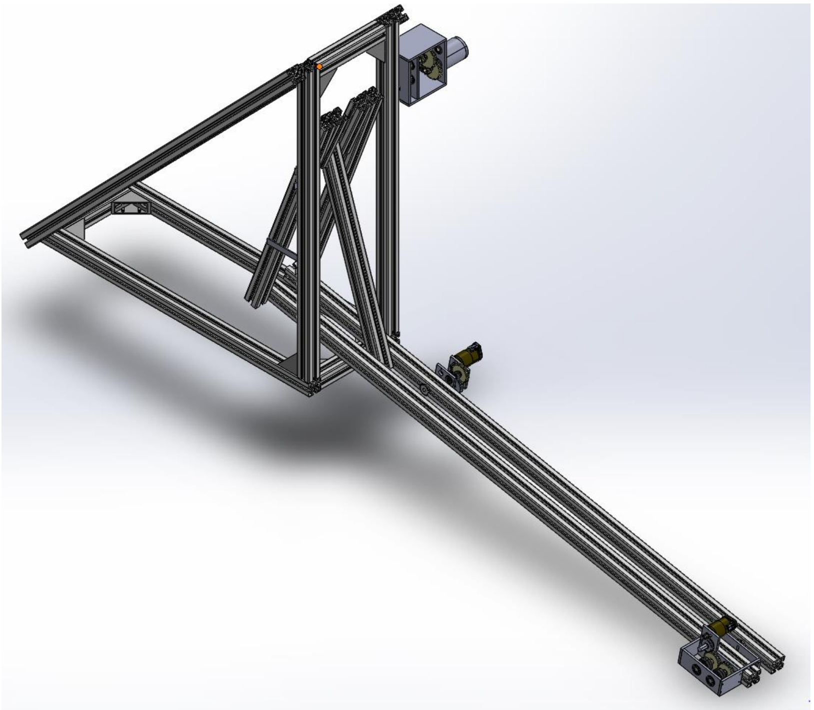
Developing a Device to Place Traffic Cones



A Major Qualifying Project
submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science in Mechanical Engineering

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Abstract

The goal of this project was to create a device to place traffic cones. Conventional methods of traffic cone placement are dangerous and inefficient, so this design aims to improve road workers' safety and use of time. The design uses a fourbar linkage, pulley system, and specially designed gripper, which work together in a cyclical motion to remove cones from a stack and place them alongside a moving vehicle. Our team fabricated this device using stock metal and robotic parts. After testing, we created recommendations for further development.

Acknowledgements

Our team would like to thank the following for their support:

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The WPI Mechanical Engineering Department
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Jim Kempton of the Worcester Department of Public Works
The George C. Gordon Library
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1. Introduction

This project aims to design a device to place traffic cones. Placing cones on the road by hand poses a risk to road workers, especially at night. In addition, current traffic cone placing devices are expensive and can only be used to place or pick up traffic cones. This device will aid road workers by setting up cones safely and efficiently, while remaining inexpensive. The intended clients for this device are public works departments and construction companies that would save money and time by streamlining their cone placing process.

The expected project outcome is for our team to design and create a prototype of a cone placing device, based on our research and functional requirements. The goal of this project is to design a device to place traffic cones.

2. Background

Cone Regulations and Sizing

To begin designing a mechanism, we need to know certain details about the cones themselves. Cones come in all shapes and sizes, depending on where and how they are used. The Federal Highway Administration produced the Manual on Uniform Traffic Control Devices (MUTCD), which specifies standards for design and placement of such devices. Since our mechanism will be used on highways, the MUTCD specifies to use the 36 inch cones with retro-reflective bands for maximum visibility. Additional details on the cone are in Table 1.

Parameter:	**Value:**
Weight	10 lbs
Base Area	14x14 inches
Material	PVC

Table 1: Traffic cone specifications

The MUTCD also specifies how the cones should be placed, depending on how workers want to control traffic. This is significant because our mechanism's cycle time will be based on the distance between cones and speed of the truck. In the case of highway control, section 6C.08 of the MUTCD specifies that cones should be placed every 20 feet.

The same section further explains how long to make tapered sections. Tapered sections are the areas before and after the work zone that are used to merge traffic into fewer lanes. The standard taper length is calculated using L = WS (W is width of the offset, and S is the speed limit). Assuming the highway lanes are a standard 12 ft wide, and the speed is 65 mph, this would make the taper length 780 ft, meaning we would need 39 cones per lane of tapering.

Pre-Existing Cone Placing Devices

There are several devices that are already used to place traffic cones. By analyzing these pre-existing mechanisms, we can determine their advantages and disadvantages and determine potential improvements to each design, thus informing our own design process. We have assessed three cone deployment devices to understand their principles and analyze advantages and disadvantages presented by each design.

Figure 1: The AutoCone 130 (youtube.com)

The first device is the AutoCone 130, a large trailer-style device that contains ten rows of twelve cones in a cylindrical arrangement (figure 1). This device uses a long metal arm to grip and place cones. This device is very consistent and effective, placing cones in the proper orientation and at regular intervals. Another advantage is that the AutoCone 130 can be pulled by a pickup truck or a larger work truck, improving its versatility. Furthermore, the AutoCone 130 is fully automatic and does not require any intervention from workers besides the truck driver. Some disadvantages of the AutoCone 130 include its size and cost. The AutoCone 130 is very large because it includes a storage space for rows of cones. Storing cones in stacks would require less space, but may be more prone to errors if adjacent cones stick together during placement. Additionally, the AutoCone costs over $50,000, making it a large investment for most public works departments. Finally, the AutoCone is very specialized, and public works departments may prefer more versatile devices.

Figure 2: The Roadrunner (royaltruckandequipment.com)

Another cone placer is the Roadrunner Cone Placement and Retrieval System by Royal Trucks and Equipment (figure 2). The Roadrunner uses a slide to place cones and a separate device to pick cones back up. In this design, a worker on the bed of the truck must individually load cones into the slide. This is not fully automatic like the AutoCone 130, but still requires much less manpower than the default practice of manually placing cones. The slide can be easily moved to either side of the truck, allowing for additional versatility. The biggest disadvantage of this device is that it relies on gravity to place the cones. Using gravity can be unpredictable and does not always place the cone in the proper orientation. Another disadvantage is that this method only works for cones with a fifteen-inch base, though the company is working on creating ways to accommodate cones of different sizes.

Figure 3: Automated Cone Machine (ucdavis.edu)

The Automated Cone Machine (figure 3) is able to store 80 cones. It is fully automatic, able to be controlled by just the truck driver with no additional workers. It includes options to place cones at a variety of intervals, including every 25, 50, or 100 feet. It is also able to retrieve traffic cones, including those that may have been knocked over. The largest disadvantage of this device is its cost, with estimated retail value at $60,000 to $80,000. Another disadvantage is that it requires the pre-existing CalTrans truck and cannot be used by other trucks. These two downfalls are significant, especially in comparison to the lower cost and greater versatility of the AutoCone130. This design would need to become less expensive to compete as a viable option.

Vehicles used to Place Traffic Cones

Though no regulations exist for how cones should be transported, most private companies have supply trucks that function as carriers for various traffic control devices. These trucks typically have a flat bed with basic barricades. For some operations, cones and other supplies are placed in crash attenuator trucks, which have an energy absorbing structure in case of a collision.

From personal conversations with Jim Kempton, the Director of Operations at Worcester Department of Public Works, traffic cones are a second thought. Public works departments such as Worcester’s do not usually have the budget to purchase vehicles for specific roles. Their trucks are outdated hand-me-downs from other departments and are not always suited to carrying large loads of cones along with other essential equipment. Often cones are racked along the front, thrown in passenger seats, or stuffed in a compartment meant for other items.

Under fortunate circumstances a few years ago, the Worcester DPW used windfall funding to purchase five brand new vehicles. The fleet welcomed several 2017 Peterbilt 348 Hooklift trucks, built by MHQ in Oxford, MA. These trucks can adapt to many different roles with less expensive equipment using their Hooklift system.

A Hooklift is a hydraulic lever system originally designed for use with dumpsters. This system uses a long arm secured at the middle of the truck bed to grip and raise a dumpster onto a horizontal frame. Though easy and fast to use, the system forces the dumpsters to sit high on the truck, and so the dumpsters are downsized. An advantage of this system is its versatility; other systems may be attached to the hooklift's skid and frame. As such, within five minutes, Worcester DPW can change a truck from a roadway deicer to a container truck, flatbed, supply, or any other specialized truck. Instead of needing to buy entirely new trucks for each role, they can purchase necessary equipment on a hooklift skid for use on the same trucks.

3. Functional Requirements

Functional requirements will provide goals and guidelines for the design process. These functional requirements are a result of background research and team discussions:

1. Must accommodate Highway Administration sized traffic cone
    a. Height: 36 inches
    b. Base size: 14 inches x 14 inches
    c. Weight: 10 pounds
2. Device should weigh around 55 lbs
3. Cones automatically pulled from stack
4. Corrosion resistant
5. Places cones
6. Picks up cones
7. Switchable to either side of the truck
8. Expected service life of 10 years
9. Picks up and places cones, no sliding mechanism
10. Modular Hooklift sled system; can be used by any hooklift fitted truck
11. Fits on 2017 Peterbilt 348 Hooklift truck
    a. Stellar Slider26 Hooklift
        i. Truck has a frame height of 40”
        ii. Hooklift system length 182.75”
        iii. Can carry up to 70 cones
12. Cone is less than a foot from the ground when released, low enough to stay standing on a variety of surfaces

4. Conceptual Designs

Part 1: The Fourbar

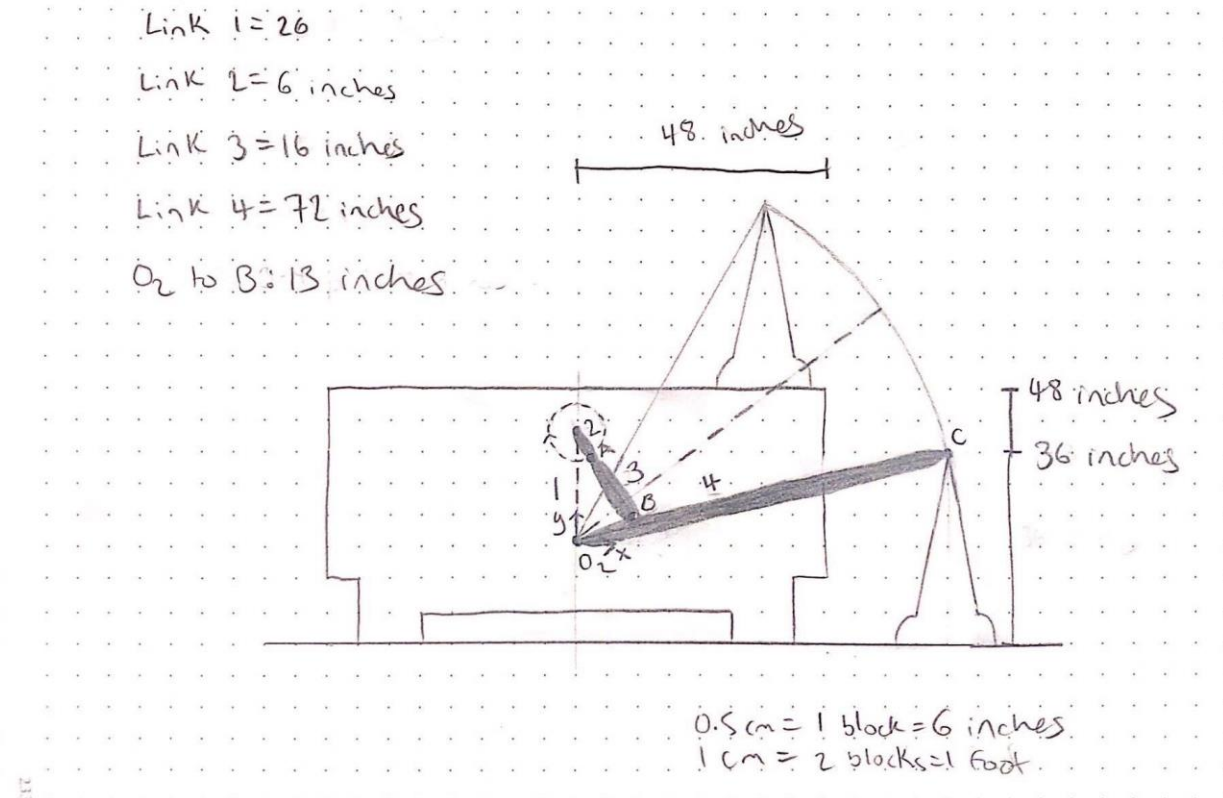


Figure 4: Hand drawing of early linkage concept

For our first design iteration, we used a hand-drawn two position synthesis to establish the motion necessary to lower a cone from the truck to the road (figure 4). From this, we determined that a fourbar with a driver dyad was best for our intended overall motion. The driver dyad rotates to raise and lower a long coupler arm, with the cone gripped at the end of the arm. We used kinematic calculations to determine appropriate lengths for each component of this linkage.

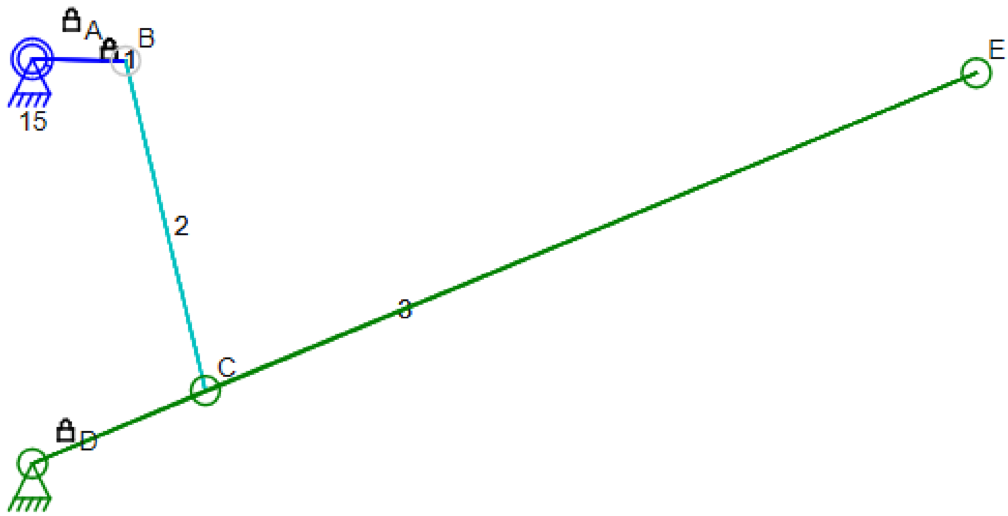


Figure 5: Computer generated model of early linkage concept

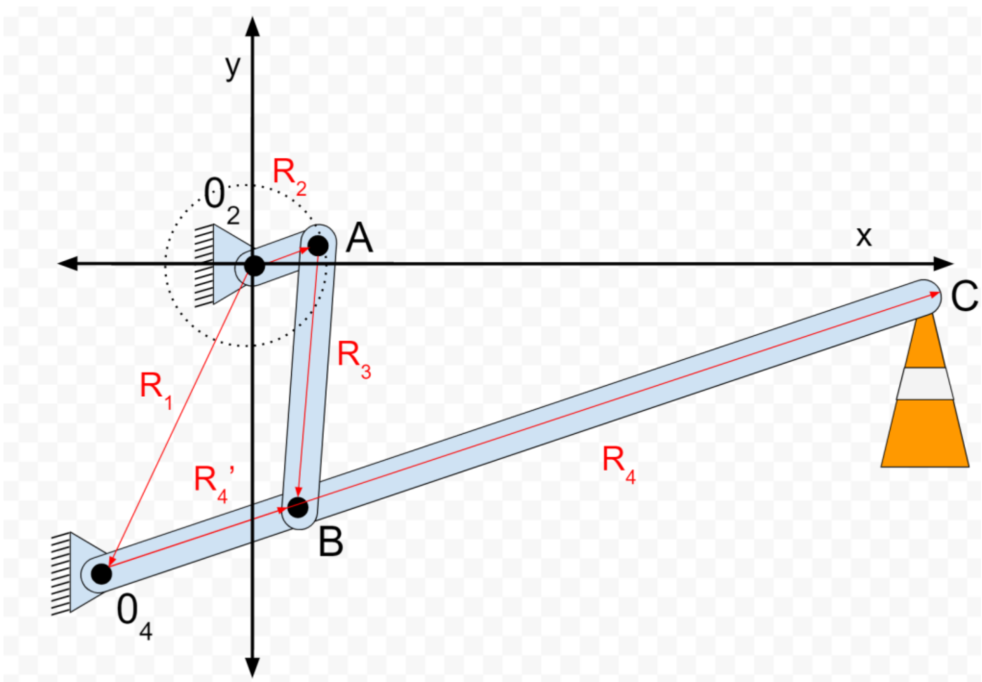


Figure 6: Improved computer generated linkage model

Using several different softwares, including Lingages (figure 5) and Google Slides (figure 6), we adjusted the ground points and lengths of links for the the fourbar. Before finalizing the lengths, we redid the process of two position synthesis in SolidWorks as a sketch. From this sketch, we created a three-dimensional model of the four bar using 80/20 stock aluminum profiles (figure 7).

