Design & Development of an Electric-Powered Hand Truck for In-Home Use

A Major Qualifying Project
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
Degree of Bachelor of Science
In Mechanical Engineering

Submitted by:

Azita Bakhtyari

Justin Nguyen

Ayushka Shrestha

Timothy Tetreault

Date:
March 28, 2019

Approved:

Prof. Selçuk Guçeri, PhD, Project Advisor

Acknowledgements

We would like to thank the Washburn Labs staff, Ian Anderson and James Loiselle, for their support as we manufactured our prototype. Their efforts and enthusiasm to help us learn how to use the machines inside the lab and to bring our prototype to fruition is a large part of our success in this MQP. We greatly appreciate the help they provided and the amount of time they gave to us so that we could continue on with our project.

We would further like to thank Todd Keiller for the time he took to meet with our team and for the information he relayed to us so that we could move forward with the patenting process. We are really excited to see where this patent takes the team and are grateful for the opportunity the WPI Patent Office is providing our team for our work and efforts with this original design.

Thank you to the WPI Mechanical Engineering Department for providing us with resources and the knowledge to complete this project. We appreciate the time and resources allocated to our MQP team, which enabled us to easily order parts for manufacturing, print our final poster, and more.

Lastly and most importantly, we would like to thank our advisor Professor Selçuk Güçeri for his continuous support and mentoring throughout the duration of this MQP. We are very grateful for the excitement and enjoyment he brought to every single meeting we had and also to the project, overall. We are thankful for the words of encouragement and motivation that Professor Güçeri provided for us throughout this project. His dedication to the design and completion of this project allowed us to successfully create a working hand truck prototype. With his commitment to our project, we were further able to prove that the ball screw mechanism concept, which is not currently being utilized in the market, works in our in-home application. We sincerely thank Professor Güçeri for working closely with us and making our MQP one of the best team work experiences we have all had here at WPI.

Authorship

All members of the MQP team contributed to the drafting, editing, and formatting of this report. The team followed a process where drafting was divided among each group member. After each team member finished writing, Azita Bakhtyari and Ayushka Shrestha acted as the primary editors for the final draft. The final submission of this report was revised and finalized together by all members in the team to ensure the report exemplified a unified team voice.

Abstract

Currently, there is a lack of an in-home automatic lifting mechanism in the hand truck industry that is low in weight and cost. This project aimed to create an original design of an automatic hand truck, suitable for in-home use, particularly assisting the elderly or injured individuals with heavy lifting. The steps taken to achieve this goal included, calculating values necessary for proper operation of the product, creating a CAD model of the design, manufacturing a ⅔ scaled prototype of the design, testing the prototype, and proposing recommendations for full scale manufacturing. At the conclusion of the project, qualitative testing demonstrated that the ball screw assembly used within the hand truck operated successfully, providing a proof of concept for the lifting mechanism.

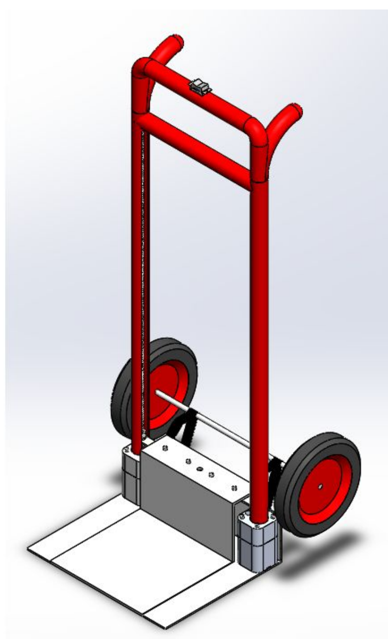


Table of Contents

List of Figures

List of Tables

1. Introduction

The current market for lift-assistive technology is filled with many products to assist the elderly or those with back and knee injuries in their daily lives. Many of these products are also used amongst the general population to ease the transportation of heavy objects. One such device that is commonly used as a lift-assistive or transportation device is a hand truck. A hand truck (or hand dolly) transfers the majority of the weight of an object onto its wheels by holding the object on a platform. The user can then easily transfer this object to its destination, by using the wheels of the machine. Often, however, the final destination requires an individual to lift the object off the truck and onto a desired level off the floor. This is where many people run into a dilemma if they are physically incapable of lifting said object. After reviewing the current mechanical lifting mechanisms in the market, it was found that there are current hand trucks that assist in transporting and lifting large objects. However, these devices are large, bulky, heavy, costly, and not effective for in-home use, which poses the problem that this project aims to solve.

The goal of this major qualifying project (MQP) is to develop a hand truck design that can be used for household applications. The intended market for this product is the elderly, who most likely do not have enough strength to carry out tasks such as bending and lifting, and also those that have injuries that affect their ability to lift objects. While these are the intended audiences for the marketing of this product, the hand truck is expected to be affordable for any individual to buy and use as they see fit. The automatic hand truck will be ideal for lifting objects up to 50 pounds to a height of approximately three feet or below.

This report will first review the current market for lift technology as well as the different mechanisms that could be utilized to create a lift hand truck appropriate for in-home use. Following this, the methodology and objectives taken to complete the project will be described. Additionally, the results of the research, designing, and manufacturing will be explained. Lastly, recommendations for improving the final proposed design and the team's conclusion of the project will be discussed.

2. Background

This chapter provides a literature review of the following elements addressed by this project:

1. The mechanics of heavy lifting and its impact on customers,
2. The current competitors in the market for heavy lifting,
3. The various mechanical lifting mechanisms that are incorporated in machines,
4. Properties of electric motors and their functions as a machine element,
5. The various types of materials that could be suitable for use in designing a hand truck.

2.1 Mechanics of Lifting

On a daily basis, individuals are faced with the burden of lifting heavy objects from one location to another. Whether it is lifting heavy objects for their job or simply raising items around their household, people are constantly exerting energy and adding strain to their bodies. The repetitive manual handling of loads can lead to the deterioration of the musculoskeletal system in the human body. The most common injuries that result from heavy lifting are associated with the lower back, but other areas including the neck, upper limbs, and lower limbs can also be negatively impacted [1].

There are four factors that contribute to the high risk of injury from lifting objects, which include the load, the task, the environment, and the individual. These include the heavy weight, large size, difficult grip, and awkward movements of the structure of these items [1]. Risk factors for carrying a certain load are impacted by the size of the object, as the larger it is, the greater the moment arm. As a result, a larger moment arm corresponds to increased forces experienced by the individual performing the task. Although people have differing abilities to lift heavy objects, 40 to 50 pounds is considered too heavy for most people. The elderly and individuals who have a weaker musculature face even more challenges when trying to move objects from one location to another.

In order to avoid the many different injuries that are correlated with heavy lifting, it is important to understand the principles of body mechanics. When lifting, one should be as close as possible to the item being raised. This is important to reduce the amount of torque that is acting on an individual's lower spine. If an object is lifted from a farther distance, the back muscles of that individual must compensate for the larger torque created by the object. Torque is equivalent to the product of the force of an object and the perpendicular distance to the point of pivot [2]. Additionally, when heavy lifting, it is important for a person to increase their base of support by widening the distance between their legs. However, although these mechanics may decrease many of the risks associated with lifting heavy items, it is impossible to prevent injuries from overuse. As a result, it is important to push, slide, or roll an object when possible [3].

2.1.1 Customer Focus

As humans age, their bones become less dense and their muscles decrease in both size and strength. As people age, they become more susceptible to having softer and more brittle bones. Additionally, many exhibit inflammation of their joints and experience a breakdown of cartilage within them, resulting in stiffness and pain as they move their limbs. Aging contributes to the loss of calcium and minerals in the bones. Furthermore, an individual's muscles are impacted, as their muscle fibers decrease in size and number. As a result, lifting for individuals over the age of 60 can become a task that many are unable to perform [4]. Similarly, individuals who are injured also experience a decreased ability to carry out tasks that involve bending and lifting. The automatic hand truck will be designed to assist these people with lifting objects weighing 50 lbs or less around their household to a height of three feet or lower.

2.2 Market Research

The hand truck has been around for a long time, dating as far back as when the wheel was invented. Since then, hand trucks have evolved and taken different forms as needed in the marketplace. The typical hand cart produced has two wheels in the back and can handle loads with different heights, weights, and widths. With time, better materials, specifically aluminum and stainless steel, have been used to optimize the durability of the product [5].

Different types of hand trucks exist in the market currently. There are basic hand trucks that were the original models, which simply allow for different loads to be transported from one location to another. Convertible hand trucks followed with an ability to function as an upright or flat hand truck to transport equipment on its platform-style bed around a factory/facility. There was then a need for appliance hand trucks that could handle very large loads, making these the largest hand trucks in the market [6]. In 2015, a company called TriFold LLC created a hand truck that could go up and down stairs. Their design used three wheels on either side of the dolly to transport items through different levels in a building. Their design also allowed for the wheels to fold in, making the bottom of the cart completely flat [6].

Many different hand trucks circulate the marketplace, from hand trucks that are not electronic to those that are. From marketplace research, we found that although there are hand trucks that are electronic, allowing for lift support, these hand trucks are made for businesses with warehouses, stores, etc [7]. Figure 1 shows two examples of existing hand trucks having different features, neither of which are applicable for in-home use. The hand trucks that are electronic are expensive to purchase and heavy to move around. These products do the job of a hand truck but are bulky, not foldable, and not proper for in-home use. There are simple hand trucks that exist that are foldable, however, they do not have the capability to lift loads as they are not electronic [7]. After examining the types of hand trucks available for purchase, it is apparent that no product exists that can both transport and lift loads electronically, can be easily stored and used inside the home, is low in cost and weight, and can be accommodated for people of all ages.

a) b)

Figure 1. Example of existing hand trucks. a) “Cylinder Hand Truck”, non-electronic for transporting objects of up to 500 lbs from one point to another. b) “Cylinder Lift Truck”, electronic for lifting heavy objects, made for factory/warehouse use.

2.3 Lifting Mechanisms

The main component of the hand truck is the lifting mechanism or main frame by which the machine functions. The focus of this project is a hand truck having a moving platform that can lift and transport weights of up to 50 lbs or higher, and is sized appropriately for in-home use. The correct lifting mechanism must be used to successfully reach all the goals of the proposed hand truck. There are different types of lifting mechanisms to be taken into consideration. They include hydraulic lifts, pulleys, scissor lifts, and a ball screw and linear guide mechanism.

2.3.1 Hydraulic Lifts

Hydraulic lift mechanisms are effectively used in existing hand trucks today. The basic principle behind hydraulics is that any pressure exerted on one end of a fluid is equally distributed throughout the other end of the fluid. This is also known as Pascal's Principle [8]. Hydraulics utilizes incompressible liquids on two surfaces so that when a pressure is applied to one surface of liquid, the other surface moves with an equal amount of pressure [8]. Two pistons acting on a small and large surface of liquid can create a hydraulic lift if a force is applied to the smaller piston, causing the larger piston to move in the opposite direction. However, a large amount of force must be applied to the small piston to move the larger piston because the large piston covers a greater surface area of liquid than the smaller piston.

Utilizing hydraulic lifts within hand trucks would allow for a large load to be transported and lifted up and down. Figure 2 shows an example of a hand truck that consists of a hydraulic lift mechanism. In order for the platform to move up, a pedal must be pumped, applying a force downward, which then pulls the platform upward. Due to the physics behind hydraulics, a large amount of force must be applied to the pedal to move the platform. This means the pedal must be pumped many times for the platform to move up a significant distance.

Figure 2. Wesco 2 Wheeled Hydraulic Lift [9].

This physics concept introduces issues when applying a hydraulic lifting mechanism to an in-home hand truck. The act of pumping a pedal several times for the platform to move a short distance is inefficient for individuals wishing to simply lift 50 lb objects from the ground to a normal table height. Having to manually pump a pedal would greatly increase the time it takes for the object to be lifted and would also add stress to the human body. Older users of a hand truck with a hydraulic lift would especially have difficulty using the product as they would have to put in a great amount of effort to pump the pedal. This analysis demonstrates that the inefficiencies caused by hydraulic lifts would not allow the project goals to be met successfully.

2.3.2 Pulley Systems

Pulleys are a form of lifting mechanisms that are utilized broadly within the hand truck market. They consist of a rope wrapped around a wheel with one end attached to an object that must be lifted and the other end attached to a motor or a person that does the lifting. Pulleys are a simple machine that redirect force, so that when one side of the pulley is pulled down with a certain amount of force, the other end lifts the desired object with the same amount of force [10]. Multiple pulleys can be put together to create a pulley system with a large mechanical advantage. However, a fixed pulley, which is a pulley system with only one pulley, does not have a mechanical advantage. Instead, it has a limitation in that it requires the same amount of force to lift an object as it would if the object was being lifted normally, without a pulley [10].

A pulley system allows hand trucks to lift large loads. However, a pulley system in an in-home hand truck would need to be small in scale. Due to the size limitation, a fixed pulley would have to be utilized, which brings with it all of its inefficiencies. It would also have to be manual, with a crankshaft, because adding a motor would increase the size and weight of the hand truck. Figure 3 gives an example of a hand truck that utilizes a pulley for the lifting mechanism.

Figure 3. Platform Lift, able to lift 750 lb through a fixed pulley system with crankshaft [11].

A manual crankshaft presents similar issues as those stated for the hydraulic lift mechanism. The crank would have to be turned multiple times for the platform to move a small distance, increasing the time it would take for an object to be lifted. Manually turning the crankshaft is inefficient because a large amount of force would have to be exerted to turn the crank. This would add a large amount of stress to the body, negatively impacting all users, especially those who are older in age. Putting the mechanism together and using a strong and durable material for the pulley would also lead to a bulky hand truck design and increased costs. Due to these issues, utilizing a pulley system in an in-home hand truck model is not efficient and would not lead to a successful final product.

2.3.3 Scissor Lifts

The scissor lift is another lifting mechanism currently used in larger hand trucks and other warehouse equipment. This lifting mechanism is made up of criss-crossed metal supports that fold and unfold to collapse and elongate, respectively. The supports are structured as parallelograms stacked on top of each other and are hinged at the intersections. These parallelograms maintain their geometric figure while changing in angle as the mechanism is powered to elongate and collapse [12]. Scissor lifts require a linear force, which can be “provided by a pneumatic or hydraulic actuator, or a mechanical input such as a lead screw or rack and pinion drive” [12].

