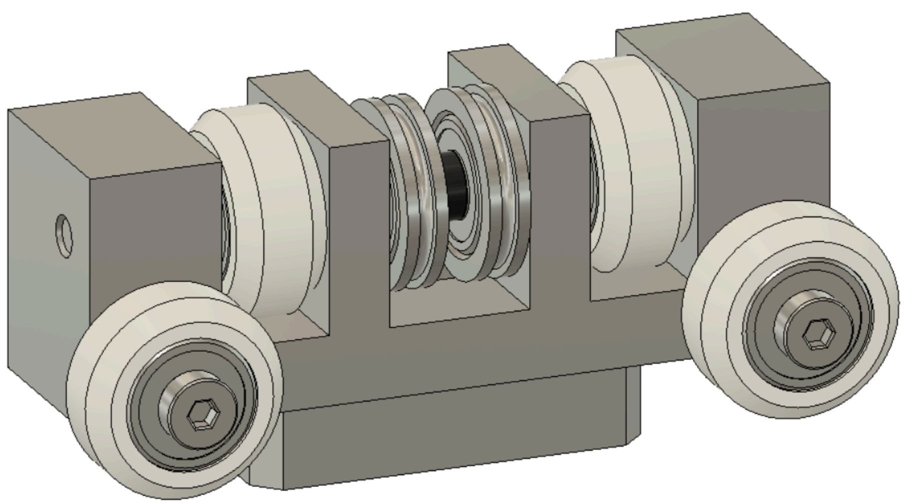
FRC Linear Slide Fitting



Edward Maddox

EDPS Table of Contents

Executive Summary or Abstract

The purpose of this design is to design a modular system that can facilitate a competitive linear motion system in First Robotics Competition (FRC). To accomplish this objective, different linear motion systems found in cranes, linear rails, linear actuators and successful FRC teams were researched. Telescoping rods, and different types of fittings that facilitated motion between 16” thick 2” x 1” aluminum stock were selected and considered through an in depth analysis.

Powered telescoping rod was an excellent solution to the problem, but it didn’t suit the particular targeted features and requirements of this project. Its complexity and manufacturing difficulties made the system unfeasible at a reasonable price and would create a tedious assembly and tuning process. The alternatives, the fittings, were much more suited to the manufacturing, modularity, and assembly goals. It came down to the practicality of each individual fitting design and the second idea was selected for its rigidity, robustness, and easy manufacturing despite its aesthetic drawbacks. Additionally, the second idea integrated a pulley system that would allow compact powered extension and retraction of the linear motion system. This pulley system wasn’t a high priority, but it was an added benefit that contributed to the selection of the solution.

The end product successfully facilitated smooth motion, handled FRC competitive loads, and provided modularity. Unfortunately, the machined version was not completed on schedule, but many tests were conducted with 3D Printed prototypes. Despite worse tolerances and weaker materials, these versions showed great promise. They facilitated extremely smooth motion and held up to loads much higher than expected.

This product can provide a reasonably priced, competitive, and simple solution to linear motion in First Robotics Competition (FRC). Despite being a semi-pre-built system, the fitting provides modularity which is essential for an educational competition. It handles the small details and provides flexibility which in turn, allows teams to focus on bigger ideas and other unique design decisions in the competition.

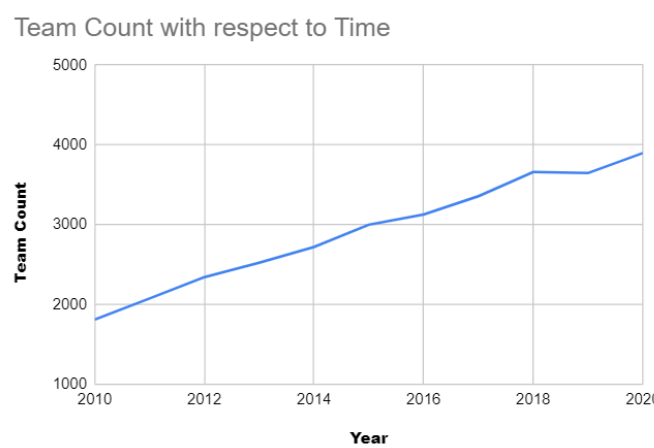
Introduction

Imagining mechanisms that can robustly carry out controlled and swift linear motion is a unique challenge that engineers and inventors have repeatedly tackled for centuries. Countless innovative designs have already been theorized, but transforming these concepts into practical, functional, real parts is an entirely new problem that countless aspiring engineering students face in FIRST Robotics Competition (FRC) every year.

This problem will be approached with the engineering design process. The steps are displayed on this diagram.

- Identify the problem
- Explore the topic and do background research
  - Look into what successful systems accomplish and what poor systems fail to do.
- Brainstorm
  - Think about and list as many potential solutions as possible, no matter how strange.
- Design an Idea
  - Use thoughtful decision matrices to carefully and systematically select the best idea from the brainstorming process
- Prototype, test and analyze the idea
  - Build a quick working prototype of the design
  - Test the prototype and list all shortcomings and failures
- Reiterate
  - Return to brainstorming and move through the process to solve remaining problems
  - Continue to reiterate until adequate results are obtained
- Finalize the product
  - Create a polished production model that will serve as the final product

In 2020 there were 3898 registered teams and the competition has been consistently growing every year this past decade.. All of these teams are required to rebuild a new robot for the challenge every year meaning there is constant, predictable demand for these parts. In five of the past six years of FRC, linear motion systems have been essential for major scoring opportunities. Many teams still incorporated linear motion systems into their robots during the one year where they weren't essential. 100% of teams surveyed used an elevator during the last 3 seasons.



Pre-built solutions already exist, but they are plagued with issues. 25% of teams found rigidity issues and had trouble assembling their kits while the rest rated their experiences as mediocre at best. 50% of teams claimed that substantial in house manufacturing and modifications to kits were necessary in order to use their kits. 75% of respondents felt that their system was excessively loud and half of all of them were completely dissatisfied.

The goal of this project is to design and sell a modular linear slide system to FRC teams that can outperform what is on the market. The main goals will be ease of assembly, limited maintenance, simplicity, noise reduction, and competitive robustness. These targeted features were selected from survey data and research results. This will allow me to spend time and resources working to improve upon the failures of competitors and It should also account for a pulley, chain, or rack and pinion system that allows powered retraction and extension of all stages of the linear motion system.

The main constraint on this project is time. The entire process, from research to finalization, must be completed in eight weeks. Additionally, the price limit is $30 per fitting to maintain reasonable pricing that will remain competitive in the FRC market. The fitting must also be machinable in a three axis CNC machine from 2"x1" or 6"x1" aluminum stock since that is what is available. Additionally, FRC has a weight limit of 125 lbs so each fitting should be under ¼ of a lb so it doesn't have a major effect on the weight restriction.

The final deliverable product is a single fitting that plugs into stock 2" x 1", 1/16" thick aluminum tubing. It will have rollers that hold the two adjacent aluminum pieces in place, be simple to attach to the aluminum tubing, and have built in rollers that allow for a pulley system that runs between stages. The piece will provide limited space between adjacent stages to keep the entire system compact. As a result, the pulley cable will need to be a specific, small size and will be provided optionally with a purchase of the fittings.

This setup allows the client to have more control over their own system. The product is flexible and meant to be a solution to the headache and expenses of custom manufacturing a linear motion system; It is not a way to completely avoid the engineering design process. Doing that would go against the mission of FRC and take away the learning students get from the competition. Teams can still decide how many stages, the length of each stage, the width of the system, and how they power it. Most importantly, the built in pulley system saves space and allows teams to focus on the meat of FRC, their scoring mechanism that they will mount to the linear slide system. Similar linear slide systems are used nearly every year in FRC, the real innovation happens in the scoring systems and my linear slide fitting will allow teams to skip a headache and focus on the real challenge.