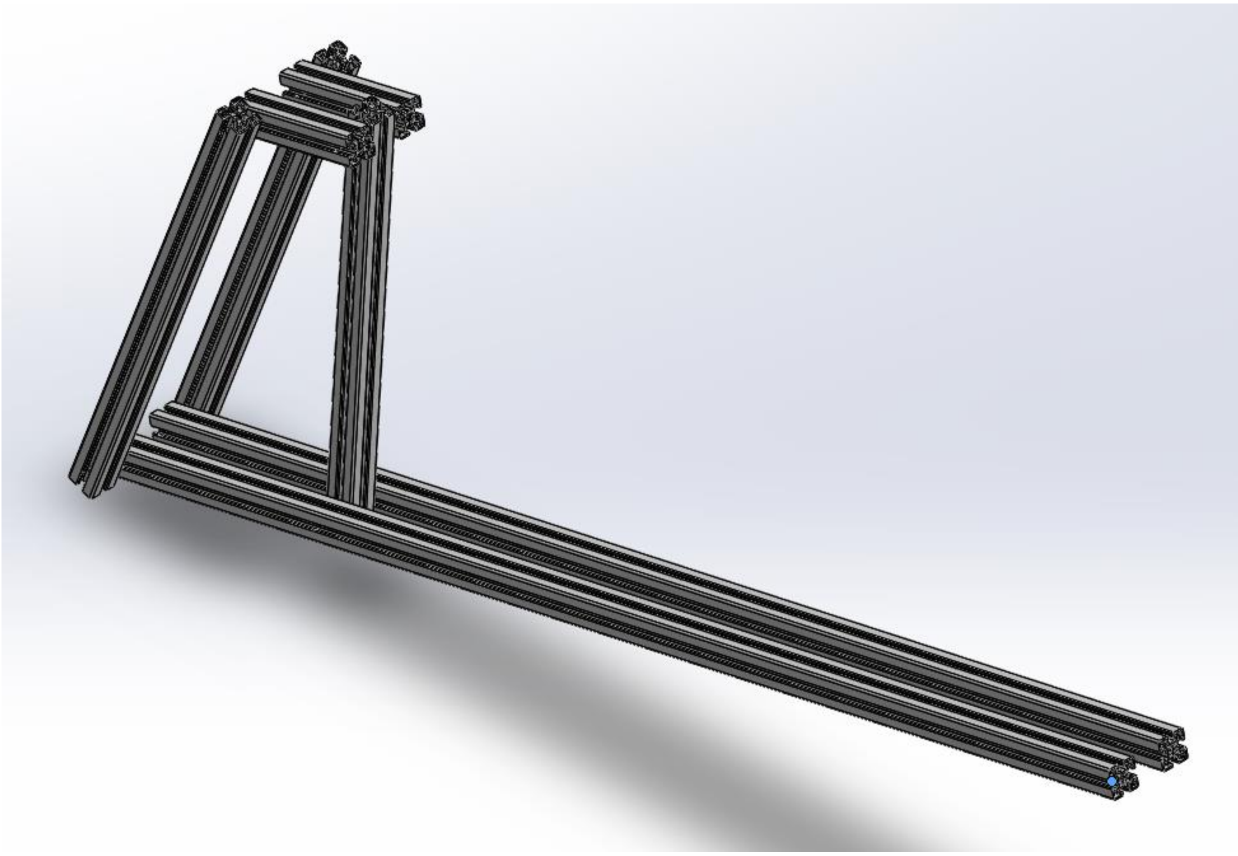


Figure 7: SolidWorks model of the fourbar

Our advisor recommended that we use 80/20 stock to create the fourbar. We researched stock profiles and materials and found options for a variety of uses. We primarily considered the 45 mm x 45 mm aluminum stock (figure 8) for its strength and durability.

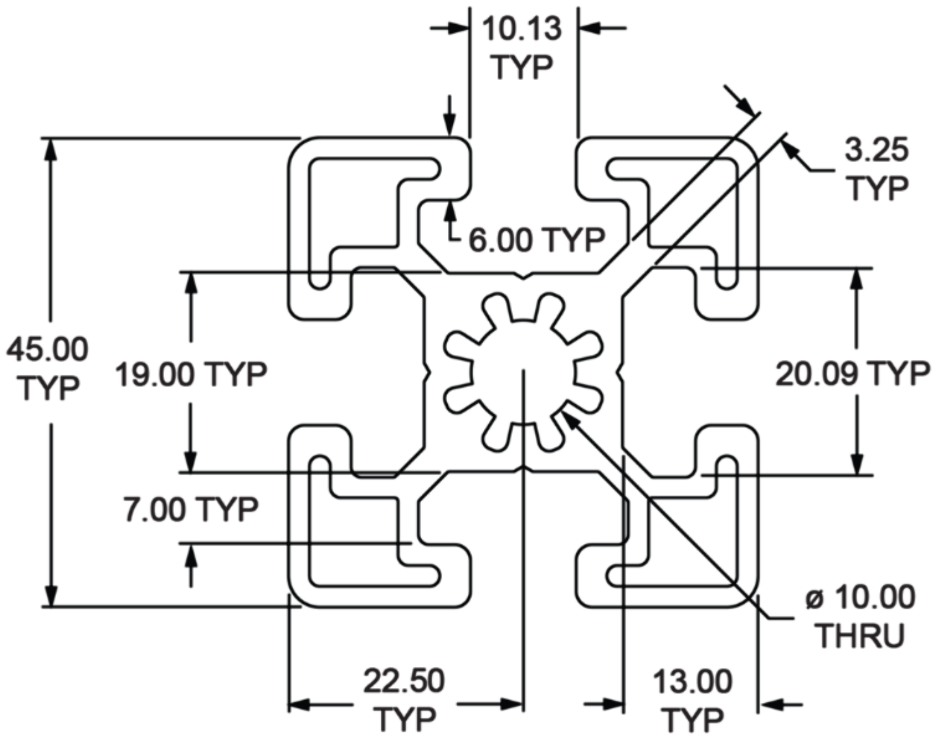


Figure 8: 45 x 45 mm stock profile dimensions

Part 2: The Skid Frame

We needed a method of securing our fourbar to the Stellar Slider26 Hooklift of the 2017 Peterbilt 348 Hooklift truck. We decided to make a skid frame out of 80/20 stock that could slot into the hooklift and support the fourbar throughout its motion. The first iteration of this design was a large rectangular box (figure 9).

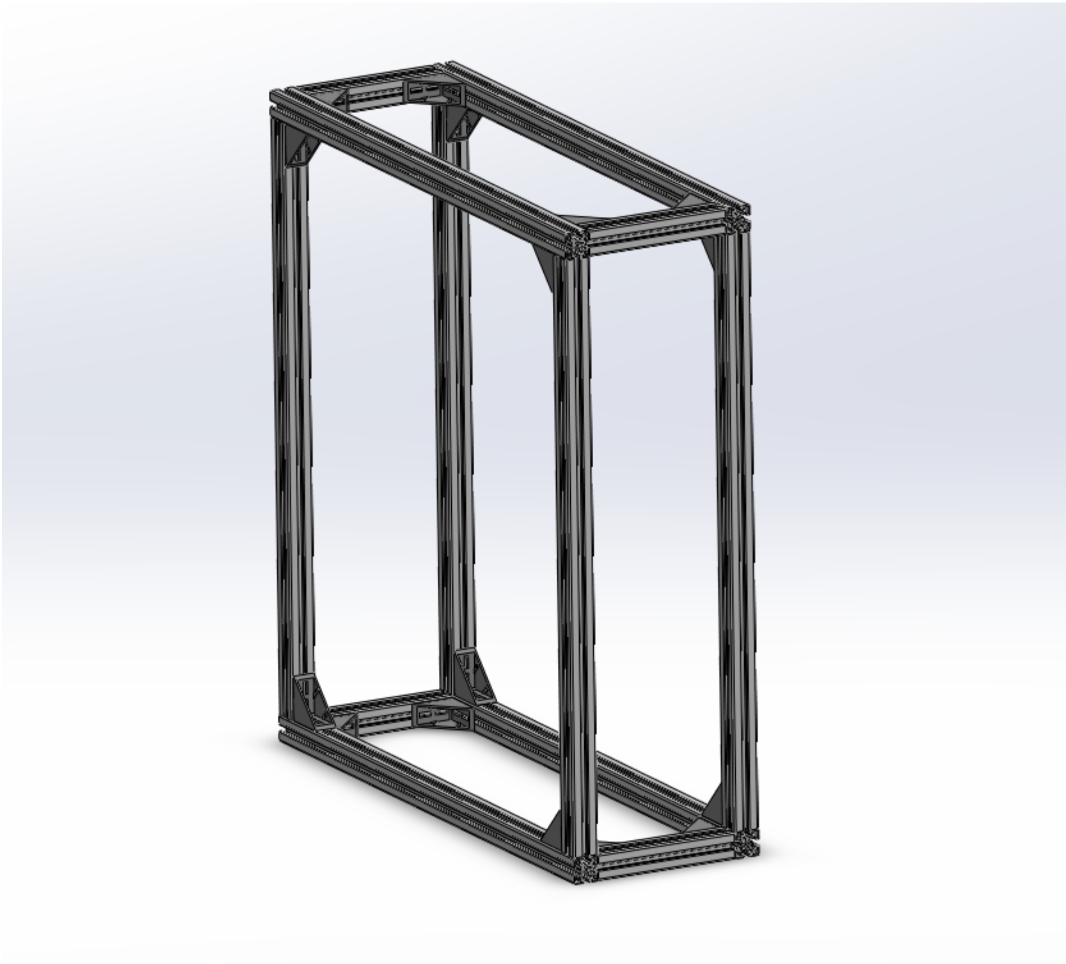


Figure 9: Rectangular skid frame iteration

As we continued to design and analyze, we discovered that this rectangular design was likely over designed and would be more than what the application required, thus wasting resources. We brainstormed alternatives such as cheaper materials or a smaller box. Our most promising alternative was to switch to a triangular design (figure 10), almost cutting material use in half and sacrificing very little stability. This triangular frame would use 80/20 stock aluminum, the same material as the fourbar.

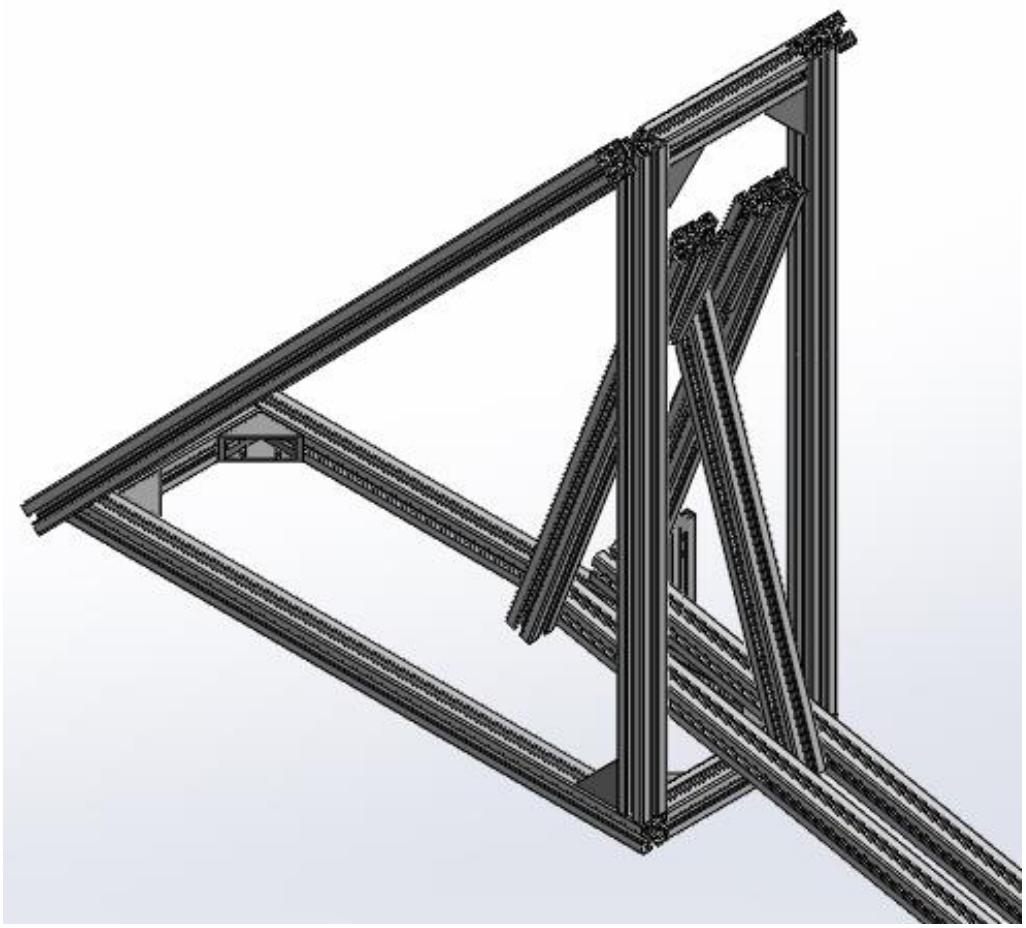


Figure 10: The triangular skid frame, shown with fourbar within

Part 3: The Gripper

We faced some difficulty when selecting a design for a cone gripper assembly. The options we had found were not specialized for gripping cones. Some of these mechanisms used flat metal bars to squeeze an object, and others used claw designs, all with small gripping surfaces in relation to the cone. These designs were imprecise for our needs and would probably not grip the cone consistently. We considered manufacturing our own attachment for the devices available, however that was also ruled out due to cost and reliability. Our final option was to design our own gripper from scratch. This had the potential to yield best results, but would likely require more troubleshooting than pre-designed options. We created a chart to compare the three most promising grippers: our own design using wheels, pneumatic parallels, and an off-the-shelf robotic gripper (table 2).

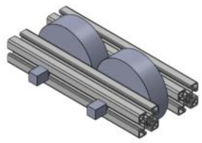
Name	Photo	Cost	Other Details
Wheels		~2.75x2 for wheels http://www.banebots.com/product/T40P-244BO-HS4.html ~$17.50 http://www.banebots.com/product/M7-RS775-18.html ~10 for arduino (we'll do this) ~$12.99 gear set ~$8.99 hex shaft ~$5 misc mounting and shaft collars	Might be better at getting cone off a stack? Don't know if the motors will be strong enough
Parallel Pneumatic		~50 for gripper ~10 for 3d printed attachment ~10 for arduino	Less chance of messing up because the moving parts come assembled
Off the Shelf		$150	Can't find a strength rating

Table 2: Gripper options

Part 4: The Pulley

For our mechanism to extend from the cone stack to the road, we needed a method of moving the gripper along the shaft. To accomplish this, we designed a pulley mechanism. Our first design (figure 11) involved small hooks on either side of the gripper. These hooks attach to a roller chain, which wraps around a sprocket on each end of the 4-bar shaft. These sprockets would be able to change rotational direction, so they can either push or pull the gripper along the shaft. This would be effective, although it would introduce the challenges of switching motor directions and timing with the overall motion of the mechanism.

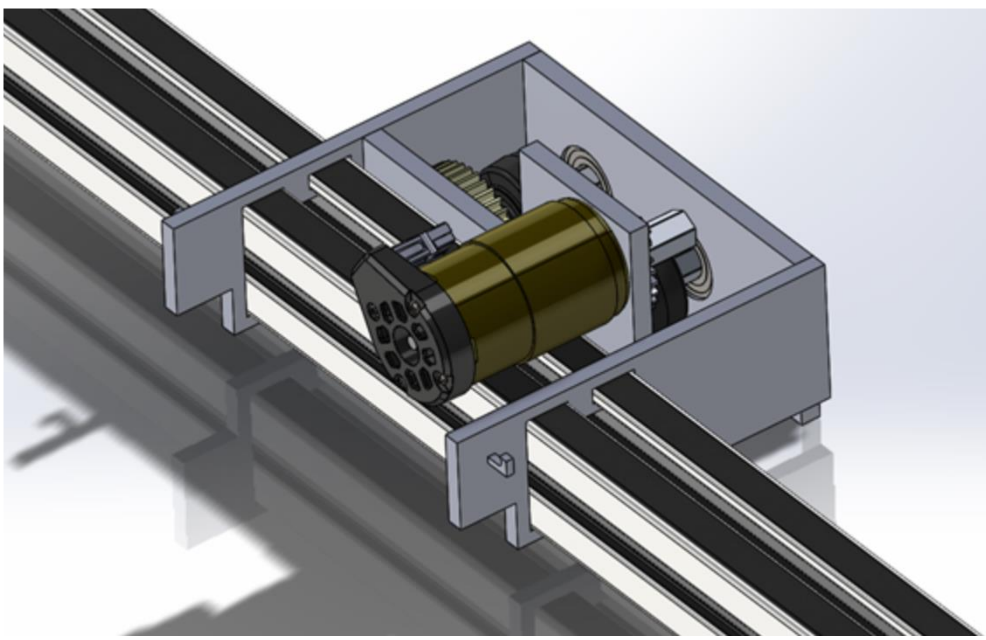


Figure 11: Initial pulley design

To solve this, we came up with a second design (figure 12). After researching alternative pulley designs, we developed a new mechanism that involved a slot cut into the gripper box. The roller chain interacts with the slot in such a way that it only needs to move in one direction. Upon reaching the sprocket, the chain rolls around and slides vertically through the slot. The chain then continues in the reverse direction, pulling the gripper with it. This design removes the challenge of changing motor direction as the mechanism moves.

