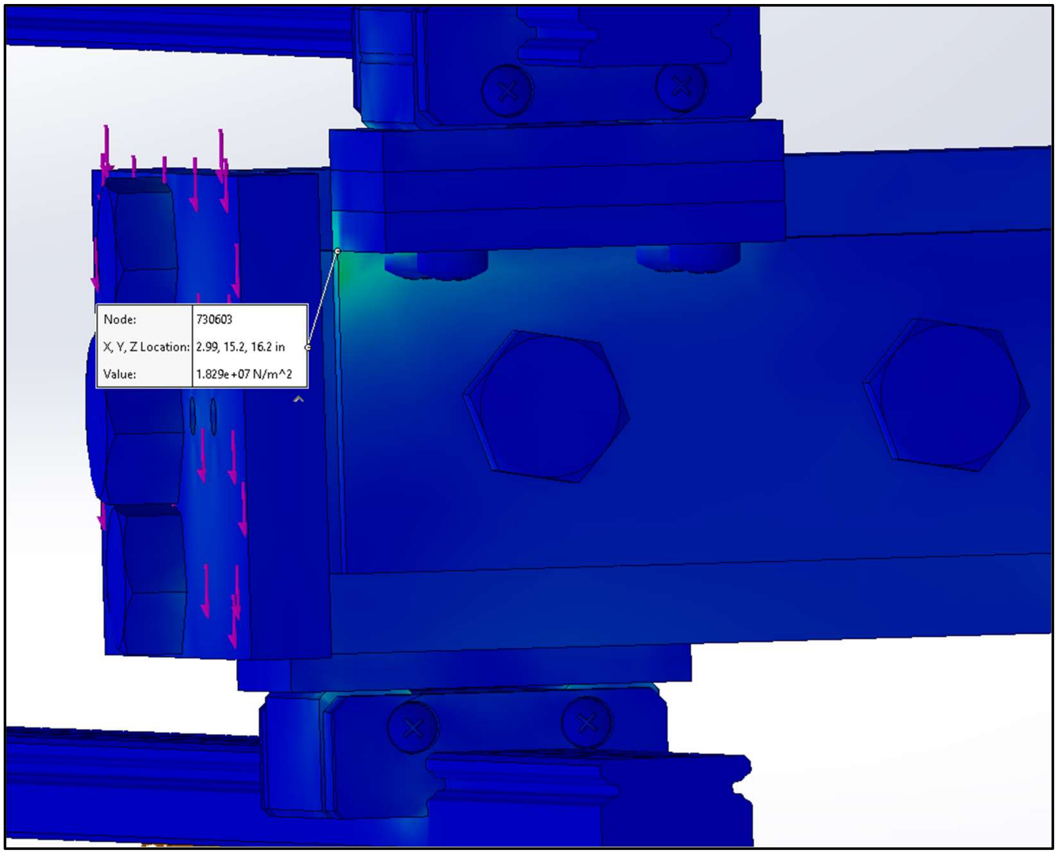

Figure 16: Stress in Guide Rail L Bracket following redesign

At the location of max stress, the value was reduced to 54.7MPa and the resulting safety factor was 6.9. The high safety factors for this simple loading scenario indicate that this design will hold up well in more drastic or dynamic loading scenarios. Having eliminated the problems with the original design as well as proving it will not break under load, this was decided to be the final central shaft assembly and hold mounting system.