Background Research & Investigation

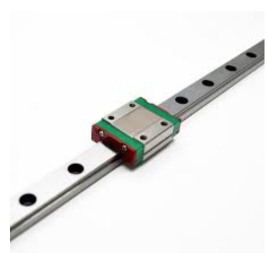
What were existing solutions to the Problem?

Common solutions to linear motion in industrial applications include telescoping tubes in forklifts and cranes, linear actuators, and linear rail.

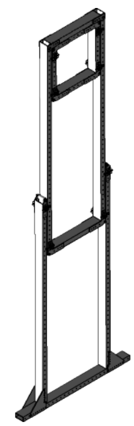
Some cranes and tall forklifts commonly use telescoping tubes, which are a series of interlocking cylinders or rectangles with bushings at each end to reduce the friction between them. Every stage of extension is thinner than the previous making these systems difficult or impossible to make and power when many stages of extensions are required; however, they are very compact and are self-contained systems when completed.

Linear actuators are very common and function like a single stage telescoping tube that has an internal lead screw that powers the single stage of motion. Since they are only one stage and powered by a lead screw, they can only extend to slightly below double their initial length, have high torque and as a result are usually slow. As a result, they are not suitable for an FRC system which requires speed and usually high extension, but they can be used in niche applications or power the first stage of an alternative cascade extensions system. A cascade system is a type of pulley system in which the first stage of motion simultaneously and equally extends or retracts all other stages.

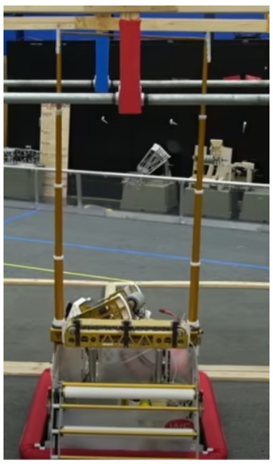
Linear rail consists of a steel guide rail with an interlocking carriage lined with bearing balls that frictionlessly moves along the rail. They are typically found in CNC and are not suitable for this application since rails are usually used in pairs and are too heavy and not strong enough to use in multi stage elevators.



How have successful FRC teams solved the problem?



Successful FRC teams typically use two adjacent and connected multi stage linear slide systems. Most teams use 1/16” thick 2” x 1” aluminum square tubing as the rail and slide stages with bearings mounted at the end to facilitate smooth motion. Some teams use 1” x 1” aluminum tubing and others use telescoping square tubing of varied sizes. They also have bearing blocks at the end.

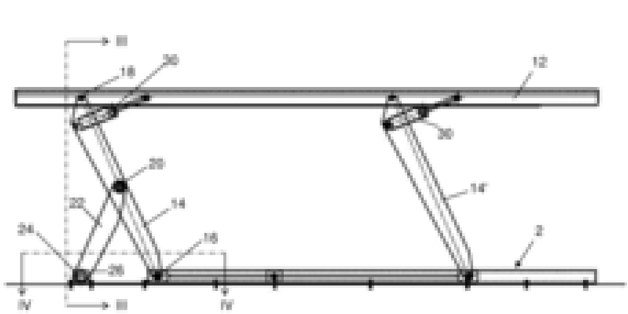


This is probably the most common solution because teams are taking advantage of resources available to them. 1/16” aluminum square tubing stock is a staple of the competition and most teams are extremely familiar with it. It is also very economical to use a mass produced stock piece as your rail and manufacture only a small interface at each end.

Rarely, top teams like 118 Robonauts or 148 Robo-Wranglers with copious amounts of resources will custom make cylindrical telescoping rods, but maintaining tight tolerances on long pieces makes manufacturing tedious, expensive and out of reach for most, including me.

What were some alternative solutions that may not have been considered?

Scissor lifts and forbar/parallelogram lifts are often ignored in FRC. Scissor lifts can be found in industrial applications for lifting heavy objects or people to high heights. Some teams found success with scissor lifts in First Tech Challenge, a smaller scale FRC style competition. Parallelograms can be found in drive-on lifts for heavy vehicles like busses, 18 wheelers, or fire trucks. They also are commonly found in VEX, a different FTC style competition.



Why have these solutions not been considered?

Scissor lifts are sturdy, but very large and heavy making them unsuitable for FRC. It is also very expensive to manufacture the countless crosses required to make one. They would probably not be viable unless a very heavy or large load needs to be raised in an unorthodox competition. Fourbars and parallelograms are probably not used because of the instability, added complexity, and extremely high torques applied to ends of the arms.

What were common problems encountered with other market solutions?

Common market solutions build upon the typical FRC solution that uses aluminum square tubing as the frame and rail with small mounts for rollers attached to the end. Usually, the end pieces are difficult to mount and configure. There are tons of holes that need to be drilled precisely and small mistakes can misalign the entire lift. It is usually a large hassle and multi-day project to set up and the final results are mediocre at best. The lifts usually have substantial amounts of play. This play makes scoring and motion inconsistent and allows the entire system to move and in turn, build up momentum that can damage the end pieces. The lifts are also very inefficient, loud and wear down over the season.

What were the root causes of said common problems?

The mounting difficulty stems from poor design that doesn't account for assembly. There are few references to align parts and large amounts of holes need to be drilled accurately and precisely. The play is a result of large clearances in the design that account for the assembly process. The inefficiencies are due to the friction between metal and metal contact. (The aluminum tubing and bearings) and the wear comes from the steel bearings grinding on the aluminum tubing.

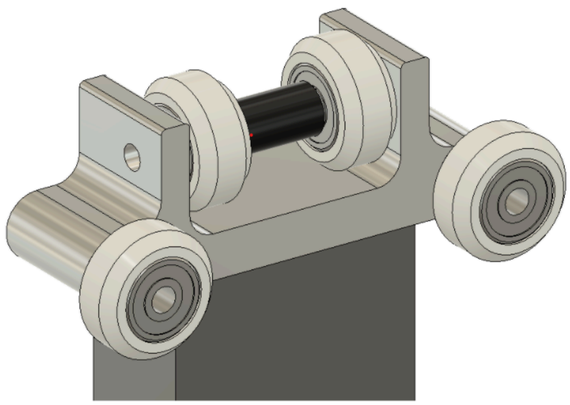
What are some existing solutions to those common problems?

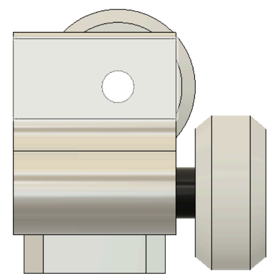
Designing end pieces for bearings that self align and require minimal work to assemble accurately would solve the alignment issues. This would allow the product to have low clearance and reduce play which would improve motion precision and prevent damage to the end pieces. To address the metal on metal grinding and inefficiencies, roller bearings coated in polycarbonate or nylon would reduce friction and prevent the bearings from wearing down the rail. The bearings can be replaced easily if necessary, but the rail is much more difficult and expensive to manufacture.

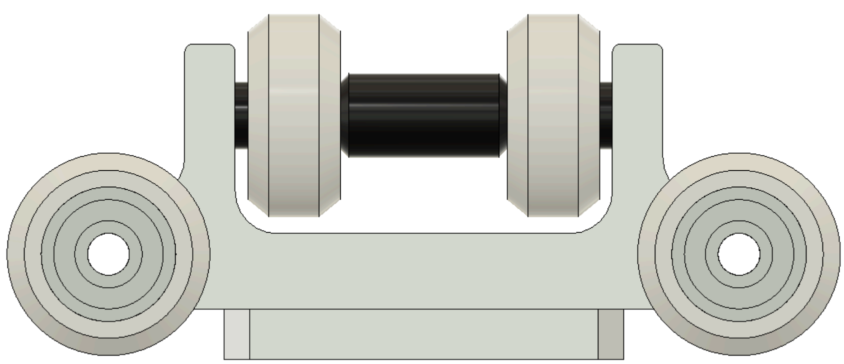
Possible Solutions

Solution #1

Design Solution #1 was my first approach to this problem. It was an interpretation of an approach common to FRC in which the bearing blocks or mounts are placed at the end of square tubing. The design was sleek and professional. It also had many core ideas that were useful later, but it didn't prioritize practicality. It was quickly tested and served as a proof of concept for the fitting concept, but the profile was structurally un-optimal, required a tedious and expensive manufacturing process difficult, and didn't allow for an integrated pulley system. It was aesthetically pleasing at the cost of functionality.