Due to the complexity of its structure, scissor lifts are typically used in larger forms for uses in warehouses or large outdoor or indoor facilities. Hand trucks utilizing this mechanism have the ability to lift large loads in an efficient manner. Figure 4 shows a form of a hand cart that uses a scissor lift mechanism. In order to incorporate scissor lifts into an in-home hand truck,

Figure 4. Manual Lift Table - Double Scissor [13].

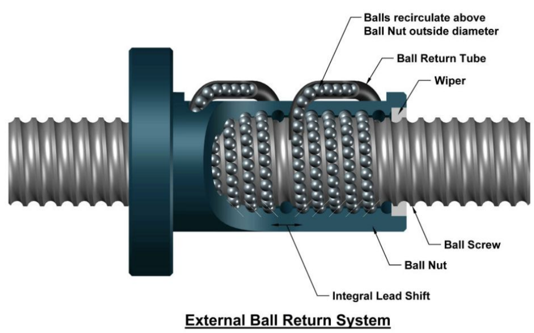
however, the entire mechanism would have to be scaled down to be sized appropriately for in-home use. The metal linkages needed for the scissor lift to function adds a large amount of weight to the hand truck and hinders users from being able to move the product around easily. Since weight concerns preexist in this mechanism, a motor cannot be added as it would add more weight to the design. For this reason, the hand truck would have to be manually powered like the example shown in Figure 4. Adding either a rack and pinion drive, that is hand operated, or a pedal, that is foot operated, would lead to similar issues previously discussed with the other mechanisms. Manually operating a hand truck would require an increased amount of effort by users and strain the body. Further, the design of the scissor lift would not allow for the base of the hand truck to lay flat on the ground for objects to be pushed onto the cart. Instead the item would have to be manually lifted and placed on the hand truck. Putting this mechanism together with the correct material for lift capability and durability would also add to the costs of manufacturing the product. With these issues and roadblocks taken into account, it is apparent that incorporating a scissor lift into an in-home hand truck is neither favorable nor efficient for a successful final design.

2.3.4 Ball Screw Assembly Mechanism

A ball screw assembly is a lifting mechanism that is not commonly found within electric hand trucks in the current market. A ball screw is made up of a screw and a nut, both of which have identical helical grooves where small metal balls roll, providing the only contact between the screw and the nut. The balls circulate in a closed circuit inside the ball nut to allow the screw and nut assembly to function. Either the screw or the nut rotates, allowing the balls to deflect into the ball return system in the ball nut. The balls then travel to the opposite side of the ball nut through the ball return system, allowing the ball nut or screw to move up and down, thereby lifting and lowering anything attached to this system [14].

There are two types of ball return systems, one is an external ball return system while the other is an internal one. Figure 5 illustrates the two systems in a ball nut that can be paired with a

a)



b)

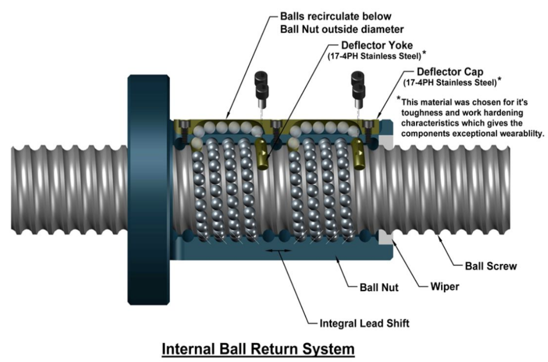


Figure 5. The two types of ball return systems in a ball nut [14].

screw for proper functionality. A ball nut further determines the load the ball screw assembly can handle along with the assembly's life expectancy. The higher the ratio between the number of threads in the ball nut circuit and the number of threads on the ball screw, the quicker the ball nut will wear out or reach fatigue failure compared to the ball screw [14].

Ball screw assemblies are durable and can handle a large amount of load in a cost efficient manner as opposed to hydraulic mechanisms. Ball screws are commonly applied to products requiring linear motion, which is applicable for a hand truck with a linearly moving platform. They are primarily used to convert motor torque into linear thrust, which directly relates to the electric portion of the hand truck design goal. With the use of a motor and ball screw(s), a hand truck would be able to carry a substantial amount of load with the torque provided by the motor and the linear thrust converted by the ball screw assembly, while also being accessible for in-home use. Further, ball screws are commercially available, easy to manufacture, and have high efficiency and load-life characteristics [15].

This assessment shows that applying a ball screw assembly to an in-home hand truck would be efficient in terms of size, weight, cost, and accessibility as opposed to the other lifting mechanisms discussed in the above sections. Using ball screws as the lifting mechanism would allow the team to assess different hand truck designs because ball screws can be used in different ways and in different numbers. For example, one ball screw can be incorporated as the spine of the hand truck with two linear guides on either side of the frame added for stability; two ball screws can be used on the two sides of the main frame; or two ball screws can be used on the two sides of the main frame with one linear guide added to the middle of the frame for extra stability.

There are minor difficulties associated with incorporating ball screws in the hand truck design. Overall costs would be slightly increased because one or more motors would have to be added to the design for the ball screw(s) to function. An electrical component would also need to be added to control the motor and the movement of the ball screw assembly. A ball screw would also add weight to the final hand truck design, however, will not negatively affect end user interaction with the product because there would be no manual labor required. The lifting platform would do all of its work through the help of the automated ball screw. The end user would simply need to flip a switch on the hand truck to power the product on and then off. With these considerations taken into account, it is evident that using a ball screw assembly within the final design would allow the lifting mechanism to be unique, efficient, and accessible for an in-home hand truck suitable for customers of all ages.

2.4 Electric Motors

Electric motors are essential for the design of the hand truck. Motors serve as a medium to convert electrical energy to mechanical energy, which is an important component of an accessible and easy to use machine/product, such as a hand truck [16]. A motor(s) is specifically needed to power the ball screw assemblies used in the main frame of the design. A motor allows for the size and weight of the hand truck to be as small as possible, while also enabling the hand truck to be automated. There are two types of electric motors, AC and DC. The main difference between the two types of motors is that AC motors are powered from alternating current, whereas, DC motors are powered from direct current, such as batteries. Another difference is that speed is controlled in varying manners for the two types of motors [16]. For the purpose of this design, a DC motor(s) will be used, as DC motors are less expensive and more practical to incorporate within the hand truck, due to their direct current characteristic, compared to AC motors.

DC motors can either be brushed or brushless. Brushed DC motors limit the motor's speed, add to the needed maintenance and upkeep of the motor, and usually reduce the life expectancy of the motor [16]. The brushes and mechanical commutator that can often cause issues in the brushed DC motor are not present in a brushless DC motor. A brushless DC motor (BLDC), instead, uses a permanent magnet as a rotor while the coils, which are located on the stators, deliver current. This design creates a more efficient, controllable, and durable motor than most other brushed DC motors. The performance boost of the BLDC makes it a viable candidate for our application. The main restriction is that BLDCs are not often used in high power applications [17]. Therefore, a brushed DC motor may be incorporated in the final design to reduce the final manufacturing costs.

Figure 6. Example of a geared DC motor with high torque and low RPM**.**

Motor specifications that must be taken into account are the motor's power, torque, RPM, axle length, and size. A compact, geared motor with enough torque and power is necessary for an in-home hand truck design. An example of a motor that may be appropriate for our application is shown in Figure 6. In terms of torque and RPM, the motor incorporated in the design must exhibit high torque with low RPM to be practical for this application. The design requires a high torque motor because the main focus is that the motor allows the ball screw assembly to hold and lift weights of up to 50 lbs. A high RPM is not necessary because the hand truck only has to lift objects up to 36 inches (3 ft) off the ground, for which the lift time can be low, allowing the motor to have a higher torque. The following chapters of this report will discuss applicable motor calculations, such as torque and power, in detail. With the types of motors and its specifications taken into account, a proper motor can be selected and incorporated into the final hand truck design.

2.5 Material Research

In order to propose the best possible design for the hand truck, different materials need to be considered for use within the product. The different materials that the team researched include stainless steel, aluminum, and rubber. Factors such as cost, weight, durability, and reliability were taken into consideration when deciding how to incorporate these materials into the design.

2.5.1 Stainless Steel

Stainless steel is a material that is commonly used in machine elements. It is a metal that is known for its ability to resist corrosion. Due to its high chromium content (minimum of 10.5% by mass), oxygen from the air is blocked from diffusing into the core of the metal [18]. As a result, stainless steel is long-lasting and experiences little to no rusting. Additionally, this metal has high strength properties. Both its yield strength and maximum tensile strength are high compared to other metals and materials. As a result, stainless steel can endure large forces before deforming or failing. Furthermore, stainless steel is relatively cheap in price when compared to other metals. A standard 304 2B sheet of stainless steel is currently sold at approximately $1.46 per pound, while 3003-H14 sheet of aluminum and TI-6-4 Bar titanium are sold at $1.66 and $25.61 per pound, respectively [19]. Stainless steel can be purchased in a vast selection of shapes and sizes, making it a good option for prototyping and working within a short time range. Shapes can be purchased ranging from sphere and hexagonal prisms to tees and beams [20]. Properties of this material include its poor conductivity of electricity and good magnetism. The weight of stainless steel is heavy compared to many other metals. For example, its weight is approximately three times that of aluminum. Furthermore, this material can withstand high temperatures and can be welded easily.

Stainless steel is a material candidate that can be incorporated into the final hand truck design and is also useful for prototyping purposes. The targeted customer for the hand truck is the elderly and those who are injured, therefore, the design must be light in weight to be easily maneuvered from one location to another. Therefore, although this material is useful for the prototype, it can not be the primary material used in the final design as it would cause the hand truck to be too heavy.

2.5.2 Aluminum

Aluminum is another metal, similar to stainless steel. It is highly corrosion resistant, as it has a coated barrier that protects oxygen from entering and rusting the metal. This property of the material is important for the hand truck design, as the machine is expected to last several years without deforming or corroding. Furthermore, aluminum is highly conductive with both electricity and temperature. Aluminum is also a light in weight, as it has a specific weight of 2.7 g/cm^3 [21]. This is about three times lighter than stainless steel, which has a specific weight of approximately 7.74 g/cm^3 [22].

Aluminum is a metal candidate that can, similar to steel, be incorporated within the final design and be used for prototyping purposes. Its lightweight characteristic makes it a more practical material to use within the hand truck design, so that the product can be easily maneuvered from one location to another. Furthermore, aluminum is a strong metal that can bear heavy loads. This metal can also be easily manufactured and welded into the desired shapes when prototyping. Although this metal tends to be more expensive than stainless steel, its properties make it the better option for the final design of the hand truck [19].

2.5.3 Rubber

One of the main components of a hand truck are the wheels that allow for easy maneuvering of the product. The forces that are added to the hand truck in the form of loads are further transmitted to the wheels when the hand truck is being moved. The simplest and most feasible design is to include two wheels on the bottom of the product. Wheels are commonly encircled by a rubber material, in order to protect the surface in which they roll over. The hand truck will be designed for household use, so the rubber material will protect the carpets, hardwood, and other flooring surfaces from being damaged during its use.

There are several different types of rubbers that exist, each with varying properties, ranging from ethylene-propylene to silicon. However, rubbers in general have great strength, are tear and abrasion resistant, and have inherent hardness [24]. When choosing what kind of wheel to incorporate into the design, it is important to consider a rubber that is strong and can withstand a heavy load. Furthermore, it is also important to consider the prices of the rubbers as the team is working with a limited budget, hence a cheaper type of rubber with similar properties to a more expensive type would be more applicable to include in the final design. When comparing the different types of rubbers together, the cheapest of this material are Buna-N (Nitrile), Butadiene, and Ethylene-Propylene [23]. Overall, rubbers in general have great tensile strength, but Buna-N, Butadiene, Chloroprene, Ethylene-Propylene, Fluorocarbon, Hydrogenated Nitrile, and Natural rubber are the best for this property [23]. For the prototype and final design of the hand truck, it is important to consider these different types of rubbers and the properties associated with them, as the hand truck must be easily moved and also be able to carry a heavy load from both the machine elements and the items being lifted.

3. Methodology

The goal of this project was to design and create an adaptation of the current hand truck device that was more compact for household storage and was also equipped with a motor(s) that allowed the user to safely raise an object of up to 50 pounds to a height up to three feet. In addition to the general public, the team hoped that this device would assist the elderly and those with injuries in transporting and lifting heavy objects in their household. To achieve this goal, the team created five steps for a successful completion of the project. The objectives are as follow:

Objective 1: Investigate the calculations required for the proper performance of the hand truck

Objective 2: Create a model of the proposed hand truck using computer aided design (CAD) technology

Objective 3: Prototype and manufacture a model of the designed model

Objective 4: Test and analyze the performance of the prototyped hand truck

Objective 5: Propose recommendations for manufacturing of the full scale hand truck model

3.1 Objective 1: Investigated the Calculations Required for the Proper Performance of the Hand Truck

In order to properly design and prototype the hand truck, the first objective was to calculate the following: the center of gravity (CoG) of the hand truck and how it changes as loads are added to the lifting platform, and the torque and power necessary for the motor to effectively rotate the ball screw assembly thereby lifting the platform along with any added load.

3.1.1 Center of Gravity Calculations

The equation used to calculate the different CoG locations of the hand truck as loads are added to the platform and moved along the ball screw is as follows:

$$CoG = (\Sigma D \times W) / \Sigma W$$

This equation states that the location of the center of gravity of the body is equal to the sum of all the distances multiplied by the weights divided by the sum of the weights. Since this is a 3-dimensional object, the CoG calculations must be done for the x, y, and z directions to find the exact location of the CoG [25]. In this equation, D stands for the distance at which the point in question is acting and W stands for the weight of the load that is affecting the body.

After understanding this equation, the team went forward with using the CoG calculation feature in SolidWorks to find CoG locations of interest as loads were added at different hand truck heights. This analysis was taken into consideration as we designed the final hand truck, allowing us to ensure that the loads on the hand truck itself were distributed evenly so that the hand truck would not tip either way when loads are added to the moving platform.