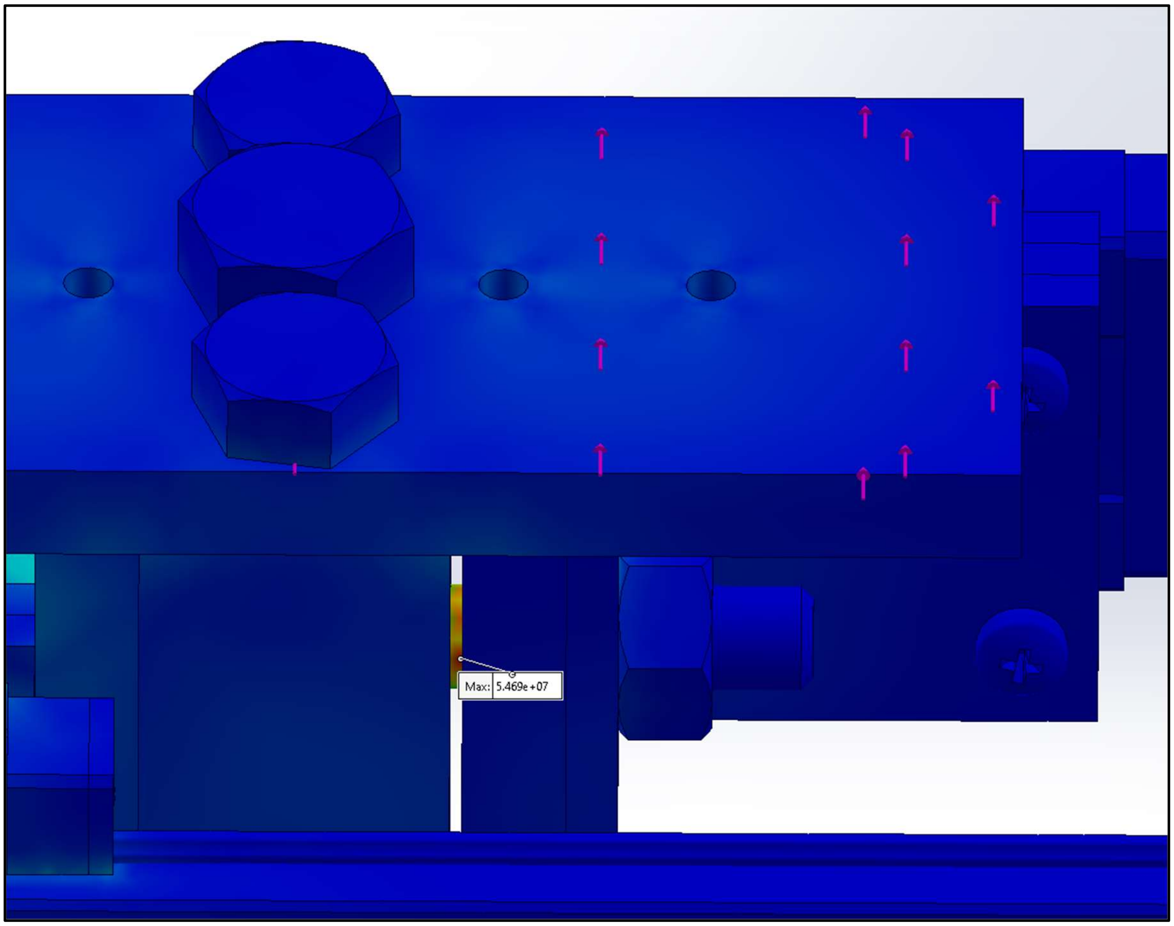

Figure 17: Maximum Stress in Top Bolt following redesign

Control of the motor was achieved using a high current motor driver board. The battery used in the design was expected to output as much as 10 amps during startup so the IBT2, dual BTS7960 module was chosen. This chip uses two IC chips to form an H-bridge and can handle up to 43 Amps. Additionally, it was readily available at a low cost by resellers on Amazon. The motor driver module was controlled using an Arduino Nano microcontroller. This microcontroller supplies the 5V needed to power the motor driver board and uses pins D4 and D5 to control the direction and speed of the motor. The final code used to power the system can be found in Appendix B. In order to power the microcontroller a DC voltage regulator was used. The LM 2596 DC-DC chip receives 18V power from a Milwaukee drill battery and steps the voltage down to 9V in order to power the microcontroller.

The motor was prevented from moving past the end of the limit switch using both a digital and physical system. Two limit switches were placed at each end of the leadscrew. The common lead (COM) of each was connected to the power supply leaving the motor driver module with the normally closed leads (NC) being connected to the motor. This leads to the motor being disconnected from power when one of the switches is flipped to the normally open position (NO). In order to allow the motor to move once it has flipped a limit switch the NO lead on each switch is connected to the NC lead through a diode, allowing the motor to move away from the limit switch but not in the direction past the limit switch. Each NO lead was also connected to a digital pin on the Nano microcontroller using a voltage divider, allowing the microcontroller to detect when a limit switch is flipped using pins D2 and D3 The voltage divider used 12kΩ and 360Ω resistors with the expected input voltage range being 18-20V leading to an expected output of 4.1-4.6V to the Arduino board. All electronics were constructed on a perfboard in the final wiring. The final circuit diagram can be seen in Figure 18.

