



# WPI

Trash Lifter

A Major Qualifying Project Report

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**Abstract:**

A full trash bag can be a difficult load to lift and drop into a dumpster, especially for the elderly. The goal of this project was to design a device that can safely and reliably assist the user in lifting a trash bag up and into a dumpster, such as those typically used by residents of an apartment building. This design is compatible with dumpsters up to five feet in height and can lift trash bags up to 50 lbs. in weight. The selected design consists of a four-bar mechanism in series with a driver dyad used to transmit power from the power source. The mechanism can be powered by either a hand crank or a 0.25 horsepower motor attached to the driver dyad.

**Acknowledgements:**

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## Chapter 1: Introduction

Dumpsters are a common receptacle used to dispose of trash in many places across the world. From construction sites to senior citizen communities, dumpsters are prevalent everywhere. In today's throwaway culture and with an increasing number of urban residence, dumpsters have become an increasingly popular method for trash removal. Dumpsters provide a communal area to store trash before it is brought to a landfill. The problem with current dumpster designs is that it is often difficult to lift a heavy trash bag or can up and over the top of a dumpster. This becomes especially difficult when the dumpster is almost filled and trash cannot be placed through a side opening. This is a problem for anyone taking out trash but becomes a serious problem for those that are not strong enough to lift heavy weights over their head. Dumpsters located in residential communities are used by all types of people but those such as the elderly or people with physical disabilities often struggle the most taking out their trash. On a construction site, there are often multiple dumpsters in use. Construction workers often spend a lot of time picking up and moving large weights up and into the dumpsters. This repeated motion can lead to long term health effects such as back pain or more serious injuries.

With this in mind, the team researched the size of various dumpsters and conducted a field assessment by evaluating multiple dumpsters located throughout local communities in Worcester, Massachusetts. The team decided that the best way to help people move their trash from the ground up and into a dumpster safely and efficiently would be to create a simple mechanism that would be compatible with standard dumpster dimensions.

## Chapter 2: Background

### 2.1: Elderly Capabilities

The elderly, or people 65 years of age or older, currently represent 12.5 percent (35 million) of the U.S. population and are estimated to increase to 20 percent (72 million) by the year 2030. A number of physiological changes occur with aging. These changes include reduced muscle strength, reduced aerobic capacity and reduced bone density. Because muscle mass and muscle strength are reduced this leads to a reduction in physical activity. As a result, this can lead to functional decline in elderly, Functional decline is defined as the inability to perform usual activities of daily living due to weakness, reduced muscle strength and reduced exercise capacity. Activities of daily living involve eating, dressing, bathing, shopping for groceries, laundry, housework and such. It is estimated that up to 8 percent of community-dwelling elders need assistance with one of more daily living activities (Kleinpell, 2008).

Recent epidemiologic data suggests that about 24% of community-dwelling older adults struggle or are completely unable to perform stooping crouching or kneeling tasks (Hernandez et al., 2008). Limitations in stooping and crouching ability are associated with an increased likelihood of limitations in other lower-body functional tasks such as lifting (Long et al., 2004).

A crucial component that is important to most elders is maintaining one's independence. One way to achieve this is to age in place, which is defined as the ability to stay in one's home as a person ages (Cutchin, 2003). According to the U.S. housing data, 80% of older adults live independently in their own homes. Many elders wish to stay in their homes as they age but may face specific challenges and daily frustrations in their everyday activities, specifically in home maintenance. On average, over one hour every day is spent doing home maintenance and is very important to ensure a healthy and safe living environment (Lawton, 1990).

When generating concepts and designs to assist with these daily living activities, the main concerns deal with the role of humans in complex systems, the design of equipment and facilities for human use, and the development of environments for comfort and safety (Salvendy, 2012).

## 2.2: Trash Bag Specifications and Requirements

Although landfill waste products are decreasing there is still a high demand for waste removal. Most waste removal for residential areas is through the use of garbage bags. (Subramanian, 2016) Standard kitchen garbage bags range from 13 gallons to 27. Kitchen trash bags range in width from 24 inches to 40 inches, but most kitchen bags are 30 inch bags. The height of trash bags are 31 inches to 45 inches. These bags also can weigh up to 75 pounds.



*Figure 1: Common Trash Bag*

Over the past few years there have been significant increases in strength of these bags with the introduction of stronger plastics. (Almeida, 2014)



## 2.3: Dumpster Specifications and Requirements

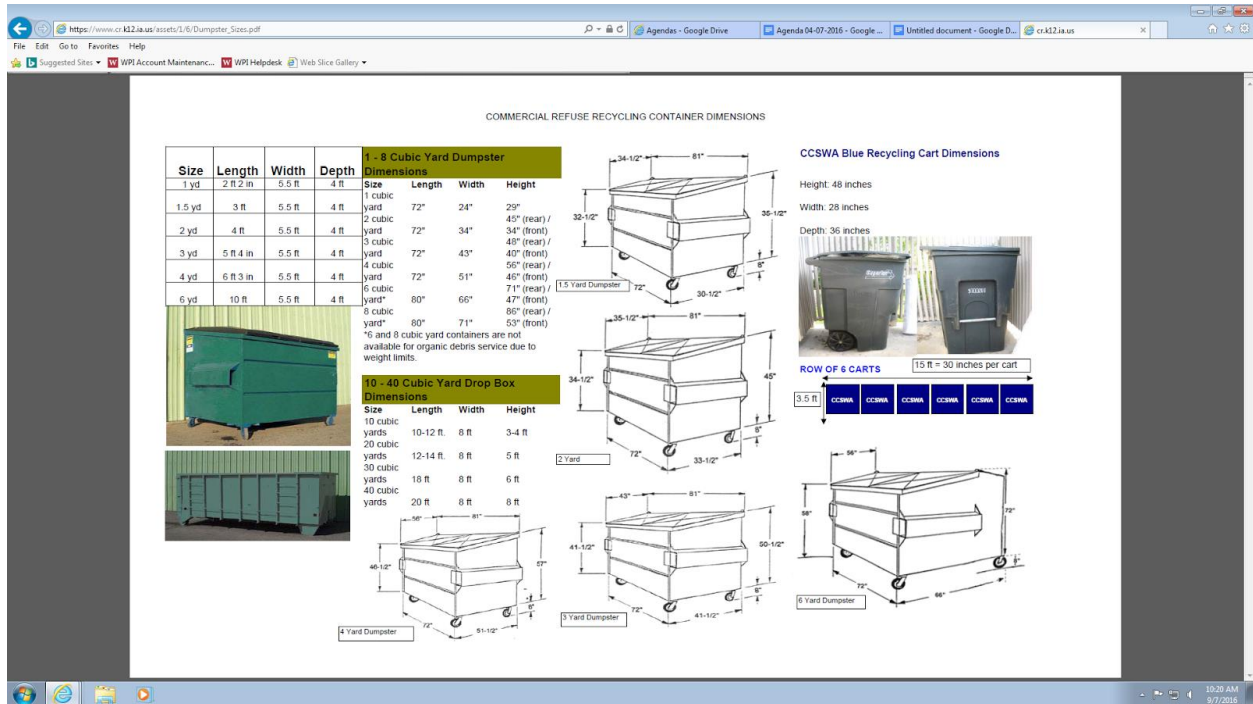


Figure 2: Dumpster Sizes

Dumpsters were created for the remote collection of garbage. Dumpsters are designed to store these garbage bags until a truck that is designed to lift and dump the dumpster, comes to collect the garbage. Dumpsters come in different sizes and many of the common sizes that can be ordered for private waste removal are listed below. The most common dumpster for private use is the 3-yard dumpster. This dumpster can be loaded by opening the top lid or the side window. This figure includes commonly ordered residential sizes, however, it does not include industrial sizes.

Dumpsters are normally located in centralized areas for larger campuses or complexes. Dumpsters may also be located in secluded areas where there is not a lot of clearance for machinery. However, this size of clearance can be determined by a garbage truck because the garbage truck must be able to park in front of the dumpster to load the garbage. The standard width of a garbage truck is around 8 feet to accommodate the standards of highway travel as well as providing a large volume for transportation. (U.S. Department of Transportation, 2016)

## 2.4: Lifting Assistance and the Current Market

Today, if an individual is looking to purchase a device to aid in their trash removal, there are a few options. Devices range from large battery powered hydraulic lifts to simple manual rail

systems, all of which aid in lifting trash into a dumpster. Devices can be portable or fix to the dumpster. The range of options cover many different consumer needs and offer flexibility to perform a number of specific lifts.

Ergodynamics, a division of 'The Automation Group' from Eugene Oregon, manufactures trash handling equipment for use by "schools, manufacturing facilities, hospitals and any organization that wants to limit injury risks to their employees." The company currently produces two lines of lifting equipment, the Auto Trash Dumper (ATD) and the GoLift series.

The Auto Trash Dumper is a hydraulic device that can dump up to 500 pounds from a range of different trash cans into dumpsters up to 72 inches in height. The device, which rests on four casters for mobility, also has feet that are used to secure the device to the ground during the dump cycle. The Auto Trash Dumper can be powered by a 12V car battery or by 120V AC current from a typical wall outlet. Additionally, it has the option of photovoltaic solar recharging in the case of battery power. In order to operate the device, the operator must first secure your trash can or cart onto the lifting platform using the built-in restraint bars which latch onto the rim of the can. The user operates the device through controls located on a handheld pendant which is wired to the machine. A hydraulic arm is used to manipulate the trash can radially about the top of the device. The trash exits the can through the dump shoot and into the dumpster. The user then brings the device back down using the pendant and it is ready for its next use.



*Figure 3: Auto Trash Dumper by Ergodynamics*

The GoLift series isn't designed exclusively for dumping trash. The idea behind this line of products is the unique ability to move the material in addition to lifting it. The devices, each primarily different in load capacities and subsequently price, all are equipped with pneumatic drive tires to power the motion of device. Like the Auto Trash Dumper, the lifting mechanism is also hydraulic. However, unique to the ATD, the GoLift series features a linear lifting mechanism. At the top of the linear lift, the part of the device which holds the trash receptacle rotates to dump the trash. This option is a much more mobile option to the Auto Trash Dumper, but for that reason, isn't quite as efficient. It has a precise lifting mechanism that takes more time to operate.



*Figure 4: GoLift 5 by Ergodynamics*

Another manufacturing company that produces devices similar to those in the GoLift series is Dump Dolly™. The standard device is very simple. It's essentially just your typical dolly that can lean against the dumpster and the trash can is manually pushed upwards on a linear track that extends the length of the dolly and into the dumpster. Further iterations of this same device include a crank to manipulate the trash up the dolly and another that utilizes a battery powered motor.

The current state of the art in trash lifting however, doesn't come from devices like these above. Trash lifters have been around and refined for years in the waste management industry as a means to lift curbside trash cans into garbage trucks. Many trucks are now highly automated and show more variety and innovation than the current products above marketed as trash lifters. There are four main types of trash trucks: front loading, rear loading, side loading and grapple. Front loading trucks typically empty the contents of large lidded dumpsters into the body of the truck. This is typically done through a large hydraulic radial lift that extends around the cab of the truck to the front bumper and rotates over top of the body of the truck. Rear loading trucks are typically either manual loading (for trash bags) or assisted manual loading (for cans) where the cans can connect to the back of the truck and are radially lifted until the trash falls into the

back of the trash truck. Grapple trucks consist of a crane with a clamshell bucket that picks up oversized trash and lifts it into the body. Grapple trucks most closely resemble your supermarket “Grab-It” machine.



*Figure 5: Standard Dump Dolly*

Side-loading trucks are likely the most applicable to this project. Their applications are to quickly lift trash over the side of the truck and into the body. They can be operated automatically or manually. The automatic side loaders have become one of the most common trash lifting methods and because of their success it’s important that this project explores their mechanics.

## Chapter 3: Methodology

Our goal was to design and build a cost-effective device to help elderly people lift trash up into dumpsters. The process we followed to accomplish this had five main components: defining, designing, optimizing, building and testing.

### 3.1: Defining the Product

#### Usage

The goal of this project is to develop a mechanism that can safely and reliably assist someone in lifting heavy trash bags up and into a dumpster. After completing detailed background research, the team specified usage requirements and technical specifications for the design. The three most important requirements we decided were ease of use, safe to use and reliable. These requirements are essential to accommodate the customer's needs. Ease of use, so the customer can achieve the objective with effectiveness, efficiency and satisfaction. Safe to use, so the customers do not harm themselves while using. Reliable, so the mechanism can operate and perform its required functions under stated conditions for a specified time.

#### Technical Specifications

To define the technical specifications of the mechanism, we had to ask ourselves what we wanted this device to do. This device must lift at least 50 lbs and be compatible with common 27-gallon standard trash bags. It must elevate to 5 feet which is the height of the dumpster we are designing around. Possible power sources for the device could be human powered, a high torque electric motor, a driver dyad, an electric assist motor, a hydraulic pump, a rechargeable DC battery or a power screw. An ideal design would have a minimal amount of degrees of freedom to decrease the chance of mechanical failure. The design should fit in a box of 4'L x 4'W x 7'H and operate in a box of 5.5'L x 4.5'W x 8'H. The design must operate with no obstructions in front of the dumpster. It must be weather resistant and operate in all weather conditions. The device shall last for 10,000 cycles at 10 years with 3 cycles per day.

<i>Lifts 50 lbs of Trash</i>
<i>Compatible with a 5' Standard Dumpster</i>
<i>Compatible with Standard 27 Gallon Trash Bag</i>
<i>Easily Powered (Human Power, DC Motor, etc...)</i>
<i>&lt; 2 Pinch Points (All Properly Labelled)</i>
<i>Stores in a 5' x 5' x 7' Space</i>
<i>Operates in a 5.5' x 5.5' x 8' Space</i>
<i>Weighs &lt; 150lbs</i>
<i>Prototype Costs &lt; \$1000</i>
<i>Weather Resistant</i>
<i>Meets OSHA General Requirements for All Machines - Standard #1910.212</i>
<i>Lasts 10,000 Cycles (10 Years at 3 Cycles per Day)</i>

Table 1: Failure Modes and Effects Analysis

Failure Mode	Effects of Failure	S	Causes of Failure	O	Detection Method	D	RPN	Recommended Action/ Design	S	O	D	RPN	Assumptions
Device Breaks	Unable to Dump Trash/ Potential Injury to User/ Device ruined	10	Stress in device exceeds failure limit of material	6	Visible failure	2	120	Complete stress analysis and adjust as necessary with proper safety factors	10	1	2	20	
Device falls over	Unable to Dump Trash/ Potential Injury to User/ Potential damage to device	9	Narrow base/poor attachment to the dumpster	6	Visible failure	2	108	Make sure device has a wide base and attaches to the dumpster well	9	2	2	36	
Device gets in the way of trash company coming to collect trash	Trash doesn't get removed from dumpster	8	Device is too bulky to move and attached to the dumpster in a poor location	10	Trash stays in the dumpster	1	80	Design a device that is easy to move and/or attaches to the dumpster in a way that doesn't impede trash collection	8	2	1	16	
User unable to supply enough mechanical force to operate it	User cannot use device to dump trash	8	User too weak/ poor mechanical advantage in the device design	4	Case study based on the strength of our target market	4	128	Provide good mechanical advantage for the device or powered dumping capabilities (VERY IMPORTANT)	8	1	4	32	Mechanical Operation
Device is susceptible to weather and breaks upon repeated weathering	Device breaks, can't complete task and potential for injury	7	Inappropriate materials used for the weather conditions	4	Rusting and/or visible failure	4	112	Research material properties and weather resistance for device/weather patterns. Also we can weather test the device.	5	2	4	40	
Device takes too long to operate to be worth using	User won't want to purchase the device/ making it worthless	5	Too many user inputs and/or the mechanical advantage is too high	7	Understanding how long market is willing to wait to operate device	3	105	Set a time limit on the length of time to run the device prior to designing it	5	2	3	30	
Device is too complex for the user to operate	User won't want to purchase the device/ making it worthless	5	Too many user inputs and/or inability of the user to judge trash variables (weight, etc.)	7	Understanding the technical capabilities of market	3	105	Keep the operations necessary for the user to complete to a minimum	5	2	3	30	
If device is powered by an external source (battery), it could die	The device will no longer operate until the battery is charged/ could fail mid operation	6	Lack of constant source of power leads to drained batteries	8	Electrical analysis/ voltmeter readings	2	96	External charging source is applied to battery (still needs to maintain mobility)/ add meter to design	6	2	1	12	Battery Powered Operation
Device leaves cover off dumpster after use	Trash gets wet	4	Device isn't designed to deal with the cover	10	Not in design	1	40	Take the cover of the dumpster into account when designing the device	4	2	1	8	
Device unable to lift cover off dumpster	Unable to get trash into dumpster	8	Device isn't designed to deal with the cover	10	Not in design	1	80	Take the cover of the dumpster into account when designing the device	8	2	1	16	
Device comes crashing down if there's an error	Weight of device can injure user	9	There is no safety lock	6	Test error or failure modes to see how the device reacts	2	108	Use a mechanism that prevents the device from crashing down in case of error	9	1	1	9	
There is not enough tilt on the device for the trash to effectively roll off	Unable to get trash into dumpster	8	Design doesn't account for proper angle of tilt	10	Analytic and experimental testing procedures	2	160	Use a device that tilts the correct amount as determined by tests and mathematics	8	1	2	16	

A Failure Mode and Effects Analysis (FMEA) table (shown below) was generated to help select a design with a high probability of successful operation and safety. This table lists as many failure modes as we could think of, what the cause and effect is, how to fix or what action to take, and how severe the failure could be. Each failure mode is assigned three numbers, a severity rating, a detection rating and an occurrence rating, each on a scale of 1-10. The product of these three metrics give you an RPN or Risk Priority Number. The Risk Priority Number highlights failure modes that should be avoided. Using this method, we were able to refine our design parameters and guide the selection of one of our concepts to move forward with. Some of the most important results of the FMEA were to pay attention to material stresses, ensure device stability and make the device portable, quick and easy for any user to operate. As we generated



concepts, the FMEA was a valuable guide to ensure it would not fail later on in the design process.