3.1.2 Torque Calculations

The equation used to calculate the minimum torque required for the motor to effectively rotate the ball screw while carrying loads of up to 50 lbs is as follows:

$$\tau = (F \times D_p) / 2\pi$$

Torque, as given by this equation, is the load (F in Newtons) multiplied by the pitch of the ball screw (D_p in meters) all divided by 2 pi, giving a torque with units of N*m.

3.1.3 Power Calculations

The equation used to calculate the minimum power required for the motor to effectively rotate the ball screw while carrying loads of up to 50 lbs is as follows:

$$P = F \times s$$

In this equation, power is equal to the force of the load (F in Newtons) multiplied by the speed at which the ball screw is projected to move (s in meters per second), giving a power with units of Watts.

3.2 Objective 2: Created a CAD Model of the Proposed Hand Truck

The second objective was to create a computer-aided design (CAD) model of the hand truck. This objective was accomplished through the use of a software called SolidWorks, which allowed for the 3-dimensional modeling of the designed product. Two CAD models of the hand truck were created, one was a full scale model of the product and the other was a ⅔ scale model that was similar but built for prototyping/manufacturing purposes.

Standard hand truck dimensions and styles were used, from current manufacturers, to determine the model shape and design. Complex features were simplified for the prototyping design in order to speed up manufacturing. The team determined individual components that were assembled to create a hand truck and created these parts in SolidWorks. Certain parts, such as the wheels, axle, and handles, were designed to act similar to market product hand trucks.

3.3 Objective 3: Prototyped and Manufactured the Designed Model

The third objective was to manufacture a prototype of the designed model using the prototype CAD model. Choosing the material of each part was the initial step. Steel was originally taken into consideration due to its strength and durability, however, since the material was too heavy the team decided to make most of the parts out of aluminum while choosing to make a few parts out of steel for weight distribution and CoG alignment purposes. In total, the team had to manufacture ten parts using various machines such as the Mini Mill, VM2, Lathe, Horizontal Band Saw, Vertical Band Saw, the Manual Drill Press, and the Super Mini Mill. These parts include two motor housings, two pipe connectors, two pipes, a crossbeam, the noseplate, and the lifting plate.

The motor housings, as the name suggests, encloses the motors and the pipe connectors keep the motor and pipe in place. Both of these parts were cut from a piece of aluminum stock on the horizontal band saw (four total parts; two for motor housings, two for pipe connectors). They were then machined in the VM2. For the motor housings, an off center through hole was made first. An endmill then machined multiple grooves in the hole so that the hole fit the profile of the motor. Next, the team drilled and tapped a hole at each corner of the block roughly two inches down from the top. The part was rotated to the back side and a hole was drilled and tapped into the block so that the wheel axle could be mounted on. Finally, the piece was flipped to the bottom face, four holes were drilled and tapped at each corner as mounting sites for the noseplate, and a slot was machined from one end of the block to the other end for wires to run through.

The machining for the pipe connector began similarly with an off center through hole on the top of the block. The end mill machined a pocket that matched the diameter of the pipe at about 1.75 inches deep. Six holes were then drilled within the pocket. These holes were used as mounting holes for the motor so that the body of the motor could stay in place without rotating inside the motor housing. Four through holes were drilled and tapped at each corner of the top surface of the pipe connector. The part was rotated to its back side so that a mounting hole for the wheel axle could be drilled and tapped. The part was again rotated so that holes could be drilled and tapped for set screws to fit in, allowing the pipe to be held in place. Both of these operations were conducted twice as the design calls for two motor housings and two pipe connectors.

The ball screw and ball nut also needed to be slightly modified. In the case of the ball screw, the team machined either end of the rod. One end was machined to the diameter of the shaft coupling inner diameter and the other end was machined to the inner diameter of the ball bearing. Further, a flat was added to the end of the ball screw that was placed into the shaft coupling so that the set screw holding the ball screw and coupling together could stay in place. All the operations needed to modify the ball screw were completed in the lathe. The rear two corners of the ball nuts were simply ground down so that they could properly fit inside the pipe. The two pipes that house the ball screw assembly were machined next. The VM2 was again used for this part of the manufacturing process. After securing the part to the machine bed, the team used an end-mill drill bit to machine a slot 28 inches down the length of the pipe.

In order to manufacture the noseplate, lift plate, and crossbeam, the team had to first cut the metal sheets (stainless steel and aluminum sheets) using the vertical band saw. The noseplate and crossbeam were made out of stainless steel and the lift plate was made out of aluminum. After cutting the sheet into the correct sizes, the crossbeam piece was placed in the VM2 so that the correct holes and contour shape could be machined. Two large holes at each end of the crossbeam and the outer shape were cut out using an endmill. Three holes were manually drilled using a manual drill press on the top surface as mounting positions for the lifting plate. The edges of the pre-cut noseplate were then ground down to a smooth finish and eight holes were drilled and counter bored into either side of the plate. These holes were used to connect the noseplate to the motor housings. Next, the lift plate, which was pre-cut into three aluminum pieces, was welded together and ground to a smooth finish. Three holes were drilled into the top face of the plate as connecting points to the crossbeam. The handle, which was the last prototype part, was made from a PVC pipe and two 90º elbows. The pipe was cut to the correct length and a dremel was used to cut out a section in the middle of the pipe for the three position rocker switch to fit inside. The two elbows linked the PVC pipe piece to the metal pipes on either side.

The initial step in assembling the prototype was connecting the motor to the pipe connector using six screws through the pocket in the pipe connector. Next, the coupling was placed on the motor shaft and tightened. The coupling spider was added onto the coupling and the second coupling attached to the ball screw was placed above. This entire sub-assembly was then fastened to the motor housing using four screws, connecting the pipe connector to the motor housing. The noseplate was then connected to the bottom face of the motor housings using eight screws for either side. The ball nuts were then placed on the ball screws followed by the crossbeam. Two ball bearings were then press fitted into the pipes (one bearing per pipe) and both pipes were placed into the pocket on the pipe connector. Set screws held the pipe in place and the handle connected the two pipes at the top. The lifting plate was then connected to the crossbeam using three screws and nuts.

Wiring the electrical components occurred at different points throughout the assembly. In general, the motors were placed in a parallel circuit with the battery. The wires were all soldered to their respective positions on the motor. The wires ran from the motors, along the pipe and through the handle to the rocker switch that controlled which direction the ball screws would rotate in, thereby lifting and lowering the lift plate and directing the operation of the hand truck.

3.4 Objective 4: Tested and Analyzed the Performance of the Prototyped Hand Truck

Once the prototype was built and wired, it was tested through observation and multiple trials of lifting and lowering the lift plate. Since the purpose of the prototype was to provide a proof of concept for the ball screw and ball nut mechanism, the testing focused on understanding whether the ball screw assembly could successfully move the lifting platform up and down. The wiring was tested by turning the three point switch on in both directions and then off multiple times, which in turn allowed us to observe how the ball screw mechanism worked. More specifically, with this three point switch test, the ability of the ball screw mechanism to rotate in opposite directions to lift and then lower the lift plate evenly was examined. After conducting multiple trials of this test, we assessed which mechanical components in the prototype must be fixed/changed/improved in order for the hand truck to work more effectively with no risk of the motor and ball screw mechanism failing.

Although the prototype was created without a requirement to lift any objects, different shaped and sized objects were placed on the lift plate so that the mechanical integrity of the plate could be further assessed. This was important to the hand truck design because we had to ensure that the loads added to the plate would not create a moment that would cause the plate to rotate inward. The prototype was then maneuvered through a predetermined course to ensure that 1) the wheels were placed correctly and 2) the hand truck was able to travel with ease. These qualitative tests were all taken into consideration when adjusting the prototype to work effectively and when proposing recommendations for improving and manufacturing the final hand truck design.

3.5 Objective 5: Proposed Recommendations for the Manufacturing of the Full Scale Model

The final objective was to make adjustments for our final hand truck prototype and to propose recommendations for large-scale manufacturing of the full-scale model. The main methods that the team used in order to accomplish this, was to analyze the results of the qualitative tests and conduct research on how to improve the product. Furthermore, the team reviewed methods of mass-scale production and researched how to lower the cost of manufacturing in order to increase the profit margin of the product.

4. Results

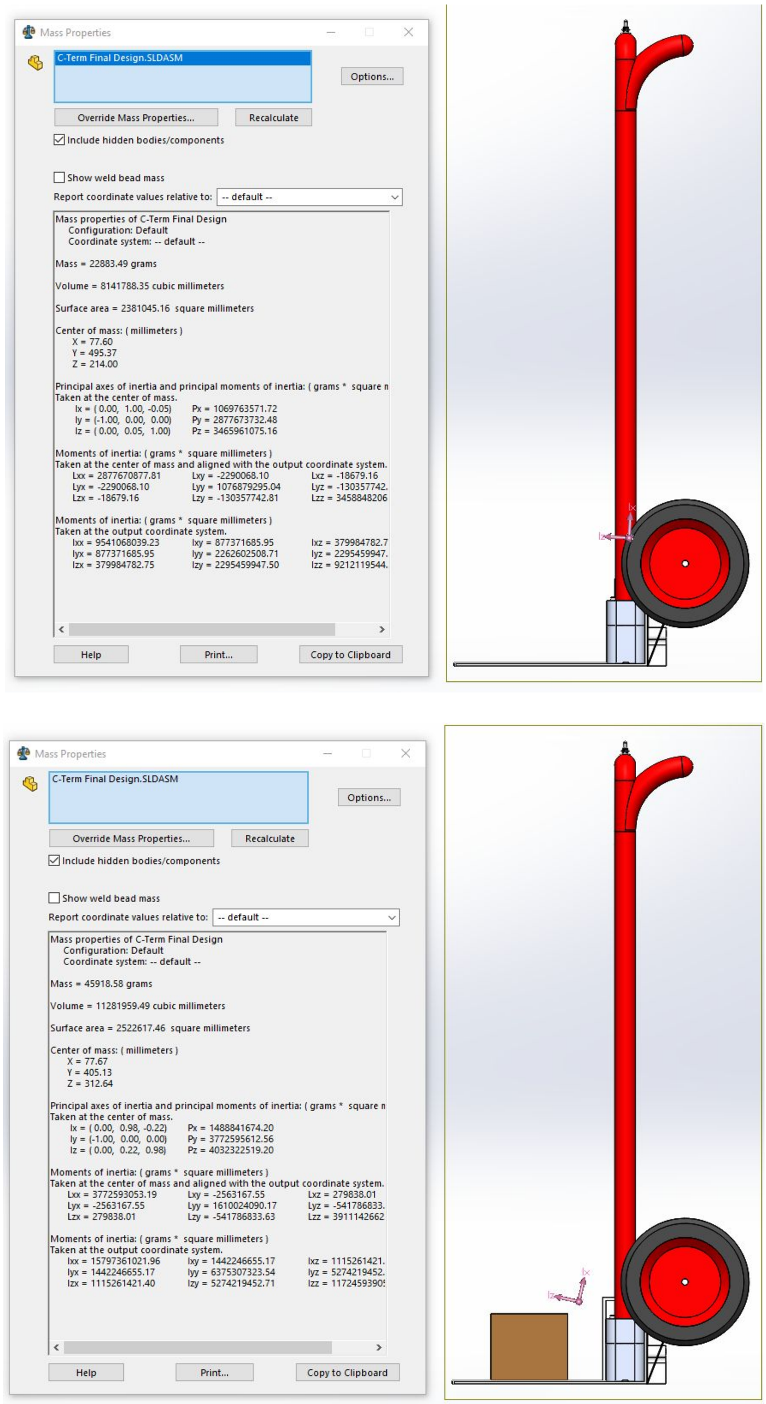
This section includes an in-depth discussion of the results of each of the objectives described in Chapter 3. A bill of materials and photographs of the manufactured prototype discussed in this chapter can be found in Appendix A & B, respectively. Images and labels of the hand truck parts referenced in this chapter can be found in Appendix C.

4.1 Objective 1: Investigated the Calculations Required for the Proper Performance of the Hand Truck

The methods of calculating the hand truck CoG locations, motor torque, and motor power described in section 3.1 of this report were utilized to carry out required calculations. The following subsections discuss the results of these calculations in detail.

4.1.1 Center of Gravity Calculations

The CoG calculations and analysis was completed through SolidWorks, since the program was available to the team as a resource and included a feature that accurately calculates CoG locations for different instances. In order to assess the weight distribution of the final hand truck design, CoG locations were found for six instances; the hand truck with the lift plate at the lowest, middle, and highest positions with no load, and the hand truck with the lift plate at the same three positions with the maximum 50 pound load.



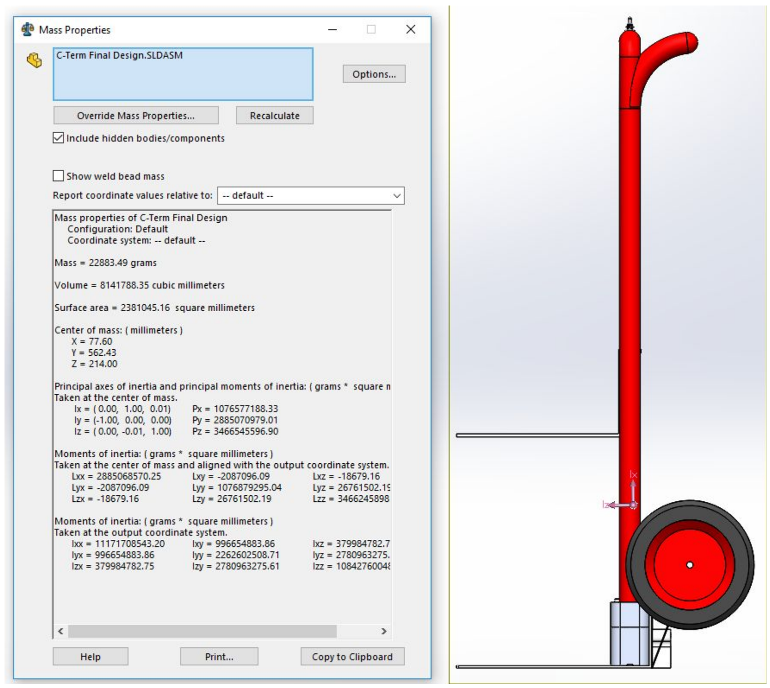
a)

b)

Figure 7. SolidWorks output for final CAD model with CoG locations shown for a) lift plate at lowest position with no load added and b) lift plate at lowest position with 50 lb load added.