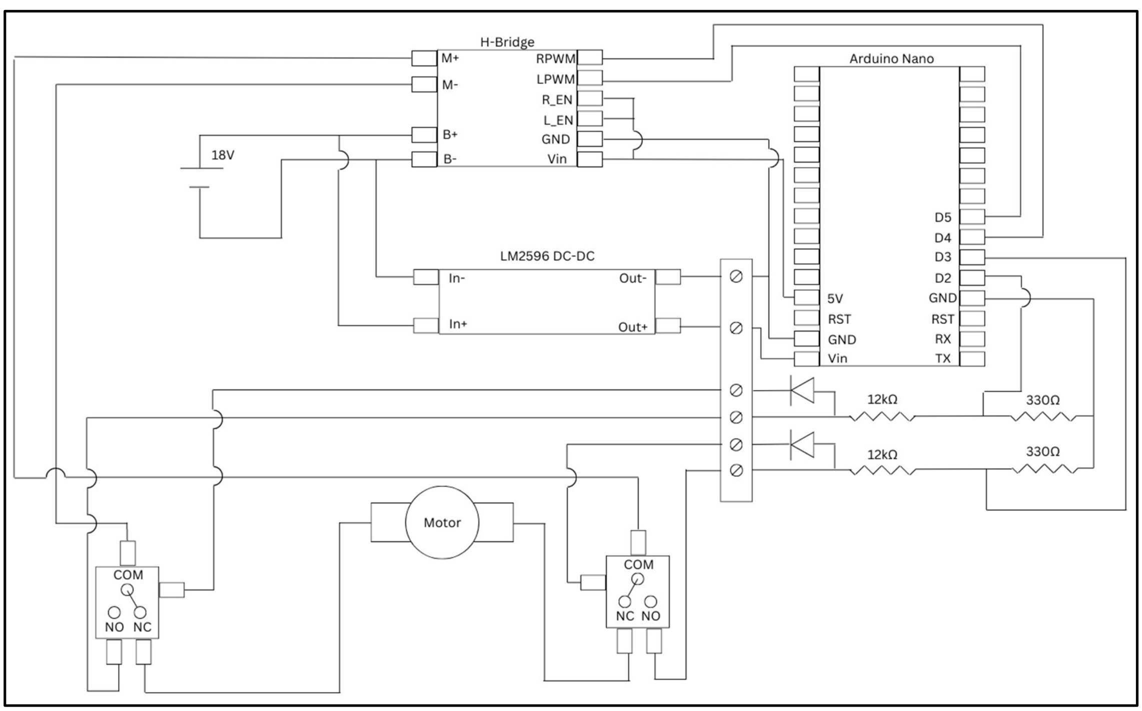

Figure 18: Final Circuit Design

Final Prototype Construction

Construction of the final prototype began with laying out in a spreadsheet the necessary cuts of the six purchased 6-foot aluminum tubing that would form the skeleton of the volume.

	Sum	Cut 1	Cut 2	Cut 3	Cut 4	Cut 5	Leftover in from 6 ft bar
Bar #1	71.500 in	34.000 in	24.000 in	6.000 in	7.500 in		0.500 in
Bar #2	71.500 in	34.000 in	24.000 in	6.000 in	7.500 in		0.500 in
Bar #3	70.786 in	34.000 in	23.393 in	13.393 in			1.214 in
Bar #4	70.786 in	34.000 in	23.393 in	13.393 in			1.214 in
Bar #5	69.286 in	23.393 in	23.393 in	7.500 in	7.500 in	7.500 in	2.714 in
Bar #6	13.500 in	7.500 in	6.000 in				58.500 in

Table 2: Cut Lengths for Aluminum Tubing

The tubes were cut to length using a band saw and then various mounting holes were added with a drill press and tapped for ¼-20 bolts by hand. Following a temporary assembly to check that all parts fit together, the tubes were marked where to be welded and were passed off to Professor Garner to be welded. Unfortunately, a number of markings were not included for the center tubes spanning the length of the skeleton, and this caused both top linear guide rail mounts to be placed each a ¼” toward the center. Originally, the ⅜” hole in the center shaft was simply to make space for the climbing hold bolt, as it would be attached via a T-nut in the hold mount, however, following the redesign that eliminated the wooden hold mount, it became necessary that the ⅜” hole was tapped. As mentioned in the Design Choices section, the linear guide rail L brackets were offset on either side of the new T-shaped center shaft to allow for it to be wider. This was necessary to have a tapped center hole as with the L brackets hugging the center shaft the shaft would have too thin of walls to be tapped.