## **3.2: Detailed Design of the Device**

### **Concept Generation**

The concept design process involved brainstorming concepts while applying our customers' needs and functional requirements to the designs. We began conceptualizing concepts by free hand sketching and came up with multiple designs that will be expanded on.

One of the first designs was a Scissor Lift with a 4 Bar Linkage Platform, shown in Figure 6 below. This design has two stages. The first stage is standard scissor lift that would be driven by a motor. The second stage is the 4 Bar Linkage. As the scissor lift raises it will pull the middle joint of two of the bar linkages to straighten and raise the platform into a tilted position, in which the trash would be sitting on and roll off.

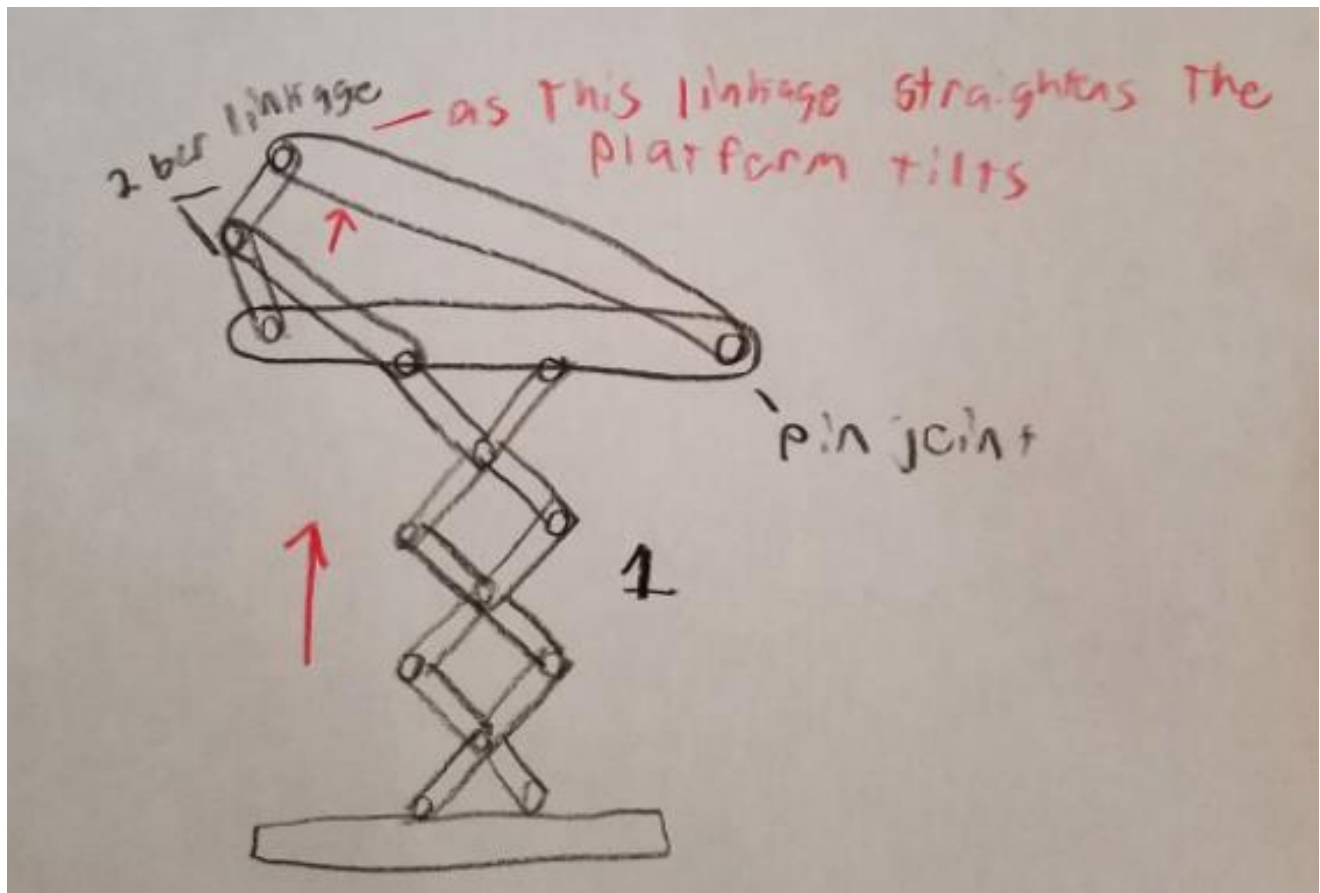
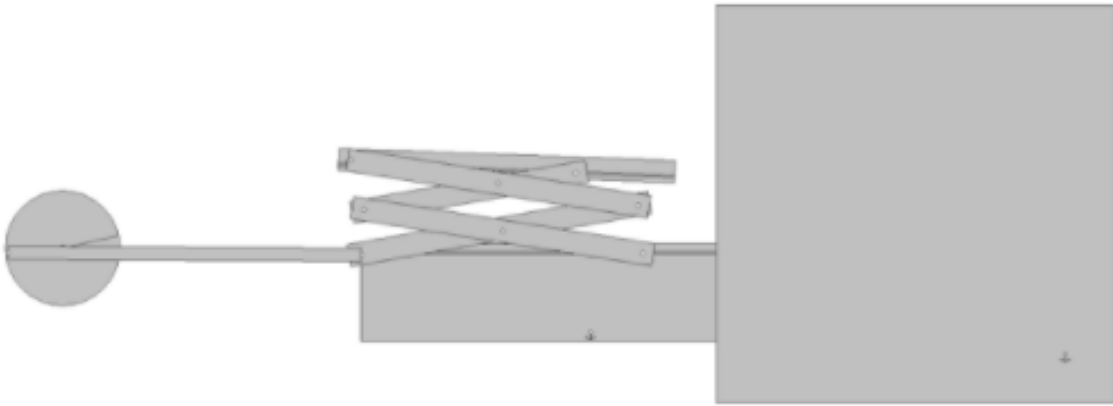
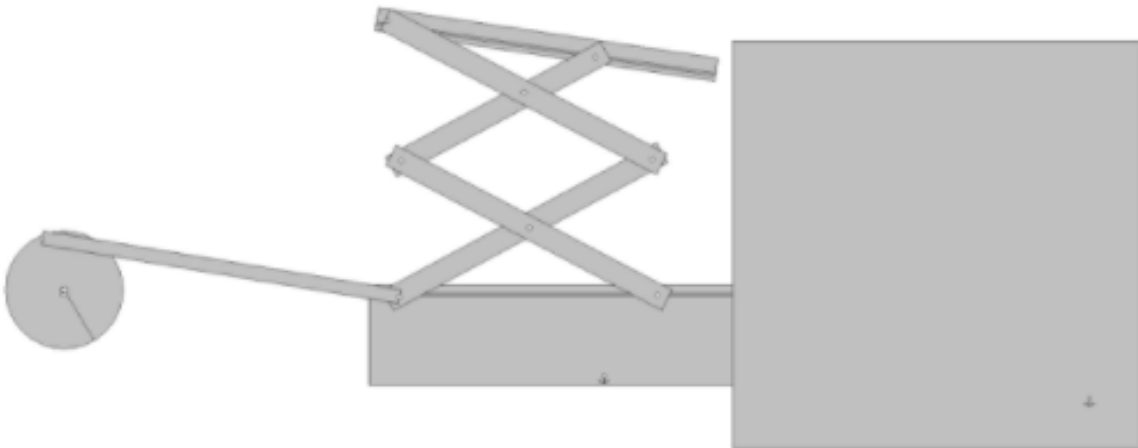


Figure 6: Double Scissor Lift

Another design was a Modified Scissor Lift with a shorter linkage bar at the top, shown in the figures below. The main concept in this design is to have a shorter bar to give it an angled tilt when it rises. This design would be driven by a power or lead screw. A power screw is suitable for this design because it can easily reverse direction so the design can ascend and descend. It is visible in the figures below how the mechanism gets an angles tilt.



*Figure 7: Scissor Lift Starting Position*



*Figure 8: Scissor Lift Middle Position*

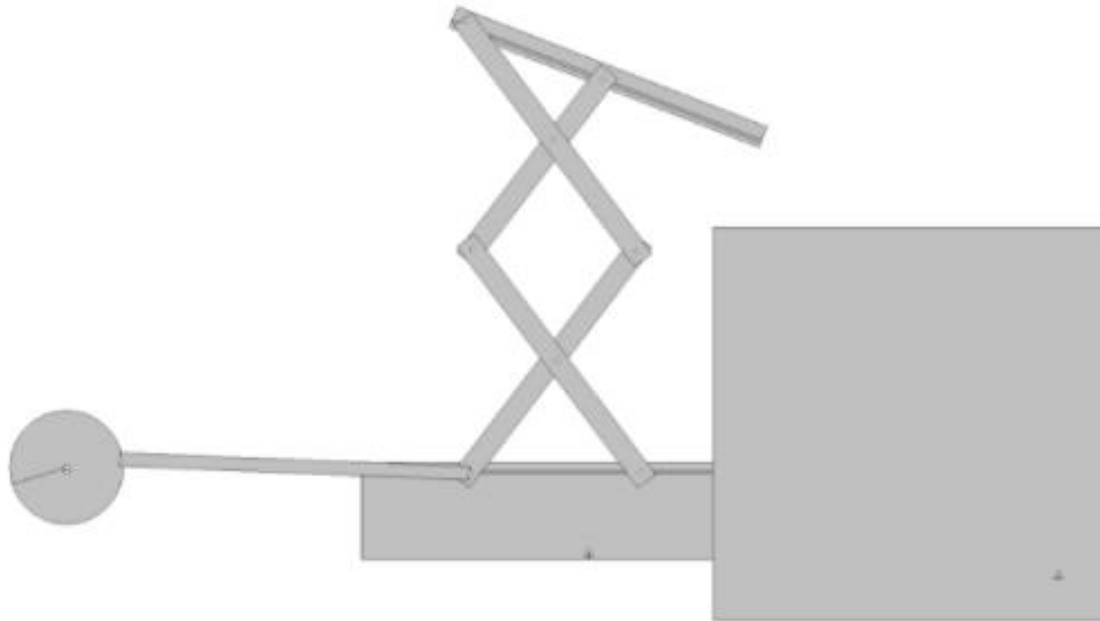


Figure 9: Scissor Lift Final Position

Another design we conceptualized was a Conveyor Belt Mechanism, in Figure 10 below. The trash bag is placed in a platform with walls attached to a conveyor belt. A motor or crank drives the gears, forcing them to rotate and revolve the conveyor belt. This would rotate the platform and lift the trash into the dumpster.

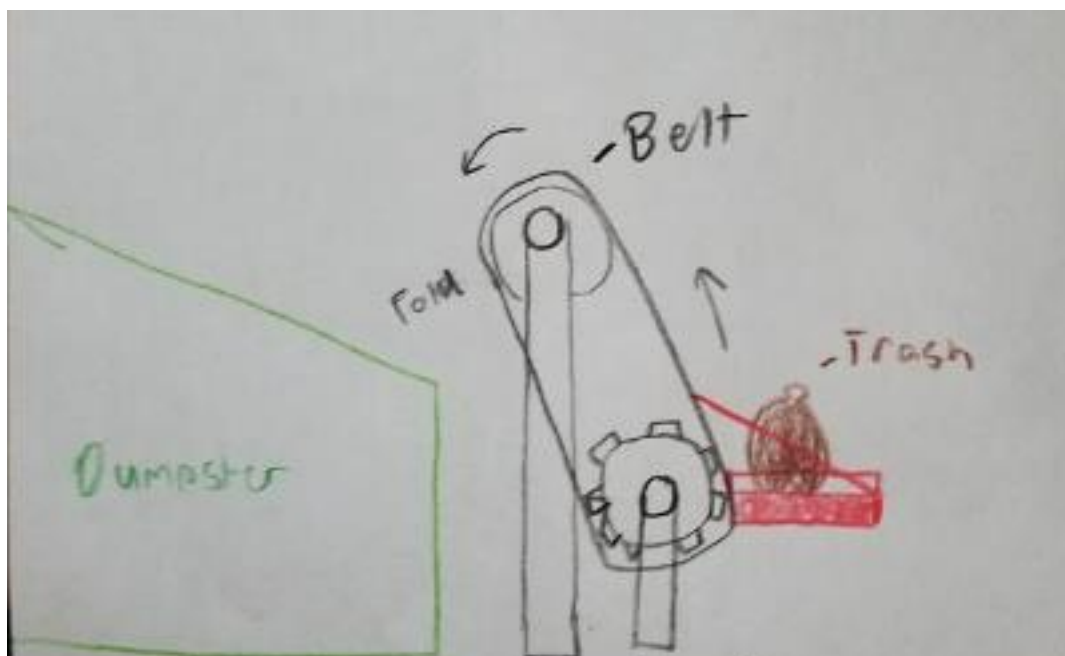
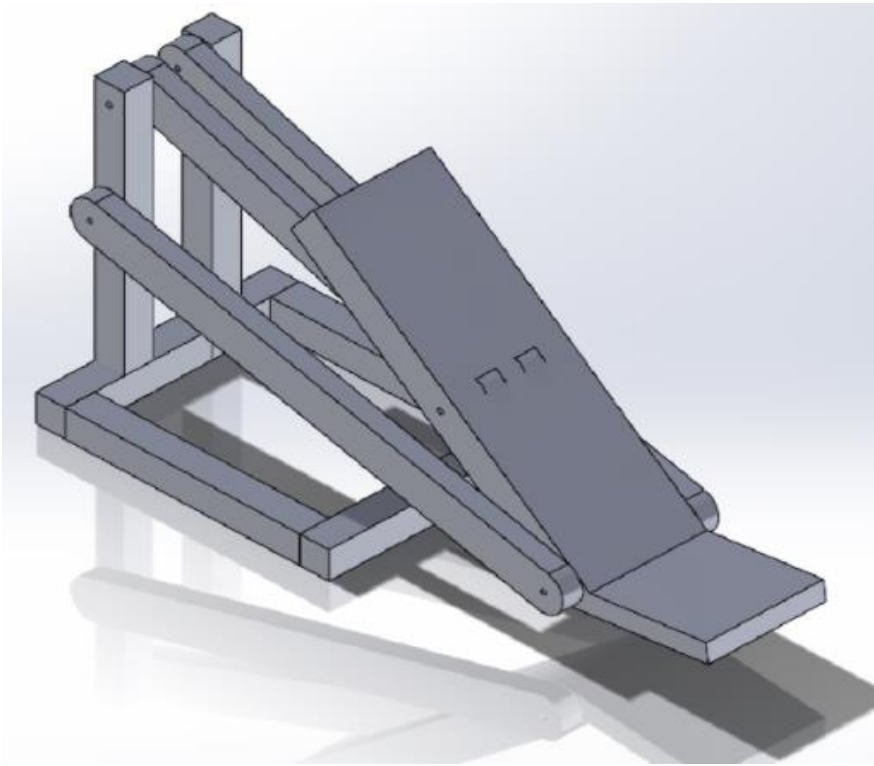
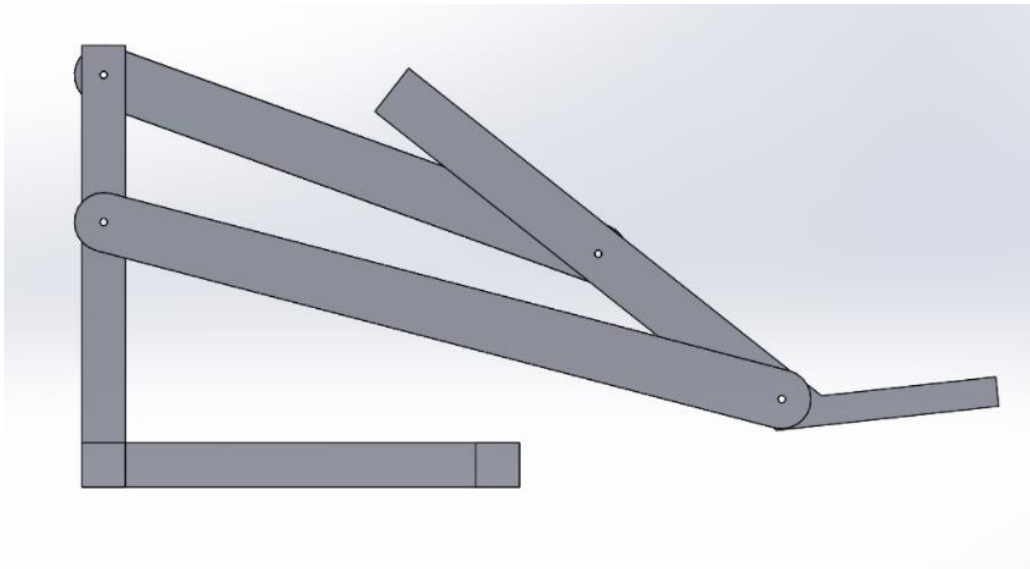