Figure 7a shows that the CoG of the hand truck at its neutral position with no load added is located at a point (X = 77.60, Y = 495.37, Z = 214.00), allowing the hand truck to stand up straight with no risk of tilting on any side. The wheel weight and placement along with the weight of the steel nose plate contribute to the stability of the hand truck design during this neutral position. The CoG location, however, moves forward in the Z direction and slightly lower in the Y direction (X = 77.67, Y = 405.13, Z = 312.64) when a 50 lb load is added to the plate (Figure 7b). The wheels' weight along with the ball screw assembly position, in this case, allows the hand truck to stay upright without tilting.

a)



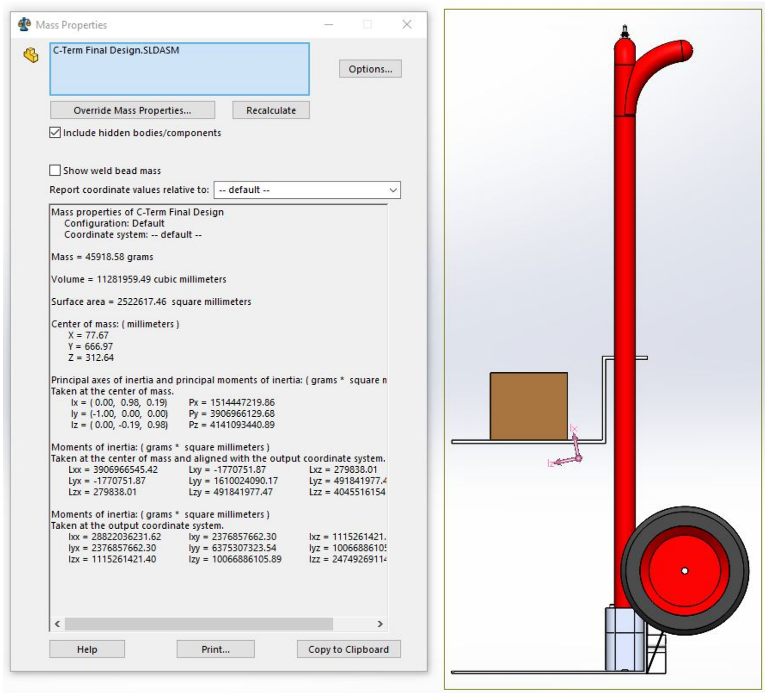
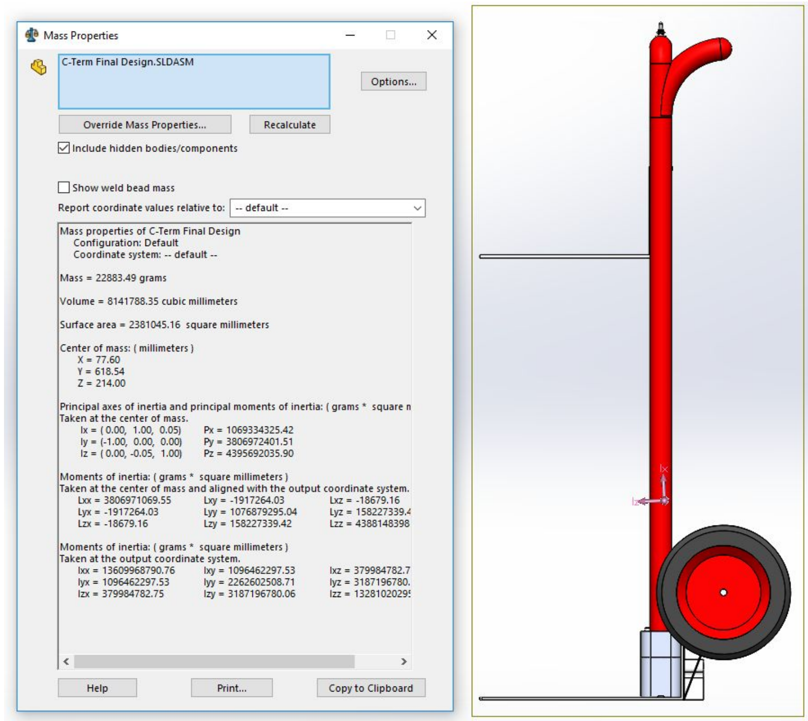
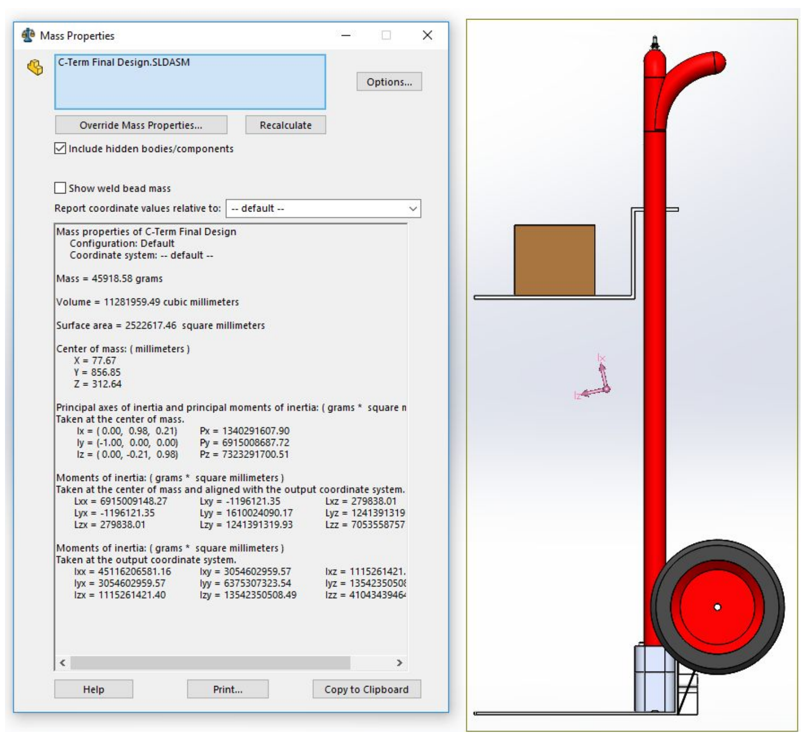
b) 

Figure 8. SolidWorks output for final CAD model with CoG locations shown for a) lift plate at middle position with no load added and b) lift plate at middle position with 50 lb load added.

Figure 8 above shows the hand truck CoG locations when the lift plate is at the middle position with and without a load added. Without any load, the CoG is located at X = 77.60, Y = 562.43, Z = 214.00, close to the bottom of the pipe frame. Similarly to the case prior, the hand truck remains upright without tilting or falling due to the weight distribution of the wheels and the nose plate. However, with the 50 lb load added, the CoG location moves higher up and forward to X = 77.67, Y = 666.97, Z = 312.64. This shows that the hand truck is more likely to tilt forward when a load is added to the lift plate at the middle position compared to the lowest position. In order to overcome this risk, the bottom portion of the hand truck was designed to be heavy enough in weight so as to bear the maximum amount of load applied to the lift plate.



a)



b)

Figure 9. SolidWorks output for final CAD model with CoG locations shown for a) lift plate at highest position with no load added and b) lift plate at highest position with 50 lb load added.

At the highest lift plate position, the CoG location of the hand truck with and without a load is generally higher up on the Y axis, which causes the hand truck to be tilted forward slightly more than the other instances discussed (Figure 9). Without any load, the CoG is located at X = 77.60, Y = 618.54, Z = 214.00. With the 50 lb load, the CoG location is found at X = 77.67, Y = 856.85, Z = 312.64. The added load causes the CoG to be the highest and most tilted out of all the instances, which was expected. The risk of the hand truck tilting forward or the lift plate rotating inward is highest at this location as well. These CoG location changes and risks were all taken into account when considering which material to use for the nose plate and how to place the motor housings and wheels so that the weight is distributed evenly to accommodate for the most extreme case of the plate being at the highest position with a max load added.

4.1.2 Torque Calculations

The torque needed for the motor to operate properly was calculated for both the prototype (τ_p) and the final design (τ_f). When calculating τ_p, a small load of approximately 1 lbm (pound mass) was used even though the prototype was not required to carry any weight so that the weight of the lift plate could be accounted for. In this case, 1 lbm converts to 42.7 lbf (pound force), which converts to 190 N. A pitch of 5 mm or 0.005 m was used in both calculations as this is the pitch of the ball screw employed in the prototype and final design. When calculating τ_f, the required maximum load of 50 lbm (= 1610 lbf = 7164.5 N) was used. The detailed calculations are as follows:

$$\tau = (F \times D_p) / 2\pi$$

$$\tau_p = (190N \times 0.005m) / 2\pi$$

$$\tau_p = 0.15\ N * m$$

$$\tau_f = (7164.5N \times 0.005m) / 2\pi$$

$$\tau_f = 5.70\ N * m$$

In order to ensure that the motor has enough torque to rotate the ball screw effectively for our application, the calculated torque values were doubled. Therefore, the torque required for the prototype and the final design were 0.30 N * m and 11.40 N * m, respectively. This also allowed the design to account for any frictional losses and assisted in decreasing any risk of motor failure, as the lift plate must be able to handle cyclic loading of maximum loads of up to 50 lbs.

4.1.3 Power Calculations

The power needed for the motor to operate properly was further calculated for both the prototype (P_p) and the final design (P_f). A speed of 0.015 m/s (1ft/20s) was used when completing these calculations because this enabled the lift plate to travel up or down the three foot long ball screw in one minute. One minute was chosen as the travel time for the lift plate because it is a practical and reasonable amount of time for an individual to wait for an object to be lifted and lowered three feet. The detailed power calculations are as follows:

$$P = F \times s$$

$$P_p = 190N \times 0.015m/s$$

$$P_p = 2.85\ W$$

$$P_f = 7164.5N \times 0.015m/s$$

$$P_f = 107.47\ W$$

Similar to the torque calculations, the calculated power values were doubled for the motor to effectively rotate the ball screw with the required weight applied to it for many cycles. Therefore, the power required for the prototype and the final design were 5.70 W and 215 W, respectively.

In order to satisfy the load capacity requirements for the hand truck, the calculated torque and power requirements must also be satisfied. To accommodate for these calculations, the design of our prototype and final hand truck consisted of two motors, which were placed in two custom motor housings. This way, the torque and power values can be split amongst the two smaller motors so as to not overwork one large motor. Further considerations regarding the motor (used within the prototype and considered for the final design) and the overall hand truck design are discussed in the following sections of this report.

4.2 Objective 2: Created a CAD Model of the Proposed Hand Truck

Two CAD models were created using the SolidWorks software; a ⅔ simplified model used for prototyping and a full-scale final model intended to showcase our final hand truck design. Every part used in the prototype model was found in the final design, while some of them were made more complex for the final CAD model. Some parts were also added to the final design. The parts that were added to increase the safety and the efficiency of the final design compared to the prototype were a battery holder, thrust bearings, and a support bar. The support bar was added to one version of the final design model and acts as a linear guide reaching through the center of the lift plate and the cross beam. However, without physical testing of a manufactured final design it is unknown whether the linear guide would be necessary for structural reasons. Therefore, two models were created for the final design.

For the parts that the models had in common, the wheel, axle, and handle were all modeled and dimensioned based off of standard hand trucks. For the full model, ten inch wheels were employed and for the scaled down model seven inch wheels were used. Certain other parts had to be modified to adapt to the function of the lift hand truck. The noseplate, or baseplate, of the common hand track had to be modified for our design so that the lift plate could fit inside of the noseplate in the lift position. The following image illustrates how the noseplate and the lift plate were placed in the final assembly.

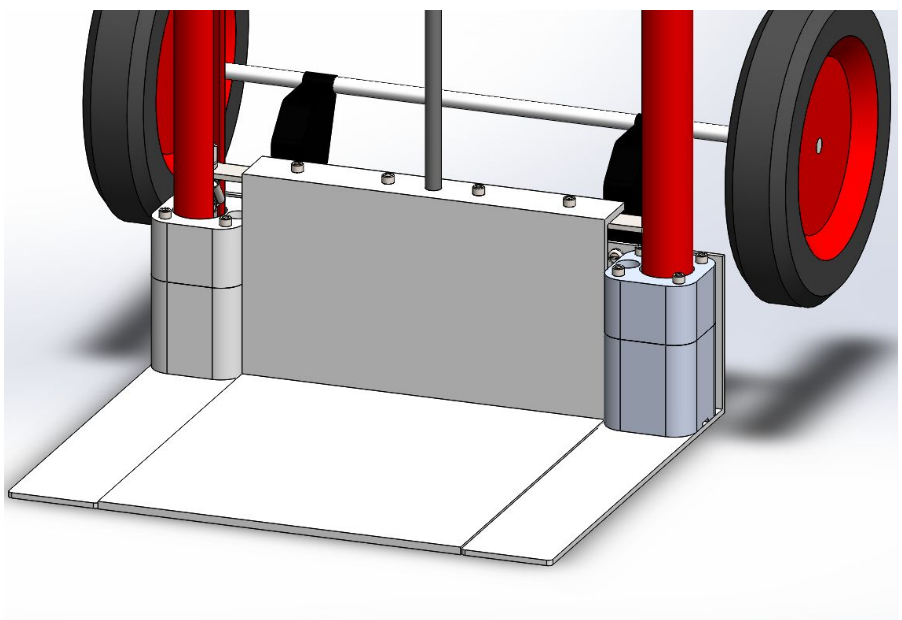


Figure 10. Noseplate and lift plate placement.

Another part of the frame that had to be modified to accommodate the lift design was the piping which holds the assembly together. Slots had to be added to the piping to allow the lift plate to be fixtured properly to both ball screw and ball nut assemblies. For the final assembly the slot was long enough to allow for the mechanism to lift three feet and for the ⅔ model the slot was long enough for the mechanism to lift two feet. The piping was held in place at the bottom of the assembly by a housing design which housed both the pipe and the motors and couplings.