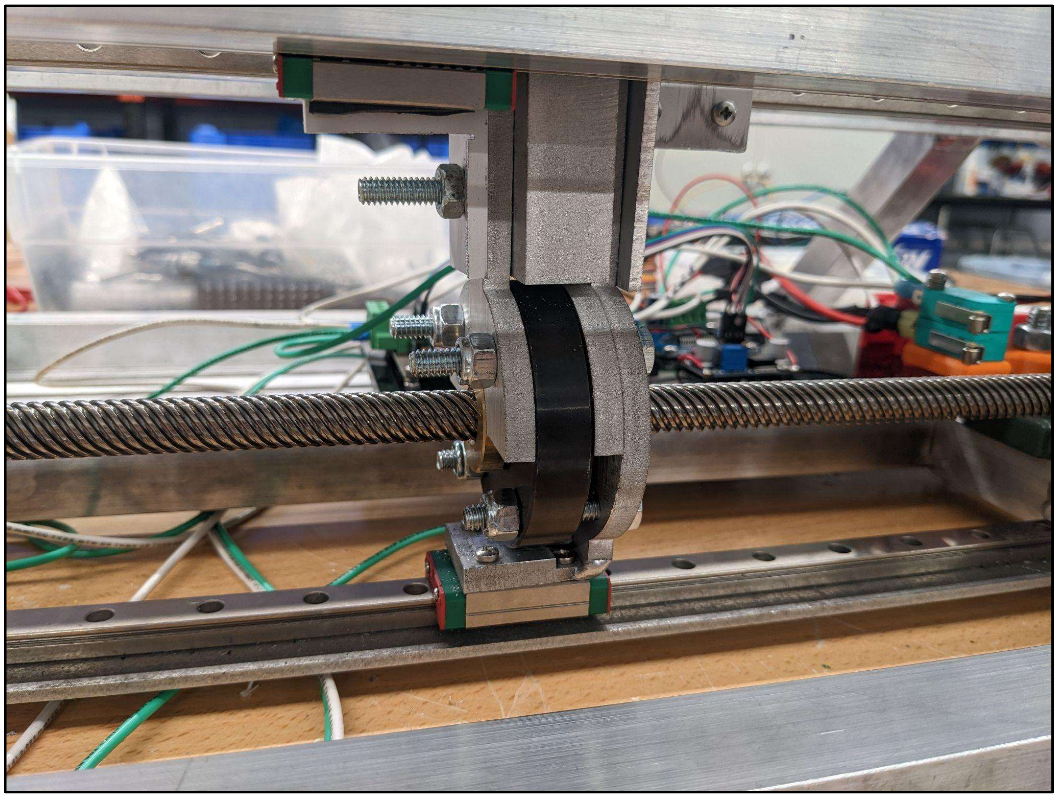

Figure 19: Leadscrew Carriage and Shaft

Components connecting the leadscrew's flange to the three linear guide rails as well as the climbing hold and the bottom linear guide rail mount were all water-jetted from scrap aluminum. Two ¼" plates as well as a ¼" spacer sandwiched the center shaft onto the flange, with one of the plates extending down towards the bottom guide rail where it was welded to a small block attached to the guide rail carriage with M3 screws cut to size. This small block had to be milled out on one side of the top to allow for clearance of the carriage's screw heads. The center shaft featured two tapped ¼" holes on either side of the center tapped ⅜" hole to allow mounting of the top plate, along with two ¼" through-holes on its side where it would be bolted to each of the side plates. The two ¼" holes of the top plate were countersunk to have a flush surface where the climbing hold would be mounted. The center hole of the top plate was a through-hole for the ⅜" hold bolt and had four additional small holes tapped by hand for 6-32 bolts in order to set the rotation of the hold. The bottom linear guide rail mount and side guide rail mounting bars were tapped by hand for M3 screws. Drill pressing the holes for the two side mounting bars proved difficult to keep in completely parallel lines.