Figure 10: Conveyor Belt Mechanism

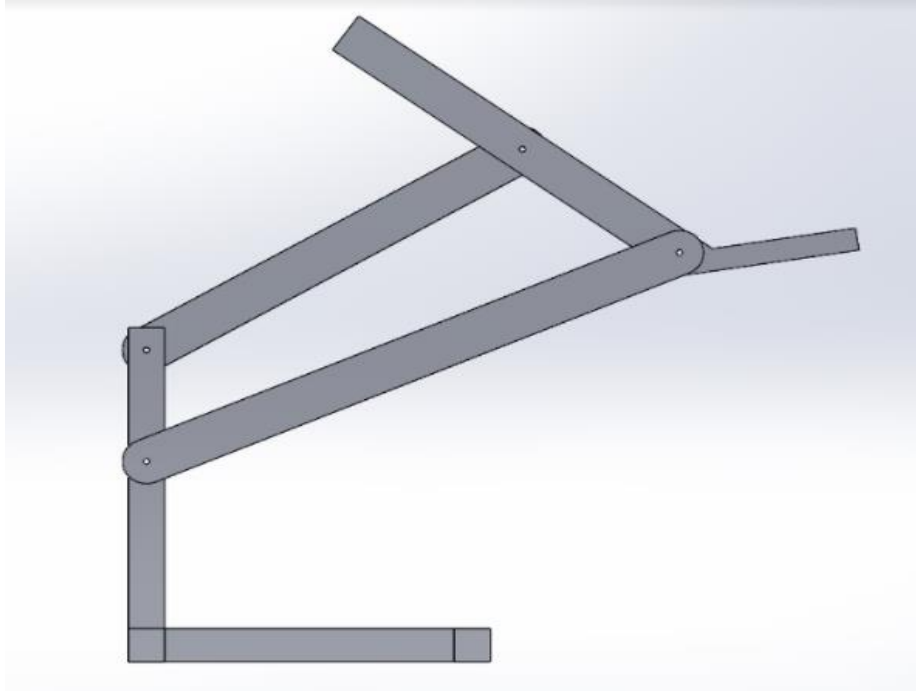
Another design was a simple Four Bar Mechanism, shown in Figure 11 below. This mechanism has four members including three moving links and one fixed link.



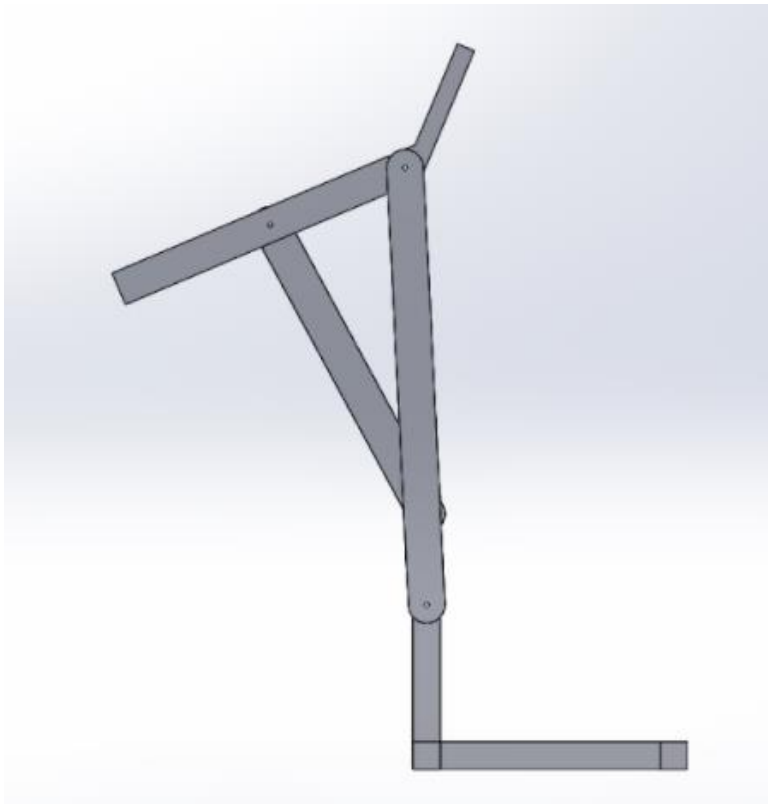
*Figure 11: Isometric View of Four bar Mechanism*



*Figure 12: Four bar Mechanism Starting Position*

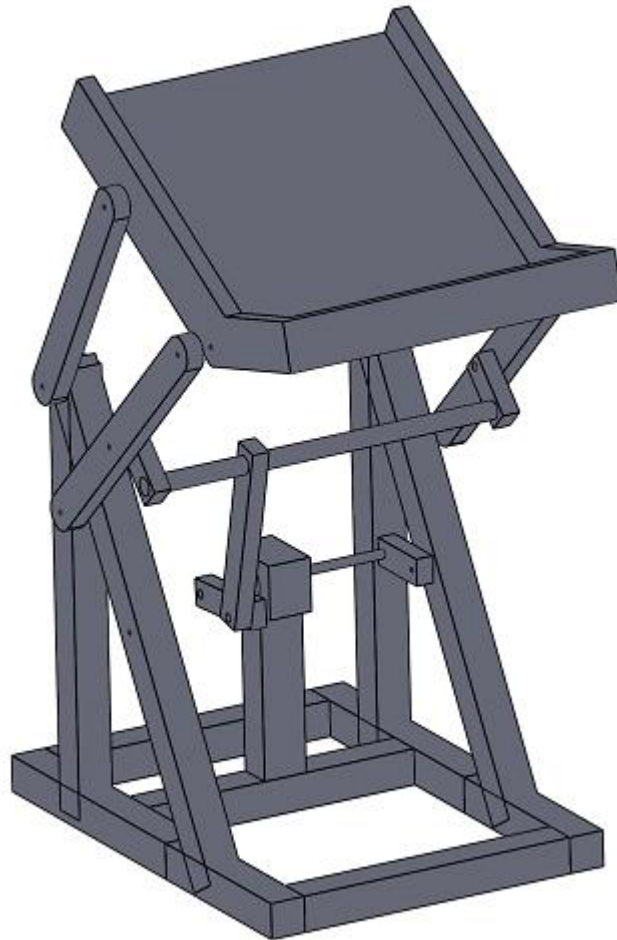


*Figure 13: Four bar Mechanism Middle Position*



*Figure 14: Four bar Mechanism Top Position*

Another design was a Double Four Bar Lifting mechanism with a Driver Dyad, shown in Figure 15 below. This is a modification from the Four Bar Lift. The driver dyad will lift the center arms of the device, raising the platform causing the trash to roll off. In this design the motor only needs to operate in one direction.



*Figure 15: Four bar Mechanism with Driver Dyad*

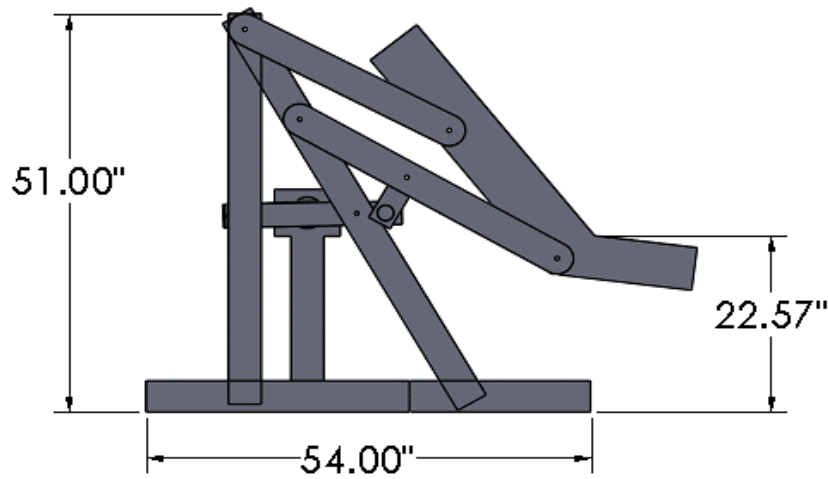


Figure 16: Four bar Mechanism with Dyad Starting Position

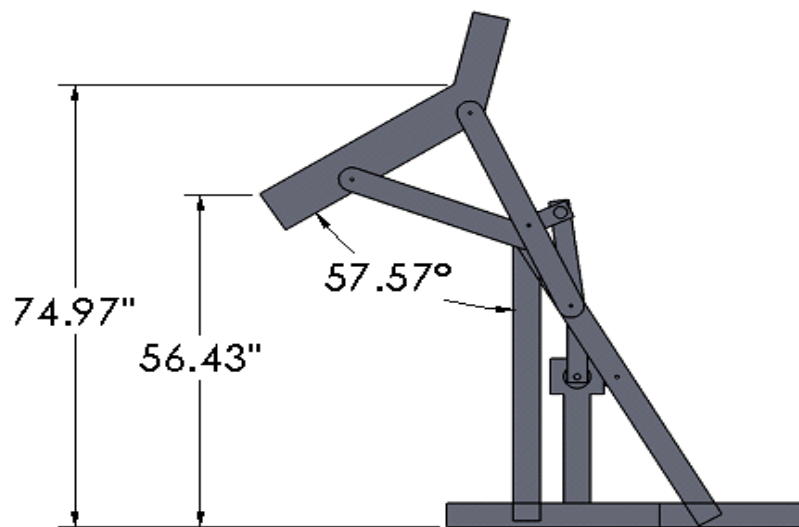


Figure 17: Four bar Mechanism with Dyad Final Position

### Design Matrix

After gathering all our design concepts, we created a decision matrix table, in Table 2 below, to help narrow down our ideas. As shown, it aided our decision making process by helping us compare each mechanism to important criteria. Each rating criteria has a weight from 1-5 (1 being the least important and 5 being the most important) determined by its importance.



Table 2: Concept Scoring Matrix

Concept Scoring Matrix							
Selection Criteria	Weight (%)	Concepts					
		A		B		C	
		Conveyor Assembly		Scissor Lift w/ Modified 4 Bar		Modified 4 Bar w/ Driver Dyad	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Durability	20	2	0.40	2	0.40	4	0.80
Stability/Balance of Load	15	5	0.75	3	0.45	5	0.75
Compatability with dumpsters	15	2	0.30	4	0.60	4	0.60
Ease of Use	10	5	0.50	4	0.40	5	0.50
Cycle Time	5	4	0.20	2	0.10	3	0.15
Power Required	5	1	0.05	3	0.15	4	0.20
Degrees of Freedom *	5	2	0.10	2	0.10	4	0.20
Complexity of Assembly	15	1	0.15	4	0.60	4	0.60
Cost	10	1	0.10	3	0.30	4	0.40
	<b>Total Score</b>		2.55		3.10		4.20
	Rank		3		2		1
	Continue?		No		No		Develop

The above concept scoring matrix rates our initial desing concepts against one another to determine which concept we should move forward with and develop. We developed selection criteria based on our technical specifications and then weighted these based on importance. We then rated each concept based on how well it matched the selected criteria. We used a rating system from 1 to 5 with 1 being the worst fit and 5 being the best. We then combined this rating with the weighted percentage given to each selection criteria to obtain a weighted score. The weighted scores for each concept were then added together and the concept with the highest total score is the concept we will develop further.

\* Degrees of Freedom ratings were calculated by giving a rating of 4 to concepts with 1 degree of freedom, a rating of 2 to concepts with 2 degrees of freedom, and a rating of 0 to concepts with 3 or more degrees of freedom

### 3.3: Optimizing the Design

After using the design matrix to choose the best design out of all our concepts, we had to determine dimensions and estimate the power requirements for the device. We needed this information to order parts and determine what size motor to use in the working prototype. Using SolidWorks, we were able to test different configurations to ensure the proper dumping motion and using MathCad, we were able to determine different forces, accelerations and velocities on the linkages.

#### Angle of Tilt

One thing we needed to understand before designing our device was the angle at which a trash bag would slide off of a platform. Our original theoretical calculations involved making a few assumptions about the center of gravity of the trash after the contents are settled.