Once common hand truck parts were modified, it was time to add the functional parts to the assembly. The functional parts of the mechanism began with the two 12 volt DC gearbox motors which were housed at the bottom of the assembly. These motors were then coupled together to the ball screws using two iron shaft couplings. In the final design, a thrust bearing was added between the motors and the first shaft coupling to add radial and axial support. The ball screw, which was three feet long in the final design and two feet long in the prototyped model, was supported at the top by a ball bearing. This ball bearing was force fitted into the piping so that its outside surface is unmovable. The ball screws both had ball nuts attached onto them. These two ball nuts were connected together using a cross beam. This cross beam supported, and was fixtured to, the lift plate.

The complete images of both the prototype CAD model and the final CAD model are shown in Figures 11 and 12 below.

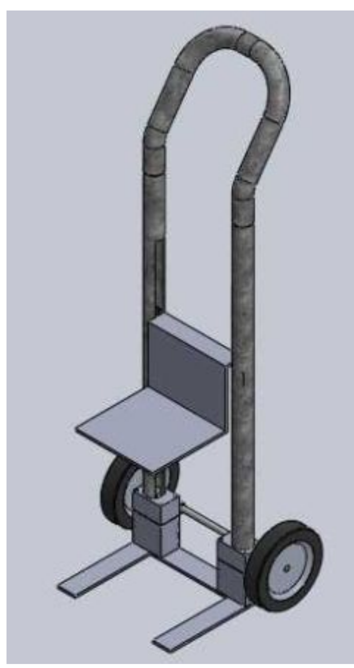


Figure 11. CAD model of the manufactured prototype.

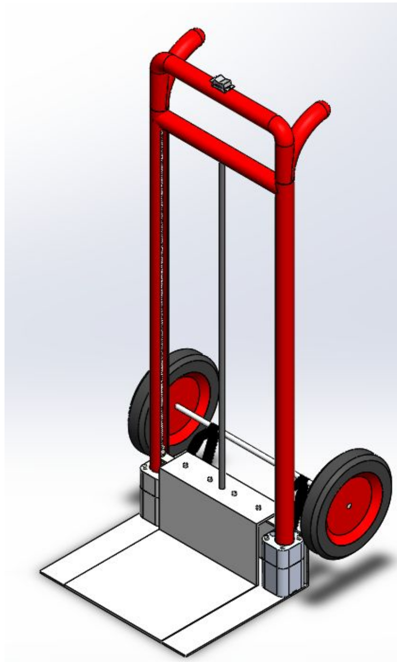
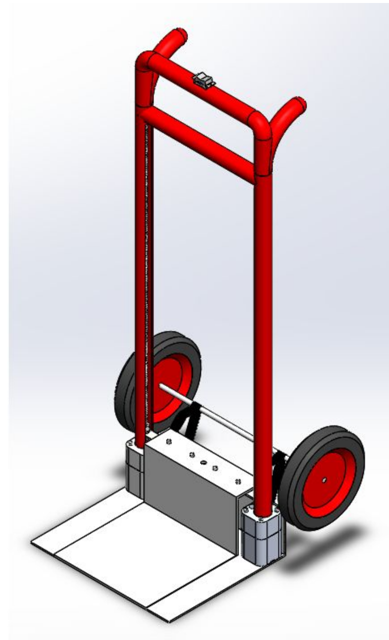
 b) 

Figure 12. Final design CAD model a) with support bar and b) without support bar to act as a linear guide for the lift plate.

The final model was analyzed in SolidWorks to determine the mass of the assembly. It was also used to determine the center of mass when the plate is at different heights and when the plate is loaded versus unloaded. The mass of the assembly was calculated to be 50.45 pounds. All of the parts in the assembly were assigned the correct material such that the mass density of every part was approximately what it would be after most of this weight is transferred to the wheels when the assembly is in use. Therefore, a weight of approximately 50 pounds was deemed light enough for household use.

An exploded view of the final model is illustrated below. Balloon numbers correspond to the part numbers detailed in Appendix C.

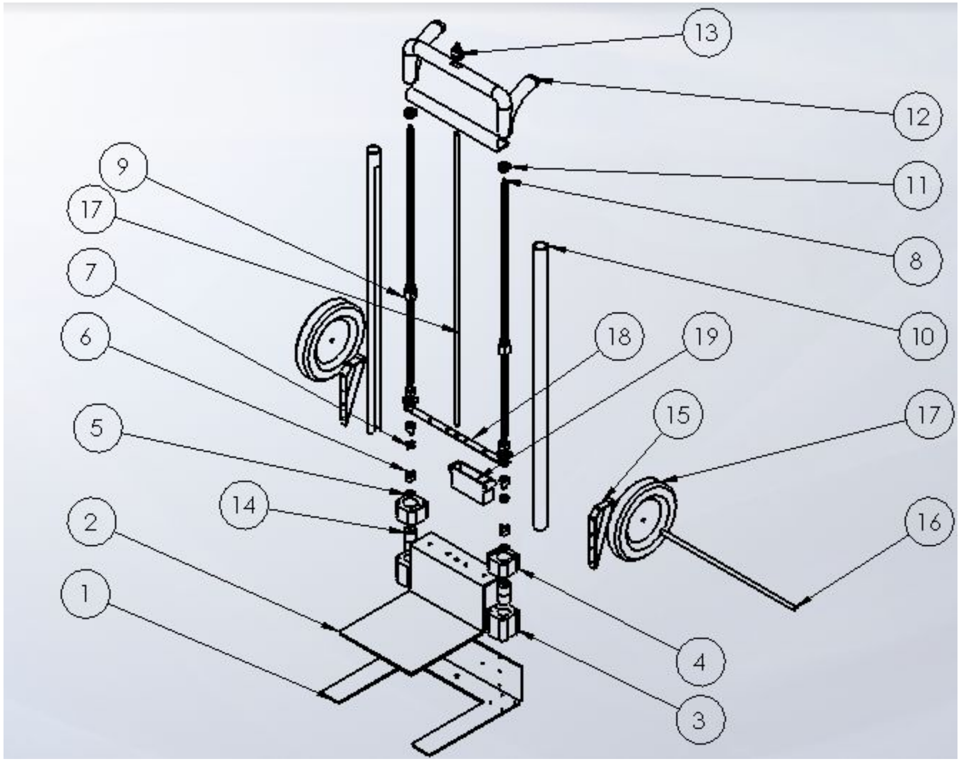


Figure 13. Exploded view of final CAD design.

4.3 Objective 3: Prototyped and Manufactured the Designed Model

Throughout the manufacturing process of the prototype, the team had the opportunity to identify problem parts and establish lessons learned that could then be used to propose recommendations for future large scale manufacturing. This section discusses the difficulties the team faced during this process and relays the insights gathered so that the results of the prototyping process can be fully depicted.

The first step in creating the prototype was assigning each part a material. The motor housing, pipe connector, pipe, and lift plate were all made from aluminum. The noseplate and crossbeam were made from steel. Manufacturing the motor housing was found to be particularly difficult. Due to the depth of the pocket that the motor had to sit in, a special drill bit had to be used. During the first attempt at machining the part, the drill bit broke due to the magnitude of force it experienced when making the pockets. After ordering a new drill bit and adjusting the program to reduce the force, the part was manufactured. Next, the pipe connector was manufactured. Unlike the motor housing, the pipe connector had more intricate details. After drilling the pocket, the team had to drill six M3 sized holes in a thirty-one millimeter diameter around the motor shaft. The process of machining the pipe connector was found to be challenging, however, was completed successfully in the first attempt as the team applied lessons learned from the motor housing machining process.

The ball screw used in the prototype was made of hardened alloy steel, which was found to be more difficult to machine compared to aluminum as steel is a stronger material. Because of this, the operation written for this part had to be completed with careful attention to precision. Furthermore, the ball nut, which was made from black-oxide alloy steel, had to have its rear corners ground off in order to fit into the slotted pipe. One of the problems encountered during the manufacturing process of this part was that one of the ball nuts was ground more than desired. This caused the ball nut to sit farther inside the pipe than the design required, leading to further complications during the testing phase, discussed in the following section of this report.

The program used for machining the pipes was simple but executing the program was found to be rather tedious. Since the length of the pipe slot was designed to be so long, the program had to be paused after machining every couple inches of the pipe so that the supports could be moved out of the tool path. In addition, the length of the slot also caused a large amount of vibrations on the open end of the pipe. These vibrations caused the supports to slip, leading the tool to cut one of the slots in an incorrect manner. Cutting out the U-shape of the noseplate, on the other hand, went smoothly. However, drilling the counter-bore holes to match the holes on the bottom of the motor housing with the manual drill press was rather difficult. Since the holes on the noseplate did not completely match the holes on the motor housings, the team was only able to use a few of the holes to connect the noseplate to the rest of the hand truck. Similar to the noseplate, cutting the three pieces of the lift plate went well. The difficult step in manufacturing this part was welding the pieces together. When welding aluminum, the metal tends to bend due to the heat utilized during the process. The part was made to the best of the team’s ability, which resulted in minimal bending.

Further, to contour the outer edge of the crossbeam, the team superglued the steel to a block of metal in order to secure the part inside the VM2. The crossbeam detached from the metal block during the operation in the first attempt, however, was re-glued onto the metal block in the second and final attempt. The following portion of the machining consisted of cutting out a small rectangular hole in the PVC pipe so that the wires and rocker switch fit inside the handle. This process was found to be simpler compared to the rest and was completed without any issues.

After overcoming the challenges presented during machining, the team assembled the hand truck prototype as described in section 3.3 of the Methodology chapter. The first issue encountered was that the thrust bearings came in three pieces and, therefore, did not stay in place on the motor's shaft. This posed a concern as the design aimed to minimize the forces placed on the motor by distributing the load onto the thrust bearings instead. Nevertheless, the team moved forward without including the thrust bearings on the motor. The chosen motor and some of its specifications are shown in Figure 14 below. This motor was chosen as it satisfied the torque and power requirements calculated in section 4.1 of this report. Due to cost and resource limitations, the team was unable to purchase customized materials, such as a motor, that met the exact calculated requirements.

Figure 14. Motor used to power the prototype with torque and power values listed. Note: The design consists of two motors, one for each ball screw, therefore, the overall prototype experiences twice the torque and power labeled in this diagram.

Further, the sides of the crossbeam had to be ground down because there was too much friction between the crossbeam and the pipe slot. The friction caused the crossbeam to jam when the prototype was powered on. Once these complications were resolved, the wiring allowed the prototype to operate properly. The electrical diagram used to wire the prototype is shown in Figure 15. The motors were wired at the beginning of the assembly since they are encased within the motor housing. These wires went through the motor housing and onto the outside surface of the pipe. The wiring setup involved putting the motors and battery in a parallel circuit and extending six wires from the bottom of the motor housing to the handle. The wiring setup along with the assembly of the parts described in this report made up the hand truck prototype. The fully assembled prototype can be found in Figure 16.

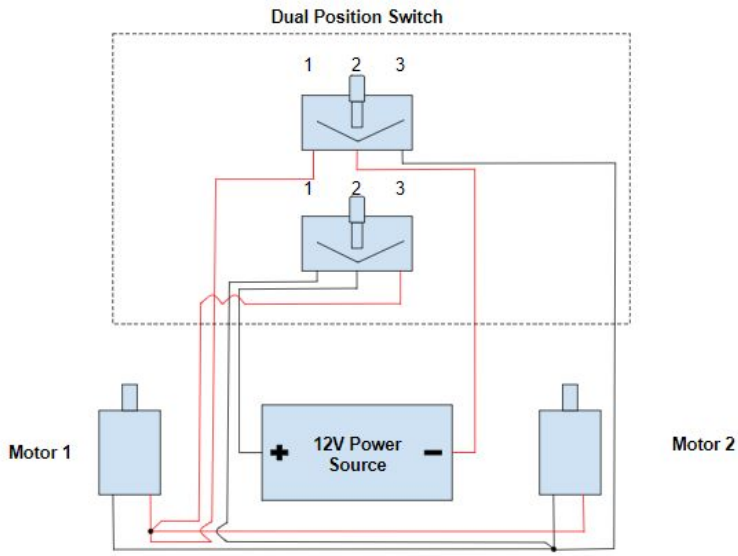


Figure 15. Electrical circuit diagram used to wire the hand truck.

a) b) c)

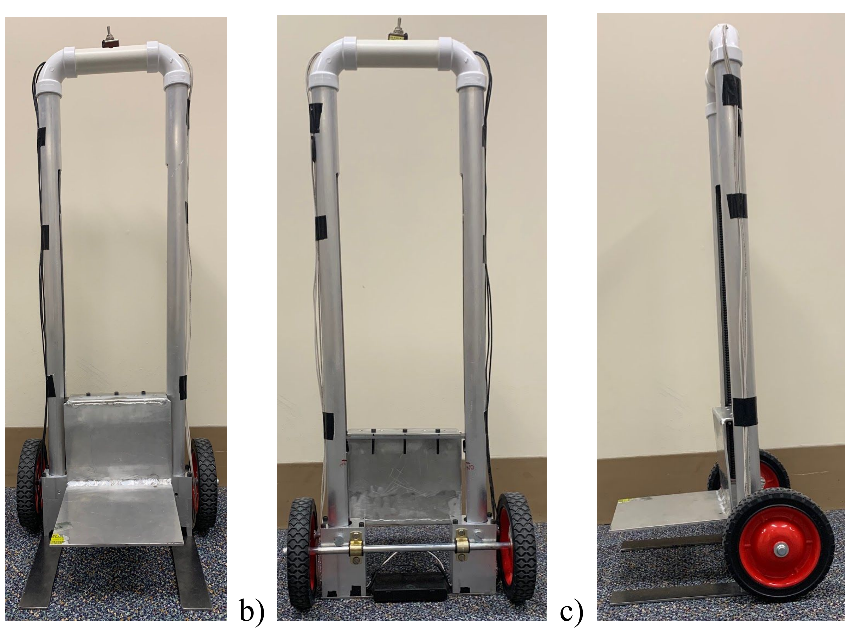


Figure 16. Fully assembled hand truck prototype a) front view, b) back view, and c) side view.