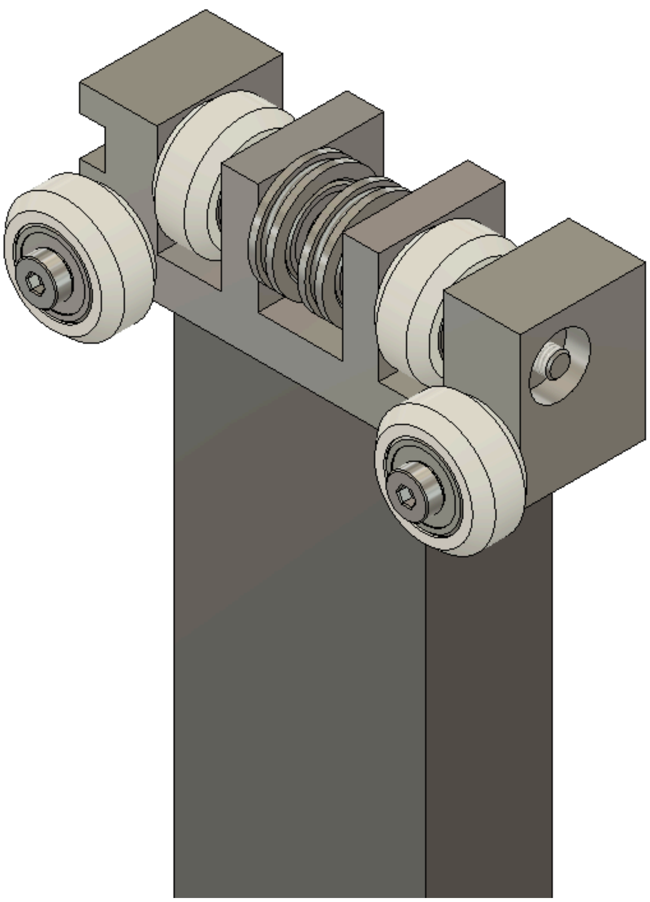


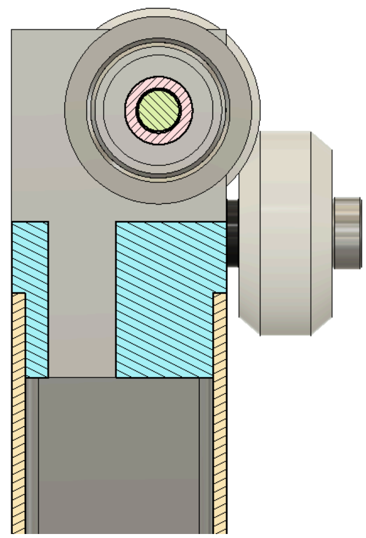


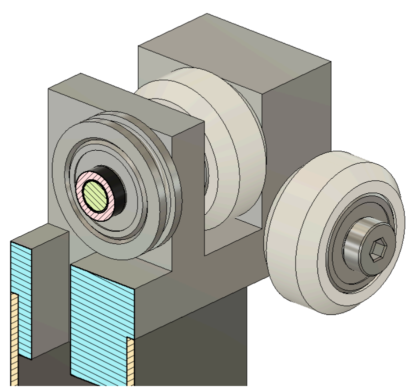
Solution #2

Solution #2 seems similar to solution 1#, but after closer inspection, it is clearly functionally different. The simple, jagged geometry allows for a robust structure, relatively easier machining, and a quicker manufacturing and assembly process. These benefits compounded with the competition tested bearing block concept and modularity of a small fitting to create an extremely practical solution. It did come with aesthetic and weight drawbacks, but the added weight was minimal and visual appeal isn't a significant factor for resource constrained FRC teams. The amount of added volume and weight was less than a 50% increase to solution #1 which is nearly insignificant when considering the minimal percentage of robot weight the fitting accounts for.

Solution #2's added rigidity and robustness provides an opportunity to incorporate an integrated pulley system for powered linear motion. The pulley system is an accessory feature that didn't have a major impact on picking a solution, but still a relevant feature of the solution

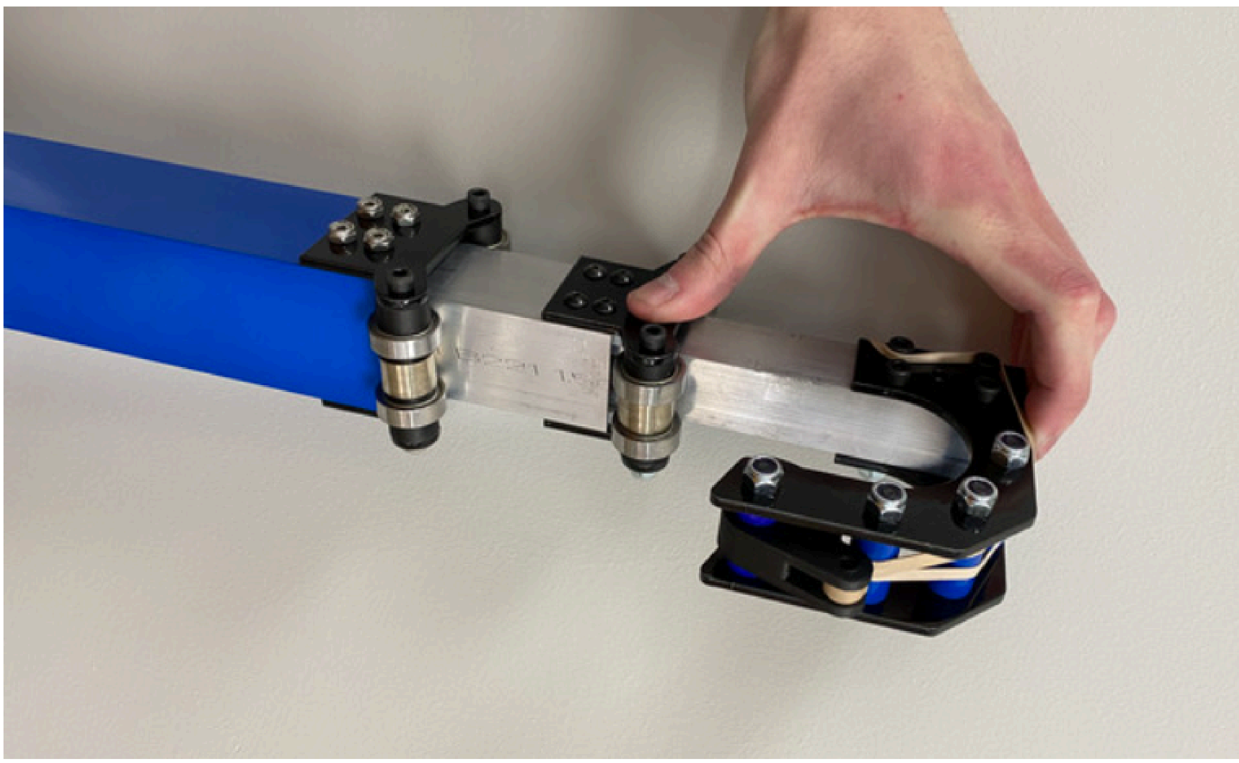






Solution #3

Telescoping elevators are an unconventional linear motion system in FRC, but some teams have found success with them. Telescoping systems are generally stronger and more compact than alternatives, but bring added cost and complexity with those benefits. They are also self-contained systems that reduce opportunities for interference with other mechanical systems on the robot and failures. Each stage of the system is progressively smaller which limits the maximum length, but this is rarely a problem in FRC as the required extension has never been greater than 3 times the robot's maximum height. However, the size changing stages do require a unique mechanism for each individual stage which makes designing the systems extremely time consuming, expensive, and non-modular.