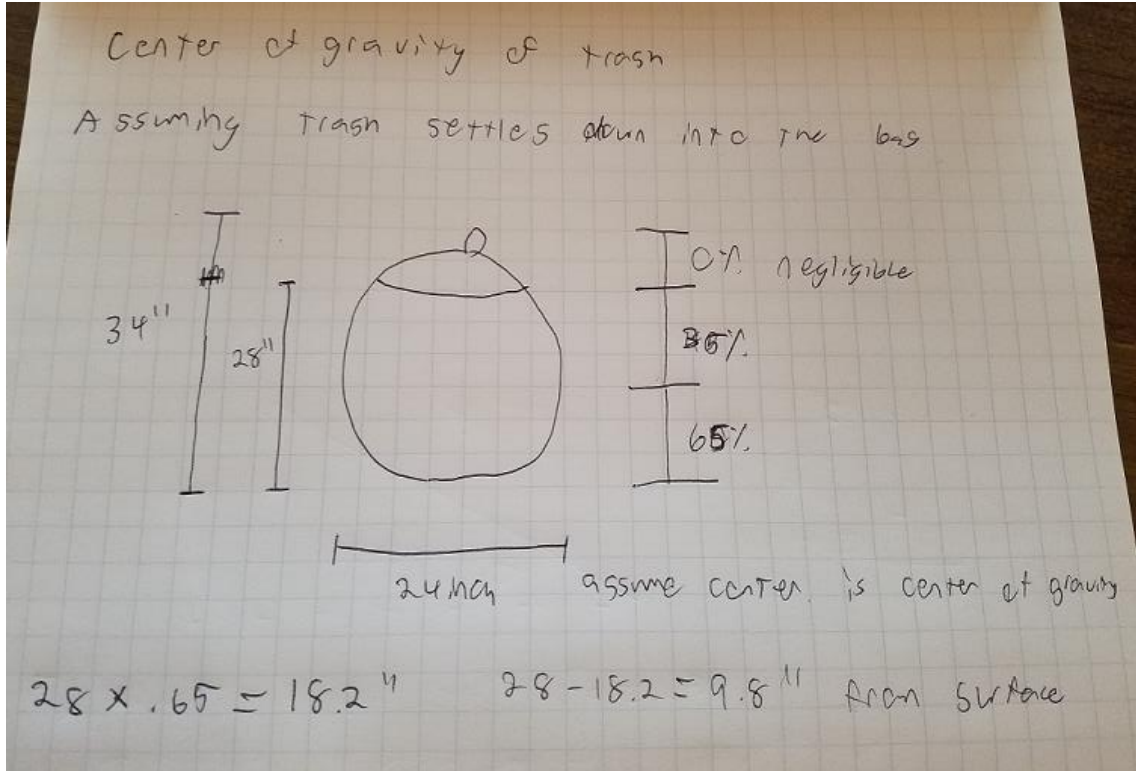


Figure 18: Settling of Contents of the Trash Bag

Problem: We need to find the angle of tilt required of the contact surface to have the component of the force of gravity in the direction of the surface to be enough to overcome friction.

Given Data:

Weight of the trash bag= 35 to 75 pounds.

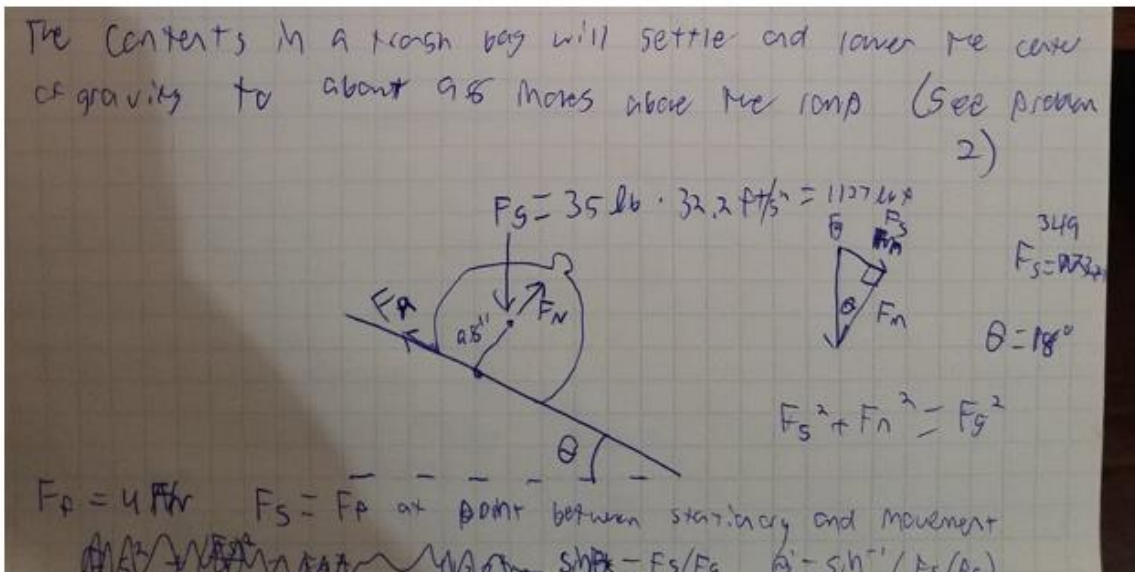
Coefficient of Friction between wood and Polyethylene is between .25 to .45

Assumptions: We will use the worst case scenarios for friction between the ramp and the bag as well as the weight of the bag.

E.g.  $W_{bag} = 35$  pounds

$\mu_f = .45$

The contents of the bag will settle and lower the center of gravity to about 9.8 inches above the ramp.



Theoretically we need about 20 degrees of tilt for the trash bag to fall off

Figure 19: Angle of Tilt Calculations

To ensure accuracy, we experimentally checked for the dumping angle of the garbage. Setting various garbage bags on a large sheet of cardboard, we tilted the cardboard until the garbage rolled or slid off. We placed an iPhone with an accelerometer, constantly reading the angle on the board. Looking at this app showed us the angle of tilt when the bag fell off. Results from these tests are shown below.



Figure 20: Tilt Experimentation

Table 3: Tilt Experimentation

Trial	1	2	3	4	5	6	7	8	9	10	11	12	AVG
Angle	19	24	22	23	19	16	21	21	20	22	18	22	20.58333

After having an angle of tilt requirement of about 21-22 degrees at the top of the devices motion, we now were able to start dimensioning the components.

### Original SolidWorks Model

The first step to determining the proper dimensions was choosing a height of the base structure. Because the device must be able to dump into a five-foot-tall dumpster, we originally chose four feet for the height of the base, but modified it as needed throughout the design iteration process. Making a 60 degree angle, the slanted member of the base is to be used to mount the primary four bar mechanism for dumping. We iterated through different dimensions on SolidWorks until we arrived at dimensions that allowed the platform to be properly loaded and dumped.

The last step in the SolidWorks dimensioning was adding a driver dyad mechanism to transfer power from the motor or hand crank with more effective transmission angles. The driver dyad gives mechanical advantage to the trash lifter. We had to carefully determine the right dimensions as to avoid Grashof's condition and make sure that the min and max rotation of the dumping four bar were correct. This took multiple iterations and we altered dimensions from the previous two dimensioning steps in order to make everything work cohesively.

### MathCad Calculations

Upon completion of dimensioning, we developed a MathCad document that determined the velocity and acceleration of each linkage at its center of gravity. To begin the calculations, we first declared the constants throughout the process. These included the individual lengths of linkages as well as operational constants. In this first section,  $\theta_2$  represents the angle of the driving linkage and it is assigned to an array of angles as to analyze every angle.  $\omega_2$  represents the angular velocity of the driving linkage, which we estimated to be about 15 seconds per cycle and  $\alpha_2$  is the angular acceleration of the driving linkage, ideally this is just zero. It also shows  $\delta\theta$ ,

which represents the angle between the two four bar mechanisms which can be seen below in the angle diagram (one in red and one in green). Likewise, the names of the linkages ( $a$ ,  $b$ ,  $c$  and  $d$ ) can be seen in the length diagram.

The next section in the MathCad is determining the Freudenstein constants. These are equations used to calculate the kinematics of a four-bar mechanism developed by Ferdinand Freudenstein, the father of modern kinematics. These constants (A-F) are used with a quadratic formula to find angles  $\theta_3$  and  $\theta_4$  as a function of  $\theta_2$ . Subsequently, we found  $\omega_3$  and  $\omega_4$ , also as a function of  $\theta_2$ . The next step allowed us to find the respective angular accelerations which are important in the virtual work calculations.

Using the angular velocity and acceleration of  $\theta_4$  in the driver dyad four bar mechanism, we can find the position, velocity and acceleration of  $\theta_{21}$ , the driving angle in the primary four bar mechanism. Using the same process to get angular velocities and accelerations for the other two angles, we had all the raw data necessary to find linear accelerations and velocities necessary to compute the virtual work. The equation shown below represents the energy balance in the device. Assuming no friction, sum of the external forces multiplied by velocity plus the power input from the motor is equal to the sum of mass multiplied by acceleration and velocity of each linkage and trash bag plus the sum of each components' mass moment of inertia times its angular acceleration.

$$\Sigma Fv + \Sigma T\omega = \Sigma mav + \Sigma I\alpha$$

By summing up all of the terms we are able to solve for the input  $T\omega$  term which represents the necessary input power from a motor to the drive shaft of the driver dyad.

# Angle Diagram

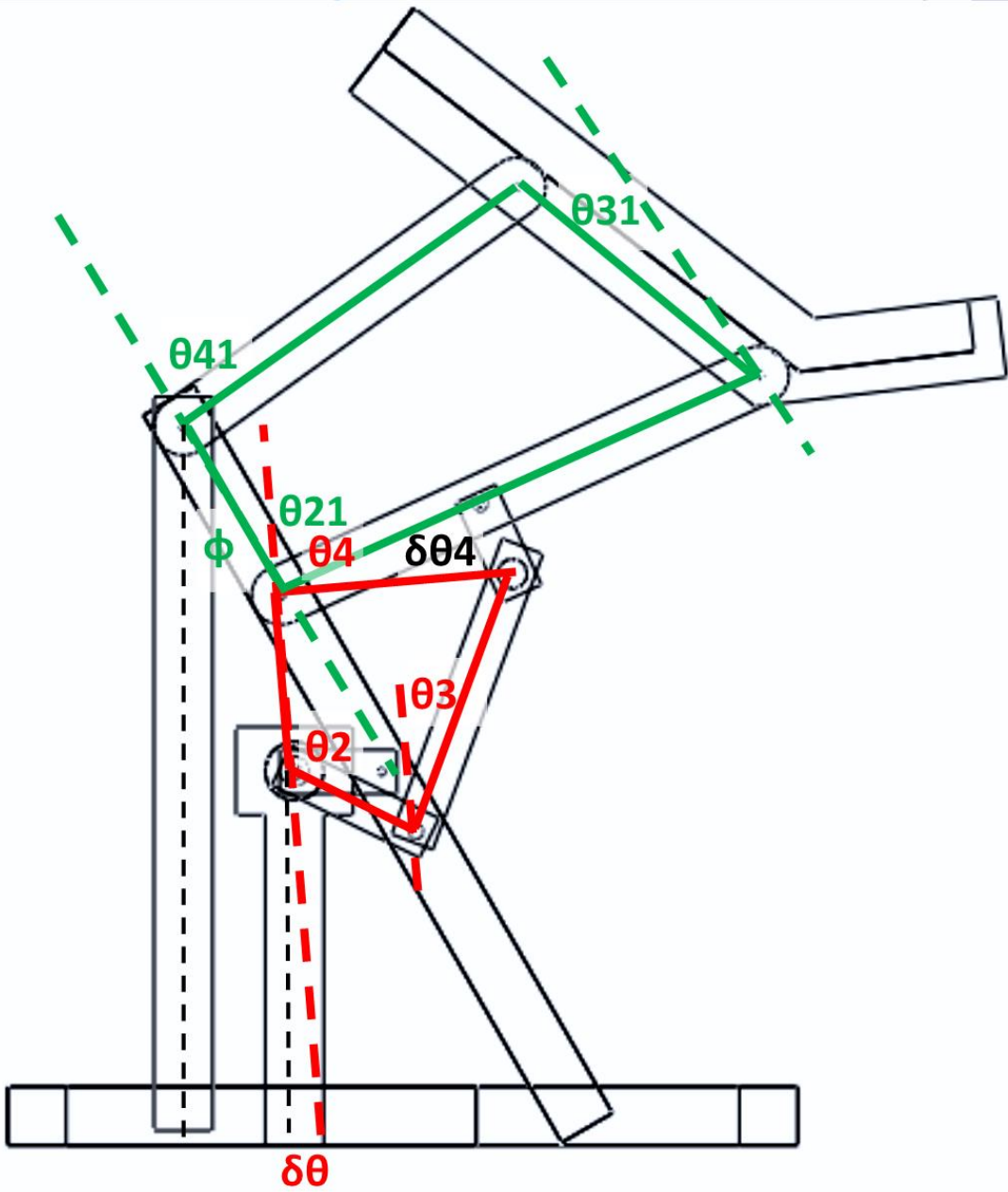


Figure 21: Angle Diagram

## Length Diagram

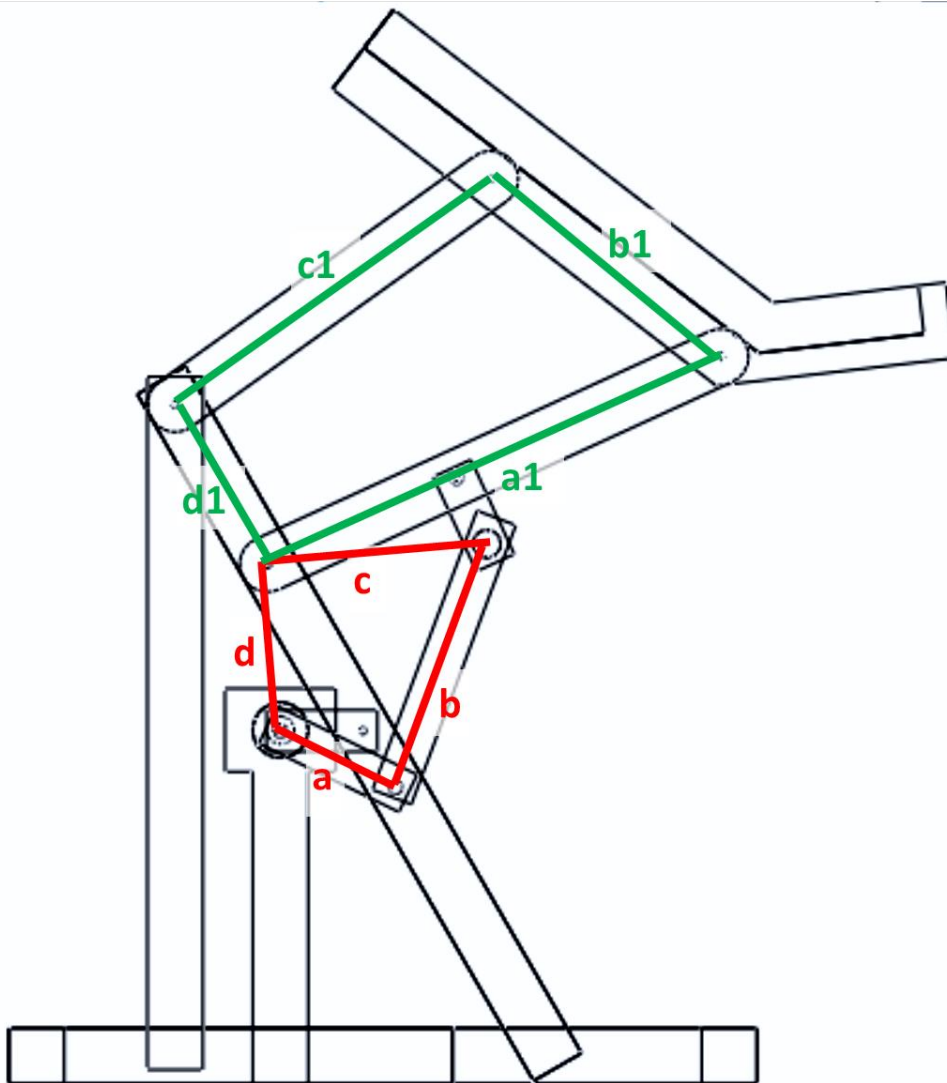


Figure 22: Length Diagram

Because the velocities and accelerations of each linkage changes as the device moves, we got the power required at every point the device's motion. The max virtual power required gave us an estimate for the power required from a theoretical motor, however, to ensure the motor would be strong enough, we added a factor of safety of three. This would account for any friction in the pins and also the effect of gravity on individual linkages. We iteratively changed some of the original constants (in conjunction with our solid works model) to optimize and try to get the lowest possible required power.

After a number of iterations, we developed a solution that had adequate motion in SolidWorks to meet our design specifications and additionally had a relatively low power requirement. Our estimated specs for a motor were about ¼ horsepower and 4rpm gear motor (or faster and we could possibly gear it down ourselves.)