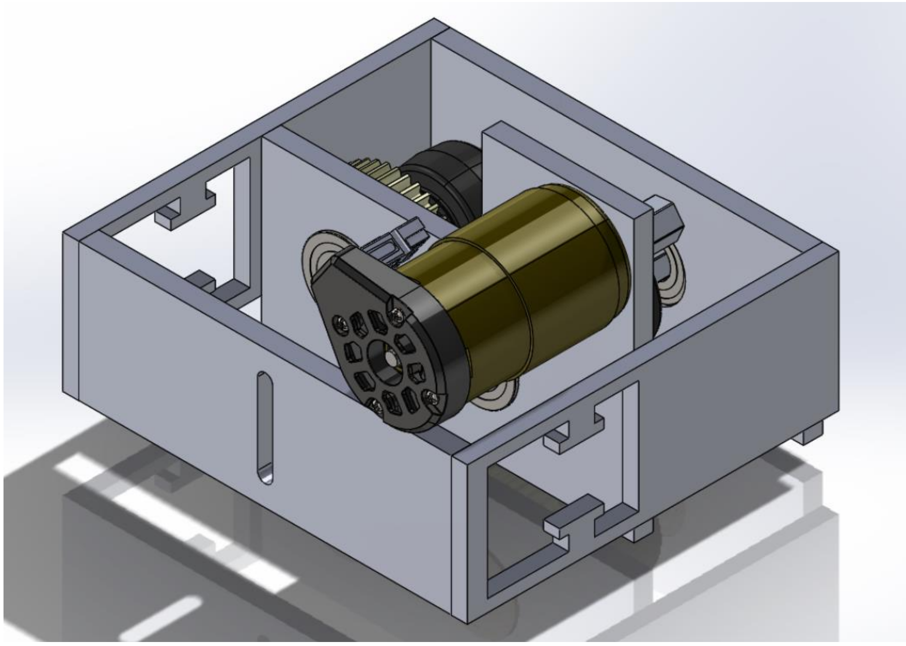


Figure 12: Edited pulley design

To achieve the speed necessary for the pulley design, the motor speed needed to be reduced significantly. We decided to develop a gearbox using hex drive gears to move the pulley. The pulley gearbox required a 3 stage design to reduce the speed. Aluminum plate held the motor, bearings, and gears together. It was mounted to the 80/20 Link 4 using nuts, bolts, and brackets.

Part 5: The Main Gearbox

We decided to use a gearbox to reduce the speed and increase the torque of the motor controlling the fourbar. We used kinematic analysis in Google Sheets to develop feasible gear ratios (Appendix C). We researched the price and availability of available gears to further inform our decisions.

5. Decision Matrix

We developed a decision matrix to use when there were multiple viable design options. The decision matrix relied on our three top priorities: safety, cost, and reliability. It considered two key questions for each priority and asked us to rank each design option in relation to these questions. The matrix is design such that low numbers are favorable, aiming to balance the weight of each question fairly (Table 3).

Category	Question Number	Question	Rating
Safety	1	Rate the probability of the device causing injury to the user, with 1 being not likely and 5 being very likely.	
	2	Rate the probability of the device causing injury to an onlooker, with 1 being not likely and 5 being very likely.	
Cost	3	Rate the potential cost of manufacturing the device, with one being relatively low and 5 being relatively high.	
	4	Rate the potential cost of maintaining the device, with one being relatively low and 5 being relatively high.	
Reliability	5	Rate the potential of the device to break within 5 years of use, with 1 being relatively low and 5 being relatively high.	
	6	Rate the potential of the device to place a cone with incorrect orientation, with 1 being relatively low and 5 being relatively high.	

Table 3: Decision matrix

6. Concept Selection and Design Description

Part 1: The Fourbar

After considering a variety of delivery mechanisms, we settled on using a fourbar linkage (figures 13a-c). This decision came about based on the requirements we wanted our design to meet. This mechanism pulls cones from a stack before placing them on the ground. The fourbar moves up and down, allowing the gripper to move over the stack, and then reaches back down to pick up a cone. In addition, the fourbar does not rely on gravity to orient cones. To make sure our cone always lands upright, we used an arm that places cones directly on the road.

Figure 13a: Fourbar isometric view

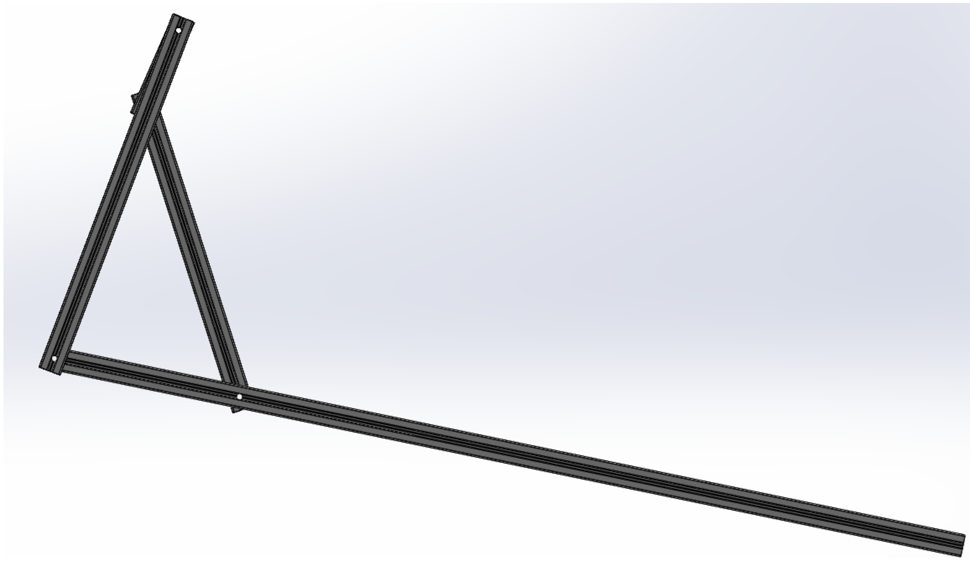


Figure 13b: Fourbar side view

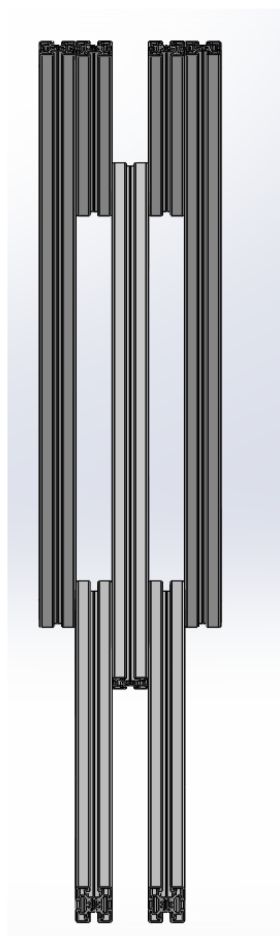


Figure 13c: Fourbar front view

Part 2: The Skid Frame

We selected the triangular skid frame (figures 14a-c) to hold the linkage in position and affix the mechanism to the larger hooklift truck frame. By attaching it to a skid, rather than designing a specialized truck, we were able to keep the mechanism at a lower cost than most cone-places currently on the market. We selected the triangular design over the rectangular design to cut down on material costs without compromising performance.

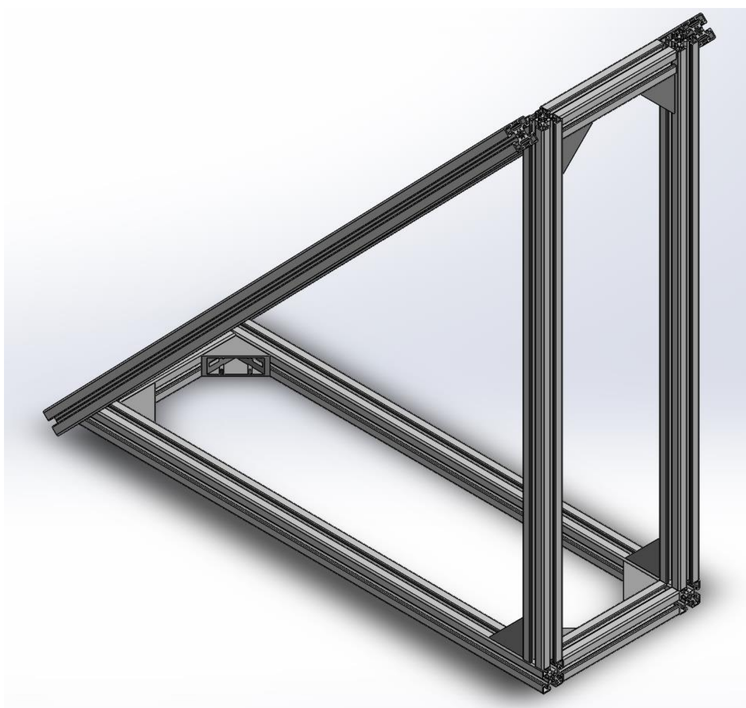


Figure 14a: Skid frame isometric view

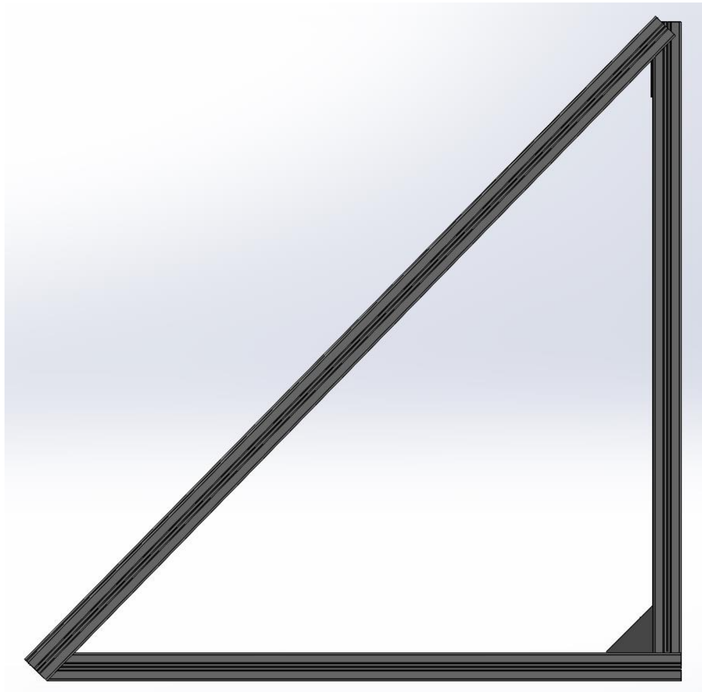


Figure 14b: Skid frame side view

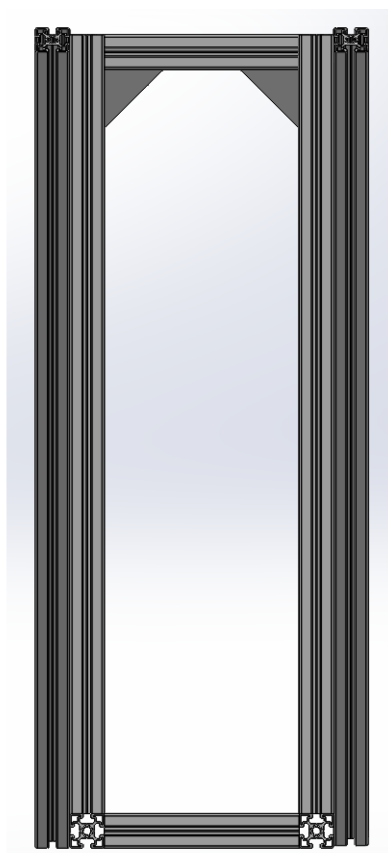


Figure 14c: Skid frame front view

Part 3: The Gripper

We decided to design a custom gripper for the mechanism (figures 15a-c). The design is an adaptation of a common FIRST Robotics design that uses two motorized wheels spinning opposite of each other to launch flat objects such as frisbees. In this setup, the frisbee comes into contact with both wheels and is launched by the wheels' opposing forces. A tapered object such as cone would jam up the mechanism as is is pulled, friction holding it in place. The cone would be released by reversing the wheels' spin directions.

To design and assemble this device, we selected VEX Robotics parts because they are standardized to interact with each other as well as typical hardware store parts. These robotic parts included shafts, two wheels, several gears, and a motor. The motor is mounted to sit above the fourbar to allow space for gear reduction. The components are held in place by ¼ inch thick aluminum plate that we machined to fit around the 80/20 profile and mount the motor and bearings. The plates are held together by 8-32 button head screws and include a back plate to interact with the pulley system. Final parts cost for the gripper was approximately $80, slightly more expensive than the $50 modified off-the-shelf gripper. We decided that the added cost of the custom design was worth its specialization for picking up cones. Detailed exploded views of this assembly are in Appendix A.