Choosing a Solution

Solution #2 was selected as the final design through a decision matrix (Appendix C) that weighted different features proportionally to their importance to the project. The criteria utilized in the decision matrix (Appendix C) were added through a combination of survey results, market research, and FRC experience. The feature weights selected based on their importance to the project which focused on out-competing competitors.

Survey results indicated dissatisfaction with certain aspects of competing pre-built linear motion systems and the criteria reflected a focus on those aspects. 50% of teams were completely dissatisfied with their kits. Half of teams said substantial in-house manufacturing and assembly was required to use the kits and 75% considered their systems loud enough to cause disruptions. To reduce the amount of in-house work and unnecessary complexity, ease-of-assembly was the highest weighted criteria on the design. Simplicity and modularity were also included with substantial weights to combat this issue. Noise reduction was also given the second highest weight as none of the available competing products mention or address the issue in any way shape or form.

In addition to beating competitors, a baseline for functionality is required. Teams won't buy a silent, modular, easy to use system if it can't fulfill basic FRC requirements. This contributes to the addition of robustness to the decision matrix with a large weight.

Feature	Feature Weight	Solution 1	Solution 2	Solution 3
Ease of Assembly	10	8	9	3
Simplicity	5	6	8	4
Robustness	7	4	6	9
Noise Reduction	7	8	8	2
Low Price	7	2	8	5
Modularity	5	8	8	4
Appearance	3	10	4	8
Integrated Pulley	3	10	0	5
		308	336	221

The three solutions were then plugged into the decision matrix and had their scores calculated. Their scores for each criterion were measured not with absolute measurements, but on a relative scale. For example, the fitting solutions #1 and #2 scored nearly identically on ease of assembly, modularity, and noise reduction as their functionalities were similar in those aspects. Comparatively, solution #3 was much more complex and specific which reduced its modularity and ease of assembly scores. It was also inherently compact which didn't allow for the space required for large, noise-reducing, silicon roller bearings and scored poorly on noise reduction.

In the robustness, solution #3 outperformed the aesthetic, impractical solution #1 due to its relatively higher strength. Alternatively, solution #1 scored highly in aesthetics, but this didn't contribute much to its score as visual appearance is a secondary concern in FRC. Teams are focused on engineering and winning the competition, not making a dysfunctional, but flashy robot.

Solution #2 was selected for its dominance in simplicity, ease of assembly, and modularity as well as its adequate robustness. These criteria were essential to the project and allowed solution 2# to rise above its alternatives who excelled in other, less essential qualities.

Project Schedule

The project schedule was designed with a methodology that balanced swiftness, and time and risk management. Each task was designated slightly more than the minimum amount of time that would allow it to be reliably completed. This allows for timesave in some sections of the project that along with the extra designated time compensate for unpredictable delays or disruptions. Early critical tasks that would have a significant impact on the project as a whole like Topic Selection and Initial Brainstorming had extra time for careful consideration due to their importance. Other Critical tasks that involved producing the final physical product like Prototyping and Final Testing had extra time because they are crucial to the project and will likely have some failures that need to be accounted for. “See Appendix E for more specific information on the the project schedule”

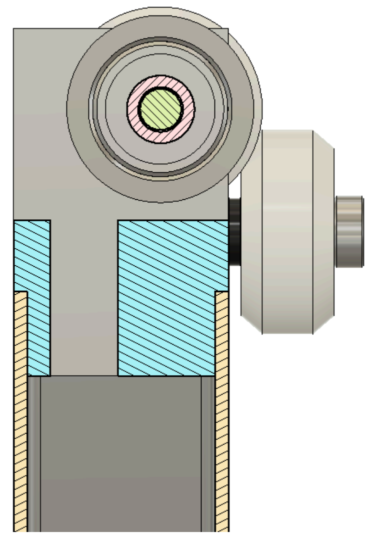
Development Work

After the concept was fleshed out, specific decisions had to be made. Material selection was made in accordance with FRC rules and the final decision was 6061 aluminum. Aluminum was selected for relatively easier machining, a high strength to weight ratio, and weldability. 6061 aluminum in particular excels due to its corrosion resistance, weldability (which is essential for this part), and high tensile strength when compared to other alloys. The dimensions of the fitting allowed for a perfect fit inside 2”x1” aluminum bar stock.

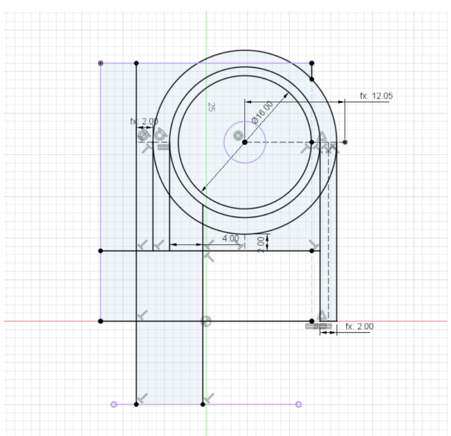
Then, mounting hardware had to be selected for the noise reducing roller bearings needed to be selected. Screws, precision shoulder screws, standoffs, and threaded rod were all considered for the project. While shoulder screws would have been the ideal option since they allow extremely high tolerances when mounting the rollers, they were exorbitantly expensive. The nylon coated roller bearings are a niche product mass produced in only one size. This meant a 5mm shoulder bolt with very particular dimensions were required for the fitting. Buying perfectly fit shoulder bolts would have doubled the cost and materials and in turn, final cost of the product. Additionally, shoulder bolts have a relative weak point between the thread and shoulder which would need to be accounted for in the part design. This increases the difficulty of machining the part and consequently, costs.

A combination of threaded rod and low profile screws were selected as the final mounting hardware. While tolerances were made less precise, this change was marginal and did not noticeably affect the performance of 3D printed tests of the part. The cost reduction massively outweighed the performance reduction.

During strength testing, we found that some variants of the nylon rollers were extremely brittle and would not be able to withstand FRC loads. Rather than flexing or holding up to stress, they would crack easily. Sometimes even a drop to the floor would crack the clear variant of the rollers. Luckily, this was not due to oversight of the issue. Different pigments in the nylon rollers substantially changed the properties of the material. It was noted that only the black variant of the selected rollers would be used since they were the strongest of all variants and cost the exact same.



The integrated pulley system was tackled after the critical design goals were addressed. To simplify the setup process, the pulleys and cable will be provided with the product. The dimensions of these parts were critical as deviations of even one millimeter would prevent the system from functioning. The integrated system ran pulleys within and between the stages meaning that precise calculations had to be made in CAD to ensure proper cable alignment.



5/64” Dyneema cable was selected for the project. Dyneema is an industrial grade fiber cable used in high load boating and fishing applications. It is also commonly used by rock climbers making thin, reliable, load bearing variants common for a reasonable price. A single strand of 5/64” is rated for 900 lbs of load, and this system allows for a maximum of 4 cables in one direction carrying a theoretical load of 3600 lbs. This is an order of magnitude above what is required for FRC and the system making the cable the final point of failure. It is also extremely economical. 100ft of 5/64” can be purchased for under $25 on Amazon.

The most difficult part of the development process was planning the machining process. Many considerations had to be made due to tool and machine limitations in our workshop. For example, our longest end mill had a maximum 1” cutting depth. Additionally, even the heavily simplified Solution #2 required a minimum of four setups for every part. This complicates the manufacturing process and if ever mass produced, this part would need to be done in bulk through fixture plating. The four operation process also introduced complexity as there are, in theory, 24 unique possible setup sequences.

We decided to do the, facing, roughing, and finishing of the part’s top surface first. This side would remove excess stock from the top of the material and cut out slots for the roller bearings and pulleys. This decision provided a flat surface, square to the rest of the part, that would allow for easier alignment for the rest of the set ups. Milling out the bottom portion with the fitting plug would cause difficulties when setting up the part for the top surface and later drilling operations.