The obstacles presented by the machining and assembling of the prototype provided the team with extended knowledge that can be applied for future manufacturing of the hand truck. Operational testing of the hand truck after the completion of the assembly was conducted next. The results of the observations made during the operational testing of the prototype are discussed in the following section.

4.4 Objective 4: Tested and Analyzed the Performance of the Prototyped Hand Truck

After the prototype parts were fully manufactured and put together, the prototype was tested using the qualitative methods described in section 3.4 of this report. Multiple trials of the three point switch test were conducted first. Overall, this test showed that the ball screw and ball nut mechanism functions properly for our application. This test provided a proof of concept for the ball screw mechanism, more specifically, that this mechanism can, in fact, be incorporated into a hand truck designed for in-home use. Specific observations made during this test can be found in Table 1 below.

Table 1. Three Point Switch Test Results

Observation	Analysis of Result - Why?
One of the ball screws would occasionally jam and stop rotating.	The team found that this happened because the corresponding ball nut turned inward as the ball screw rotated. The corners of this specific ball nut were grinded down more than the other ball nut so it fit too deeply inside the pipe, causing it to turn inward. In order to solve this issue, new ball nuts were ordered and re-grinded correctly.
The ball nuts would get jammed towards the bottom of the pipe.	The team found that this was caused by the manufacturing of the pipe. Both pipe slots on the two pipes were machined, however, the bottom of the slots are not smooth or wide enough for the ball nuts to smoothly move up. The team also found that the ball nut moves up and down smoothly about 2 inches off the top of the pipe connector. This issue was due to human inefficiencies and can be mitigated with proper machining for the future.
The crossbeam, which holds the lift plate, became uneven from time to time as the ball nuts traveled up and down multiple times.	The team found that the jamming of the ball nuts discussed prior caused the two ball nuts to become uneven instead of being perfectly aligned. Since the crossbeam is placed on these ball nuts, misalignment of the ball nuts caused the crossbeam to also become uneven. Further, the crossbeam was not fixed to the ball nuts because the correct sized lock nuts were not readily available for purchase. The team found that the lock nuts we needed had to be custom made, for which the team did not have enough time or resources.
The electrical wiring proved to work as expected, however, was bulky.	The wiring allowed the motor to switch polarities, which in turn allowed the ball screws to rotate in both directions so that the lift plate could travel upwards and downwards. The team found that the bulkiness of the wires was due the wire gauge being too low. In order to improve the wiring setup, thinner wires were used to replace the thick wires.
Thrust bearings will be an important component in the final design.	To decrease direct load on the motors, it is imperative that thrust bearings be added to the lifting mechanism. This way, a majority of the weight is felt by the bearings, allowing the motors to solely rotate the ball screws and avoiding motor failure.

Two different objects were then added to the prototype to test the integrity of the lift plate. The first object was a notebook, weighing 2.00 lbs, and the second object was a water bottle with water in it, weighing approximately 1.27 lbs. Both objects were lifted and lowered successfully, showing that the design of the lift plate is sufficient for objects of different shapes and sizes to be loaded onto the hand truck without risk of slipping off. Details of this test can be found in Table 2. Additionally, the moment about the lift plate did not cause the plate to rotate even though the prototype was not designed to handle any load, further solidifying that the lift plate design is appropriate for our application.

Table 2. Results of Prototype Testing with Loads Added

Object	Weight (lbs)	Travel Time to Lift (s)	Travel Time to Lower (s)
Water bottle	1.27	221	220
Notebook	2.00	225	224

Finally, the prototype was moved along a predetermined course with turns included. We found that the hand truck maneuvered around the course with ease, successfully completing turns without any difficulty. This showed that the wheels were placed correctly and that the hand truck has the ability to travel from place to place inside the home. The insight gained through these tests allowed the team to make further adjustments to the prototype as described in this section. These results further led us to recognize improvements that must be made to the final design. These improvements could not be incorporated and tested by our team due to the time constraints of this project, however, from our experience designing and prototyping this product, we believe the suggested improvements would increase the efficiency and effectiveness of the hand truck.

4.5 Objective 5: Proposed Recommendations for the Manufacturing of the Full Scale Model

Based on the testing and analysis of our prototype, the team proposed various recommendations that should be incorporated in order to improve the overall design. The following recommendations are indicated below.

1. The first recommendation is to utilize thinner wires with a higher gauge (approximately 16-20 gauge wires). This will allow for the wires to be secured within the piping and through the motor housing, hiding and protecting it from the outside.
2. The slot within the pipe should be covered with a rubber guard, hiding and protecting the ball screw mechanism within it.
3. Customized lock nuts (thread size of ⅝”-5) should be found that fit over the cross beam, holding it down and securing it onto the ball nuts.
4. Customized motors should be obtained to match the final design calculations, as described in section 4.1 of this report. This will enable the hand truck to fulfill its operating requirements. The final design motors will, more likely than not, have to be custom ordered through an outside vendor and ordered in bulk to reduce costs.
5. In order to decrease overall product weight for ease of use, excess material throughout the design should be removed, keeping the weight distribution and CoG in mind. This includes decreasing the pipe thickness and casting the motor housing and pipe connector.
6. In the future, the mechanism that holds and stabilizes the lift plate should be improved upon. This mechanism can be improved by adding sliders to the back of the lift plate, enabling the plate to glide smoothly up and down without rubbing against the pipes, while also decreasing the risk of the plate rotating inward when a load is added.
7. The final design should also have a safety factor of at least 5 (for the motor), as it promotes increased safety for household use.
8. Additionally, the battery should be replaced with one that is rechargeable. This would increase the practicality of the hand truck as having to replace batteries is a tedious task that may turn customers away. The team recommends that a lithium ion battery be used to disperse more voltage, supplying a constant current throughout the hand truck.

9. Ball screws with a smaller diameter should be considered for the final design. Although the diameter of the ball screw used in the prototype may be the best option, the team did not have enough time or resources to consider/test smaller diameters. A thinner ball screw would reduce the weight of the product. Additionally, it would create enough room inside the piping for the wires to be secured and hidden within the pipes.
10. A layer made up of a material with a high static friction coefficient should be bonded to the surface of the lift plate (i.e. rubber). This would ensure that objects loaded onto the plate do not slip.
11. Lastly, an encoder should be added to the motors so that they are synchronized at all times. This can be accomplished by switching the brushed motors to servo motors with encoders and adding a corresponding controller. This would allow users to precisely determine if both motors have travelled the same distance. With this information, the controller can adjust the motors accordingly to ensure that the crossbeam is perfectly level, minimizing stress on the system caused by a misaligned crossbeam.

These recommendations were made based off of the lessons learned from manufacturing the prototype and the observations made during the testing phase. The team could not implement these recommendations due to the time constraints of this project, however, we believe that incorporating these suggestions would increase ease of large-scale manufacturability while making the product more marketable with an overall lifetime goal of 10 years.

5. Conclusion

The gap that this project aimed to address was the lack of an in-home automatic lifting mechanism in the hand truck industry. There is a need for an in-home hand truck for the elderly, who have reduced abilities to bend and lift objects, and for those who are injured, who cannot strain their bodies further by lifting objects. An automatic lifting mechanism for use inside a home would also be able to assist the general public in completing daily tasks that involve lifting. Market research showed that there are many variations of hand trucks available today, however, they are bulky, heavy, costly, and made for industrial/warehouse use. Furthermore, the hand trucks in the market use lifting mechanisms such as pulley systems and hydraulic lifts. The goal of this project was to design an affordable automatic hand truck suitable for in-home use that utilizes a lifting mechanism appropriate for its application. The hand truck must be able to lift and lower objects of up to 50 lbs to a height of three feet, while being low in weight and cost.

The steps taken to achieve this goal included, calculating values necessary for proper operation of the product, creating a CAD model of the design, manufacturing a ⅔ scaled prototype of the design, testing the prototype, and proposing recommendations for full scale manufacturing. The CoG calculation results illustrated that the higher the lift plate and load travel up the ball screw assembly, the more likely it is for the entire hand truck to tilt forward. These calculations also influenced the materials chosen for each component of the design. Stainless steel was the chosen material for the noseplate, while the tires were standard rubber, both adding weight to the bottom of the hand truck and mitigating the risk of the hand truck tilting forwards or backwards. Aluminum was chosen as the material for all other parts. Further calculations showed that the motors used in the final design must each have a torque and power of 11.40 N*m and 215 W, respectively. Taking these calculations into consideration, two CAD models were created, one for a ⅔ scaled prototype that could be manufactured and another one for the final proposed design.

As the prototype was manufactured and constructed, the final design CAD model was modified to incorporate lessons learned. A ball screw and ball nut assembly was chosen as the desired lifting mechanism and was incorporated into the design. Since a ball screw and ball nut assembly has not been utilized within the hand truck industry, the main goal of this prototype was to provide a proof of concept for this lifting mechanism. Qualitative testing conducted on the fully assembled prototype showed that the ball screw mechanism successfully lifted and lowered the lift plate by rotating in both directions and stopping and starting as directed by the switch. This provided a proof of concept that the ball screw and ball nut assembly does, in fact, properly operate within the given application, while also allowing the hand truck to be suitable for in-home use.

The ability of our original design to utilize a unique ball screw mechanism and minimize weight and cost, while being practical for in-home use, makes this a widely marketable product. Current hand trucks range anywhere from \$50 to thousands of dollars. The cheaper end of the spectrum includes smaller but non-automated hand trucks, while expensive products include large, industrial forklifts/machines with high load capacities. This original design would fit into the cheaper end of the spectrum, with a target price of \$99, so that it is affordable for families to purchase. Although the total price to manufacture the prototype was \$474.15, large scale manufacturing is expected to significantly lower the final price of the product. Factors that further affect the price are the materials used, the customized motors, and the load factor. Aluminum, which is used to manufacture most of the hand truck parts, plays a critical role in decreasing the price of the product as the material is low in cost and weight. The motors, on the other hand, may increase costs due to the calculated specifications needed, however, ordering the motors in bulk will drive down costs to a reasonable point as that is the purpose of ordering items in large quantities. Lastly, the price is directly related to the desired load the hand truck can operate under; increasing the maximum load would require more powerful motors that are more costly, and decreasing the load would require less powerful motors that are less costly.

Overall, the team was able to design, prototype, and test an original automated hand truck. The ball screw assembly utilized within the design was found to operate successfully, providing a proof of concept for the lifting mechanism within the given application of the product. The team is hopeful that a combination of the unique design and bulk production of the product will promote economic feasibility in terms of production and marketability to customers.

References

[1] OSHA, “Hazards and risks associated with manual handling in the workplace,” *E-Facts*, n.d. [Online]. Available: http://www.osha.mddsz.gov.si/resources/files/pdf/E-fact_14_-_Hazards_and_risks_associated_with_manual_handling_in_the_workplace.pdf. [Accessed: Feb. 21, 2019].

[2] “What levers does your body use?,” *Science Learning Hub*, Jun. 21, 2007. [Online]. Available: https://www.sciencelearn.org.nz/resources/1924-what-levers-does-your-body-use. [Accessed: Dec. 18, 2018].

[3] “Body Mechanics,” n.d. [Online]. Available: http://www.mccc.edu/~behrensb/documents/210wk3BodyMechanics_000.pdf. [Accessed: Dec. 20, 2018].

[4] “Ageing - muscles bones and joints,” *Better Health Channel*, n.d. [Online]. Available: https://www.betterhealth.vic.gov.au/health/conditionsandtreatments/ageing-muscles-bones-and-joints?viewAsPdf=true. [Accessed: Dec. 20, 2018].

[5] “The History and Evolution of the Hand Truck,” *UpCart Blog*, Jan. 30, 2018. [Online]. Available: https://www.upcart.com/blog/2018/01/30/history-evolution-hand-cart/. [Accessed: Dec. 18, 2018].

[6] “The Evolution of Hand Trucks,” *Douglas Equipment Company*, 2019. [Online]. Available: https://www.douglasequipment.com/hand-trucks/the-evolution-of-hand-trucks/ [Accessed: December 18, 2018].

[7] “Hand Trucks,” *Grainger,* n.d. [Online]. Available: https://www.grainger.com/category/hand-trucks/carts-and-trucks/material-handling/ecatalog/N-9pn. [Accessed: December 18, 2018].

[8] A. Webber, “How it works,” *Hydraulics*, Mar. 16, 2005. [Online]. Available: http://ffden-2.phys.uaf.edu/212_spring2005.web.dir/annie_weber/page2.html. [Accessed: December 18, 2018].

[9] “Wesco 2 Wheeled Hydraulic Lift,” *Hand Trucks R Us,* n.d. [Online]. Available: https://www.handtrucksrus.com/product-details.aspx?id=987&cx=lift#. [Accessed: Dec. 18, 2018].

[10] "Powerful Pulleys - Lesson," *TeachEngineering,* n.d. [Online]. Available: https://www.teachengineering.org/lessons/view/cub_simple_lesson05. [Accessed: Dec. 18, 2018].

[11] "Platform Lift, 750 lb.," *Zoro*, n.d. [Online]. Available: https://www.zoro.com/zoro-select-platform-lift-750-lb-260016/i/G2288441/. [Accessed: Dec. 18, 2018].

[12] "Scissor Lifts Information," *Engineering 360*, n.d. [Online]. Available: https://www.globalspec.com/learnmore/material_handling_packaging_equipment/material_handling_equipment/scissor_lifts. [Accessed: Dec. 18, 2018].

[13] "Manual Lift Table - Double Scissor, 770 lb, 36 x 20,'" *Uline*, n.d. [Online]. Available: https://www.uline.com/Product/Detail/H-1784/Lift-Tables/Manual-Lift-Table-Double-Scissor-770-lb-36-x-20?pricode=WA9216&gadtype=pla&id=H-1784&gclid=EAIaIQobChMIxa2Jr7Cu3gIVjODICh2DEAY4EAQYAyABEgLIyPD_BwE&gclsrc=aw.ds. [Accessed: Dec. 18, 2018].

[14] "How A Ball Screw Works," *Barnes Industries, Inc.*, 2014. [Online]. Available: http://www.barnesballscrew.com/how-a-ball-screw-works/. [Accessed: Dec. 18, 2018].