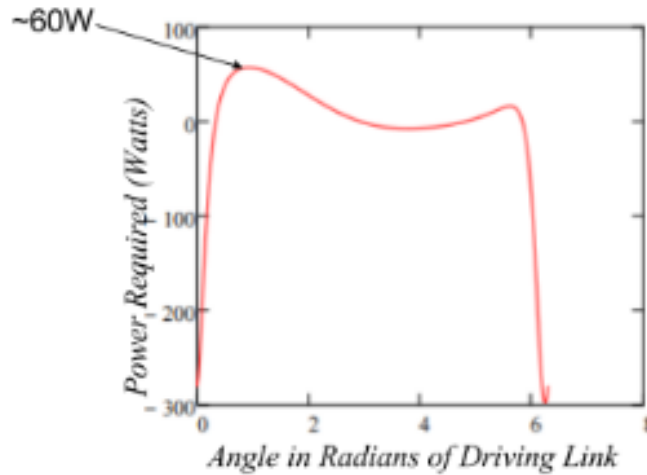


Figure 23: Power Requirements

An interesting thing we noticed from this graph was the tremendous force the device would come crashing down with. This needed to be mitigated and we took note of the massive negative values on the latter half of the machines motion after dumping the trash. A few ideas to decrease the effects of this motion were to attach springs from the dumping platform to the base, applying a force to assist in lifting and setting down the platform. Additionally, a gear motor with significant enough gear ratios will naturally resist this motion. Because of this, we initially took no action in regards to this phenomenon.

### 3.4: Building the Device

Before construction of the final prototype could begin, it was necessary to select materials and components. We selected 80/20 aluminum extrusions for the base and moving components of our device. The base consists of 80/20 10 series extrusions, which are 1x1 inch cross sections. The driver dyad and moving components in our device consist of 80/20 15 series extrusions, which are 1.5x1.5 inch cross sections. Depending on the components purpose in the device, the parts were fastened together by inside corner brackets, variable angle structural pivot



connections or  $\frac{1}{4}$  inch diameter steel pins through holes we drilled through the extrusions. A  $\frac{3}{4}$  inch diameter steel key shaft was attached to the driver dyad in order to drive the device.

Our original design made use of a gear motor to power the mechanism, however after talking with sales representatives from Leeson and Grainger, we found that a gear motor with the horsepower needed was outside the budget of our project. The MSRP of such a motor and its necessary controls were upwards of \$1000. So instead, we decided to mimic a flywheel by attaching a bicycle wheel to the keyed drive shaft. Two sheets of plywood were used for the platform in which the trash sits on.

Assembly of the base began with the 10 series extrusions placed to form a 60x32 inch rectangle with a 32 inch extrusion across placed roughly  $\frac{3}{4}$  of the way from the end. These extrusions were secured using inside corner brackets. The 80/20 aluminum extrusions were precut from the supplier to our specified lengths. A 50 inch 10 series extrusions was placed vertically on each of the 60 inch sides of the base and secured with inside corner brackets. A 57.2 inch 10 series extrusion was placed at a 30 degree angle from the top of both vertical extrusions to the base and secured using a variable angle pivot fastener. The assembled base is shown in Figure 24 below.



*Figure 24: Base Assembly*

To assemble the moving components, including the upper and lower arms, driver dyad and platform sides, it was necessary to drill holes through the necessary extrusions for the pins. Using a drill press,  $5/16$ th holes were bored through the 80/20 extrusions and bushings were press fitted in and reinforced with epoxy. One end of the dyad and the drive shaft post required a  $7/8$ th inch hole for the shaft to fit through.

After all the necessary components were drilled, assembly of the moving components could begin. The upper and lower arms, 38 inches and 40 inches respectively, were attached to the diagonal members using a pin, washer and shaft collar assembly, shown in Figure 25, to prevent it from slipping. Plastic spacers were added between components to ensure alignment. Cross beams were added to keep the arm assemblies parallel.



*Figure 25: 80/20 Links and Pin Joint*

The next step was to add the driver dyad along with the drive shaft and power source. For the prototype a bicycle wheel was used to act as a flywheel for mechanical advantage when turning the drive shaft. Finally a 38 x 48 inch plywood basket was cut and attached to the arms. The final prototype is shown in Figure 26 below.



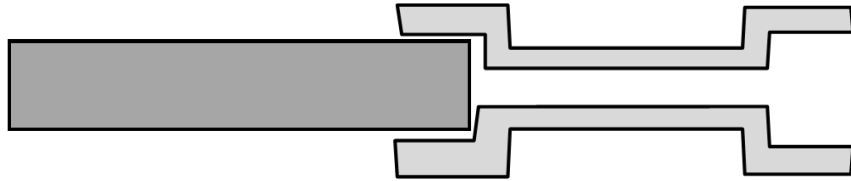
*Figure 26: Final Design*

### **3.5: Testing the Finished Product**

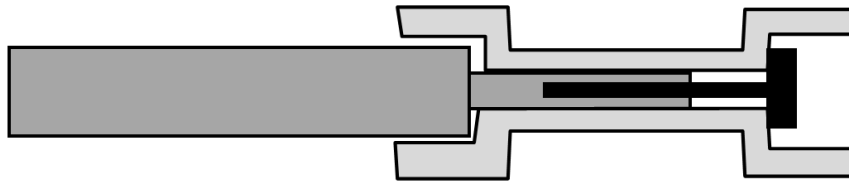
One of the most challenging components of the physical assembly was transmitting power from the bicycle wheel to the drive shaft. The axle system of the bicycle wheel was essentially a  $\frac{3}{8}$  inch hole with a  $\frac{3}{4}$  inch counter bore. Because our drive shaft fit perfectly in the counter bore, our original intent was to weld it in place. Unfortunately, after further consideration, we determined that it was not feasible. The thin metal cross section of the bicycle wheel would heat up much quicker than our 24 inch drive shaft, which would act as a heat sink. By the time the drive shaft was at the right temperature, the wheel would be too hot and the weld would be ruined.

Our second concept to attach the wheel to the drive shaft involved altering the shaft. We turned the end of it down in a lathe to  $\frac{3}{8}$  inch diameter, so it could fit through the axle system of the wheel. Then, we drilled and tapped a hole in the center of this lathed area so we could have a bolt transmit power from the wheel to the shaft. However, due to geometry constraints, the largest bolt we could fit in the assembly was  $\frac{1}{4}$  inch-20, which is rated for a mere 8ft-lbs of torque. Our original calculations called for about 100ft-lbs of torque and we estimate the actual torque required to be upwards of 200 ft-lbs including the plywood basket and heavy linkages. Needless to say, when we first tested this, it immediately failed. Not only did this show us that our design to transmit power from the wheel to the shaft was insufficient, but it alerted us to the insufficient strength of other set screws in the assembly.

### Option 1: Welding



### Option 2: Tapped Hole



### Option 3: 8020 w/ Set Screw

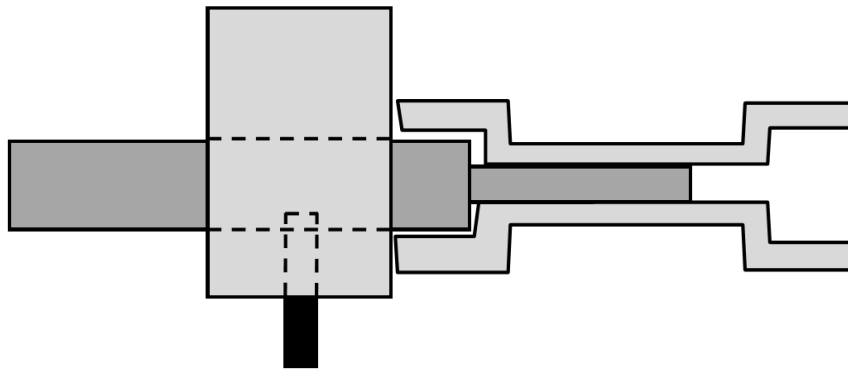


Figure 27: Connecting Driveshaft to Bicycle Wheel



*Figure 28: Bicycle Wheel Attached to Drive Shaft*

To securely attach the wheel to the drive shaft, we took another piece of 80/20 and secured it in the same fashion as we did the driver dyad on the other side, using a set screw in conjunction with the keyed slot. After securing the 80/20, we used a lot 10 gauge wire to secure the 80/20 to the wheel's spokes, effectively transmitting power. However, because we felt a number of set screws were not strong enough for the new high torque levels caused by extra weight, not considered in our original calculations, we decided not to try to lift the device solely using the wheel and drive shaft. Instead for our trial runs, we had two people assist the motion of the device as to not break the device in the days leading up to project presentation day.

Tests revealed the devices capabilities as well as its weaknesses. We manipulated it without much assistance and the drive shaft really did supply a lot of the power to the mechanism. However, on the way down, it was difficult for the drive shaft to slow down its motion and without assistance, it's likely the basket would have come crashing down, something we had neglected to mitigate after deciding to move away from the gear motor for our prototype. This crashing motion was shown clearly in our original calculations.

The device was successful in picking up trash from a 32 inch height and dumping it at a height of about 78 inches or 6.5 feet. This well exceed our original design specifications of 36 inch loading height and 60 inch dumping height. The dumping angle was about 26 degrees, which was sufficient as we originally calculated 21 degrees to be the appropriate angle of tilt necessary.



## Chapter 5: Results

Upon completion of our test runs, we noticed a number of key attributes of our device. First, it was heavy. The weight added from a lot of our post-design phase additions, like the 54 pound plywood dumping platform, really added up and it took all four of our team members to effectively move the device. Second, many of the pins did not sit straight in their bushings. Manufacturing error driven by the difficulty of drilling holes in the irregular shapes of 80/20 extrusions resulted in pins that were not perfectly parallel. This affected the motion of the device and added a lot more friction than was originally calculated for. Lastly, the device was stable. One of our primary concerns when designing the trash lifter was trying to keep it from falling over during the different phases of its motion. After testing it out, it was clear that we did in fact accomplish that goal.

Had the driveshaft been big enough to support larger set screws, our device would have been strong enough to do the motion required for dumping trash. However, turning the wheel was still a very difficult task and our final prototype was definitely not market ready for the elderly. There are a number of improvements that can be made in the future and we discuss these in the sections below.

## Chapter 6: Discussion

As we put our final device together it became more and more apparent that the weight of each linkage could not be ignored. At the linear density of 0.09 lbm/in, the entire device is very heavy without even having trash on the platform. The estimated max torque of 100 ft lbs could really be upwards of 250 ft lb and those forces are too high for our budget. Had we been more conscious of weight when designing the device, we would have been able to reduce the applied torque required to move the device, easing the user and allowing the drive shaft to work appropriately.

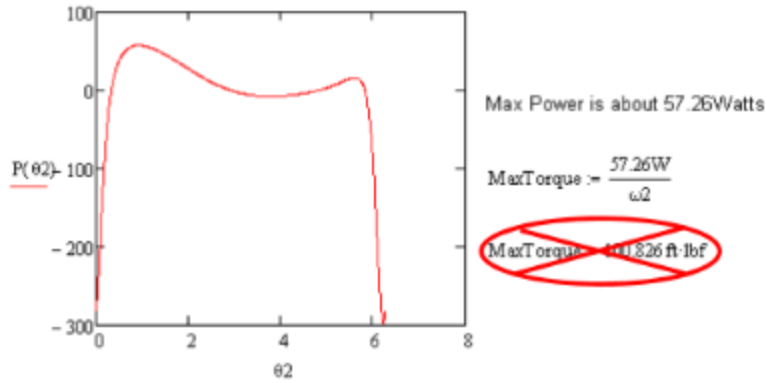


Figure 29: Power Calculations

Larger torque requires two primary design adaptations: larger fastening components (pins, set screws, etc.) and more mechanical advantage. For the trash lifter to be a product that is ready for the market, it's important that future designs look at increasing the size of the fastening components and gearing down the power source, whether that's a gear motor or a hand crank. In fact, even without a motor and a lot of mechanical advantage due to gears, our prototype could be transformed into something as easy to use as a conventional boat lift shown in the picture below.



Figure 30: Example of a Conventional Boat Lift

## Chapter 7: Recommendations

Upon completion of our project we came up with a number of recommendations that can be used to improve our design in the future. Due to budgeting issues we were not able to add a motor and microcontroller to the trash lifter which would have automated the process and eliminated the need for a flywheel. With a larger budget, future designs of the trash lifter should include a motor located underneath or in line with the driver dyad inside of the device. This eliminates the need for a long drive shaft that extends to the outside of the device. This coupled with a simple microcontroller would allow the user to easily start and stop the device. Automating the process would make the trash lifter more easily accessible for senior citizens and improve the process overall.

Another recommendation we came up with involves our basket design. Our current design utilizes plywood and 2x4's screwed together and attached directly to the 80/20 extrusions. The basket alone weighs 56 pounds which coupled with a large bag of trash makes for a difficult load to dump. In future designs, we recommend using a thin molded plastic which can be attached directly to the 80/20 extrusions and eliminate a significant amount of weight on the device. This would also allow the basket to reach a lower point during its loading phase which would further ease the burden on lifting the bag onto the lifter.

Throughout our design process and even our manufacturing process we were concerned with the power requirements of our lifter. The modifications we made to overcome problems such as link and pin strength, stability, and manufacturability kept adding weight. Our first recommendation from this experience is to find more mechanical advantages to require less input torque to drive the mechanism. This could include using gears, torsion springs, and lighter materials. Springs attached to the top four bar linkage could be used to assist the device on its way up and as a braking mechanism when the basket is being lowered back to the ground. This would help prevent the mechanism from crashing down if the power source is cut off during use.

Lastly, the materials we used for the majority of our mechanism could be improved in future models. We used 80/20 extrusions which are industrial aluminum erector sets that can be easily assembled. However one problem with these extrusions is that it is difficult to drill holes

into the unique cross sections that are located on the exterior of the extrusions. We also determined that we could use the “lite” version of 80/20 instead of the traditional version. By light weighting the moving four bar linkages, we can further reduce the amount of power needed to move our device. Ideally a lighter extrusion such as a hollow aluminum would be more beneficial and allow for easier drilling. This would also be a cheaper alternative when mass produced.