Assembly began with mounting the bottom linear guide rail, as access to it would be difficult once other components were added. The motor and motor mount were screwed into place, followed by the pillow block bearings, leadscrew, coupling, flange, and the one plate that needed to fit around the leadscrew. These were added in one step as access to them would be impossible without removing the pillow block bearings. The plate was screwed onto the bottom linear guide rail carriage then the plates were slid onto the flange and secured by the ¼-20 bolts. The L brackets, cut out of L channel aluminum, had to be first secured with the rubber gaskets to each of the side linear guide rails before the rails could be screwed onto the skeleton due to space constraints. Once the rails were placed on the skeleton, the center shaft and the L brackets could be slid into place and bolted together. The top plate and climbing hold were then bolted on.

A mounting plate for all the electronics was sketched up in SolidWorks and cut out of acrylic on a laser cutter. It was attached to the frame via ¼-20 bolts and held all the electronics with M3 nuts and bolts. Soldered onto a perfboard were the Arduino Nano and all connections to other parts of the system. Pins of the screw terminals and diodes were too large for the perfboard and thus the holes were widened using a small drill bit.

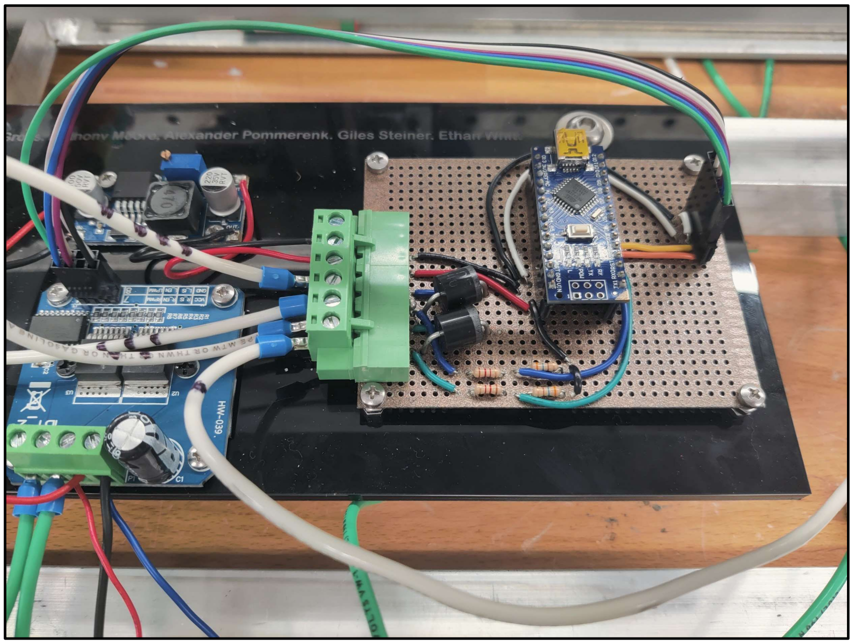

Figure 20: Electronics on the Final Prototype before Additional Terminals

Final Prototype Testing

During the final stage of construction, a number of issues came up during the final testing of the product. The circuitry was designed to turn off the motor and then reverse it when a limit switch is hit. The current then would run from the normally open side of the limit switch, through a diode, and to the reverse side of the H-bridge. When implementing this design, it was discovered that the current flowed in the reverse direction than was anticipated. This prevented the initial circuit from functioning correctly. When the motor hit a limit switch, the motor would be unable to move off of the limit switch because that limit switch would be on the grounded half of the H-bridge used to control the motor. This meant no current was present to flow from the NO lead to the motor on the side which had been triggered and no current could flow to the arduino board. Fixing this would require inverting the logic of the normally open side of each limit switch. Due to the limited amount of time remaining before presentation, this was not able to be achieved as part of the final design. Instead, two additional limit switches, independent of the H-bridge, were added to achieve the same result. This change allowed the Arduino to receive the signal to reverse the motor while preserving the H-bridge's ability to cut power off to the motor. These two new limit switches used the necessary inverted logic and were wired to pins D7 and D9.