[15] T. Schneider and P. Hannifin, "Pros and cons of linear screw drive actuators," *Linear Motion Tips*, Mar. 26, 2017. [Online]. Available: https://www.linearmotiontips.com/as-the-screw-turns/. [Accessed: Dec. 18, 2018].

[16] "What is the difference between an AC motor and a DC motor?," *Ohio Electric Motors*, Jul. 21, 2015. [Online]. Available: http://www.ohioelectricmotors.com/2015/07/what-is-the-difference-between-an-ac-motor-and-a-dc-motor/. [Accessed: Feb. 25, 2019].

[17] "What are Brushless DC Motors," *Renesas Electronics,* n.d. [Online]. Available: https://www.renesas.com/us/en/support/technical-resources/engineer-school/brushless-dc-motor-01-overview.html. [Accessed: Feb. 25, 2019].

[18] "Aalco," *Stainless Steel - General Information - Alloying Elements in Stainless Steel*. [Online]. Available:

http://www.aalco.co.uk/datasheets/Stainless-Steel-Alloying-Elements-in-Stainless-Steel_98.ashx. [Accessed: Feb. 25, 2019].

[19] "Metal Prices - Steel, Aluminum, Copper, Stainless, Rare Earth, Metal Prices, Forecasting," *MetalMiner*. [Online]. Available: https://agmetalminer.com/metal-prices/. [Accessed: Feb. 25, 2019].

[20] "Steel Structural Shapes," *Industrial Metal Supply,* n.d. [Online]. Available: https://www.industrialmetalsupply.com/products/steel/structural-shapes#1. [Accessed: Feb. 25, 2019].

[21] AZOM, "Aluminium - Advantages and Properties of Aluminium," *AZO Materials*, Jan. 11, 2018. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=1446. [Accessed: Feb. 25, 2019].

[22] S. Alessandri, "Specific weight metal and alloy," *Unit of measure conversions equivalences*. [Online]. Available: http://www.themeter.net/pesi-spec_e.htm. [Accessed: Feb. 25, 2019].

[23] "Rubber Properties," *Mykin Inc.* [Online]. Available: http://mykin.com/rubber-properties. [Accessed: Feb. 25, 2019].

[24] "Physical Properties of Rubber – a Buyer and Designer's Guide," *AZO Materials*, Dec. 18, 2018. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=11914. [Accessed: Feb. 25, 2019].

[25] L. Hatton, "How to Determine the Center of Gravity of Any Load," *Sims Crane & Equipment*, Oct. 19, 2018. [Online]. Available: http://www.simscrane.com/how-determine-center-gravity-any-load/. [Accessed: Feb. 25, 2019].

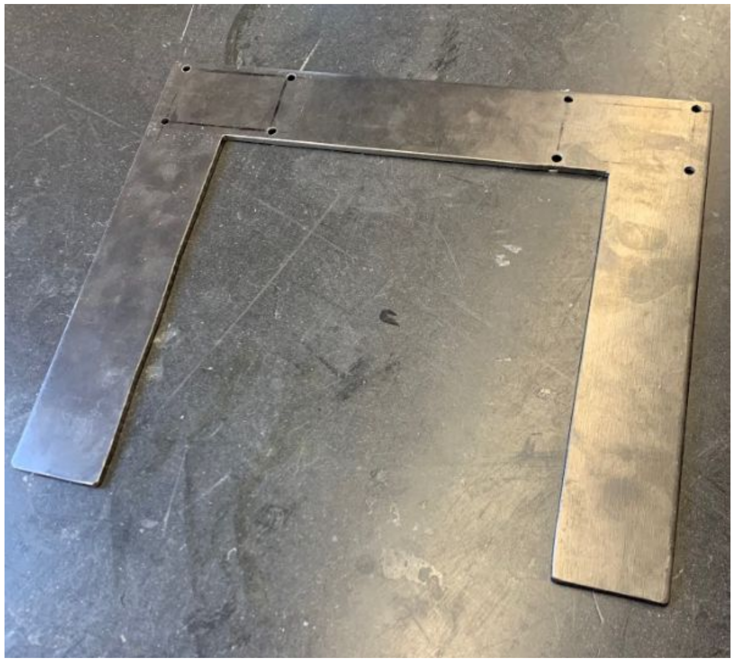
Appendices

Appendix A: Prototype Bill of Materials

Bill of Materials for Hand Truck Prototype				
Item #	**Item Qty.**	**Description**	**Price Per Unit**	**Price Total**
1	1	0.188” Thick Aluminum Plate Stock, 12” x 24” W x L	$49.02	$49.02
2	1	0.187” Thick Carbon Steel Plate Stock, 12” x 12” W x L	$20.96	$20.96
3	1	6061 Aluminum Rectangular Bar Stock, 12” x 2” x 3”	$40.26	$40.26
4	2	12 V, 30 RPM Gear Motor High Torque Electric DC Motor	$15.98	$31.96
5	4	Flexible Shaft Coupling Iron Hub	$4.03	$16.12
6	2	Rubber Spider for Shaft Coupling	$2.64	$5.28
7	2	⅝”-5 Ball Screw, 2 ft. Long	$46.04	$92.08
8	2	External Thread ⅝”-5 Ball Nut	$36.90	$73.80
9	1	6063-T6 Aluminum Pipe, 1.66” OD 1.38” ID	$23.43	$23.43
10	2	Ball Bearing, Sealed 17mm	$10.13	$20.26

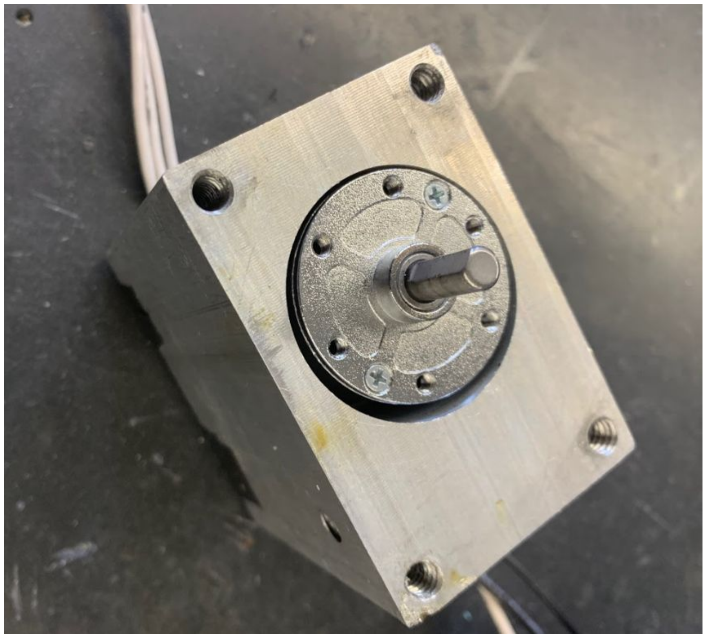
		Shaft Diameter		
11	2	7” Rubber Tires	$10.38	$20.76
12	1	Zinc Smooth Rod, ½” OD x 36” L	$13.38	$13.38
13	2	½” Zinc Axle Nut	$4.69	$9.38
14	2	90 Deg. PVC Elbow	$7.54	$15.14
15	1	PVC Pipe	$7.08	$7.08
16	12 ½ ft	14 Gauge White Stranded Wire	$0.28	$3.50
17	12 ½ ft	14 Gauge Black Wire	$0.28	$3.50
18	1	12 V. Battery Pack, Pack of 2	$8.00	$8.00
19	1	Pack of 24 AA Batteries	$8.25	$8.25
20	1	3 Position Universal Heavy Duty 20A 125V 6 Terminal ON/Off/ON Rocker Toggle Switch	$11.99	$11.99
			Total:	**$474.15**