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# Appendix A

## Process Constants

$\theta_2 := 0, 0.001 \cdot 2\pi \dots 2 \cdot \pi$  variable used during calculations to represent each position of motor

$\omega_2 := 0.41888 \text{ s}^{-1}$  4 rpms

$\alpha_2 := 0 \text{ s}^{-2}$  no acceleration by the motor

*a b c and d refer to the lengths of members of the driver dyad mechanism found in the diagram*

$a := 9.00 \text{ in}$        $b := 18.75 \text{ in}$        $c := 16.53 \text{ in}$        $d := 12.37 \text{ in}$

$\delta\theta := \text{atan}\left(\frac{-0.94}{12.02}\right) = -4.472 \text{ deg}$        $\text{dens8020} := 0.0868 \frac{\text{lbm}}{\text{in}}$

$m_a := 2a \cdot \text{dens8020} = 1.562 \text{ lbm}$        $m_b := 2b \cdot \text{dens8020} = 3.255 \text{ lbm}$

## Freudenstein's Constants

$$\begin{aligned} K1 &:= \frac{d}{a} & K2 &:= \frac{d}{c} & K3 &:= \frac{(a^2 - b^2 + c^2 + d^2)}{2a \cdot c} & K4 &:= \frac{d}{b} & K5 &:= \frac{(c^2 - d^2 - a^2 - b^2)}{2 \cdot a \cdot b} \end{aligned}$$

$$A(\theta_2) := \cos(\theta_2) - K1 - K2 \cdot \cos(\theta_2) + K3$$

$$B(\theta_2) := -2 \sin(\theta_2)$$

$$C(\theta_2) := K1 - (K2 + 1) \cos(\theta_2) + K3$$

$$D(\theta_2) := \cos(\theta_2) - K1 + K4 \cos(\theta_2) + K5$$

$$E(\theta_2) := -2 \sin(\theta_2)$$

$$F(\theta_2) := K1 + (K4 - 1) \cos(\theta_2) + K5$$

## Determining the Angles and Angular Velocities of the System (based on Freudenstein)

$$\theta_3(\theta_2) := 2 \cdot \text{atan}\left[\frac{(-E(\theta_2) - \sqrt{E(\theta_2)^2 - 4 \cdot D(\theta_2) \cdot F(\theta_2)})}{2 \cdot D(\theta_2)}\right]$$

$$\theta_4(\theta_2) := 2 \cdot \text{atan}\left[\frac{(-B(\theta_2) - \sqrt{B(\theta_2)^2 - 4 \cdot A(\theta_2) \cdot C(\theta_2)})}{2 \cdot A(\theta_2)}\right]$$

$$\omega_3(\theta_2) := \frac{a}{b} \cdot \omega_2 \cdot \frac{\sin(\theta_4(\theta_2) - \theta_2)}{\sin(\theta_3(\theta_2) - \theta_4(\theta_2))}$$

$$\omega_4(\theta_2) := \frac{a}{c} \cdot \omega_2 \cdot \frac{\sin(\theta_2 - \theta_3(\theta_2))}{\sin(\theta_4(\theta_2) - \theta_3(\theta_2))}$$

## Acceleration Calculations

$$\underline{G}(\theta_2) := c \cdot \sin(\theta_4(\theta_2))$$

$$\underline{H}(\theta_2) := b \cdot \sin(\theta_3(\theta_2))$$

$$I(\theta_2) := a \cdot \alpha_2 \cdot \sin(\theta_2) + a \cdot \omega_2^2 \cdot \cos(\theta_2) + b \cdot \omega_3(\theta_2)^2 \cdot \cos(\theta_3(\theta_2)) - c \cdot \omega_4(\theta_2)^2 \cdot \cos(\theta_4(\theta_2))$$

$$\underline{J}(\theta_2) := c \cdot \cos(\theta_4(\theta_2))$$

$$\underline{K}(\theta_2) := b \cdot \cos(\theta_3(\theta_2))$$

$$\underline{L}(\theta_2) := a \cdot \alpha_2 \cdot \cos(\theta_2) + a \cdot \omega_2^2 \cdot \sin(\theta_2) + b \cdot \omega_3(\theta_2)^2 \cdot \sin(\theta_3(\theta_2)) - c \cdot \omega_4(\theta_2)^2 \cdot \sin(\theta_4(\theta_2))$$

$$\alpha_3(\theta_2) := \frac{(I(\theta_2) \cdot J(\theta_2) - G(\theta_2) \cdot L(\theta_2))}{(G(\theta_2) \cdot K(\theta_2) - H(\theta_2) \cdot J(\theta_2))}$$

$$\alpha_4(\theta_2) := \frac{(I(\theta_2) \cdot K(\theta_2) - H(\theta_2) \cdot L(\theta_2))}{(G(\theta_2) \cdot K(\theta_2) - H(\theta_2) \cdot J(\theta_2))}$$

## Transfer of Power from Driver Dyad to Dumping Four Bar

Now we use the driver dyad system and angle 4, angular velocity 4 and angular acceleration 4 to find the driving parameters for the primary four bar of the system.

$$\phi := 30 \text{deg} \quad \delta\theta_4 := \text{atan}\left(\frac{5.25}{15.25}\right) = 18.997 \cdot \text{deg}$$

$a_1$   $b_1$   $c_1$  and  $d_1$  refer to the lengths of members of the driver dyad mechanism found in the diagram

$$a_1 := 36 \text{in} \quad b_1 := 21 \text{in} \quad c_1 := 28 \text{in} \quad d_1 := 13.32 \text{in}$$

$$\theta_{21}(\theta_2) := \theta_4(\theta_2) + \delta\theta + \phi - \delta\theta_4 \quad \text{This is the driving angle for the second four bar}$$

$$\omega_{21}(\theta_2) := \omega_4(\theta_2)$$

$$\alpha_{21}(\theta_2) := \alpha_4(\theta_2) \quad m_{a1} := \text{dens8020} \cdot 2a_1 = 6.25 \cdot \text{lbf} \quad m_{b1} := \text{dens8020} \cdot 2b_1 = 3.646 \cdot \text{lbf}$$

$$m_{c1} := \text{dens8020} \cdot 2c_1 = 4.861 \cdot \text{lbf}$$

## Freudenstein's Constants

$$K_{11} := \frac{d_1}{a_1} \quad K_{21} := \frac{d_1}{c_1} \quad K_{31} := \frac{(a_1^2 - b_1^2 + c_1^2 + d_1^2)}{2a_1 \cdot c_1} \quad K_{41} := \frac{d_1}{b_1} \quad K_{51} := \frac{(c_1^2 - d_1^2 - a_1^2 - b_1^2)}{2 \cdot a_1 \cdot b_1}$$

$$A_1(\theta_2) := \cos(\theta_{21}(\theta_2)) - K_{11} - K_{21} \cdot \cos(\theta_{21}(\theta_2)) + K_{31}$$

$$B_1(\theta_2) := -2 \sin(\theta_{21}(\theta_2))$$

$$C_1(\theta_2) := K_{11} - (K_{21} + 1) \cos(\theta_{21}(\theta_2)) + K_{31}$$

$$D_1(\theta_2) := \cos(\theta_{21}(\theta_2)) - K_{11} + K_{41} \cdot \cos(\theta_{21}(\theta_2)) + K_{51}$$

$$E_1(\theta_2) := -2 \sin(\theta_{21}(\theta_2))$$

$$F_1(\theta_2) := K_{11} + (K_{41} - 1) \cos(\theta_{21}(\theta_2)) + K_{51}$$

### Determining Angles and Angular Velocities based on Freudenstein Constants

$$\theta_{31}(\theta_2) := 2 \cdot \operatorname{atan} \left[ \frac{(-E1(\theta_2) - \sqrt{E1(\theta_2)^2 - 4 \cdot D1(\theta_2) \cdot F1(\theta_2)})}{2 \cdot D1(\theta_2)} \right]$$

$$\theta_{41}(\theta_2) := 2 \cdot \operatorname{atan} \left[ \frac{(-B1(\theta_2) - \sqrt{B1(\theta_2)^2 - 4 \cdot A1(\theta_2) \cdot C1(\theta_2)})}{2 \cdot A1(\theta_2)} \right]$$

$$\omega_{31}(\theta_2) := \frac{a_1}{b_1} \cdot \omega_{21}(\theta_2) \cdot \frac{\sin(\theta_{41}(\theta_2) - \theta_{21}(\theta_2))}{\sin(\theta_{31}(\theta_2) - \theta_{41}(\theta_2))}$$

$$\omega_{41}(\theta_2) := \frac{a_1}{c_1} \cdot \omega_{21}(\theta_2) \cdot \frac{\sin(\theta_{21}(\theta_2) - \theta_{31}(\theta_2))}{\sin(\theta_{41}(\theta_2) - \theta_{31}(\theta_2))}$$

### Acceleration Calculations

$$G1(\theta_2) := c_1 \cdot \sin(\theta_{41}(\theta_2))$$

$$H1(\theta_2) := b_1 \cdot \sin(\theta_{31}(\theta_2))$$

$$I1(\theta_2) := a_1 \cdot \alpha_{21}(\theta_2) \cdot \sin(\theta_{21}(\theta_2)) + a_1 \cdot \omega_{21}(\theta_2)^2 \cdot \cos(\theta_{21}(\theta_2)) \dots \\ + b_1 \cdot \omega_{31}(\theta_2)^2 \cdot \cos(\theta_{31}(\theta_2)) - c_1 \cdot \omega_{41}(\theta_2)^2 \cdot \cos(\theta_{41}(\theta_2))$$

$$J1(\theta_2) := c_1 \cdot \cos(\theta_{41}(\theta_2))$$

$$K1(\theta_2) := b_1 \cdot \cos(\theta_{31}(\theta_2))$$

$$L1(\theta_2) := a_1 \cdot \alpha_{21}(\theta_2) \cdot \cos(\theta_{21}(\theta_2)) + a_1 \cdot \omega_{21}(\theta_2)^2 \cdot \sin(\theta_{21}(\theta_2)) \dots \\ + b_1 \cdot \omega_{31}(\theta_2)^2 \cdot \sin(\theta_{31}(\theta_2)) - c_1 \cdot \omega_{41}(\theta_2)^2 \cdot \sin(\theta_{41}(\theta_2))$$

$$\alpha_{31}(\theta_2) := \frac{(I1(\theta_2) \cdot J1(\theta_2) - G1(\theta_2) \cdot L1(\theta_2))}{(G1(\theta_2) \cdot K1(\theta_2) - H1(\theta_2) \cdot J1(\theta_2))}$$

$$\alpha_{41}(\theta_2) := \frac{(I1(\theta_2) \cdot K1(\theta_2) - H1(\theta_2) \cdot L1(\theta_2))}{(G1(\theta_2) \cdot K1(\theta_2) - H1(\theta_2) \cdot J1(\theta_2))}$$



### Determining the Position of the Garbage

$$\delta b1 := 3\text{in} \quad CGx := 12\text{in} \quad CGy := 12\text{in} \quad \phi2 := 150\text{deg} \quad mgarb := 50\text{lbm}$$

$$\delta xgarb := -\delta b1 - CGx \cdot \cos(180 - \phi2) + CGy \cdot \cos(\phi2 - 90)$$

$$\delta ygarb := CGx \cdot \sin(180 - \phi2) + CGy \cdot \sin(\phi2 - 90)$$

$$lgarb := \sqrt{\delta xgarb^2 + \delta ygarb^2}$$

$$\theta garb := \text{atan}\left(\frac{\delta ygarb}{\delta xgarb}\right)$$

### Linear Acceleration of Each Member's Center of Gravity (x and y components)

$$A_{acgx}(\theta_2) := \frac{-a}{2} \cdot \alpha_2 \cdot \sin(\theta_2 + \delta\theta) - \frac{a}{2} \cdot \omega_2^2 \cdot \cos(\theta_2 + \delta\theta)$$

$$A_{acgy}(\theta_2) := \frac{a}{2} \cdot \alpha_2 \cdot \cos(\theta_2 + \delta\theta) - \frac{a}{2} \cdot \omega_2^2 \cdot \sin(\theta_2 + \delta\theta)$$

*notice how "a/2" is the coefficient compared to just "a" because we want the acceleration of the center of gravity, which is halfway up the member rather than the full length*

$$A_{bcgx}(\theta_2) := \frac{-b}{2} \cdot \alpha_3(\theta_2) \cdot \sin(\theta_3(\theta_2) + \delta\theta) - \frac{b}{2} \cdot \omega_3(\theta_2)^2 \cdot \cos(\theta_3(\theta_2) + \delta\theta) \dots$$

$$+ -a \cdot \alpha_2 \cdot \sin(\theta_2 + \delta\theta) - a \cdot \omega_2^2 \cdot \cos(\theta_2 + \delta\theta)$$

$$A_{bcgy}(\theta_2) := \frac{b}{2} \cdot \alpha_3(\theta_2) \cdot \cos(\theta_3(\theta_2) + \delta\theta) - \frac{b}{2} \cdot \omega_3(\theta_2)^2 \cdot \sin(\theta_3(\theta_2) + \delta\theta) \dots$$

$$+ a \cdot \alpha_2 \cdot \cos(\theta_2 + \delta\theta) - a \cdot \omega_2^2 \cdot \sin(\theta_2 + \delta\theta)$$

$$A_{a1cgx}(\theta_2) := \frac{-a1}{2} \cdot \alpha_{21}(\theta_2) \cdot \sin(\theta_{21}(\theta_2) - \phi) - \frac{a1}{2} \cdot \omega_{21}(\theta_2)^2 \cdot \cos(\theta_{21}(\theta_2) - \phi)$$

$$A_{a1cgy}(\theta_2) := \frac{a1}{2} \cdot \alpha_{21}(\theta_2) \cdot \cos(\theta_{21}(\theta_2) - \phi) - \frac{a1}{2} \cdot \omega_{21}(\theta_2)^2 \cdot \sin(\theta_{21}(\theta_2) - \phi)$$

$$A_{b1cgx}(\theta_2) := \frac{-b1}{2} \cdot \alpha_{31}(\theta_2) \cdot \sin(\theta_{31}(\theta_2) - \phi) - \frac{b1}{2} \cdot \omega_{31}(\theta_2)^2 \cdot \cos(\theta_{31}(\theta_2) - \phi) \dots$$

$$+ -a1 \cdot \alpha_{21}(\theta_2) \cdot \sin(\theta_{21}(\theta_2) - \phi) - a1 \cdot \omega_{21}(\theta_2)^2 \cdot \cos(\theta_{21}(\theta_2) - \phi)$$

$$A_{b1cgy}(\theta_2) := \frac{b1}{2} \cdot \alpha_{31}(\theta_2) \cdot \cos(\theta_{31}(\theta_2) - \phi) - \frac{b1}{2} \cdot \omega_{31}(\theta_2)^2 \cdot \sin(\theta_{31}(\theta_2) - \phi) \dots$$

$$+ a1 \cdot \alpha_{21}(\theta_2) \cdot \cos(\theta_{21}(\theta_2) - \phi) - a1 \cdot \omega_{21}(\theta_2)^2 \cdot \sin(\theta_{21}(\theta_2) - \phi)$$

$$A_{c1cgx}(\theta_2) := \frac{-c1}{2} \cdot \alpha_{41}(\theta_2) \cdot \sin(\theta_{41}(\theta_2) - \phi) - \frac{c1}{2} \cdot \omega_{41}(\theta_2)^2 \cdot \cos(\theta_{41}(\theta_2) - \phi)$$

$$A_{c1cgy}(\theta_2) := \frac{c1}{2} \cdot \alpha_{41}(\theta_2) \cdot \cos(\theta_{41}(\theta_2) - \phi) - \frac{c1}{2} \cdot \omega_{41}(\theta_2)^2 \cdot \sin(\theta_{41}(\theta_2) - \phi)$$

$$A_{garbx}(\theta_2) := \frac{-l_{garb}}{2} \cdot \alpha_{31}(\theta_2) \cdot \sin(\theta_{31}(\theta_2) - \phi + \theta_{garb}) - \frac{l_{garb}}{2} \cdot \omega_{31}(\theta_2)^2 \cdot \cos(\theta_{31}(\theta_2) - \phi + \theta_{garb})$$

$$+ -a1 \cdot \alpha_{21}(\theta_2) \cdot \sin(\theta_{21}(\theta_2) - \phi) - a1 \cdot \omega_{21}(\theta_2)^2 \cdot \cos(\theta_{21}(\theta_2) - \phi)$$

$$A_{garby}(\theta_2) := \frac{l_{garb}}{2} \cdot \alpha_{31}(\theta_2) \cdot \cos(\theta_{31}(\theta_2) - \phi + \theta_{garb}) - \frac{l_{garb}}{2} \cdot \omega_{31}(\theta_2)^2 \cdot \sin(\theta_{31}(\theta_2) - \phi + \theta_{garb})$$

$$+ a1 \cdot \alpha_{21}(\theta_2) \cdot \cos(\theta_{21}(\theta_2) - \phi) - a1 \cdot \omega_{21}(\theta_2)^2 \cdot \sin(\theta_{21}(\theta_2) - \phi)$$