Additionally, the motor had a great deal of difficulty moving through a specific section of the shaft. It was determined this was caused by a vertical misalignment of the bottom guide rail. When testing the movement of the hold using a weaker power supply, the motor would simply stall in this section. However, when the battery was installed and tested, it was capable of supplying more amperage to the motor than the power supply. This additional amperage allowed the motor to move along the misaligned area, but the stress that was translated to the coupling caused it to break.

The failure of the coupling as a result of the misalignment issue prevented the design from being fully tested before the conclusion of the project. In the end, Gorilla tape was used to demonstrate movement for the final presentation but would have been insufficient to support a climber. A new coupling needs to be purchased and installed to provide the required support. This was achieved along with all manufacturing and assembly of the final design. The final assembly design can be seen in Figure 21.

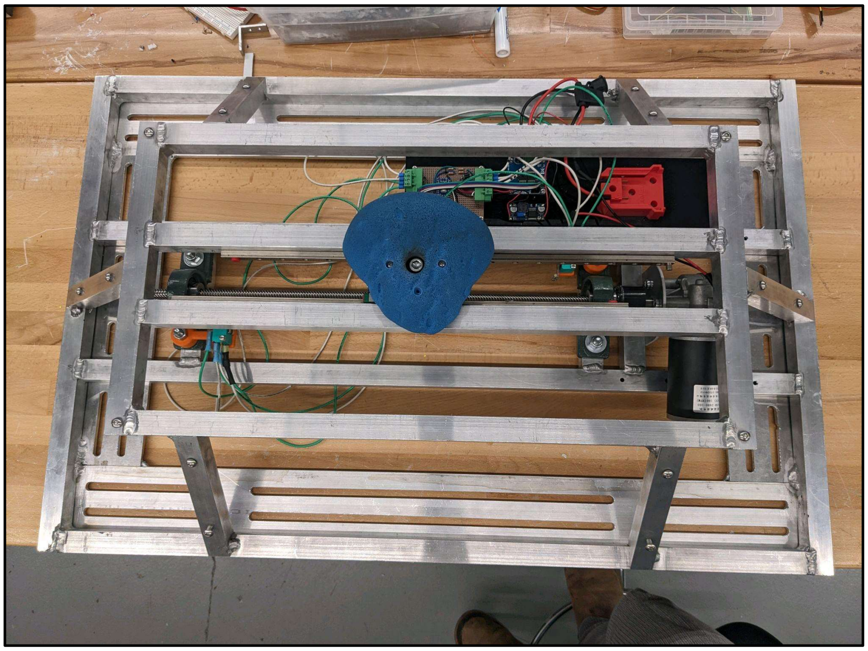

Figure 21: Picture of Final Prototype Assembly

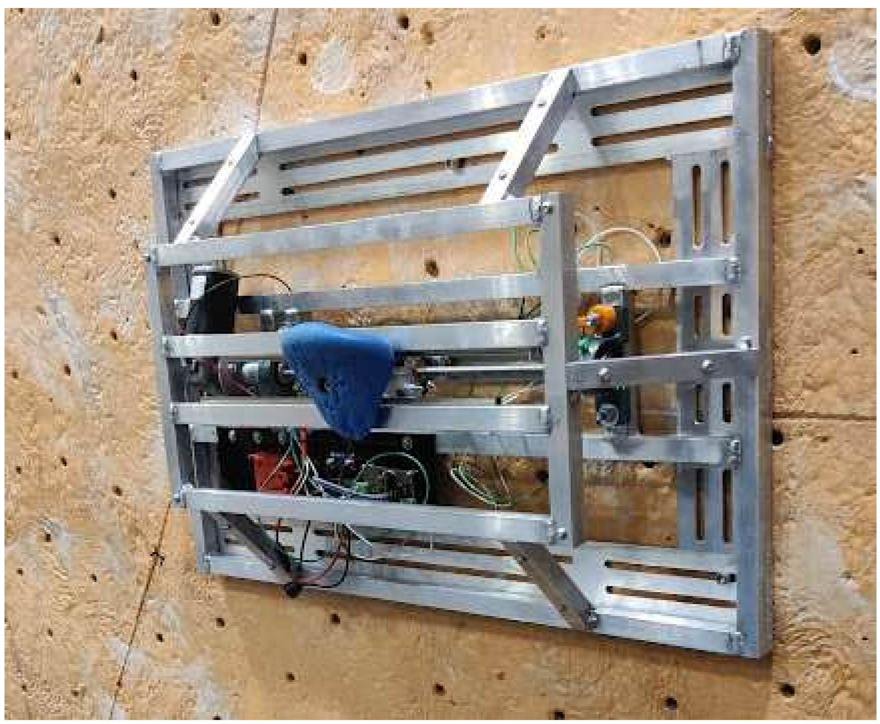

Figure 22: Picture of Final Prototype Assembly Mounted

Future Work

Though there were some successes, several objectives were not met due to time constraints. The most significant goal not accomplished was mounting the structure to the climbing wall and applying human weight. As this is the primary function of the design, this is a priority for future progress. One main issue prevented this from occurring during the final testing phase of this project, the misalignment of the linear guide rails and the subsequent failure of the shaft coupling. During fabrication the aluminum supporting the guide rails were not properly aligned. This is primarily due to the welding manufacturing process, which is not precise enough to ensure proper leveling. This should have been foreseen as an issue before assembly but was not fixed in time. Without fixing this alignment issue the design will not work properly. The team believes that the use of shims should be able to fix this issue, preventing the load from being transferred to the leadscrew.

Some other more minor problems included wiring limit switches and creating the side paneling. As mentioned, two limit switches were added to each side of the linear guide rail to prevent movement beyond the range intended. One switch turned off the power while the other instructed the motor to turn in the opposite direction, creating an oscillating motion. While this was effective for the large prototype, the finalized wiring will include single switches and more elegant wiring to provide the same function without the risk of only tripping one of the two switches. For the finished product, side paneling created from wood and a front aluminum panel will also be included. The wood side panels will have a textured surface and T-nuts included so that it may be used as a traditional volume in addition to the moving feature. Finally, a belt system similar to the one implemented on the original prototype will need to be added to prevent users from putting their fingers through the front plate.