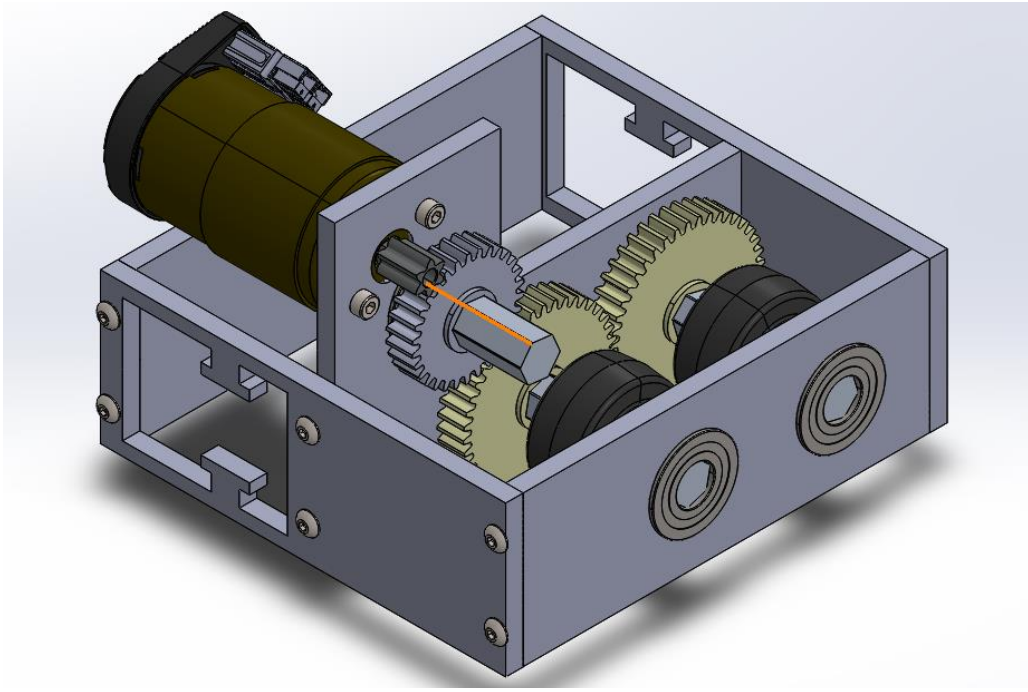


Figure 15a: Gripper isometric view

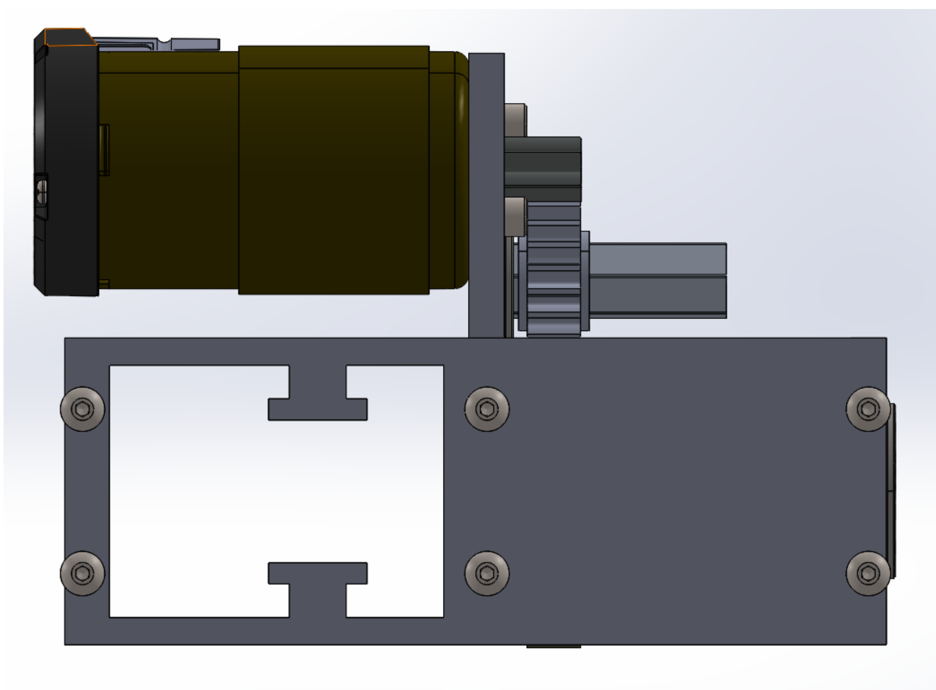


Figure 15b: Gripper side view

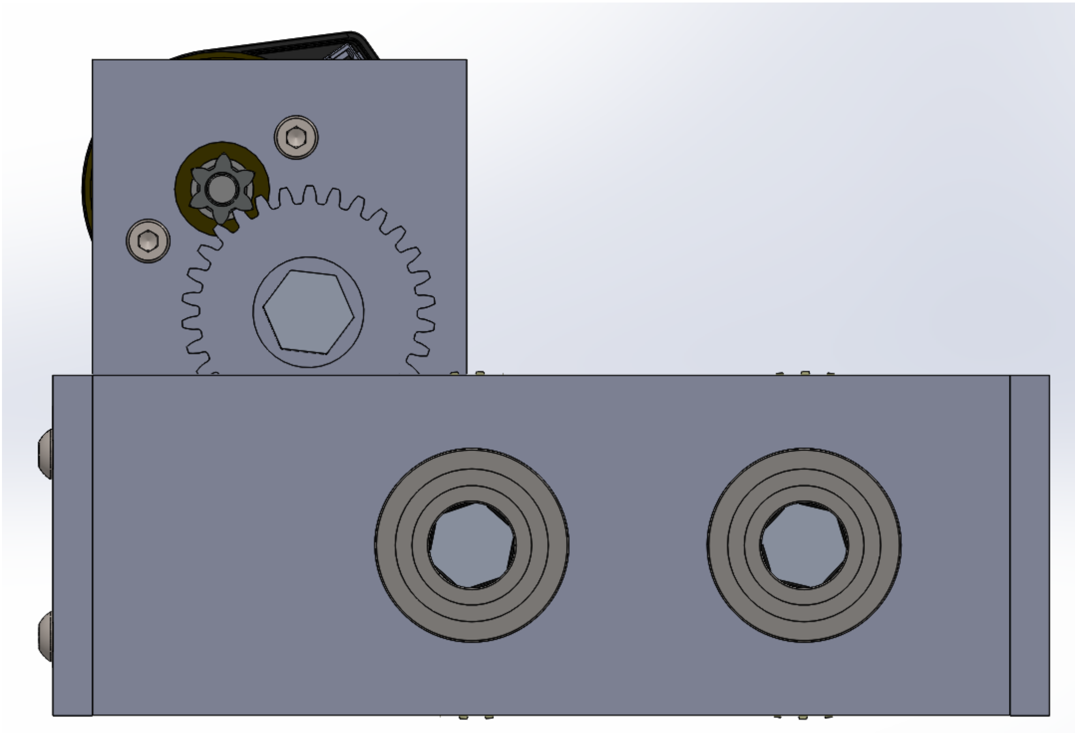


Figure 15c: Gripper front view

Part 4: The Pulley

We developed a final pulley design (figures 16a-d) to complete our cycle of device motion. To attach the pulley and gripper, we decided to slide a protrusion on the pulley's roller chain into a vertical slot in the gripper box, allowing the roller chain to pull the gripper as it moves. We designed the vertical slot such that the roller chain rotates in one direction, but the gripper is pulled in two directions via a sprocket. Upon reaching the sprocket, the chain rolls over and slides vertically through the slot. The chain then continues to move, pulling the gripper in the reverse direction. This design removes the challenge of changing motor direction as the mechanism moves. Detailed exploded views of this assembly are in Appendix A.

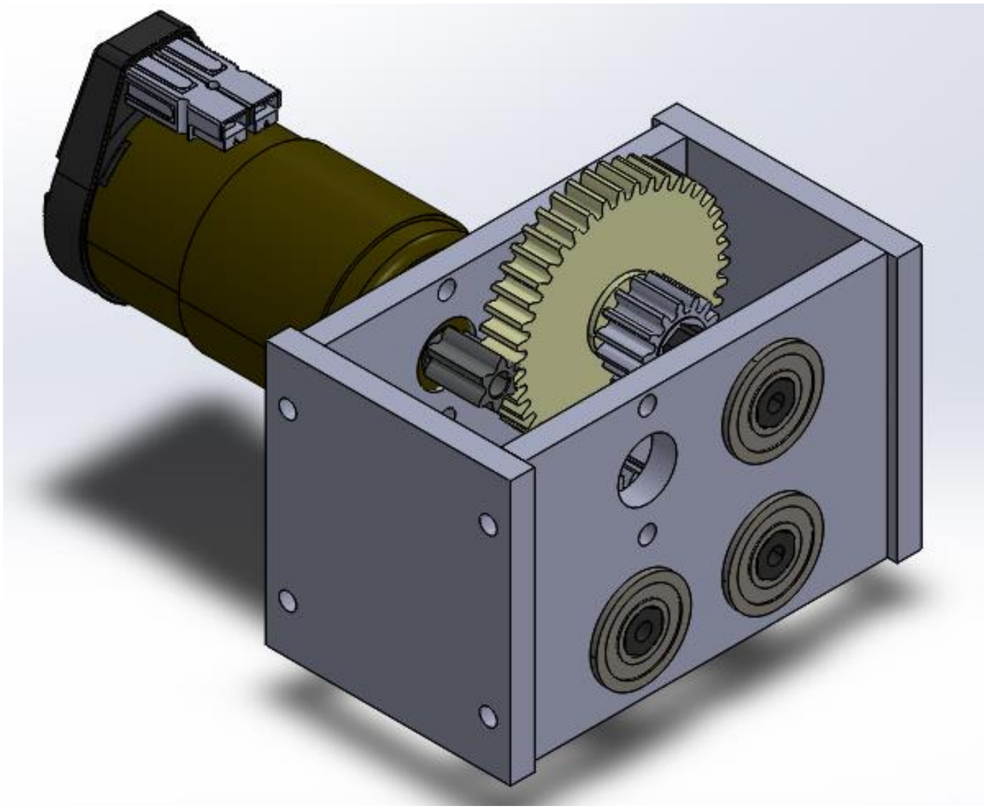


Figure 16a: Pulley gearbox isometric view

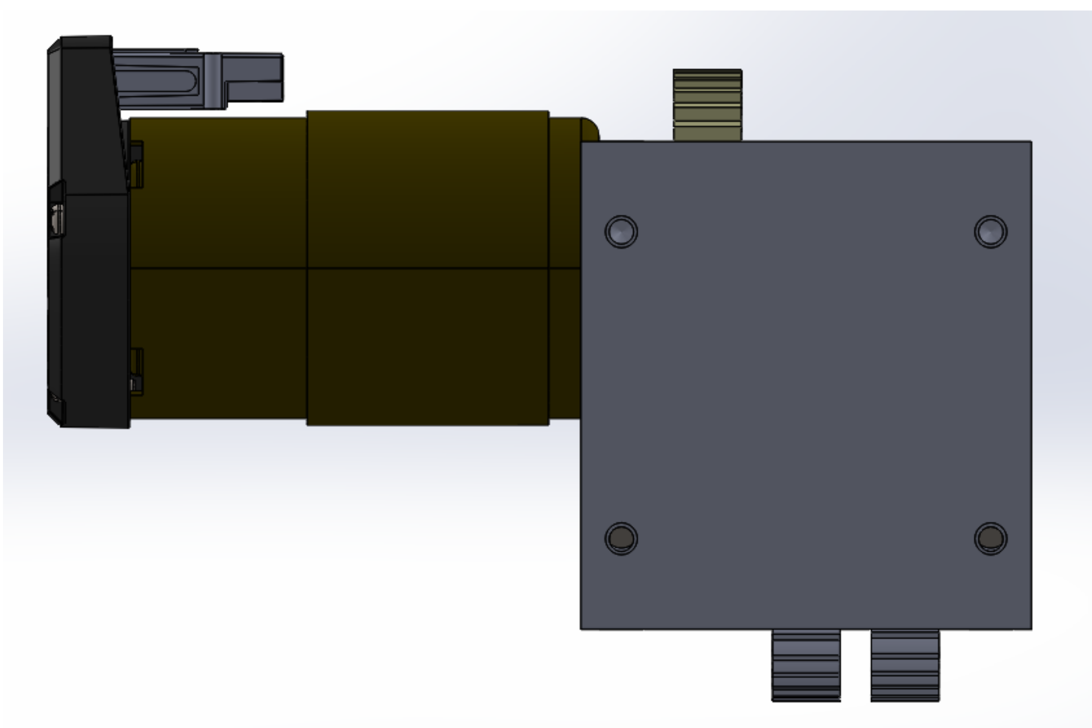


Figure 16b: Pulley gearbox side view

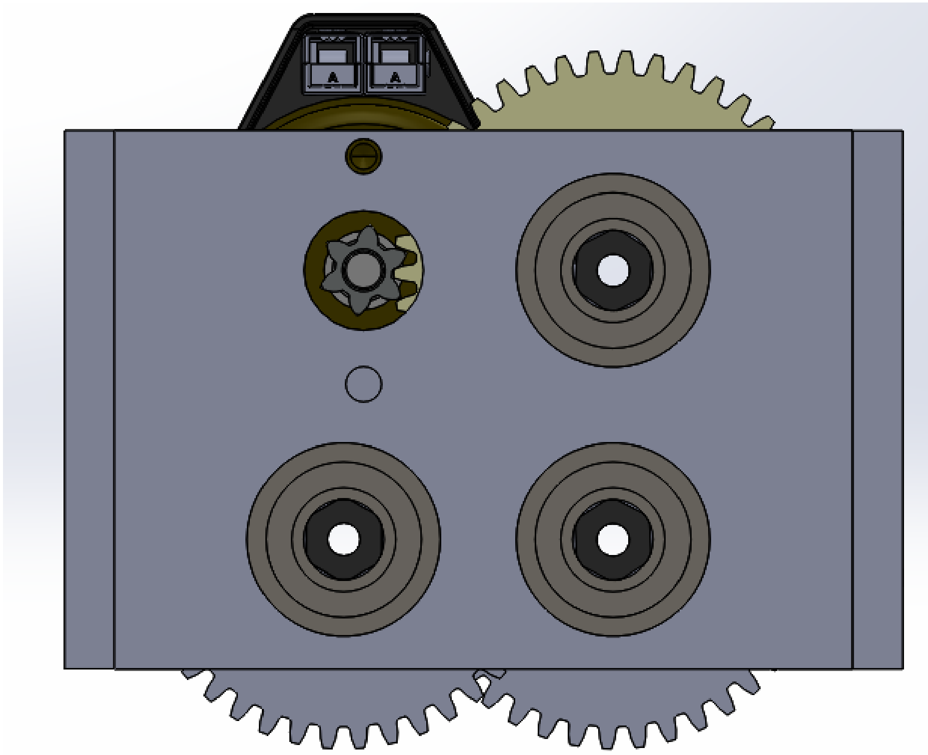


Figure 16c: Pulley gearbox front view

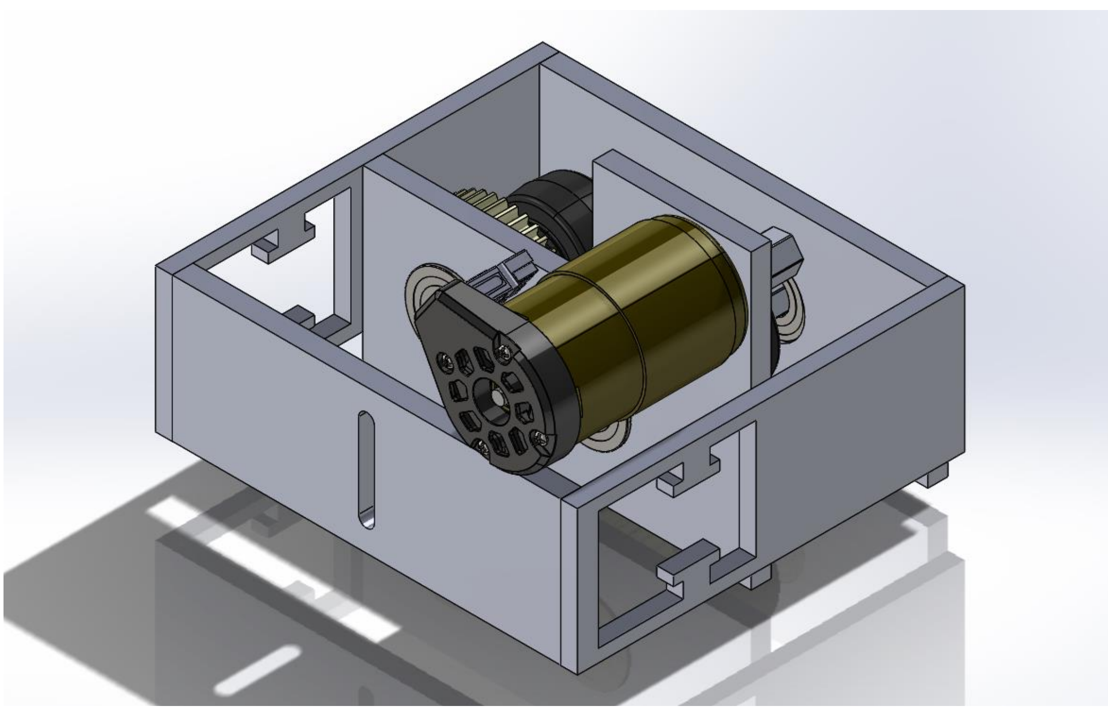


Figure 16d: Pulley slot of gripper assembly

Part 5: The Main Gearbox

We designed a five stage gearbox (figure 17a-c) for our fourbar to reach 30 rotations per minute. We selected VEX robotics parts for this assembly, including a VEX Pro motor. Based on our calculations (Appendix C), this was the only VEX motor with a high enough torque to move the fourbar as desired. This gearbox is constructed of aluminum plate with a third internal plate to prevent interference between the gears. The gearbox is mounted to the frame using brackets. Detailed exploded views of this assembly are in Appendix A.

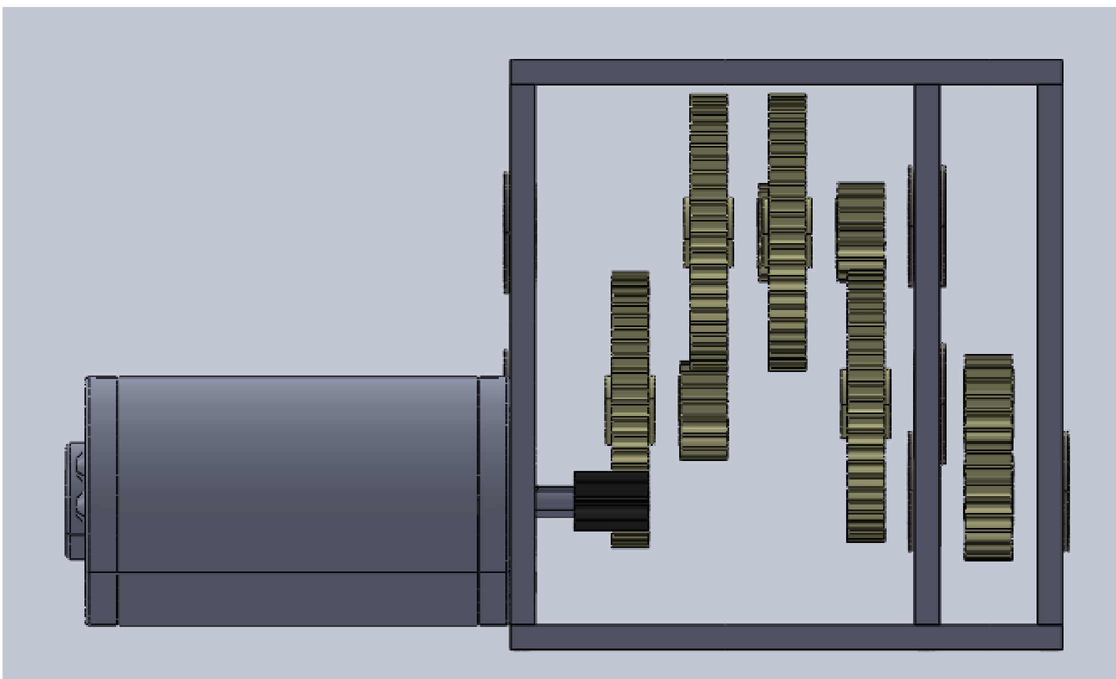


Figure 17a: Gearbox side view

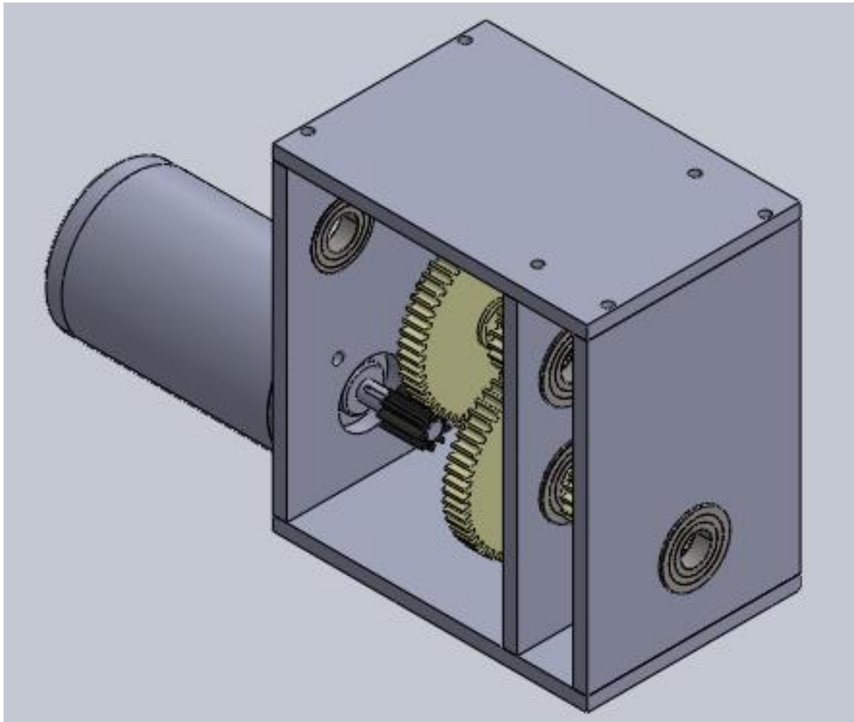


Figure 17b: Gearbox isometric view

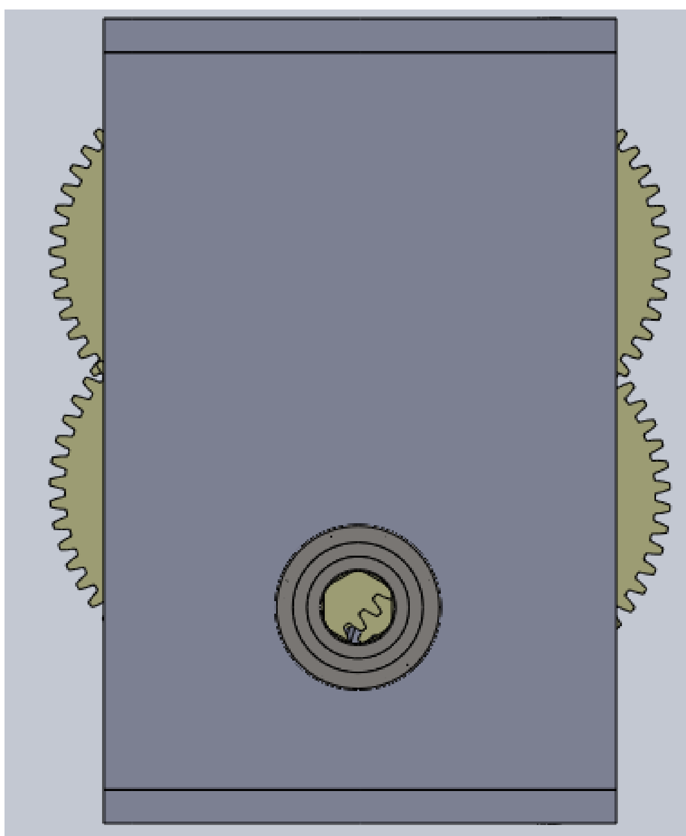


Figure 17c: Gearbox front view

Part 6: The Complete Assembly

The fourbar, skid frame, gripper, and pulley combine to form the complete device assembly. We created a three-dimensional model of the complete assembly in SolidWorks (figure 18a-c)