The next set up and operation was the bottom side of the part. This operation would remove excess material from the sides and precision cut the piece of the fitting that would plug into the aluminum tubing used in the system. This section needed to be cut out before the drilling operations that made the mounting holes for the rollers and pulleys. This was important because the plug section of the fitting is the piece that would directly interface with the 2"x1" aluminum tubing. This part would determine the position of the fitting and refining critical dimensions to it will create perfect spacing for holes and give the final part superb alignment and fit.

The final operations were the two drilling operations. As mentioned previously, these will be referenced to the bottom plug of the fitting. The final drilling operation is the single long hole that holds the threaded rod for two roller bearings and the pulleys. This hole needs to be 90mm (~3.5 in) deep which will cause many difficulty machining. A specialized extra long drill bit is required for such a deep drilling operation. The cut also has to be done slowly and carefully to compensate for the high head and friction caused by that kind of operation. Even after taking these precautions, there is still a high risk of breaking the bit and losing the part with this kind of operation. We decided to drill the first half of the hole with the CNC mill to provide a precision milled pilot hole and to drill the last bit by hand. Doing this operation with a CNC milling machine is finicky and risky. Hand drilling the last section will be tedious, but will break less drill bits and save valuable time, materials, and money. The pilot hole will also provide alignment for the hand drilling operation and allow it to maintain tight tolerances.

Evaluation

The project was successful in most regards, but poor time management, material ordering delays, and machining inexperience caused enough delays to prevent me from machining the final aluminum versions. Despite this significant failure, the project was successful in other regards.

For example, the design was thoroughly examined in CAD and had several 3D printed iterations that tested the proof of concept. Even with weak plastics like PLA, the fittings were surprisingly sturdy. Multiple 3D printed iterations increased the rigidity and strength of the design beyond that. Furthermore, the tested motion displayed by the 3D printed tests was substantially smoother and had much tighter tolerances than a tested competing linear motion system. (https://www.andymark.com/products/2x1-single-stage-hd-elevator-bearing-and-structure-kit) Despite having substantially less precise tolerances that the Tormach 770 CNC machine, the hobby level 3D printers like the CR-10 could produce excellent results. The current design shows great promise. All that is left is to machine it and hammer out any possible unexpected design issues that could be left.

Nearly all of the required design criteria will definitely be met, and the overwhelming majority of other, less desired goals were still achieved. The design criteria feature matrix (Appendix C) lists easy assembly, the ability to lift and hoist 150 lbs, smooth, frictionless motion, weldable to 2”x1” aluminum square tubing, and a price below $35 per fitting as the “Must Have” criteria. The design is on track to lift well above the 150 lb load and well below the $35 per fitting cost requirement. This leaves a lot of room for matching costs in the price requirement. The rest of the criteria are met completely through material and hardware selection.

Other, non-essential, but strongly desired criteria were met such as, an integrated pulley system for two-way powered motion, low maintenance, and sound reduction. On the entire part, there are only two screws that may need to be occasionally tightened. If they are locked into place with a threadlocker like loctite, they will stay in place permanently. All the other components will be assembled and locked in place by welds. Sound reduction is achieved through the selected nylon roller bearing that prevents loud, inefficient metal-on-metal contact.

Unfortunately, Adjustable tightening for the roller bearings was not achieved. Ideally, there would be some way to adjust the fit of each fitting onto its mating slider. An assembly like this would be too complex, drive up costs, and require added maintenance. Additionally, a CNC machined part will have tolerances within 2 thousandths of an inch ensuring an adequate, but not perfect fit. With more time available, I would have taken more time to research this possibility and test potential
solutions, but for reasons mentioned above, it would likely be time and resources wasted.

Recommendations and Future Work

After manufacturing the first aluminum machined versions of the product, any potential problems will be ironed out and the next step will be moving into high volume production. A fixture plating system can allow for potentially 12 setups at a time in the machining process on a single CNC mill. The process can also be moved to a specialized software like Mastercam to maximize speed and efficiency when generating these complex tooth paths. At the moment, Fusion 360 is being used for the sake of speed and convenience.

After gaining experience and learning from the fixture plating and high volume production process, the design will need to be reevaluated. More modifications or even a complete redesign of the part with previous experiences in mind will optimize the manufacturing process and will reduce costs and time spent manufacturing.

Welding could also be reevaluated as the primary mounting solution as it is inaccessible to many teams and too permanent for complete modularity. It was selected to reduce in house manufacturing difficulties, especially the amount of holes that needed to be drilled into the 2”x1” aluminum square tubing. This did make the assembly process substantially easier, but more possibilities exist that could potentially combine that benefit with increased accessibility.

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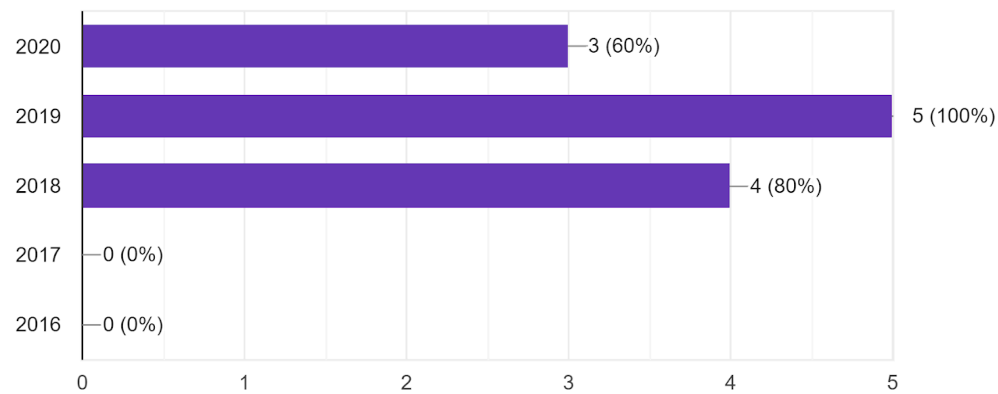
Appendices

Appendix A: Market Research Survey

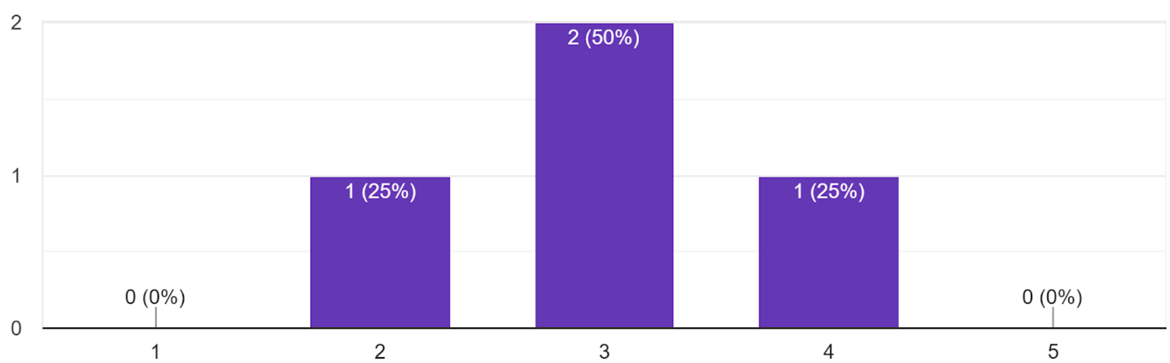
What year(s) did your team use a lift/elevator system?