Conclusions

Through the process of designing and manufacturing the Rock-slide, the team has learned a number of very important lessons about design and engineering. The first of these lessons was the importance of accounting for tolerancing of CAD models to reflect how they would be built in the real world. Numerous unforeseen fitting difficulties were encountered over the build process that resulted in re-drilling holes, filing down edges, or remaking parts altogether. The most drastic manufacturing imprecision was the welding of the frame. To account for the relatively large inaccuracies associated with the welding process, all the components of the drivetrain were designed to bolt through slots instead of holes. Over the course of the build, the team learned the value in oversizing holes, leaving room for free fits, and using slots when applicable.

Another challenge over the course of the build was designing components that could be realistically manufactured and assembled easily. With the manufacturing limitations in mind, metal components had to be made on the waterjet or with basic milling operations. This constrained the metal components to being mostly two-dimensional, avoiding complex three-dimensional shapes. It was a further challenge to design components in a way that could be quickly and easily assembled. This proved to be difficult to anticipate in the CAD models and the difficulties were largely only discovered when the physical product was made. The biggest difficulties proved to be the process of installing/removing the leadscrew, tightening the bolts of the central shaft, and installing the guide rails.

Perhaps the biggest lesson learned from this project was the fact that tasks will most definitely take longer than planned. The majority of the semester was devoted to the design process and little time was left for product assembly. As mentioned before, many unforeseen challenges arose with tolerancing and assembling which caused a number of setbacks. Allowing more time for this process would surely have created a more polished product.

Finally, although the final product still needs work before it can be used on the climbing wall, the process of designing and building the Rock-slide has improved the engineering skills of each individual on the team. This project has provided a window into the real world design, manufacturing, implementation, and troubleshooting process in an engineering application and has improved the skills of everyone on the team.