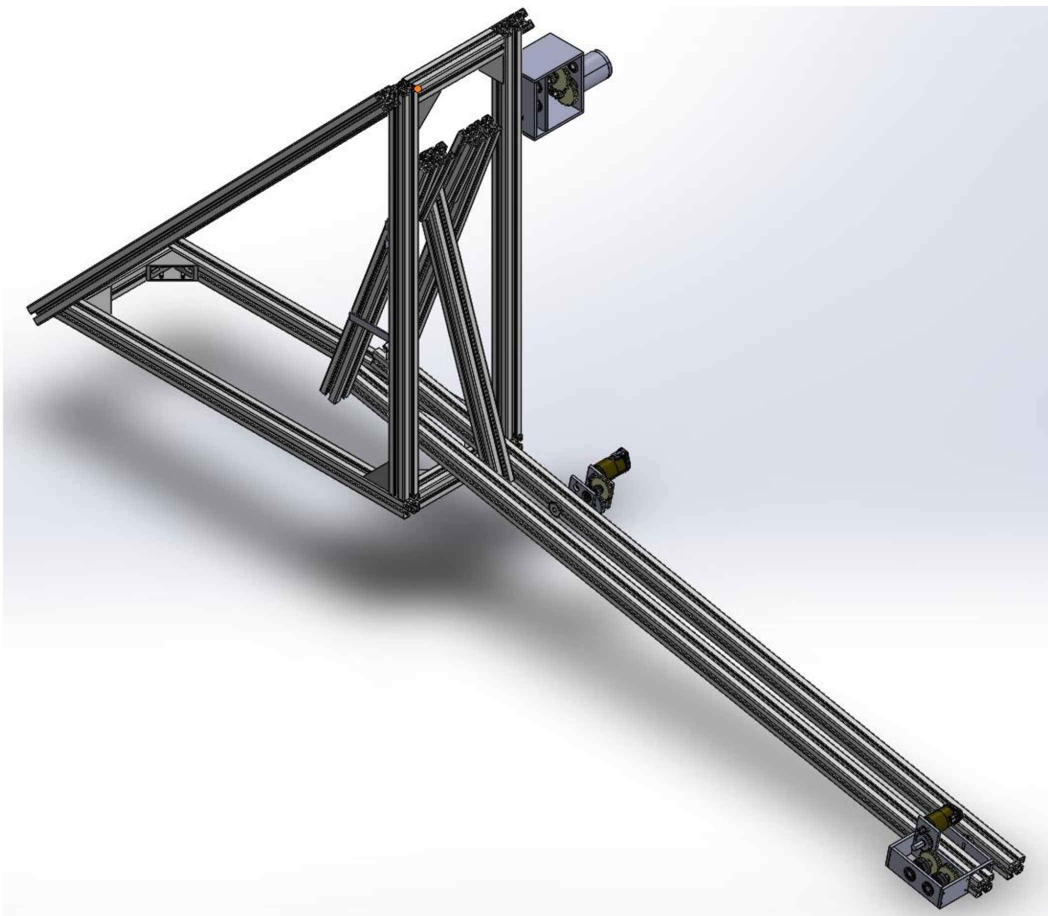


Figure 18a: Complete assembly isometric view

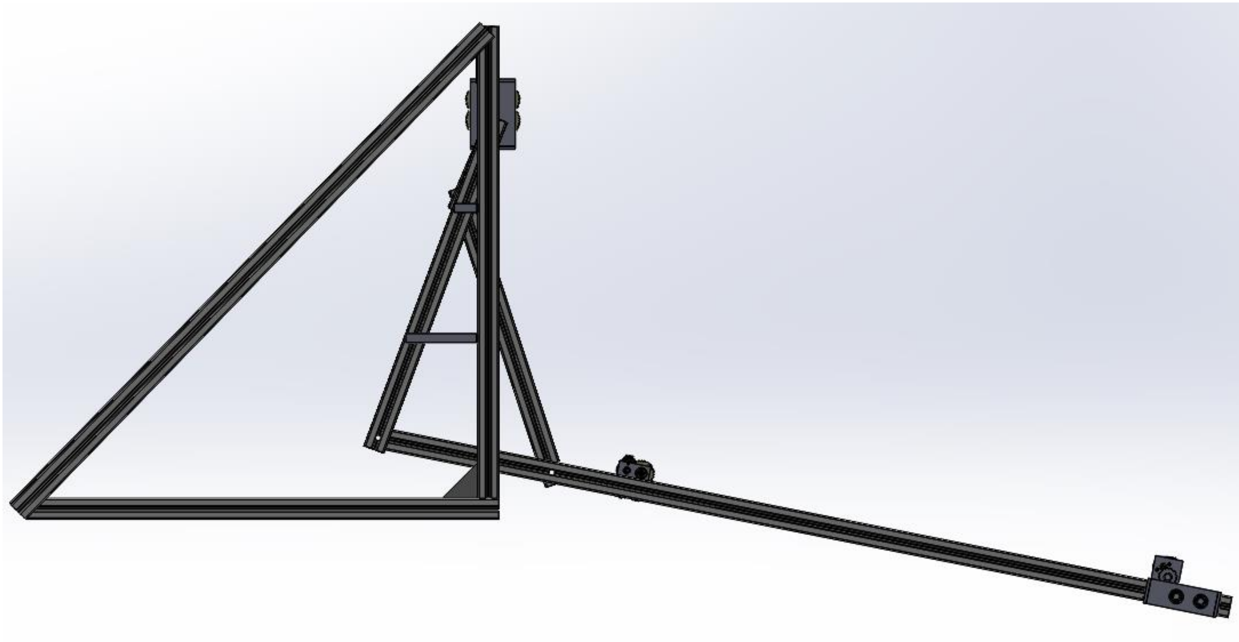


Figure 18b: Complete assembly side view

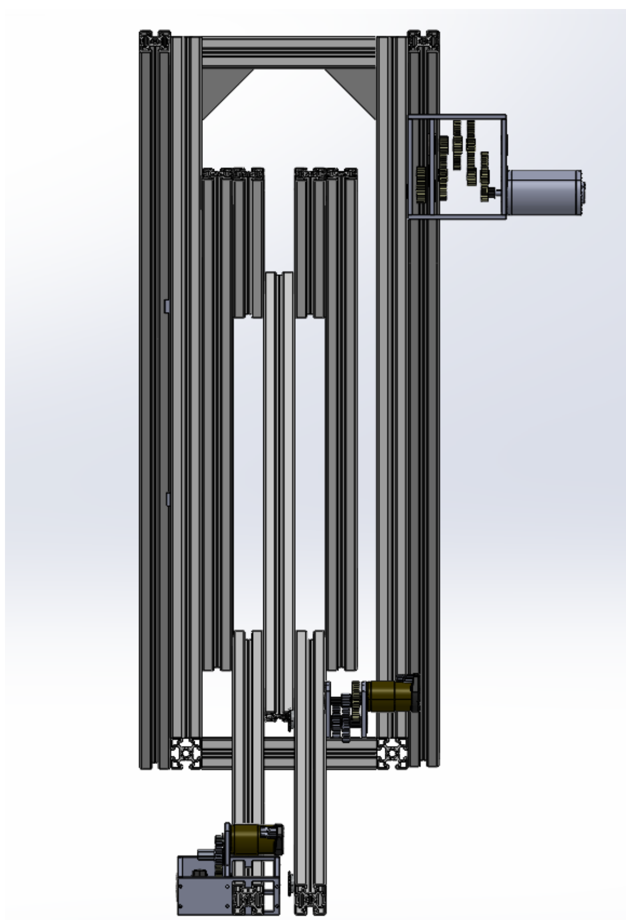


Figure 18c: Complete assembly front view

Part 7: Cycle of Device Motion

This device creates motion to lift the cone from the stack and place it on the road alongside a moving truck. We created a visual representation to illustrate the cycle of motion of our device (figure 19a-f).

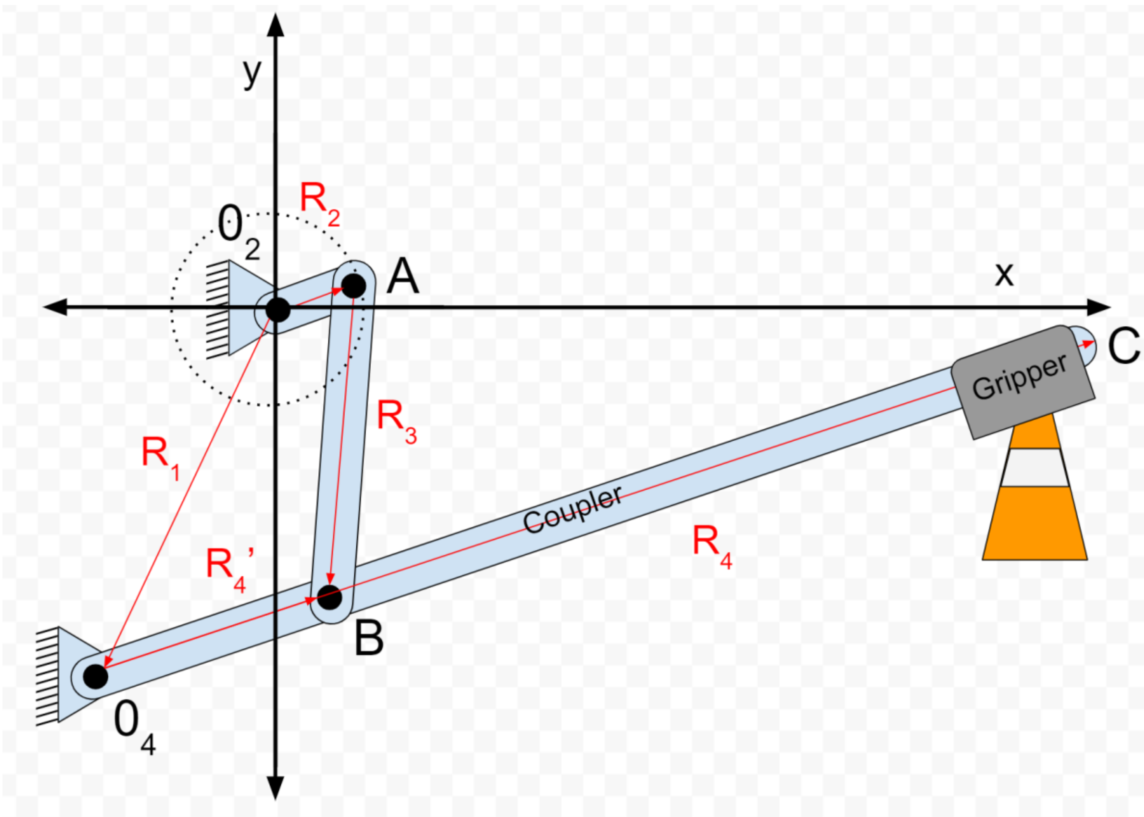


Figure 19a: Motion diagram with labels

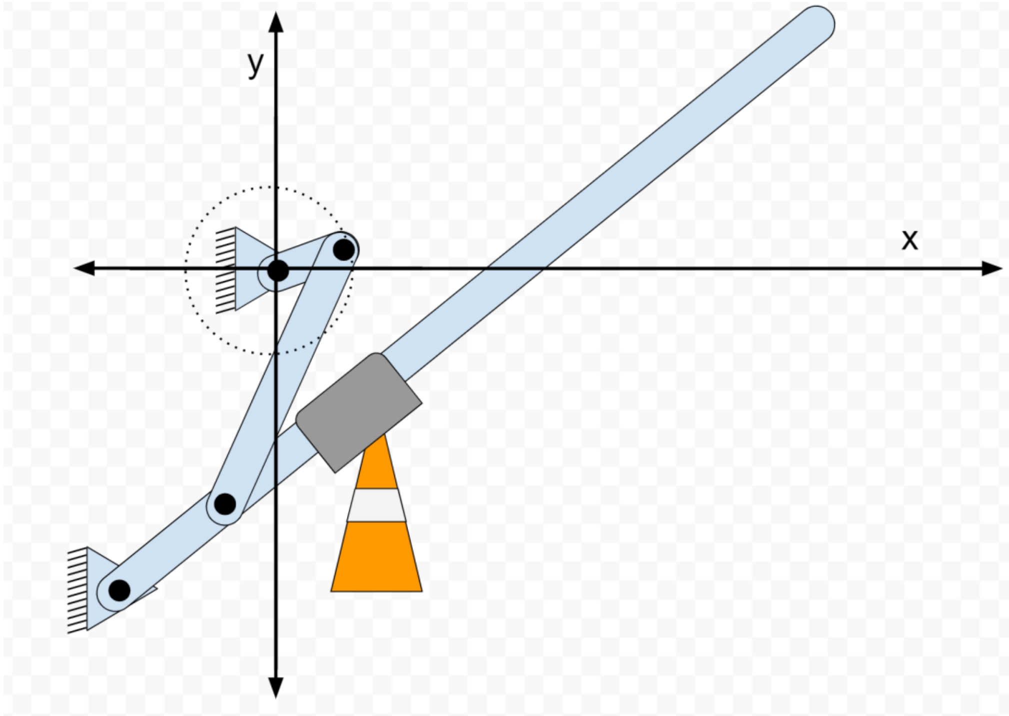


Figure 19b: Step 1- Grip Cone: The coupler is raised and the gripper is pulled in the negative x direction.

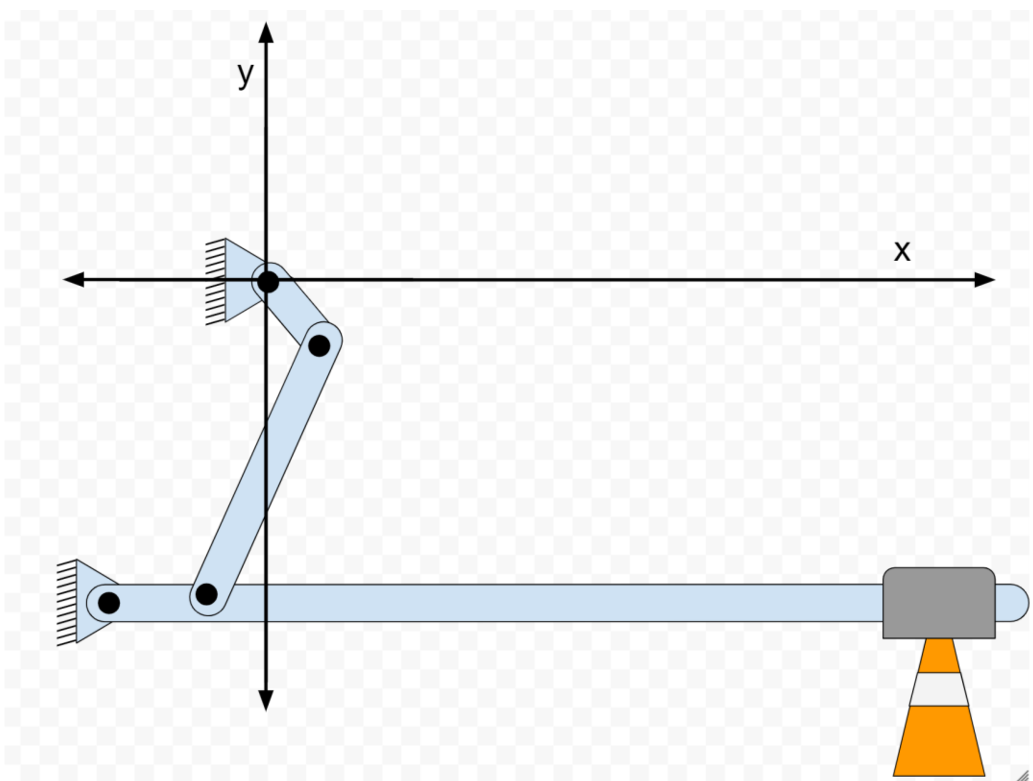


Figure 19c: Step 2- Place Cone: The coupler is lowered and the gripper is pulled in the positive x direction.