### Linear Velocity of Each Member's Center of Gravity (x and y components)

$$V_{acgx}(\theta_2) := \frac{-a}{2} \cdot \omega_2 \cdot \sin(\theta_2 + \delta\theta)$$

$$V_{acgy}(\theta_2) := \frac{a}{2} \cdot \omega_2 \cdot \cos(\theta_2 + \delta\theta)$$

$$V_{bcgx}(\theta_2) := \frac{-b}{2} \cdot \omega_3(\theta_2) \cdot \sin(\theta_3(\theta_2) + \delta\theta) + 2 V_{acgx}(\theta_2)$$

$$V_{bcgy}(\theta_2) := \frac{b}{2} \cdot \omega_3(\theta_2) \cdot \cos(\theta_3(\theta_2) + \delta\theta) + 2 V_{acgy}(\theta_2)$$

$$V_{a1cgx}(\theta_2) := \frac{-a1}{2} \cdot \omega_{21}(\theta_2) \cdot \sin(\theta_{21}(\theta_2) - \phi)$$

$$V_{a1cgy}(\theta_2) := \frac{a1}{2} \cdot \omega_{21}(\theta_2) \cdot \cos(\theta_{21}(\theta_2) - \phi)$$

$$V_{b1cgx}(\theta_2) := \frac{-b1}{2} \cdot \omega_{31}(\theta_2) \cdot \sin(\theta_{31}(\theta_2) - \phi) + 2 V_{a1cgx}(\theta_2)$$

$$V_{b1cgy}(\theta_2) := \frac{b1}{2} \cdot \omega_{31}(\theta_2) \cdot \cos(\theta_{31}(\theta_2) - \phi) + 2 V_{a1cgy}(\theta_2)$$

$$V_{c1cgx}(\theta_2) := \frac{-c1}{2} \cdot \omega_{41}(\theta_2) \cdot \sin(\theta_{41}(\theta_2) - \phi)$$

$$V_{c1cgy}(\theta_2) := \frac{c1}{2} \cdot \omega_{41}(\theta_2) \cdot \cos(\theta_{41}(\theta_2) - \phi)$$

$$V_{garbx}(\theta_2) := \frac{-l_{garb}}{2} \cdot \omega_{31}(\theta_2) \cdot \sin(\theta_{31}(\theta_2) - \phi + \theta_{garb}) + 2 V_{a1cgx}(\theta_2)$$

$$V_{garby}(\theta_2) := \frac{l_{garb}}{2} \cdot \omega_{31}(\theta_2) \cdot \cos(\theta_{31}(\theta_2) - \phi + \theta_{garb}) + 2 V_{a1cgy}(\theta_2)$$

### Mass Moment of Inertia of Each Member

$$I_a := \frac{1}{12} \cdot m_a \cdot a^2 \quad I_b := \frac{1}{12} \cdot m_b \cdot b^2 \quad I_{a1} := \frac{1}{12} \cdot m_{a1} \cdot a_1^2$$

$$I_{b1} := \frac{1}{12} \cdot m_{b1} \cdot b_1^2 \quad I_{c1} := \frac{1}{12} \cdot m_{c1} \cdot c_1^2$$

### Virtual Work Equation

$$\Sigma F_v(\theta_2) := -9.81 \frac{m}{s^2} \cdot m_{garb} \cdot V_{garby}(\theta_2)$$

$$\Sigma m_{avx}(\theta_2) := m_a \cdot A_{acgx}(\theta_2) \cdot V_{acgx}(\theta_2) + m_b \cdot A_{bcgx}(\theta_2) \cdot V_{bcgx}(\theta_2) + m_{a1} \cdot A_{a1cgx}(\theta_2) \cdot V_{a1cgx}(\theta_2) \\ + m_{b1} \cdot A_{b1cgx}(\theta_2) \cdot V_{b1cgx}(\theta_2) + m_{c1} \cdot A_{c1cgx}(\theta_2) \cdot V_{c1cgx}(\theta_2) \dots \\ + m_{garb} \cdot A_{garbx}(\theta_2) \cdot V_{garbx}(\theta_2)$$

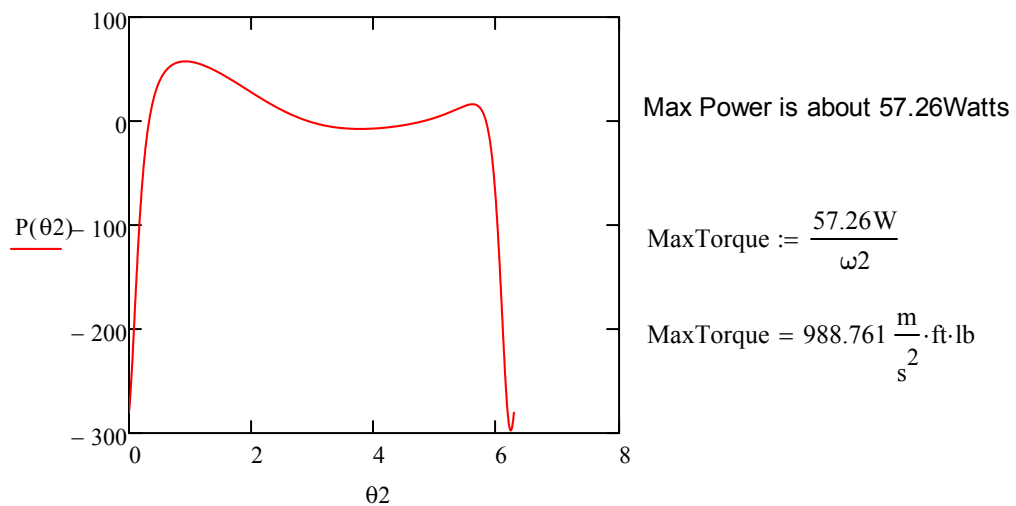
$$\Sigma m_{avy}(\theta_2) := m_a \cdot A_{acgy}(\theta_2) \cdot V_{acgy}(\theta_2) + m_b \cdot A_{bcgy}(\theta_2) \cdot V_{bcgy}(\theta_2) + m_{a1} \cdot A_{a1cgy}(\theta_2) \cdot V_{a1cgy}(\theta_2) \\ + m_{b1} \cdot A_{b1cgy}(\theta_2) \cdot V_{b1cgy}(\theta_2) + m_{c1} \cdot A_{c1cgy}(\theta_2) \cdot V_{c1cgy}(\theta_2) \dots \\ + m_{garb} \cdot A_{garby}(\theta_2) \cdot V_{garby}(\theta_2)$$

$$\Sigma I \alpha \omega(\theta_2) := I_a \cdot \alpha_2 \cdot \omega_2 + I_b \cdot \alpha_3(\theta_2) \cdot \omega_3(\theta_2) + I_{a1} \cdot \alpha_{21}(\theta_2) \cdot \omega_{21}(\theta_2) + I_{b1} \cdot \alpha_{31}(\theta_2) \cdot \omega_{31}(\theta_2) \dots \\ + I_{c1} \cdot \alpha_{41}(\theta_2) \cdot \omega_{41}(\theta_2)$$

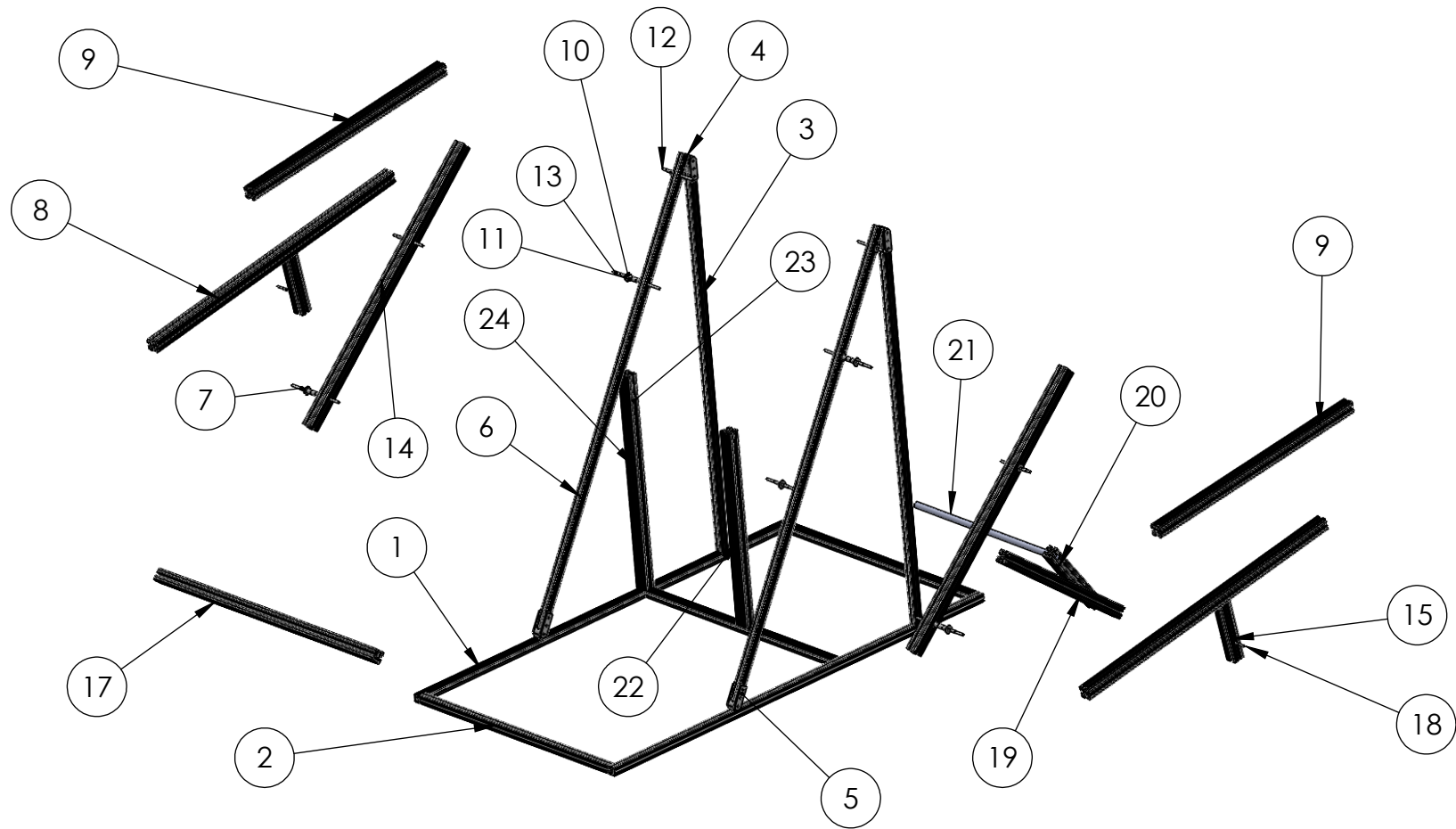
Based on the Virtual Work Equation which is:

$\Sigma F_v + \Sigma T \omega = \Sigma m_{av} + \Sigma I \alpha \omega$  where  $\Sigma T \omega$  represents the input power from the motor

$$P(\theta_2) := \Sigma m_{avx}(\theta_2) + \Sigma m_{avy}(\theta_2) + |\Sigma I \alpha \omega(\theta_2)| - \Sigma F_v(\theta_2)$$



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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE: <b>Exploded View</b>
		DIMENSIONS ARE IN INCHES	DRAWN			
		TOLERANCES:	CHECKED			
		FRACTIONAL $\pm$	ENG APPR.			
		ANGULAR: MACH $\pm$ BEND $\pm$	MFG APPR.			
		TWO PLACE DECIMAL $\pm$	Q.A.			
		THREE PLACE DECIMAL $\pm$	COMMENTS:			
		INTERPRET GEOMETRIC TOLERANCING PER:				SIZE DWG. NO. REV
		MATERIAL				<b>A</b> exploded view
	NEXT ASSY	USED ON	FINISH			SCALE: 1:48 WEIGHT: SHEET 1 OF 2
		APPLICATION	DO NOT SCALE DRAWING			

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ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1002 x 12	Base Long	2
2	1002 x 12	Base Short	3
3	1010 x 12	Base Vertical	2
4	_4188_n_2	Angle Connector Bracket	4
5	_4196_4	Angle Connector Bracket	8
6	1010 x 12	Base Diagonal	2
7	6391K401	Spacer	18
8	rev9 x 40	Lower Arm	2
9	rev6 x 32	Upper Arm	2
10	91525A120	Washer	38
11	92510A767	Bushing	12
12	1327K115	Pin	5
13	1327K117	Shaft Collar	4
14	rev8 x 38	Arm Connector	2
15	rev2 x 8	Arm Extension	2
16	6391K124	Pin	2
17	rev7 x 37	Arm Cross Piece	1
18	1327K104	Pin	2
19	rev4 x 22	Driver Dyad Long	1
20	rev3 x 11	Driver Dyad	1
21	1497K62	Key Shaft	1
22	rev5 x 25	Dyad Post	1
23	6391K207	Bearing	2
24	rev5 x 25	Dyad Post Tall	1

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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
		INTERPRET GEOMETRIC TOLERANCING PER:	CHECKED		
		MATERIAL	ENG APPR.		
		FINISH	MFG APPR.		
NEXT ASSY	USED ON		Q.A.		
	APPLICATION	DO NOT SCALE DRAWING	COMMENTS:		

TITLE:  
**Bill of Materials**

SIZE **A** DWG. NO. REV

SCALE: 1:48 WEIGHT: SHEET 2 OF 2

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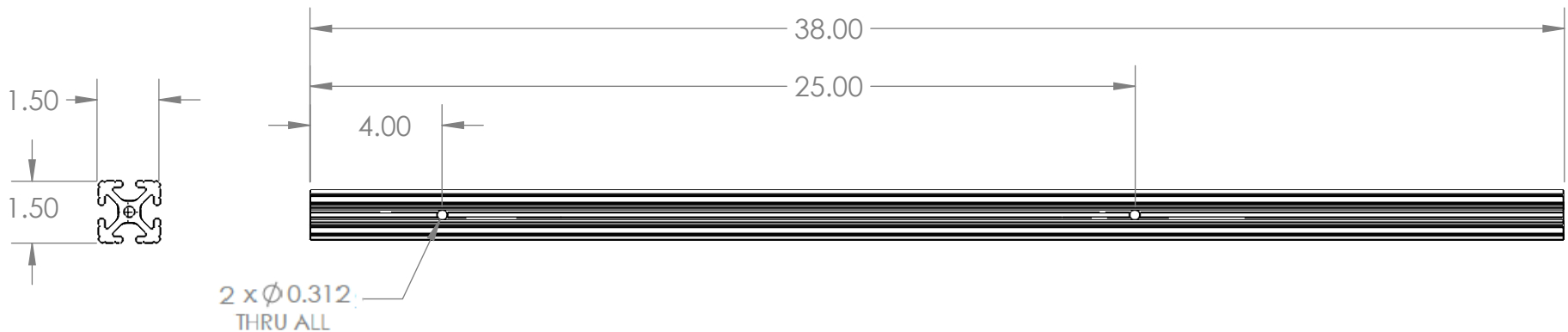
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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:  
**Arm Connector**

SIZE	DWG. NO.	REV
<b>A</b>	<b>8020 15 Series</b>	
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

2

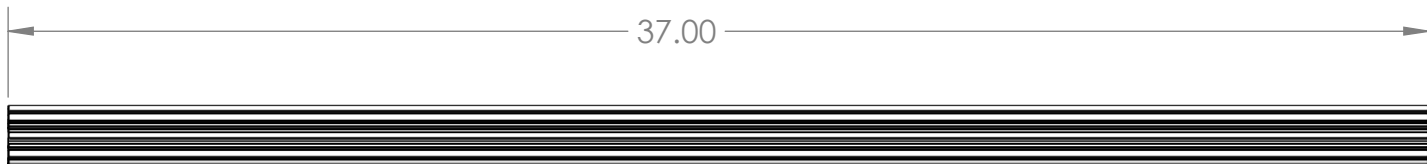
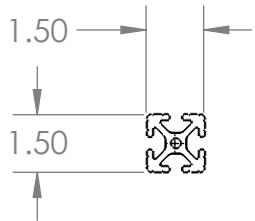
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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:  
**Arm Cross Piece**

SIZE	DWG. NO.	REV
<b>A</b>	8020 15 Series	
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

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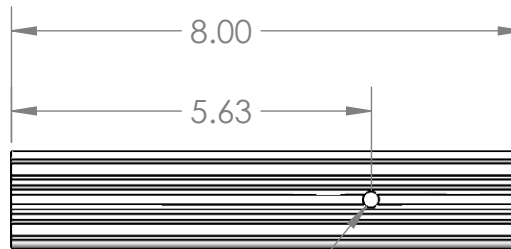
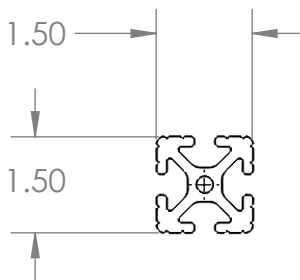


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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Arm Extension