5 responses



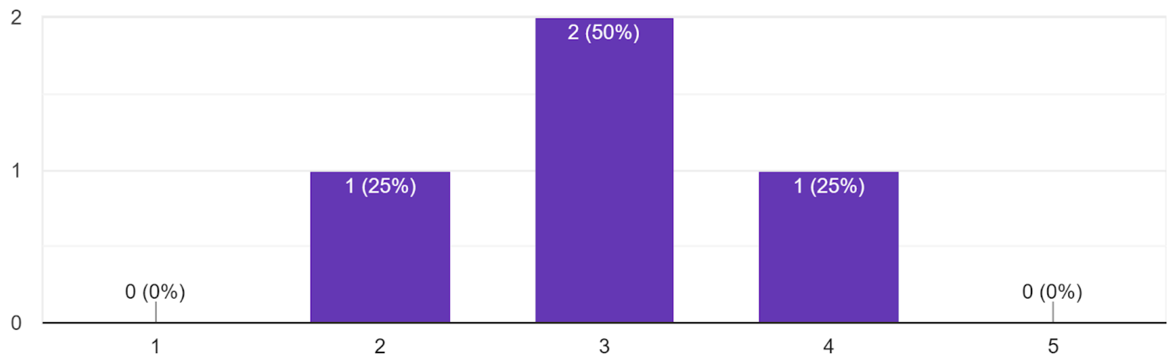
How robust was the lift?

4 responses



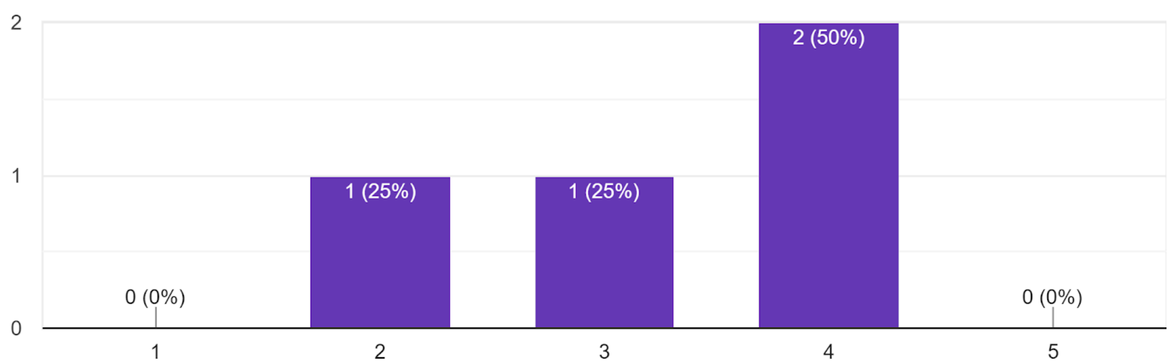
How was the assembly process?

4 responses



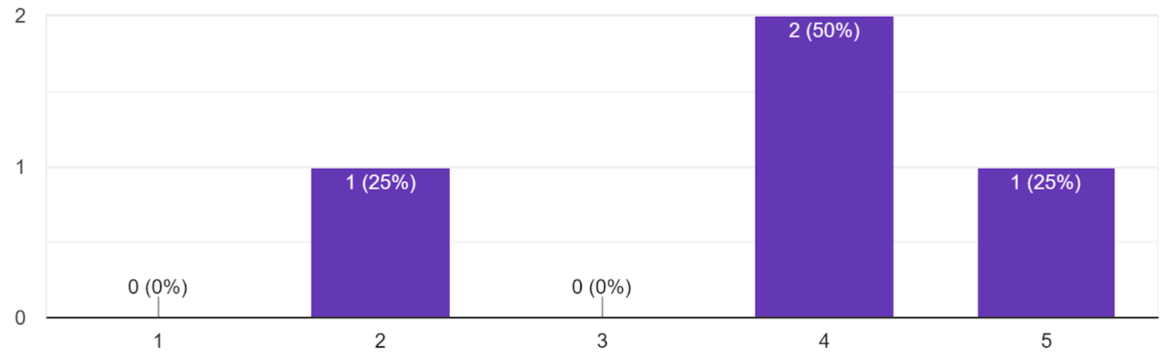
How much in house manufacturing and/or modification was required to use the lift

4 responses



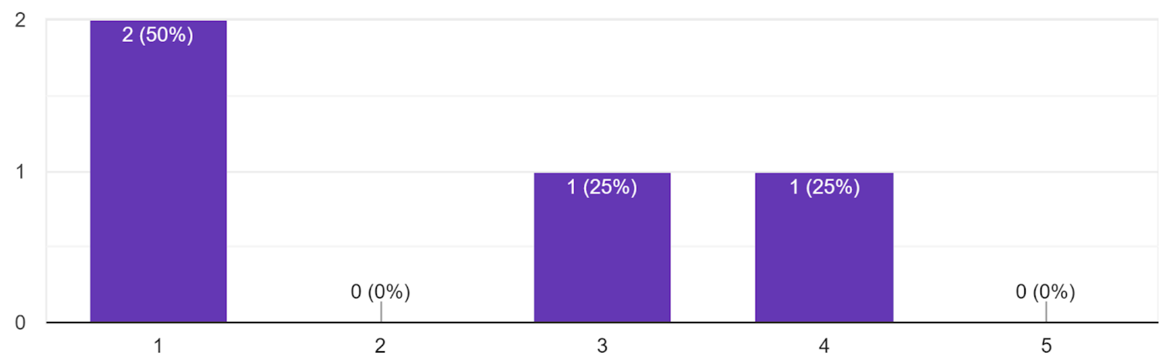
How quiet or loud was the lift?

4 responses



Overall, how satisfied were you with the kit?

4 responses



Appendix B: Feature Matrix

Percieved Need:	Criteria:
Must Have	- Easy of assembly
	- Capable of lifting and hoisting at least 150 pound loads
	- Roll smoothly and minimize friction
	- Weldable to Alluminum 2"x1" 1/16" thick aluminum square tubing
	- Under $35 per fiiting
Strongly Desired	- Integrated pulley system for powered motion
	- Two way powered motion
	- Adjustable tightening for rollers
	- Low maintnence
	- Low sound
	- Under $30 per fitting
Marginally Desired	- Low sound
	- Under $25 per fitting
Not Desired	- Unintentional spontaneous deconstruction
	- Instablity and unprecise motion
	- Rough motion
	- Over 0.5 pounds per-fitting

Appendix C: Decision Matrices

Feature	Feature Weight	Solution 1	Solution 2	Solution 3
Ease of Assembly	10	8	9	3
Simplicity	5	6	8	4
Robustness	7	4	6	9
Noise Reduction	7	8	8	2
Low Price	7	2	8	5
Modularity	5	8	8	4
Appearance	3	10	4	8
Integrated Pulley	3	10	0	5
		308	336	221