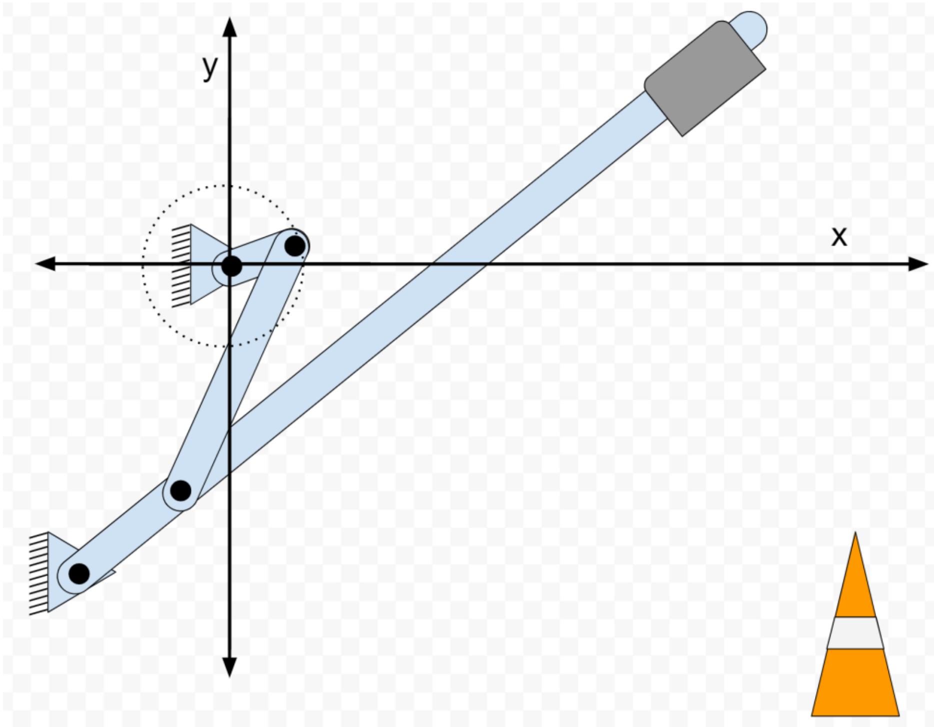


Figure 19d: Step 3- Drop Cone and Raise fourbar: The cone is released and the coupler is raised.

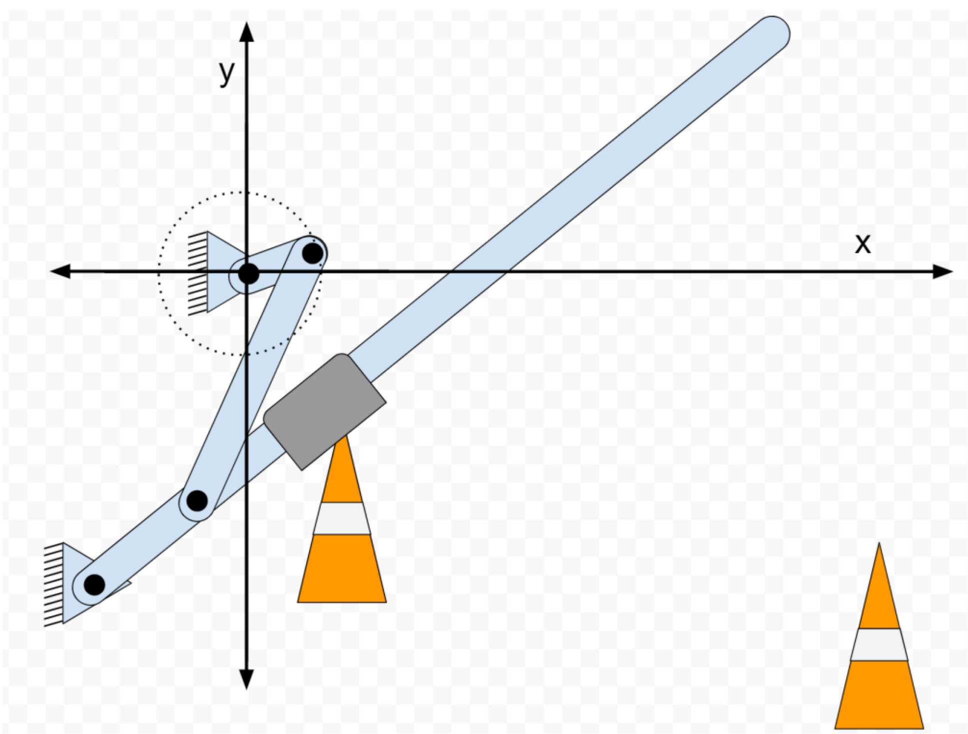


Figure 19e: Step 4- Grip Next Cone: Equivalent to step 1, the coupler stays raised and the gripper is pulled in the negative x direction. The cycle repeats.

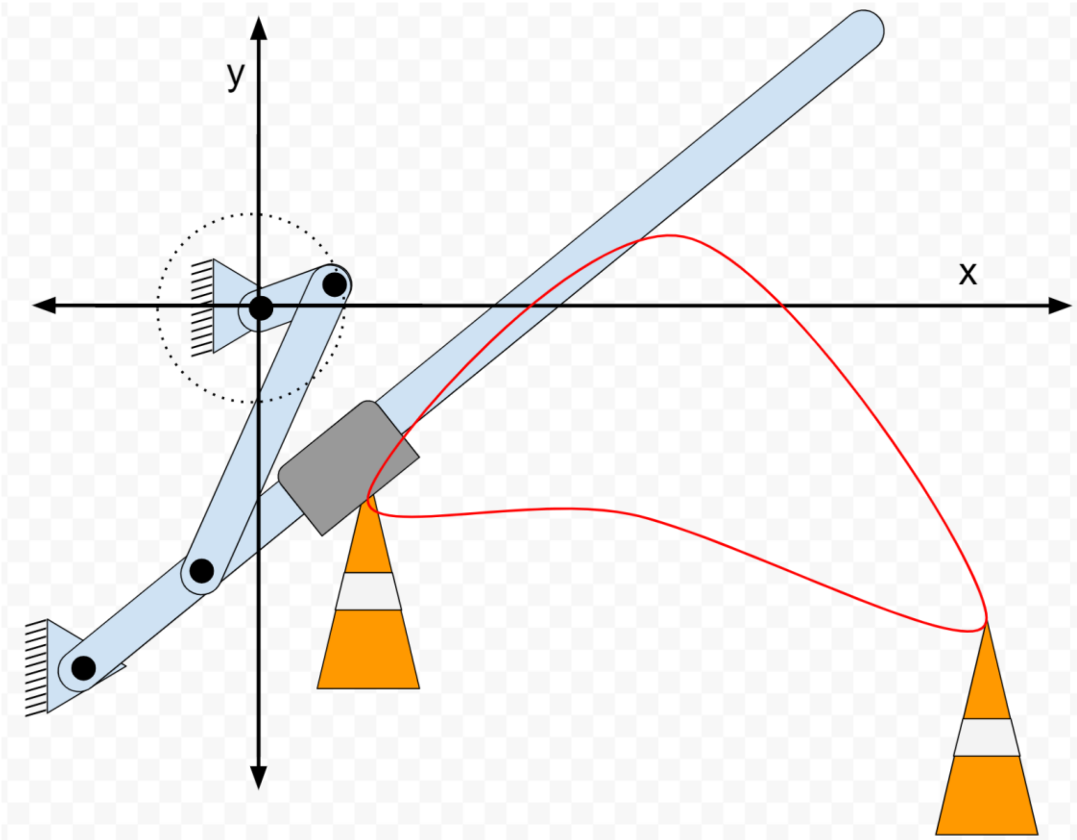


Figure 19f: Computer generated image with coupler curve

7. Manufacturing

Our first step of fabrication was to cut the 80/20 stock metal to size for the fourbar and skid frame. We marked cut points on the stock using the lengths from our SolidWorks models of each component. We brought the stock to Washburn shops and cut it to size. We assembled the skid frame first, securing the bars together with nuts, bolts, and brackets. For the 90 degree angles of the frame, we used square brackets from 80/20 (figure 20). At first, we weren't sure what to use to secure the acute angles. We decided to get simple brackets from the hardware store and hammered them into the correct angles (figure 21). This worked well and the skid frame was the first portion of our device to be fully assembled.

Figure 20: A 90 degree bracket


Figure 21: Hammering a bracket to make an acute angle

The next component we assembled was the fourbar. We cut the remaining 80/20 stock to the appropriate lengths and drilled holes for the fasteners. During assembly (figure 22), we realized that the shaft collars prevented a full range of motion, so we brought the stock back to Washburn shops to drill wide holes to inlay the shaft collars. Once the additional drilling was complete, we attached the shaft collars and finished the fourbar assembly.

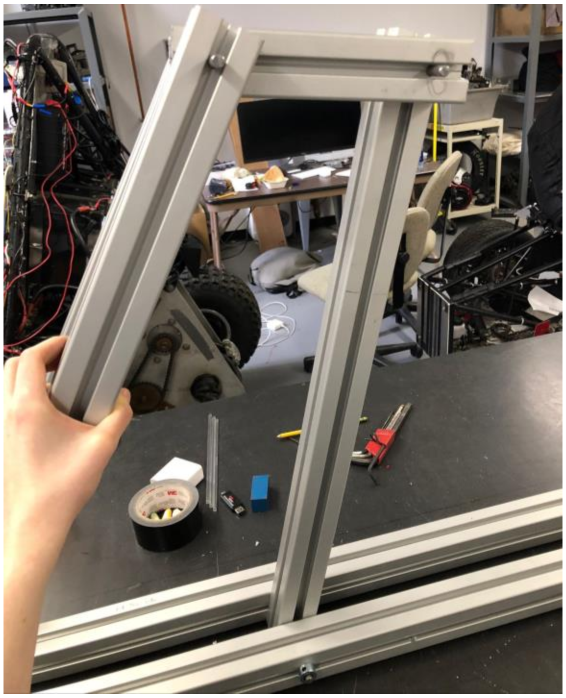


Figure 22: The partially assembled fourbar

We used nuts, bolts, and brackets to attach the fourbar to the skid frame. This was a challenging process because both pieces were unwieldy, the tolerances were tight, and the brackets were starting to bend while the assembly was incomplete. After some troubleshooting, we successfully secured the fourbar to the frame and were able to move it by hand as intended (figure 23).


Figure 23: Assembled fourbar and skid frame

The next step of device fabrication was to create the gearboxes. We developed computer aided machining (CAM) programs and used a MiniMill machine to cut our sheet metal to the desired size and shape. We assembled the gripper gearbox first. We screwed the sheet metal together, inserted bearings and shafts, and loaded gears into place. We then had to file the edges of the hole for the fourbar because it's tolerances were very tight (figure 24).

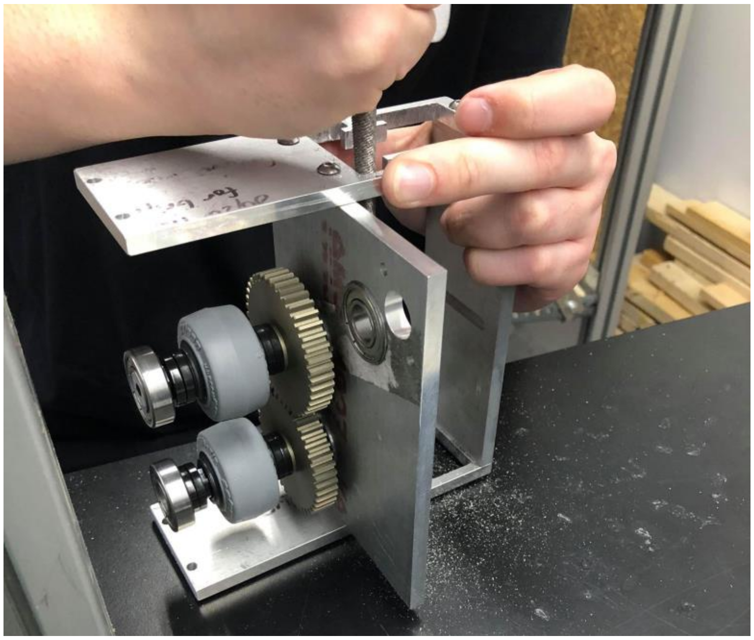


Figure 24: Filing the gripper gearbox

Next, we proceeded with assembling the other two gearboxes. As of the completion of this report, the pulley and main gearboxes are still under construction. We plan to complete the gearboxes, attach them to the fourbar assembly, and power them using the arduino in the next three days.

Conclusion and Recommendations

After fabrication and testing, our team developed a list of recommendations for further development of the device. Primary recommendations include reducing the device’s degrees of freedom, reducing materials and cost, and using hydraulic power rather than electric power. These advancements would make the device simpler and more economic, improving its feasibility for use on the road.

If this project were to be picked up by a future team, we recommend that that team includes a robotics or electrical engineering major. We found that some of the electrical and programming skills necessary for this device were outside the scope of a mechanical engineering project. Having one person dedicated to designing and working on those components would have been helpful for the team throughout all stages of the project. Consulting with Robotics students about our MQP was a productive course of action when designing the motion and power of our device. A team member with in-depth knowledge of these topics would have allowed us more time to focus on designing and fine-tuning the mechanical aspects of the device.

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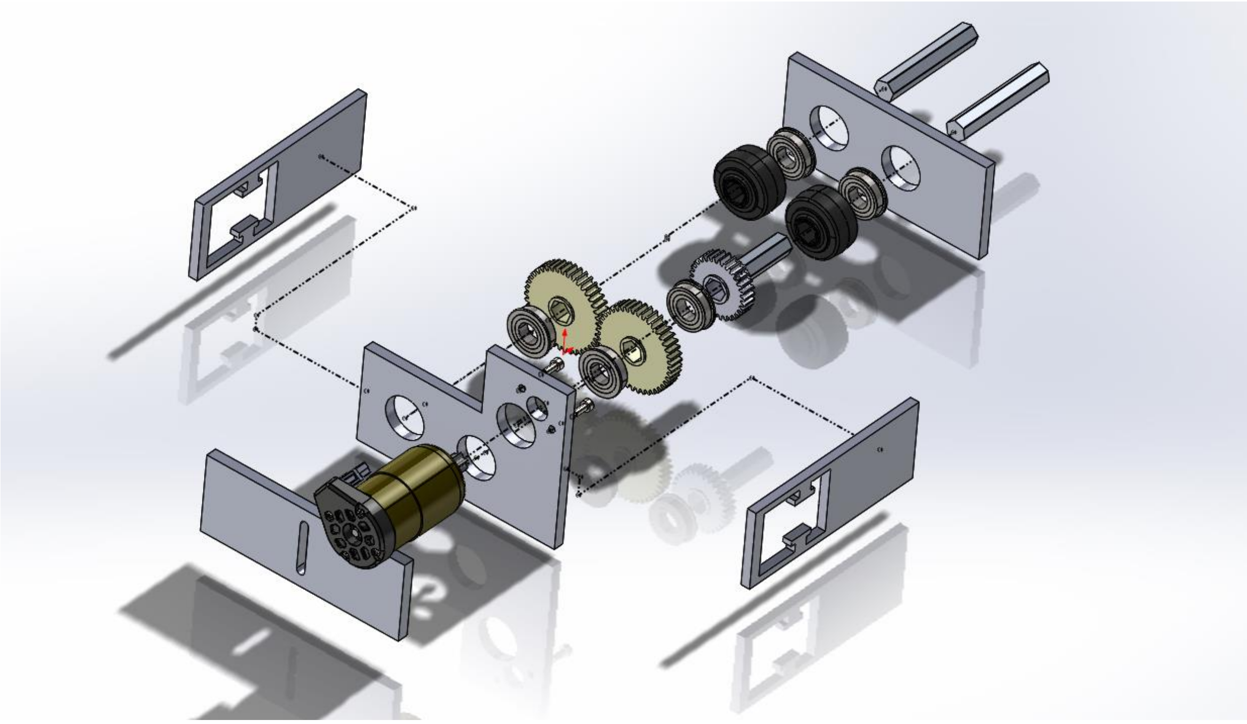
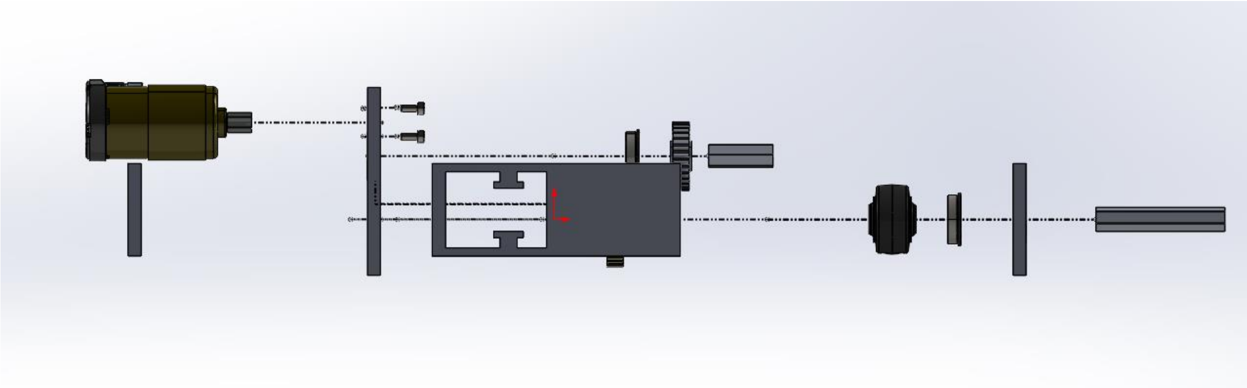
Appendix A: Components Drawing