SIZE	DWG. NO.	REV
<b>A</b>	8020 15 Series	
SCALE: 1:4	WEIGHT:	SHEET 1 OF 1

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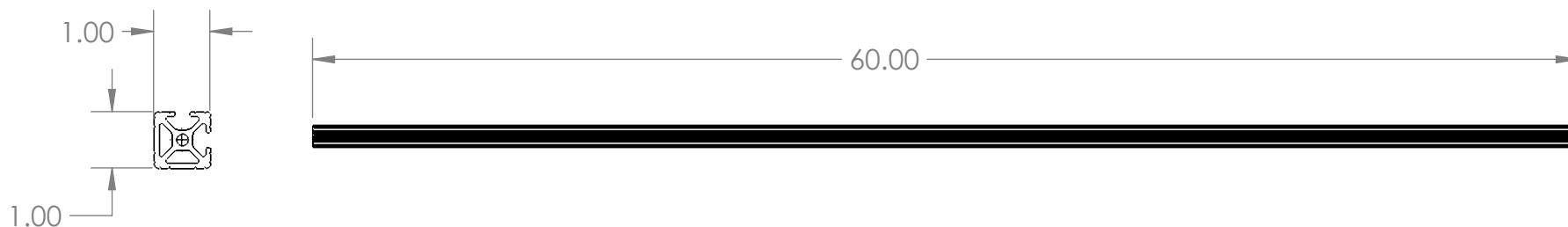
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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE: <b>Base Long</b>		
		DIMENSIONS ARE IN INCHES	DRAWN					
		TOLERANCES:	CHECKED					
		FRACTIONAL ±	ENG APPR.					
		ANGULAR: MACH ± BEND ±	MFG APPR.					
		TWO PLACE DECIMAL ±	Q.A.			SIZE	DWG. NO.	REV
		THREE PLACE DECIMAL ±	COMMENTS:			<b>A</b>	<b>8020 10 Series</b>	
		INTERPRET GEOMETRIC TOLERANCING PER:				SCALE: 1:16	WEIGHT:	SHEET 1 OF 1
		MATERIAL						
		6105-T5 Aluminum						
		FINISH						
	NEXT ASSY	USED ON						
	APPLICATION							
		DO NOT SCALE DRAWING						

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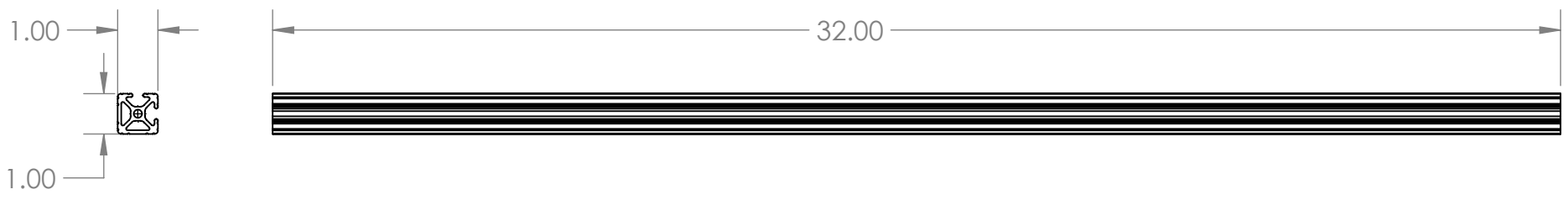
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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		6105-T5 Aluminum			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
BaseShort		
SIZE	DWG. NO.	REV
<b>A</b>	8020 10 Series	
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

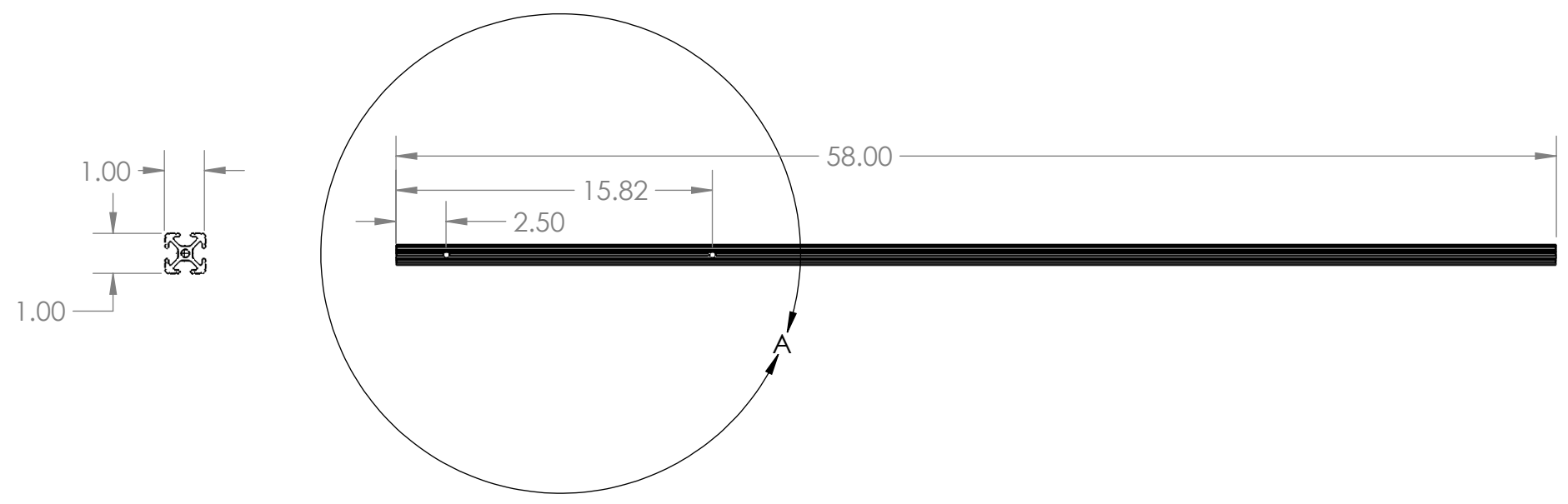
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SCALE 1 : 4

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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		6105-T5 Aluminum			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE:  
**Base Diagonal**

SIZE	DWG. NO.	REV
<b>A</b>	8020 10 Series	
SCALE: 1:16	WEIGHT:	SHEET 1 OF 1

2

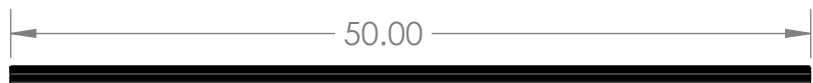
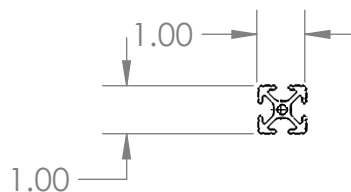
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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		6105-T5 Aluminum			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
Base Vertical		
SIZE	DWG. NO.	REV
<b>A</b>	8020 10 Series	
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

2

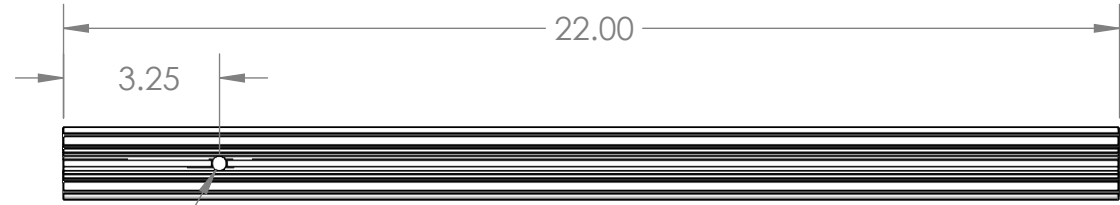
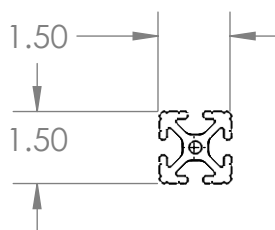
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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:  
**Driver Dyad Long**

SIZE	DWG. NO.	REV
<b>A</b>	<b>8020 15 Series</b>	
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

2

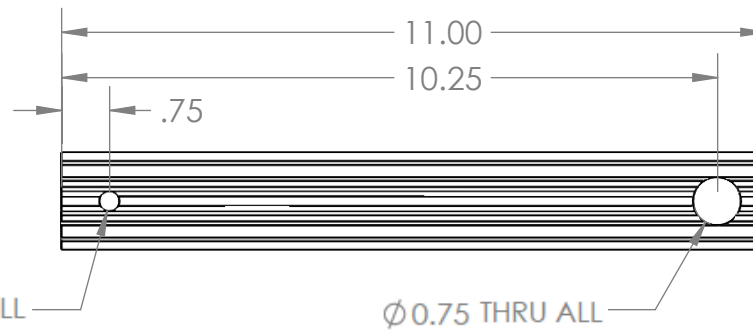
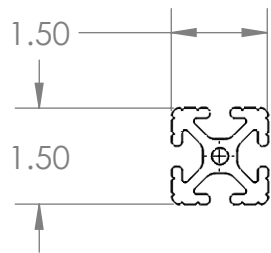
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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
<h1>Driver Dyad</h1>		
SIZE	DWG. NO.	REV
<b>A</b>	8020 15 Series	
SCALE: 1:4	WEIGHT:	SHEET 1 OF 1

2

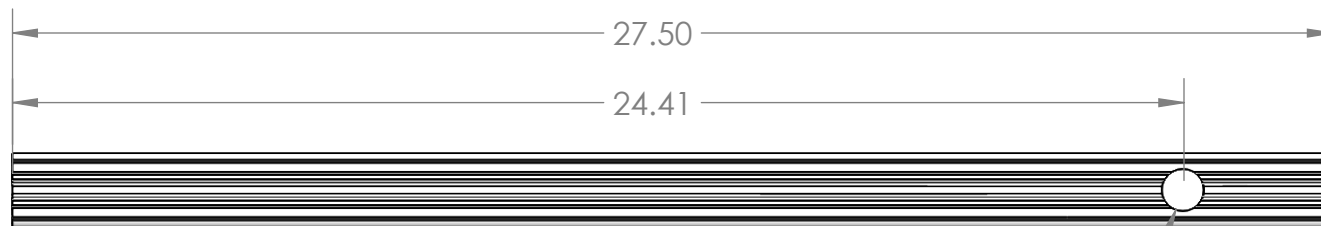
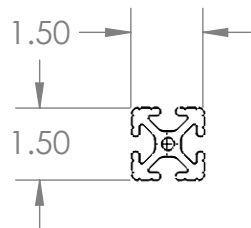
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		TOLERANCES:	CHECKED		
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		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Dyad Post Long

SIZE	DWG. NO.	REV
<b>A</b>	8020 15 Series	

SCALE: 1:8	WEIGHT:	SHEET 1 OF 1
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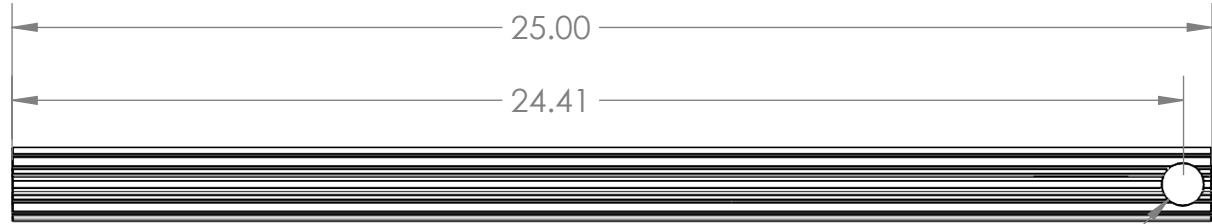
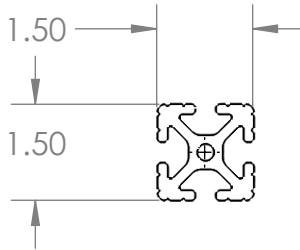


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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE: <b>Dyad Post</b>		
		DIMENSIONS ARE IN INCHES	DRAWN					
		TOLERANCES:	CHECKED					
		FRACTIONAL ±	ENG APPR.					
		ANGULAR: MACH ± BEND ±	MFG APPR.					
		TWO PLACE DECIMAL ±	Q.A.			SIZE	DWG. NO.	REV
		THREE PLACE DECIMAL ±	COMMENTS:			<b>A</b>	8020 15 Series	
		INTERPRET GEOMETRIC TOLERANCING PER:				SCALE: 1:8	WEIGHT:	SHEET 1 OF 1
		MATERIAL						
		FINISH						
	NEXT ASSY	USED ON						
	APPLICATION		DO NOT SCALE DRAWING					

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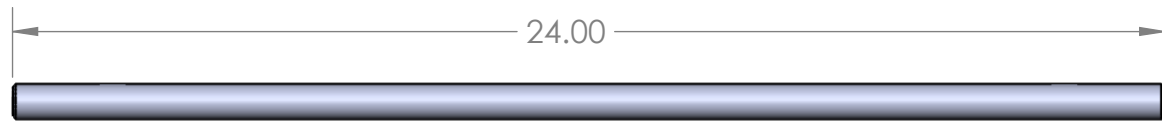
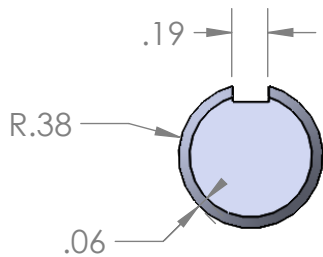
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		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

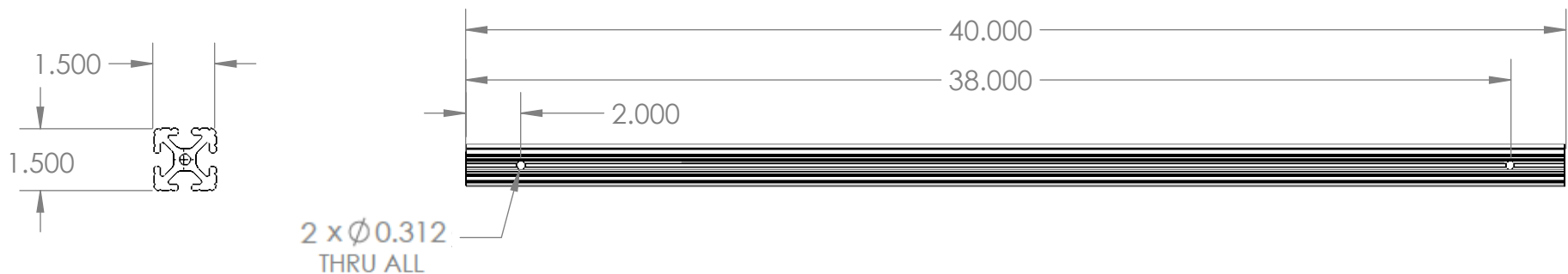
TITLE: <b>Key Shaft</b>		
SIZE <b>A</b>	DWG. NO.	REV
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

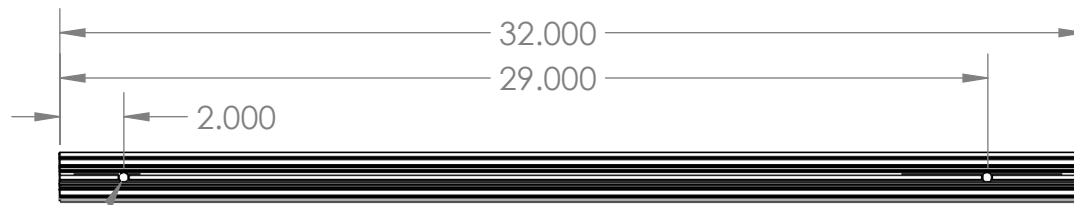
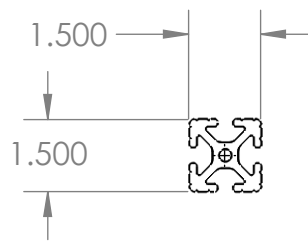
TITLE: <b>Lower Arm</b>		
SIZE <b>A</b>	DWG. NO. <b>8020 15 Series</b>	REV
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL $\pm$	ENG APPR.		
		ANGULAR: MACH $\pm$ BEND $\pm$	MFG APPR.		
		TWO PLACE DECIMAL $\pm$	Q.A.		
		THREE PLACE DECIMAL $\pm$	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

# Upper Arm

SIZE

## A

DWG. NO.

# 8020 15 Series

REV

SCALE: 1:8

WEIGHT:

SHEET 1 OF 1

2

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