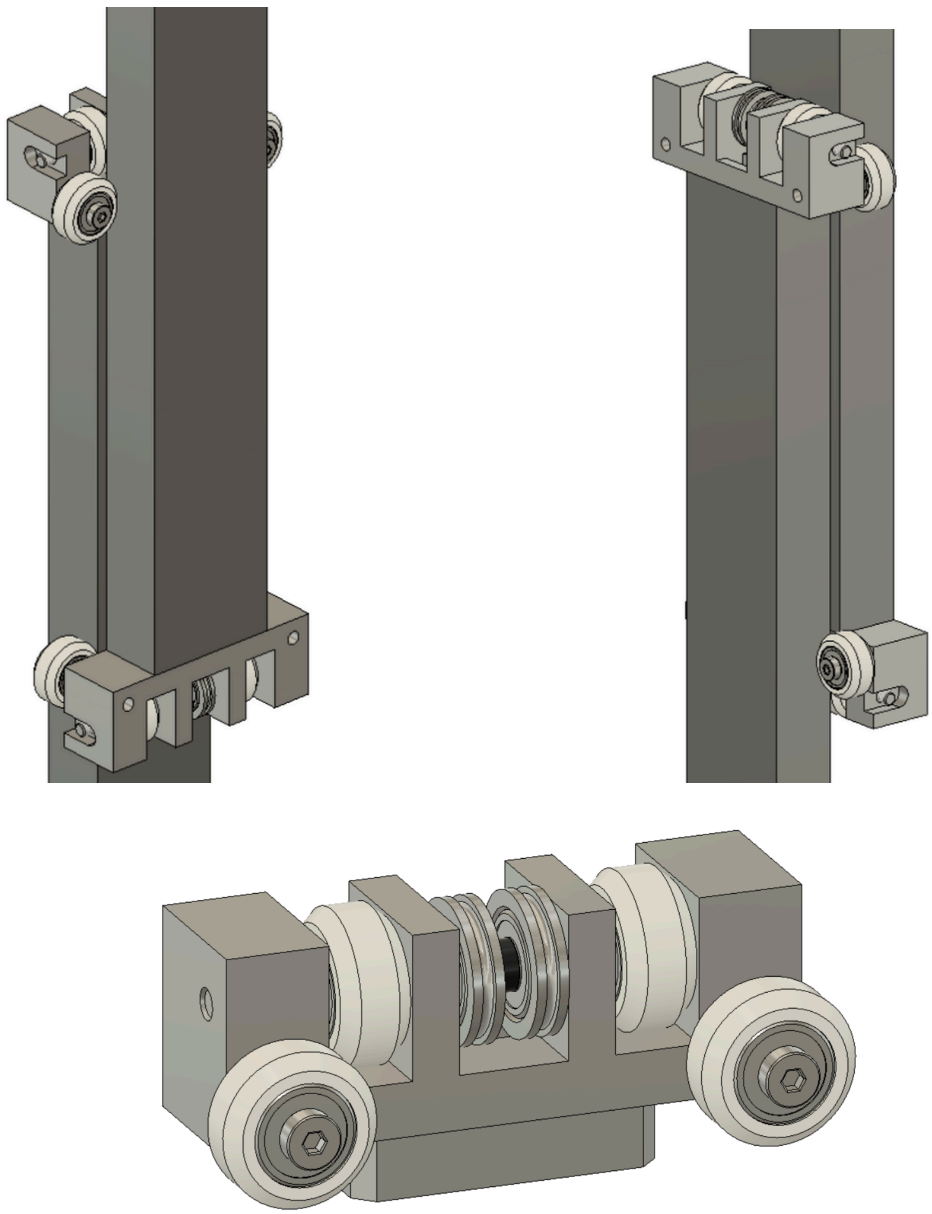
Appendix D: Design Brief

Client	School and educational robotics clubs and orgs that compete in FIRST Robotics Competition.
Designer	Edward Maddox
Problem Statement: *The problem statement should only state what the underlying problem/s are. There should be no mention of solutions or design intent.*	A robot needs a system to linearly translate heavy objects and items with a simple, robust mechanism. The system needs to be fast, simple to assemble, and can't cause noise disruptions.
Design Statement: *The design statement should be very clear. The performance specifications should be quantifiable. Avoid generalizations and/or opinions. There should be several performance specifications (5+).* ****Criteria/Specifications***	The product is a CNC machined aluminum fitting that plugs into hollow 2" x 1" aluminum channel. It has roller bearings attached that allow you to use two adjacent channels as a linear slide. The piece plugs into the end of the channel and can be used modularly for multiple stages of motion. It also has a self contained pulley system that allows for powered extension and retraction of the slides.
Constraints: *Include time, budget, materials, size, weight, manufacturing methods, skills, etc.*	The part must be designed and tested in 8 weeks, has a limit of $30 per fitting, must be machinable from solid 2" x 1" aluminum stock, weigh under ¼ of a pound and must be manufacturable in a 3 axis CNC machine.
Deliverables: *What will you be producing?*	The final fitting will be a pre-assembled fitting with its rollers and pulleys attached. The fittings will be to the 2" x 1" channel by the client.

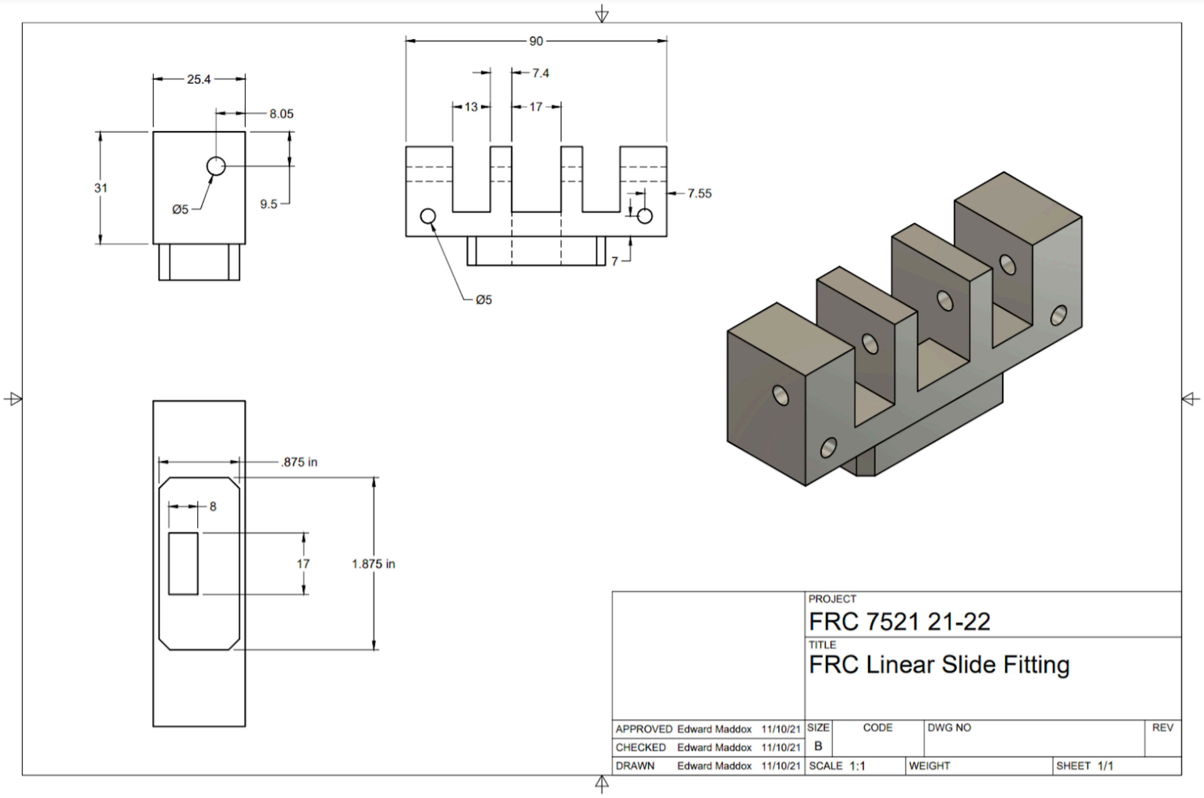
Appendix E: Project Schedule

WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	PHASE ONE														
					WEEK 1					WEEK 2					WEEK 3				
					M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
1	**Project Conception and Initiation**																		
1.1	Background Research	Edward M	8/20/21	8/22/21															
1.2	Topic Decision	Edward M	8/25/21	8/27/21															
1.3	Research	Edward M	8/28/21	8/28/21															
1.4	Brainstorming	Edward M	8/29/21	9/2/21															
1.5	Possible Solutions	Edward M	9/3/21	9/3/21															
1.6	Choosing Solution	Edward M	9/4/21	9/4/21															
1.7	misc	Edward M																	
2	**Project Definition and Planning**																		
2.1	Overall Schedule	Edward M	9/5/21	9/5/21															
2.2	Schedule Critial Tasks	Edward M	9/8/21	9/8/21															
2.3	Incorporate into Notebook	Edward M	9/9/21	9/10/21															
2.4	Manage Delays/Difficulties	Edward M	9/11/21	9/12/21															
3	**Project Conception and Initiation**																		
3.1.1	Early Prototyping	Edward M	9/15/21	9/17/21															
3.1.2	Prototype Analysis	Edward M	9/18/21	9/18/21															
3.1.3	Major Desing Decisions	Edward M	9/19/21	9/22/21															
3.2	Near Final Testing	Edward M	9/23/21	9/25/21															
3.3	Final Fine Tuning & Polish	Edward M	9/26/21	9/29/21															
3.3.1	Final Product	Edward M	9/30/21	9/30/21															
4	**Project Tesing / Monitoring**																		
4.1.1	Product Evaluation	Edward M	10/1/21	10/1/21															
4.1.2	Design Criteria Success	Edward M	10/2/21	10/2/21															
4.1.3	Desing Criteria Failures	Edward M	10/3/21	10/3/21															
4.4	Recommendations for Future Work	Edward M	10/6/21	10/7/21															