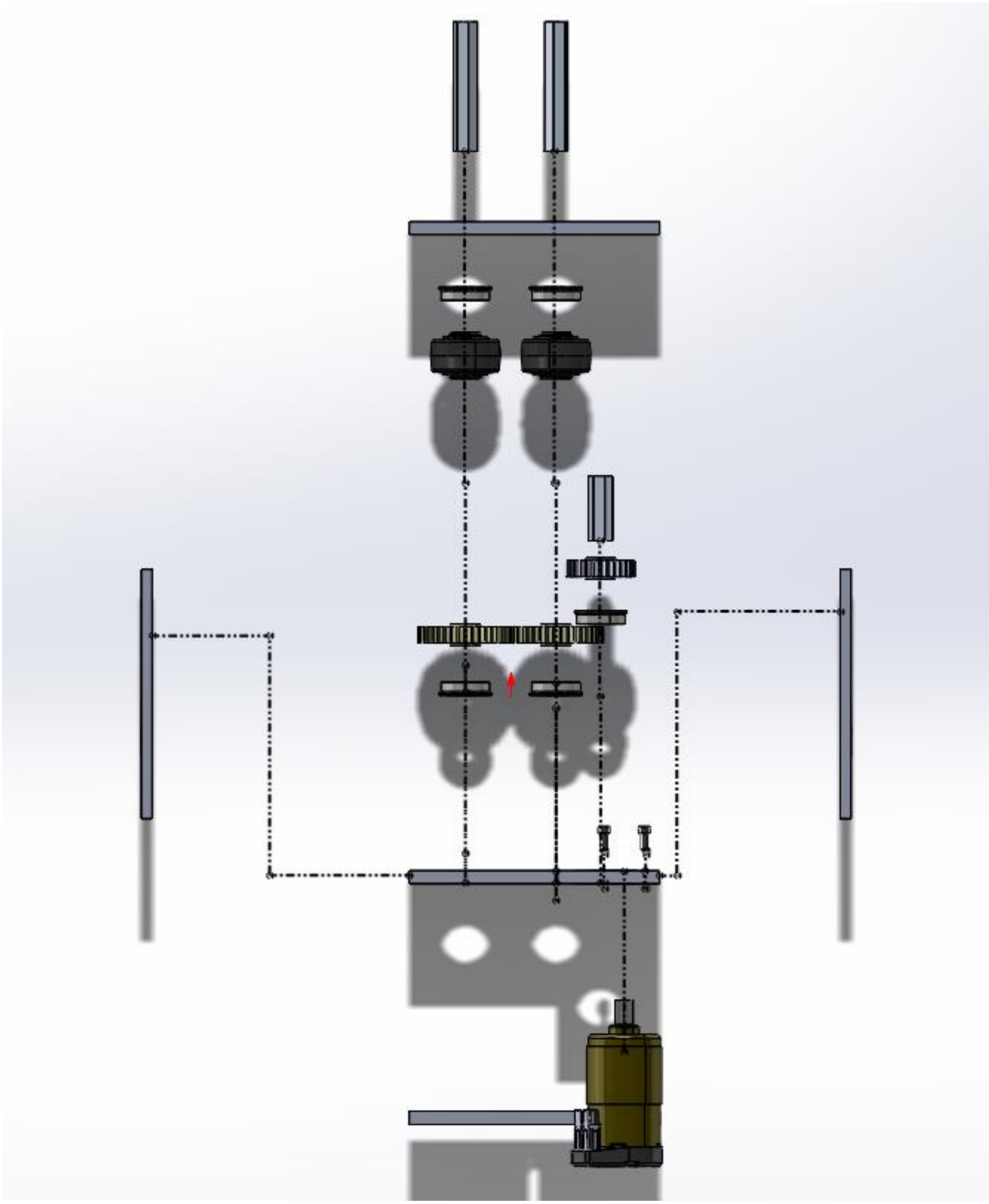
Gripper Gearbox Detailed Design



Gripper Gearbox: Exploded isometric view

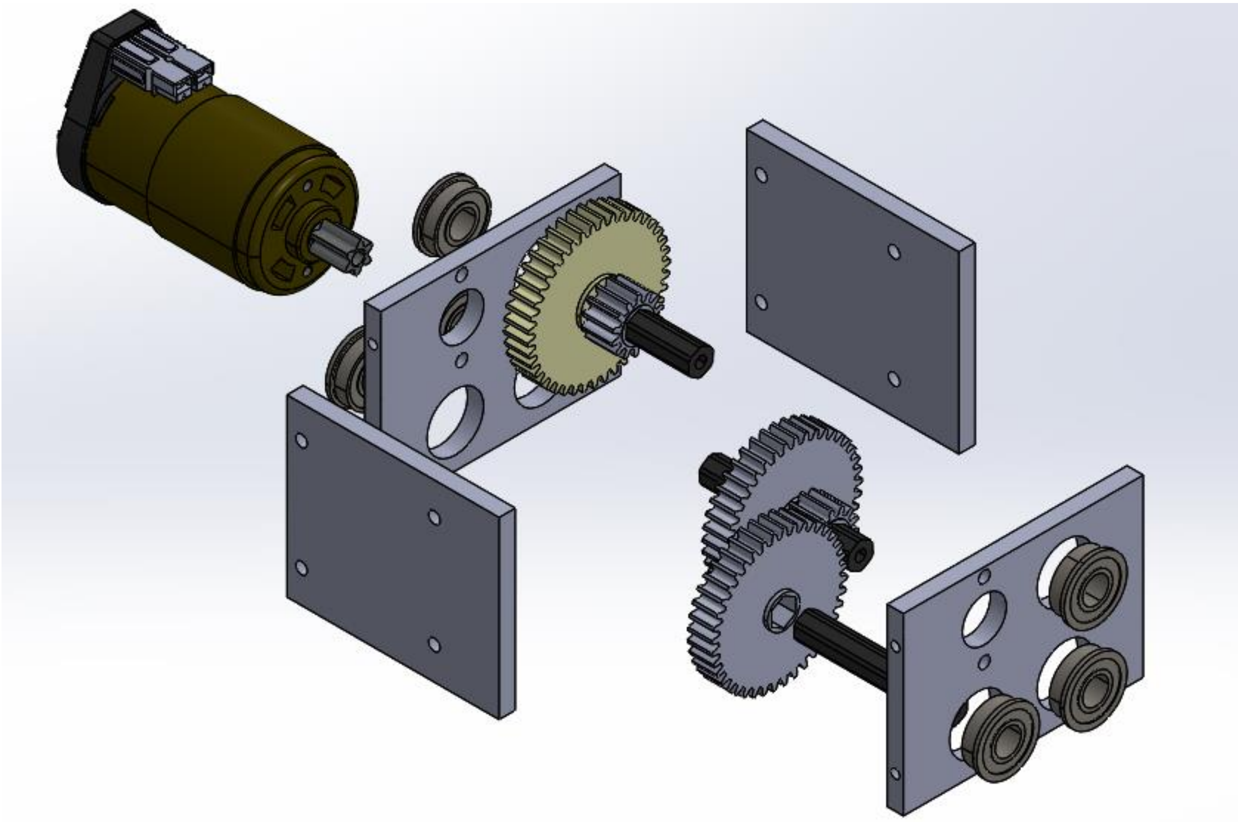


Gripper Gearbox: Exploded side view

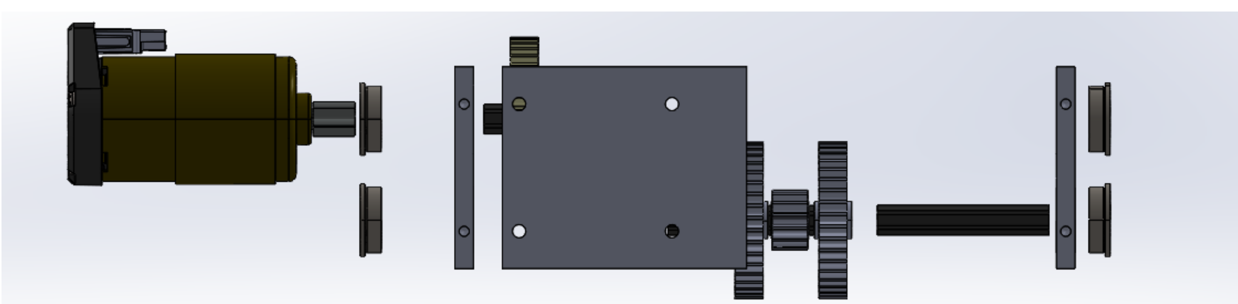


Gripper Gearbox: Exploded top view

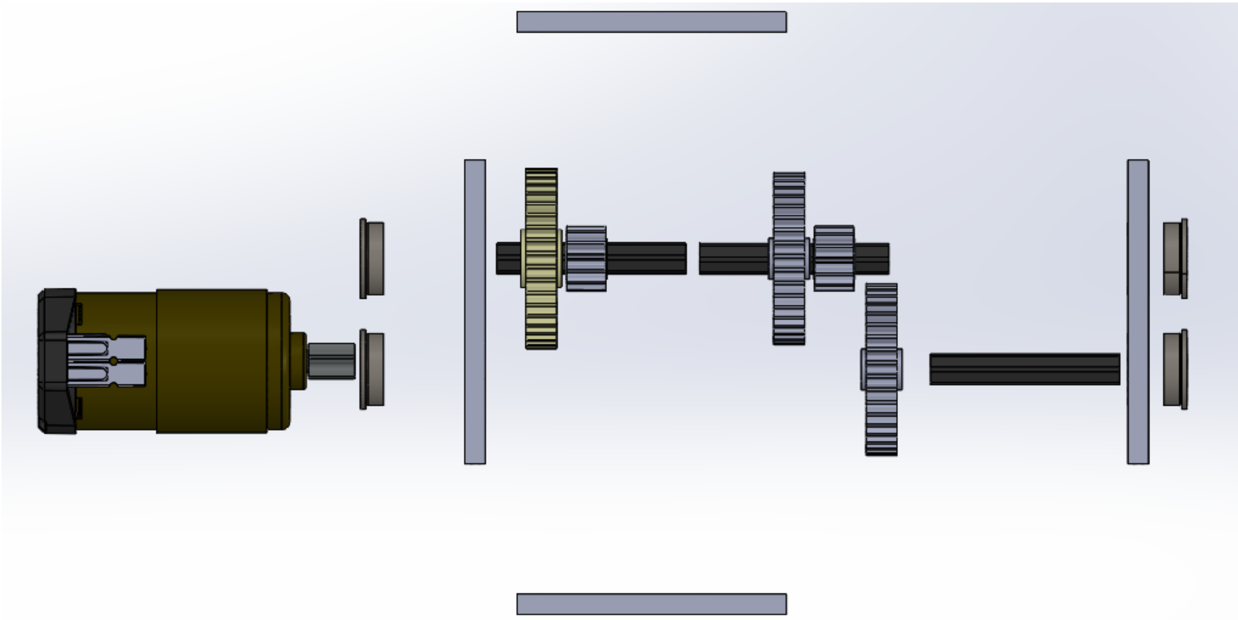
Pulley Gearbox Detail Design



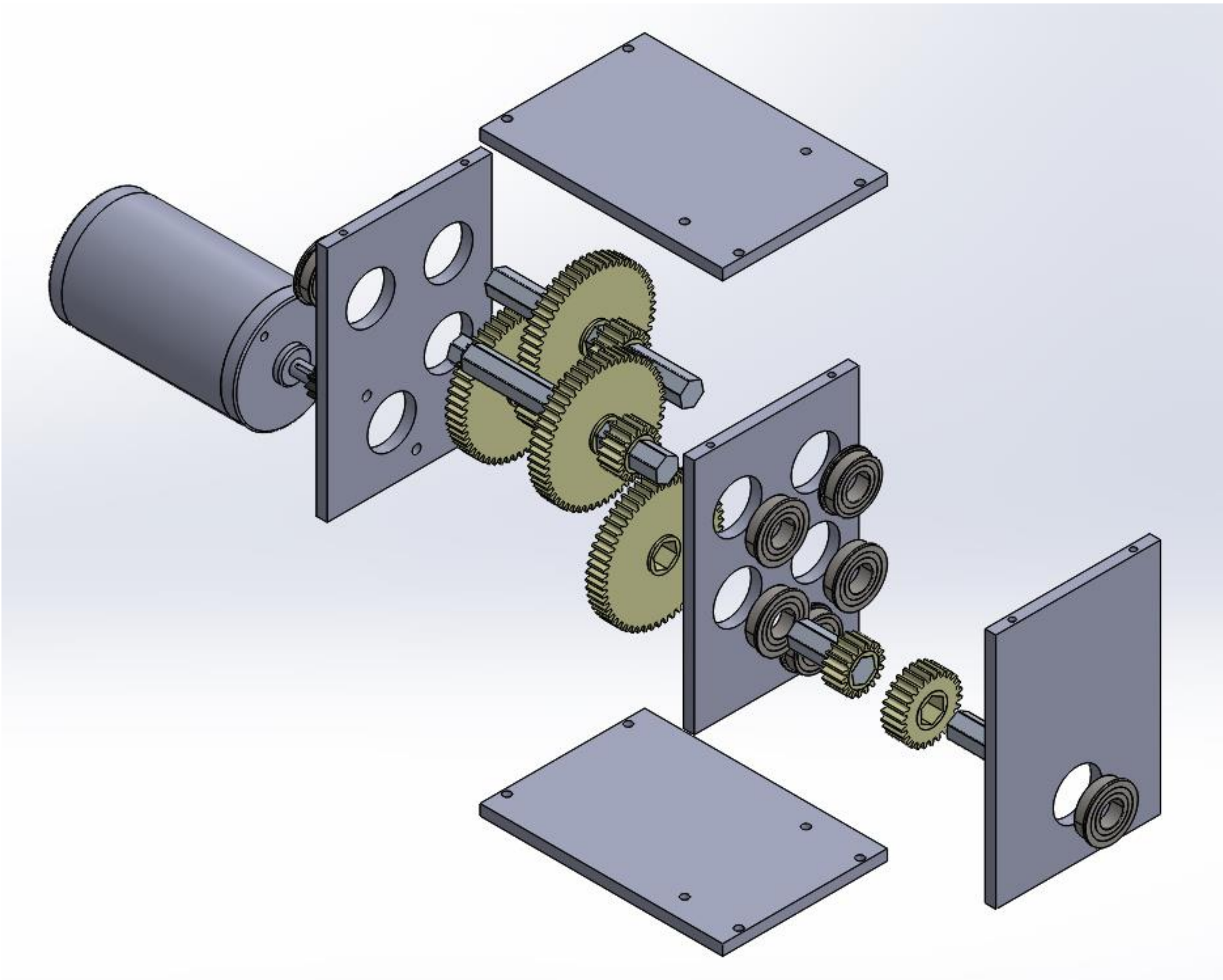
Pulley Gearbox: Exploded isometric view



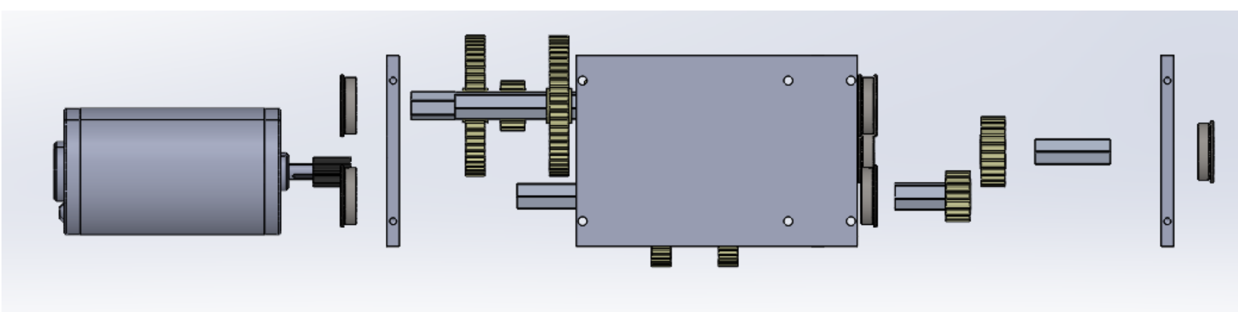
Pulley Gearbox: Exploded side view


Pulley Gearbox: Exploded top view

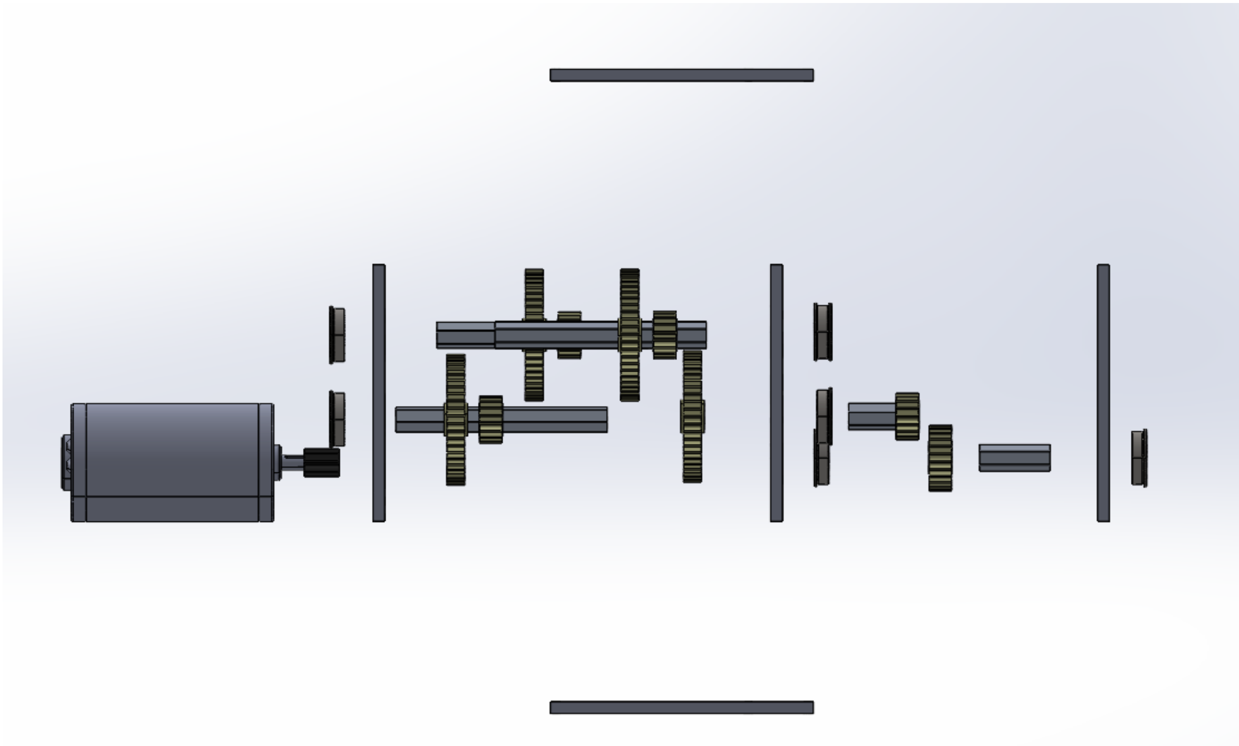
Main Gearbox Detailed Design



Main Gearbox: Exploded Isometric View



Main Gearbox: Exploded side view



Main Gearbox: Exploded top view

Appendix B: Bill of Materials

Hardware and Components List		
QTY	**Description**	**Use**
2	775 VEX Pro Motor	Fourbar and pulley motors
4	45mm x 45mm T-slotted profile stock, 72 inches	Stock metal
3	45mm x 45mm T-slotted profile stock, 10 inches	Stock metal
4	45mm x 45mm T-slotted profile stock, 40 inches	Stock metal
2	45mm x 45mm T-slotted profile stock, 57 inches	Stock metal
1	3/8th inch shaft, 36 inches long	Shaft for fourbar
6	15, 40, 45 series 4-hole inside corner bracket	Fasteners for stock metal
2	16 T aluminum hub sprocket #25 ⅜”	Pulley sprocket
1	#25 roller chain 10”	Pulley roller chain
4	6” x 6” aluminum alloy plate stock	Gear box
1	12” x 12” aluminum alloy plate stock	Gear box
4	18T aluminum spur gear	Fourbar gear
4	54T aluminum spur gear	Fourbar gear
1	26T aluminum spur gear	Fourbar gear
1	9T aluminum spur gear	Fourbar gear
2	20 degree plastic gear, 12 teeth	Pulley gear
1	20 degree plastic gear, 24 teeth	Pulley gear
1	20 degree plastic gear, 40 teeth	Pulley gear
1	20 degree plastic gear, 48 teeth	Pulley gear
2	10” zinc corner brace	Attach fourbar to skid frame
2	2” zinc corner brace	Attach fourbar to skid frame
8	1.5 inch ¼-20 bolt	Attach fourbar to skid frame
8	1.5 inch ¼-20 washer	Attach fourbar to skid frame

20	½” ID x 1” OD steel zinc shaft collar	Shaft collars for gear boxes
20	½” ID x 1.125” OD 1 row radial ball bearing	Shaft collars for gear boxes
12	⅜” ID x ¾” OD steel zinc shaft collar	Shaft collars for gear boxes
1	Arduino mega	Control motors
1	Power cable	Power device

Appendix C: Calculations and Analysis

We completed the majority of our calculations and analysis in Google Sheets. This sections contains screenshots of those documents.

Initial Fourbar Analysis

//First we need to find velocity of links					
1. Find end velocity of cone placing link					
Cone spacing=	20	ft			
Speed of truck=	5	mph			
	7.333333333	ft/s			
Cycle Time=	2.727272727	seconds		RPM=	22
Link Lengths					
Link 1	27.81	inches			
Link 2	6.43	inches			
Link 3	24.29	inches			
Link 4	15	inches	Link4 extra lengtl	57	inches
Cone Height	18	inches			
80/20					
0.0781 lbs per inch					
Weight of Links					
Link 1	2.171961	lbs			
Link 2	0.502183	lbs			
Link 3	1.897049	lbs			
Link 4	5.6232	lbs			
Mass of Links					
Link 1	0.9851841339	kg			
Link 2	0.2277861913	kg			
Link 3	0.86048625	kg			
Link 4	2.550638534	kg			
Position angles					
bottom (negative)	16.96	degrees			
top (positive)	33.75	degrees			

link 3/4 angle (min)	64.65	degrees			
link 3/4 angle (max)	115.35	degrees			
fullrangeofmotion	50.71	degrees			
Pos1					
	x	y			
Ground1	9.86	26			
joint2	8.93	32.36			
joint3	12.47	8.33			
ground2	0	0			
Pos2					
	x	y			
Ground1	9.86	26			
joint2	10.8	19.65			
joint3	14.35	-4.37			
ground2	0	0			

Properties Pulled From SolidWorks

Mass properties of Link 1-V2						
Configuration: 45-4545						
Coordinate system: -- default --						
The center of mass and the moments of inertia are output in the coordinate system of Mechanism-V2-Drilledpinholes						
Density = 0.04 pounds per cubic inch						
Mass = 1.29 pounds						
Volume = 34.92 cubic inches						
Surface area = 706.61 square inches						
Center of mass: (inches)						
	X = 4.93					
	Y = 13.00					
	Z = 0.00					
Principal axes of inertia and principal moments of inertia: (pounds * square inches)						
Taken at the center of mass.						
	Ix = (0.35, 0.93,	Px = 0.74				
	Iy = (-0.93, 0.35,	Py = 95.65				
	Iz = (0.00, 0.00,	Pz = 95.65				
Moments of inertia: (pounds * square inches)						
Taken at the center of mass and aligned with the output coordinate system.						
	Lxx = 83.71	Lxy = 31.47	Lxz = 0.00			
	Lyx = 31.47	Lyy = 12.68	Lyz = 0.00			
	Lzx = 0.00	Lzy = 0.00	Lzz = 95.65			
Moments of inertia: (pounds * square inches)						
Taken at the output coordinate system.						

	Ixx = 301.22	Ixy = 113.99	Ixz = 0.00			
	Iyx = 113.99	Iyy = 43.98	Iyz = 0.00			
	Izx = 0.00	Izy = 0.00	Izz = 344.46			
Mass properties of Link 2-V2						
Configuration: 45-4545						
Coordinate system: -- default --						
The center of mass and the moments of inertia are output in the coordinate system of Mechanism-V2-Drilledpinholes						
Density = 0.04 pounds per cubic inch						
Mass = 0.36 pounds						
Volume = 9.85 cubic inches						
Surface area = 202.15 square inches						
Center of mass: (inches)						
	X = 13.08					
	Y = 25.95					
	Z = -1.77					
Principal axes of inertia and principal moments of inertia: (pounds * square inches)						
Taken at the center of mass.						
	Ix = (1.00, -0.01,	Px = 0.21				
	Iy = (0.01, 1.00,	Py = 2.28				
	Iz = (0.00, 0.00,	Pz = 2.28				
Moments of inertia: (pounds * square inches)						
Taken at the center of mass and aligned with the output coordinate system.						
	Lxx = 0.21	Lxy = -0.03	Lxz = 0.00			

	Lyx = -0.03	Lyy = 2.28	Lyz = 0.00			
	Lzx = 0.00	Lzy = 0.00	Lzz = 2.28			
Moments of inertia: (pounds * square inches)						
Taken at the output coordinate system.						
	Ixx = 245.90	Ixy = 123.20	Ixz = -8.41			
	Iyx = 123.20	Iyy = 65.52	Iyz = -16.69			
	Izx = -8.41	Izy = -16.69	Izz = 308.93			
Mass properties of Link 3-V2						
Configuration: 45-4545						
Coordinate system: -- default --						
The center of mass and the moments of inertia are output in the coordinate system of Mechanism-V2-Drilledpinholes						
Density = 0.04 pounds per cubic inch						
Mass = 1.13 pounds						
Volume = 30.79 cubic inches						
Surface area = 623.56 square inches						
Center of mass: (inches)						
	X = 15.60					
	Y = 13.78					
	Z = -3.54					
Principal axes of inertia and principal moments of inertia: (pounds * square inches)						