References

Climbing Business Journal. (2022, February 15). Gyms and trends 2021. Retrieved October 25, 2022, from https://www.climbingbusinessjournal.com/gyms-and-trends-2021/#:~:text=Taken%20together%2C%20the%20growth%20rate,for%20the%20past%20eleven%20years

Engineering ToolBox. (n.d.). Steel bolts - SAE grades. Retrieved December 12, 2022, from https://www.engineeringtoolbox.com/steel-bolts-sae-grades-d_1426.html

MatWeb Material Property Data. (n.d.). *Aluminum 1060-H12 Material Properties*. Aluminum 1060-H12. Retrieved December 12, 2022, from https://www.matweb.com/search/DataSheet.aspx?MatGUID=0df660ac8b87434ca82af7681a6098e1

Zeberoxyz 1PCS Mini Linear Rail Guide Slide Actuator T6X1 Leadscrew ... (n.d.). Retrieved December 11, 2022, from https://www.amazon.com/Zeberoxyz-Linear-Actuator-NEMA11-Stepper/dp/B08Y6YS8D4

Appendices

Appendix A - Parts List

Drivetrain	**Electronics**	**Metal**	**Misc**	**Bolts**
80W 160rpm Reversible Worm Gear Motor	Milwaukee 18V Battery	**Frame:**	**Electronics Mount:**	M3 Varies Lengths (x40)
1/2" Pillow Block Bearing (x2)	Milwaukee 18V Battery Adapter with Fuse	6' 1/8" Walled 1"x1" 6061 Aluminum Rectangular Tubing (x6)	Scrap 1/4" Acrylic	1/4" 20 Hex Head 2" (x2)
1/2"-8 Thread 3' Fast Travel Leadscrew	Arduino Nano	**Mounting Plate:**	**Limit Switch Mount:**	1/4" 20 Hex Head 1.5" (x6)
1/2"-8 Thread Fast Travel Nut	43A High Power Motor Driver H Bridge	4"x48" 1/4" Thick 6061 Aluminum Plates	<1in^3 ABS (x2)	1/4" 20 Round Socket Head 0.75" (x16)
Leadscrew Nut Flange	LM 2596 DC-DC Voltage Regulator	**Misc. Aluminum Plates:**		1/4" 20 Countersunk Head 0.5" (x2)
10mm Shaft Coupling	High Voltage Diode (x2)	[Motor Mount, Bottom Guide Rail Mounting Bar, Central Shaft Plates (x3), Center Shaft, Hold Mounting Plate , Support Guide Rail L Brackets (x2)]		3/8" 16 Socket Head 0.75" (x2)
480mm Linear Guide Rail with Carriage (x3)	1200 ohm resistor (x2)			3/8" 16 Socket Head 1.5" (x2)
6"x6" 1/8" Thick 30A Neoprene Sheet	360 ohm resistor (x2)			
	Limit Switch (x4)			
	Medium sized Perfboard			
	6 Port Screw-in terminal			
	4 Port Screw-in terminal			
	14 Gauge, high amperage wire			

Appendix B - Motor Control Code

```
int rightLimitPin = 9;
int leftLimitPin = 7;
int leftOutputPin = 4;
int rightOutputPin = 5;
int leftLimitReading = 0;
int rightLimitReading = 0;

/* MOTOR SETTINGS
 *  dir = -1 ---> move left initially
 *  dir = 1  ---> move right initially
 */
int dir = 1;

void setup() {
  // put your setup code here, to run once:
  pinMode(leftLimitPin, INPUT);
  pinMode(rightLimitPin, INPUT);
  pinMode(leftOutputPin, OUTPUT);
  pinMode(rightOutputPin, OUTPUT);
  pinMode(LED_BUILTIN, OUTPUT);
}

void loop() {
  leftLimitReading = digitalRead(leftLimitPin);
  rightLimitReading = digitalRead(rightLimitPin);


  if(rightLimitReading == LOW){
    dir = -1;
    digitalWrite(LED_BUILTIN, HIGH);
  }

  if(leftLimitReading == LOW){
    dir = 1;
    digitalWrite(LED_BUILTIN, LOW);
  }

  if(dir == 1){
    moveRight();
  } else if (dir == -1){
    moveLeft();
  }
}

void stopMotor(){
  digitalWrite(leftOutputPin, LOW);
  digitalWrite(rightOutputPin, LOW);
}

void moveRight(){
  digitalWrite(rightOutputPin, LOW);
  digitalWrite(leftOutputPin, HIGH);
```

```
}

void moveLeft(){
  digitalWrite(leftOutputPin, LOW);
  digitalWrite(rightOutputPin, HIGH);
}
```