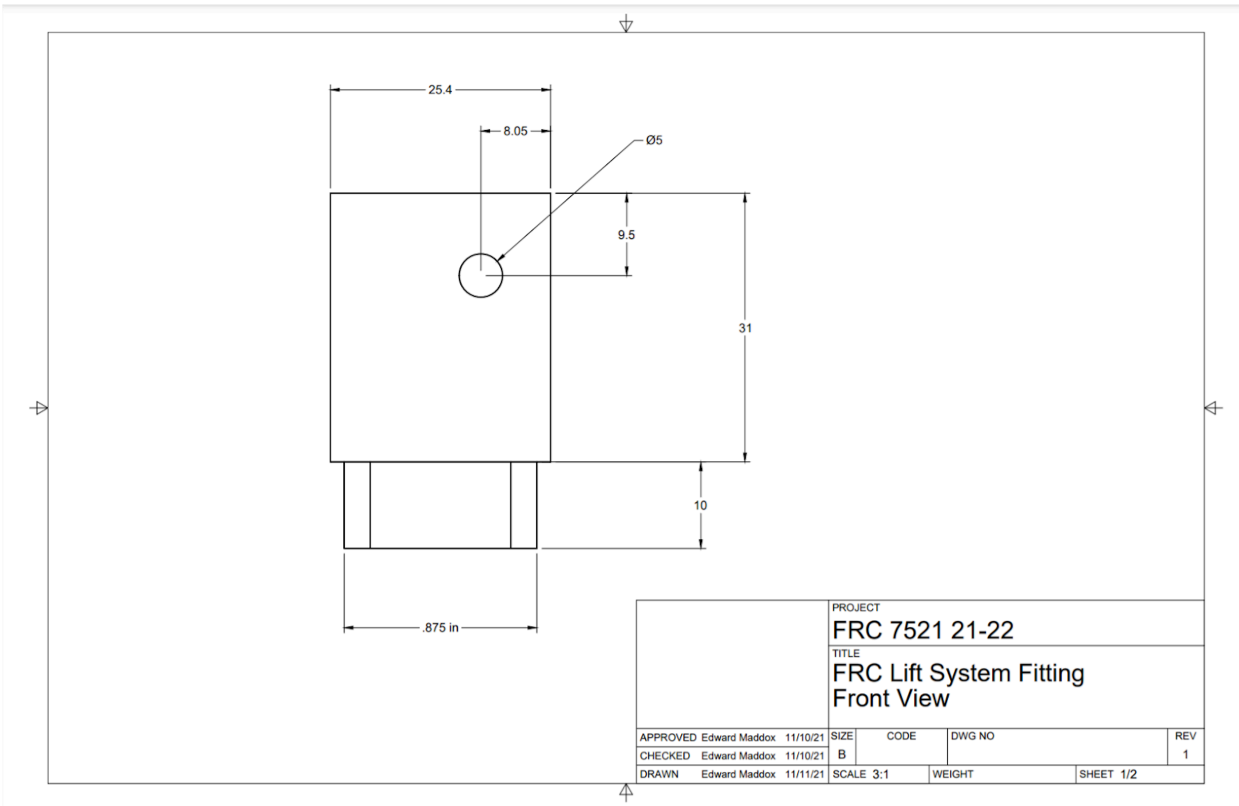
Appendix F: Final Design Marketing Renderings.

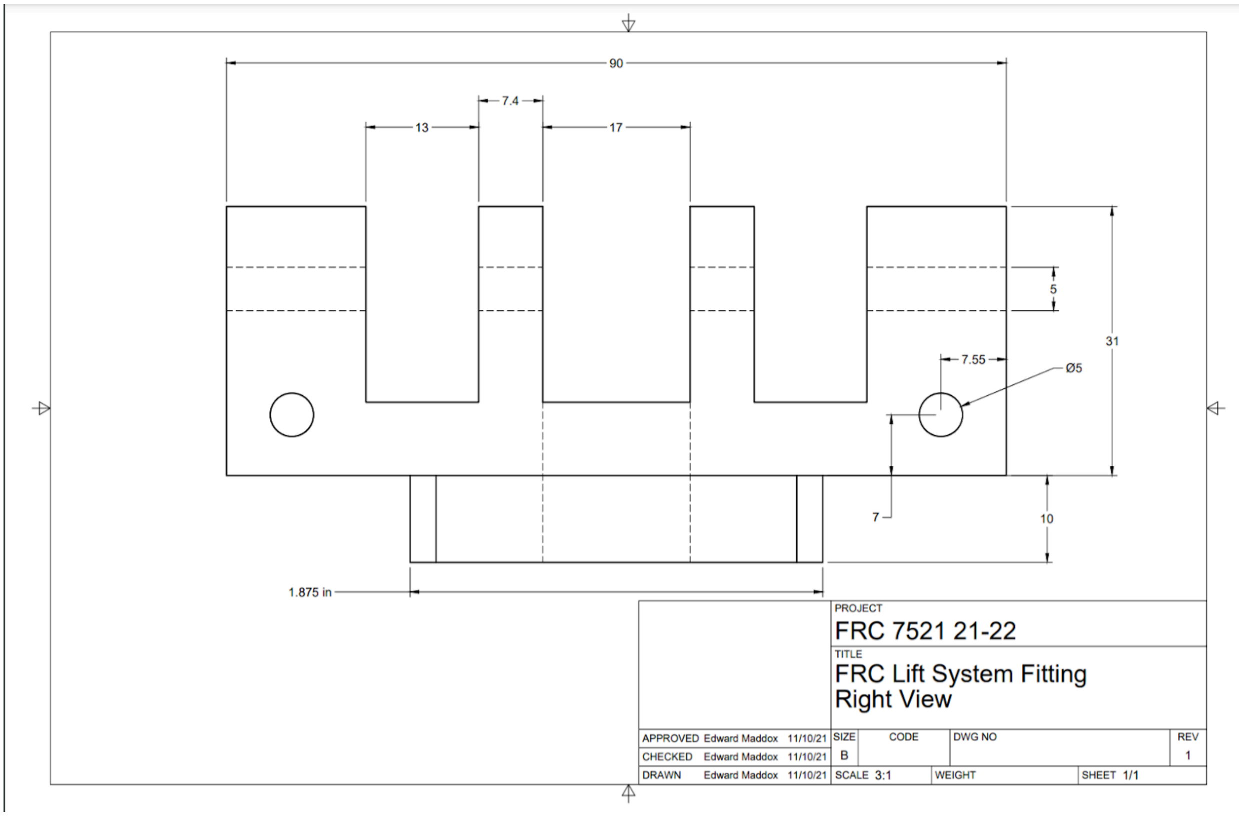


Appendix G: Final Design Orthographic Drawings.



Appendix H: Final Design Technical Drawings.




90
7.4
13
17
5
31
7.55
Ø5
7
10
1.875 in
PROJECT
FRC 7521 21-22
TITLE
FRC Lift System Fitting
Right View
APPROVED Edward Maddox 11/10/21
CHECKED Edward Maddox 11/10/21
DRAWN Edward Maddox 11/10/21
SIZE
B
CODE
DWG NO
REV
1
SCALE 3:1
WEIGHT
SHEET 1/1