Taken at the center of mass.						
	Ix = (0.06, 1.00,	Px = 0.65				
	Iy = (-1.00, 0.06,	Py = 65.69				

	Iz = (0.00, 0.00,	Pz = 65.69				
Moments of inertia: (pounds * square inches)						
Taken at the center of mass and aligned with the output coordinate system.						
	Lxx = 65.48	Lxy = 3.70	Lxz = 0.00			
	Lyx = 3.70	Lyy = 0.86	Lyz = 0.00			
	Lzx = 0.00	Lzy = 0.00	Lzz = 65.69			
Moments of inertia: (pounds * square inches)						
Taken at the output coordinate system.						
	Ixx = 295.24	Ixy = 247.67	Ixz = -62.73			
	Iyx = 247.67	Iyy = 291.29	Iyz = -55.41			
	Izx = -62.73	Izy = -55.41	Izz = 557.39			
Mass properties of Link 4-V2						
Configuration: 45-4545						
Coordinate system: -- default --						
The center of mass and the moments of inertia are output in the coordinate system of Mechanism-V2-Drilledpinholes						
Density = 0.04 pounds per cubic inch						
Mass = 3.20 pounds						
Volume = 86.74 cubic inches						
Surface area = 1749.28 square inches						
Center of mass: (inches)						
	X = 36.38					
	Y = 4.04					
	Z = -1.77					
Principal axes of inertia and principal moments of inertia: (pounds * square inches)						
Taken at the center of mass.						
	Ix = (0.99, 0.11,	Px = 1.83				
	Iy = (-0.08, 0.70,	Py = 1460.98				
	Iz = (-0.08, 0.70,	Pz = 1460.98				
Moments of inertia: (pounds * square inches)						
Taken at the center of mass and aligned with the output coordinate system.						
	Lxx = 19.62	Lxy = 160.12	Lxz = 0.00			
	Lyx = 160.12	Lyy = 1443.19	Lyz = 0.00			
	Lzx = 0.00	Lzy = 0.00	Lzz = 1460.98			
Moments of inertia: (pounds * square inches)						
Taken at the output coordinate system.						
	Ixx = 81.85	Ixy = 629.97	Ixz = -205.99			
	Iyx = 629.97	Iyy = 5682.73	Iyz = -22.88			
	Izx = -205.99	Izy = -22.88	Izz = 5742.69			

Calculating Torque

T = Iα	0					
I = rotational inertia	6.918379933					
α = angular acceleration						
I = (1/3) mL^2	6.918379933	pounds per inch squared				
m = mass	0.502	lbs				
L = length	6.43	inches				
α						
angular motion=	6.283184	rad				
cycle time =	2.727	sec				
angular velocity (w) =	2.30406454	rad/sec				
tangential acceleration =	0, v is constant					
centripital acceleration = w^2 * r	17.06751359	radians/s^2	*used r=L/2 for this to account for the center of mass being at L/2			
			*also the usits are all messed up			
			*also need to account for weight of cone			

Calculating Forces on Link 4

Cone Height	18	in				
Link length=	15	in				
link mass=	2.550638534	kg				
cone weight	3	lbs				
mass	1.360776	kg				
Position 1				Position 2		
Point A height=	0	in		Point A height=	0	in
Point B height=	18	in		Point B height=	66	in

Sample of PKMS Data

Dynamic Analysis								
Max Torque:	-11957.02781							
Units:	English							
Length:	Inch (in)							
Mass:	Pound-Mass (lbm)							
Force:	Pound-Force (lbm·ft/s²)							
Density:	Pounds-Mass per Cubic Inch (lbm/in³)							
Pressure:	Pound-Force per Square Inch (PSI)							
Links:								
Material:	Aluminum 6061							
Density:	2.7							
Yield Strength:	276							
Pins:								
Material:	Carbon Steel 1065							
Density:	7.85							
Yield Strength:	490							
Dimensions:								
Link Width:	0.04495797572							
Link Depth:	0.04495797572							
Pin Diameter:	0.01269999314							
The mechanism to be analyzed is as follows:								
Joint:	Links attached:							
(0, 0)	ground, input							
(-0.94, 6.36)	input, a							
(2.61, -17.67)	a, b							
(-9.86, -26)	b, ground							

Links and their layers:								
Link:	ground	Layer: 1						
Link:	input	Layer: 0						
Link:	a	Layer: 1						
Link:	b	Layer: 0						
Forces:								
Link:	X Location:	Y Location:	X Magnitude:	Y Magnitude:				
input	-0.47	3.18	0	-0.5				
a	0.835	-5.655	0	-1.9				
a	2.61	-17.67	0	-15				
Link Centers of Mass and Mass Moments of Inertia								
Link:	CoM x:	CoM y:	Mass Moment of Inertia:					
input	-0.47	3.18	403.0359498					
a	0.835	-5.655	19230.20383					
b	-3.625	-21.835	4656.311882					
Dynamic Analysis of position number 1.								
The input is at an angle of 98.4073784890165 degrees (1.71753276288958 radians).								
Current Forces:								
Link:	X Location:	Y Location:	X Magnitude:	Y Magnitude:				
input	-0.47	3.18	0	-0.5				
a	0.835	-5.655	0	-1.9				
a	2.61	-17.67	0	-15				
Here is the solution reaction forces and input torque:								

943.39		Reaction Force X	[ground, input]					
-5061.8		Reaction Force Y	[ground, input]					
-870.68		Reaction Force X	[input, a]					
4570.3		Reaction Force Y	[input, a]					
126.2		Reaction Force X	[a, b]					
1810.9		Reaction Force Y	[a, b]					
604.42		Reaction Force X	[b, ground]					
1095		Reaction Force Y	[b, ground]					
-1241.7		Torque Required at input.						
Here is the coefficient matrix:								
1	0	1	0	0	0	0	0	0
0	1	0	1	0	0	0	0	0
0	0	-1	0	1	0	0	0	0
0	0	0	-1	0	1	0	0	0
0	0	0	0	-1	0	1	0	0
0	0	0	0	0	-1	0	1	0
0	0	-6.36	-0.94	0	0	0	0	1
0	0	0	0	24.03	3.55	0	0	0
0	0	0	0	0	0	8.33	-12.47	0
Here is the known matrix:								
72.718								
-491.5								
996.87								
-2759.4								
478.22								
-715.9								
-0.235								
9461.2								
-8620.1								

Gear Ratio Calculations

		Power (W)					851.3636364	242.2727273		
Mechanism RPM	22			Roller Length	117.9992474					
Vex 775Pro RPM	18730	347		Sprocket rotations	29.50536294		Final Torque of Motors (N*m)	=Power (W)/2*pi*Final RPM*(1/60)		
Vex CIM Motor	5330	337		Sprocket RPM	324.5589924	(example)->	0.6037735365	=775Pro Power/775Pro Free RPM		
Sprocket Diameter	1.273			Gear Ratio (sprocket/motor)	57.70907737		146.2778613	=target torque (CIM power/ mech rpm)		
Length	57									
							Gear Ratio Calculator			
				Output Gear teeth=	6		7	=(driven number of teeth)/(driver number of teeth)		
					9		2.857142857		Final Reduction	
				Reduction Gear teeth options=	14		2.857142857		57.14285714	
					16					
					18					
					20		6			
					22		3		Final Reduction	
					24		3		234	
					26		3			
					28		1.444444444			
					30					
					32					
					34					
					36					
					38					
					40			9.333333333		290.3703704
					42			9.333333333		
					44			3.333333333		
					46					
					48					
					50					
					52					
					54					

Teeth	Quantity		
6	1	Pulley	
14	2		775pro
42	1		
40	2		
9	1	Main Assembly	
18	4		CIM
26	1		
54	4		
	53.33333333		
6.666666667			
2			
4			