Appendix B: Prototype Photographs

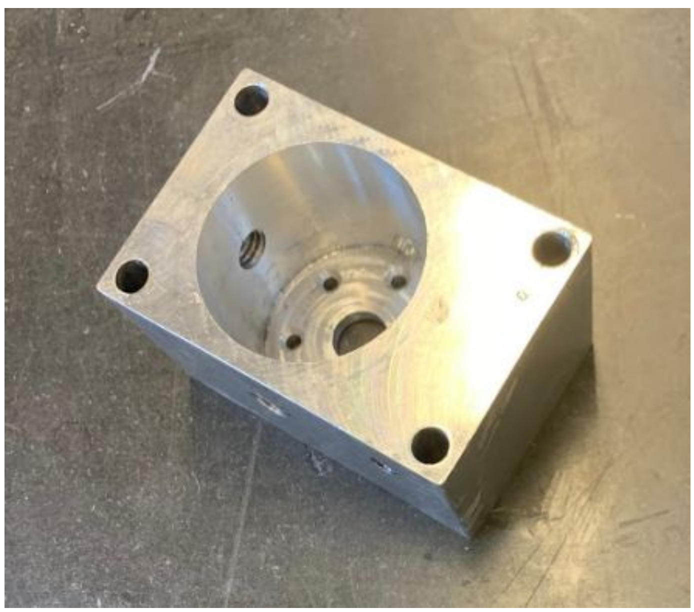


Nose Plate

Lift Plate



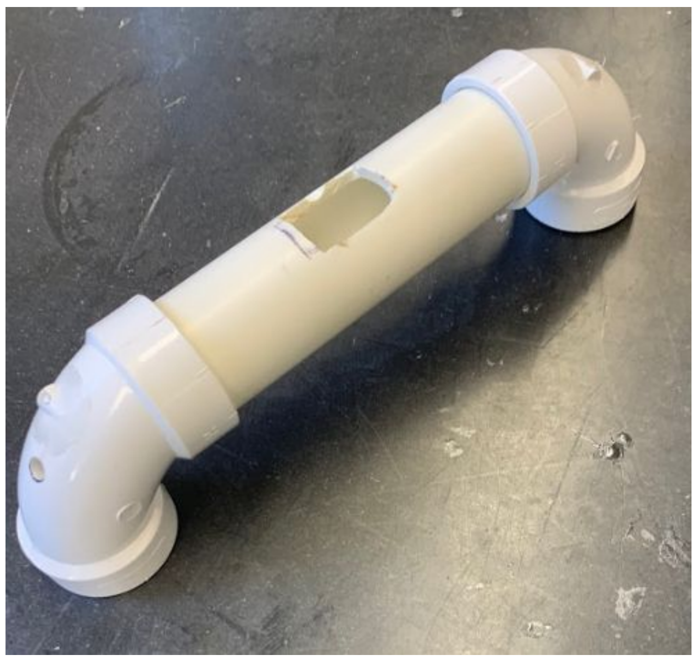
Motor Housing with Motor



Pipe Housing

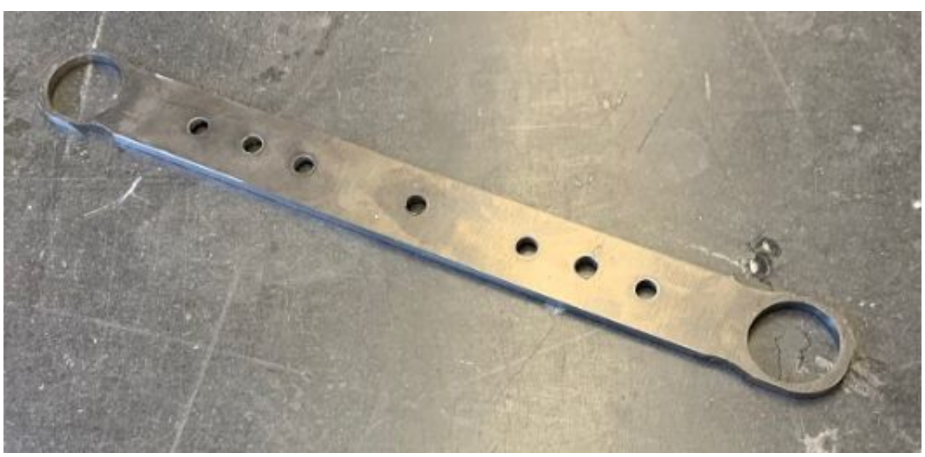
Ball Screw Assembly

Frame with Ball Bearing



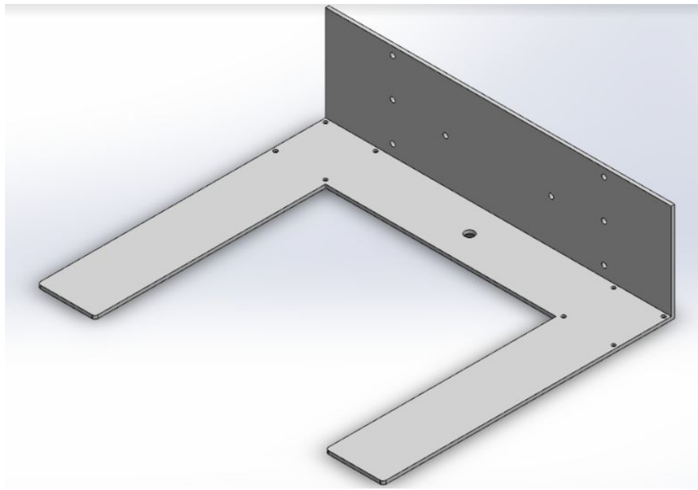
Handle

Tire Assembly

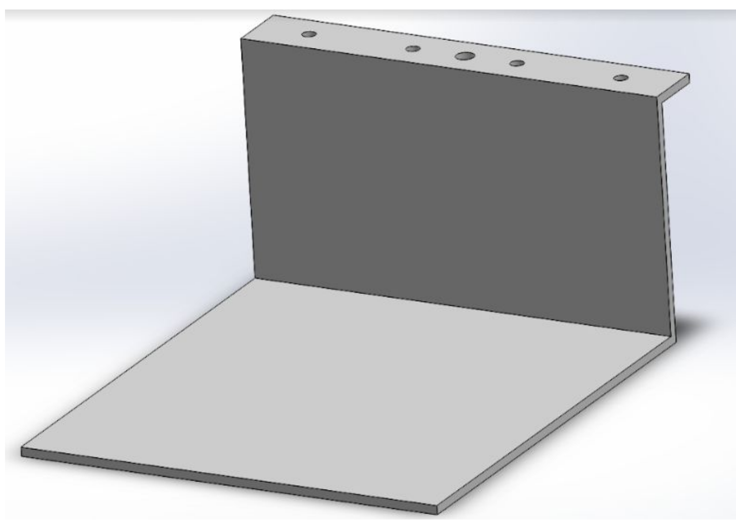


Cross Beam

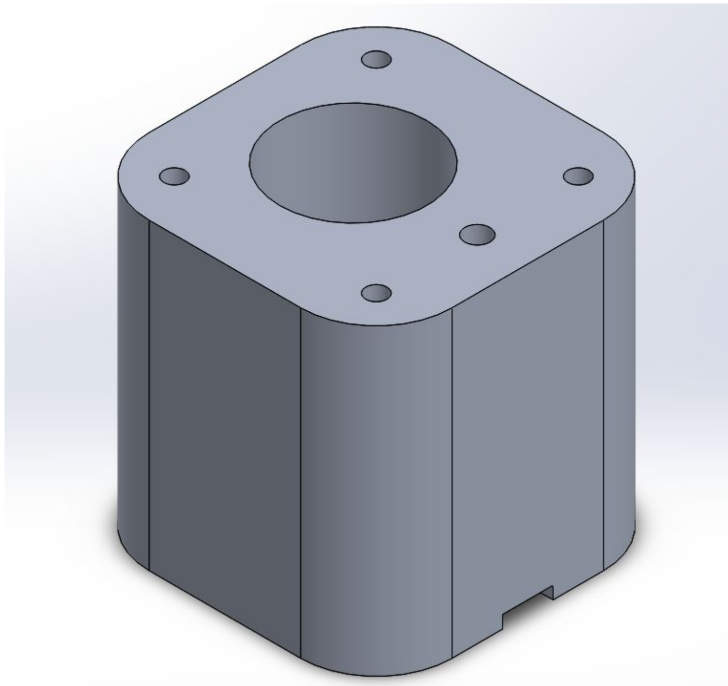
Appendix C: Final Design CAD Parts



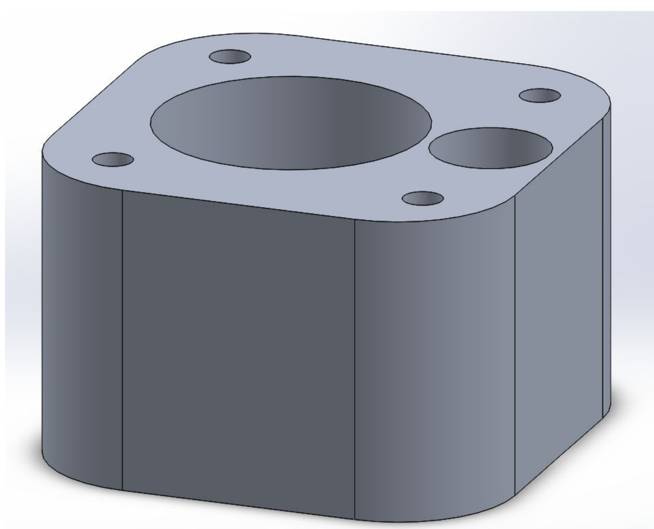
(1) Nose Plate



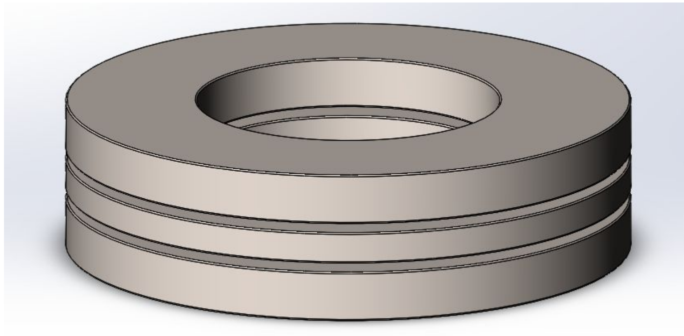
(2) Lift Plate



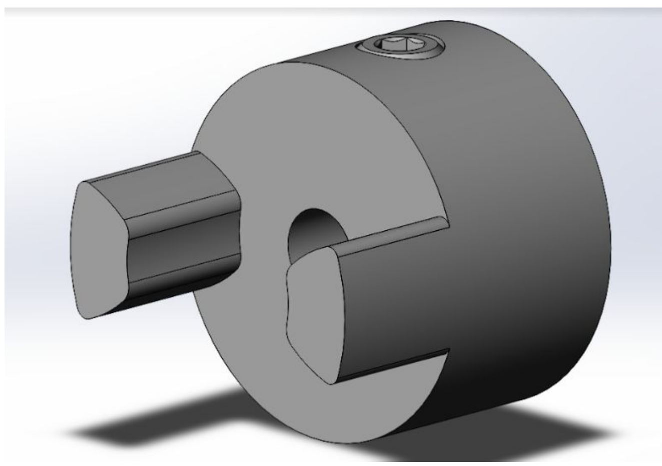
(3) Motor Housing



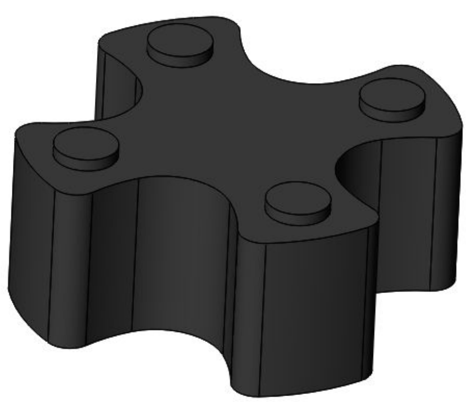
(4) Pipe Housing



(5) Thrust Bearing (Property of McMaster Carr Supply Company)

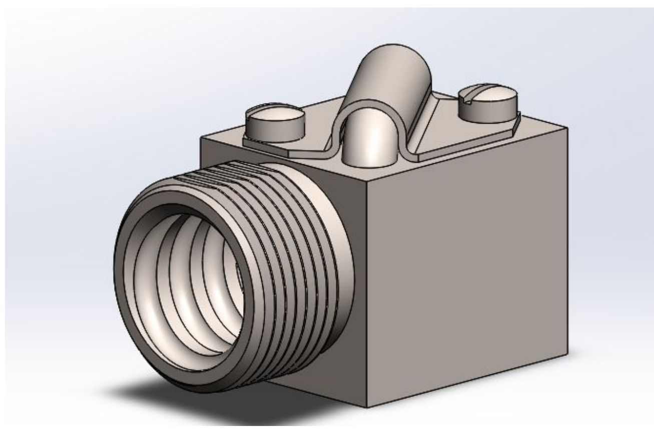


(6) Shaft Coupling (Property of McMaster Carr Supply Company)

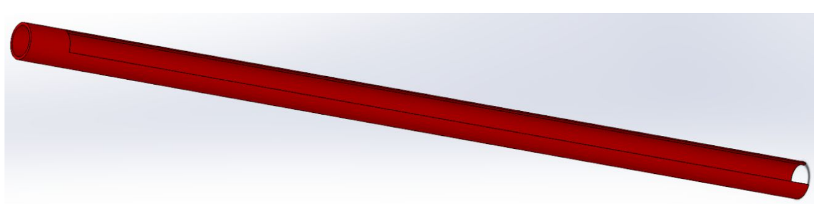


(7) Shaft Rubber Spider (Property of McMaster Carr Supply Company)

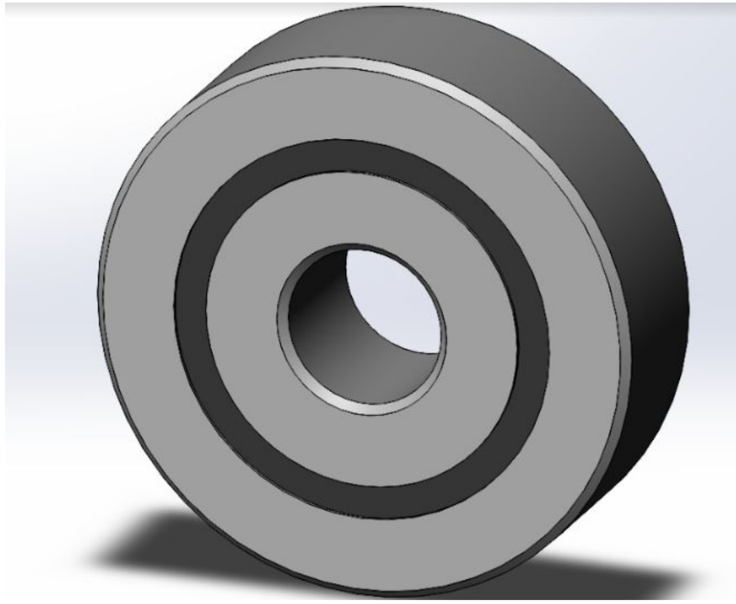
(8) Ball Screw



(9) Ball Nut (Property of McMaster Carr Supply Company)

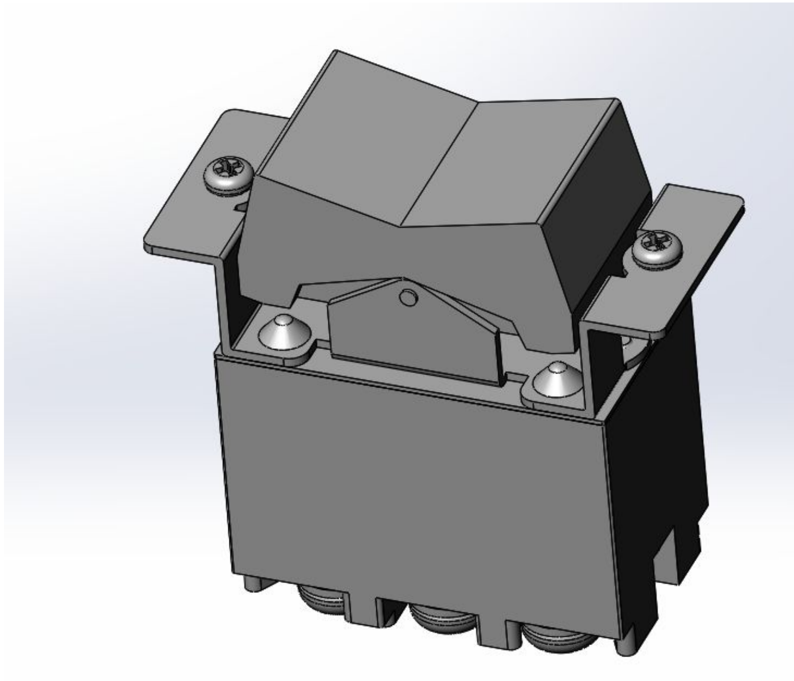


(10) Frame

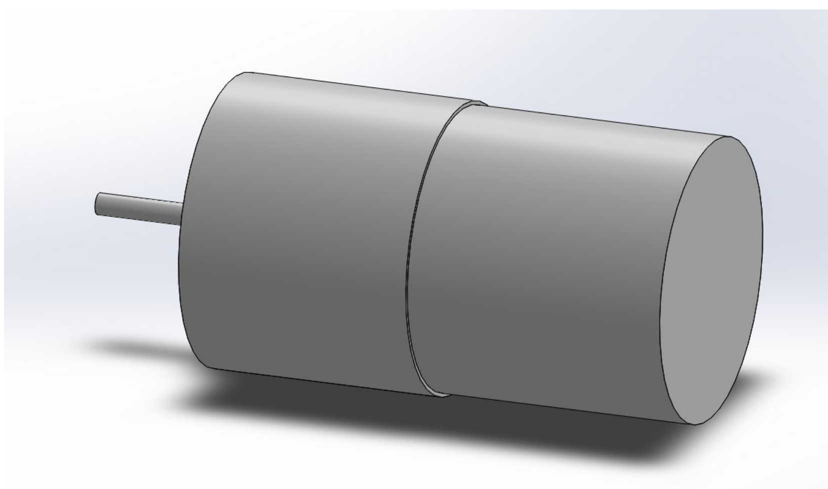


(11) Ball Bearing (Property of McMaster Carr Supply Company)

(12) Handle

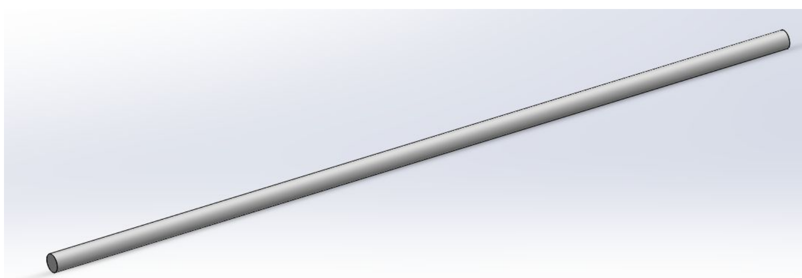


(13) 3 Way ON/OFF/ON Switch (Property of McMaster Carr Supply Company)

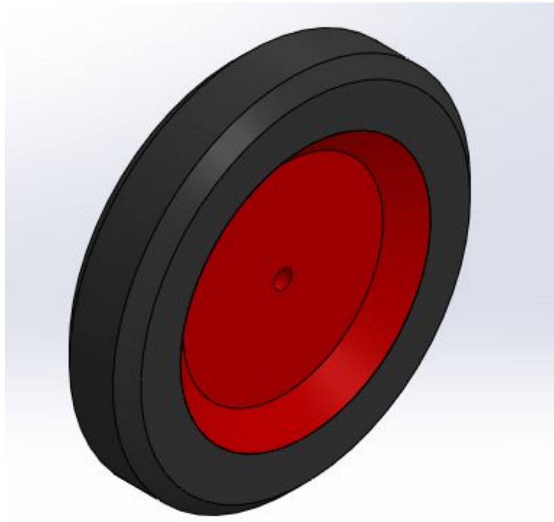


(14) Body of Motor

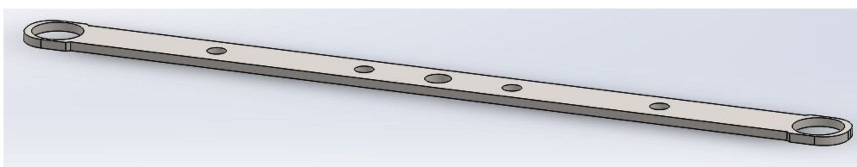
(15) Axle Attachment



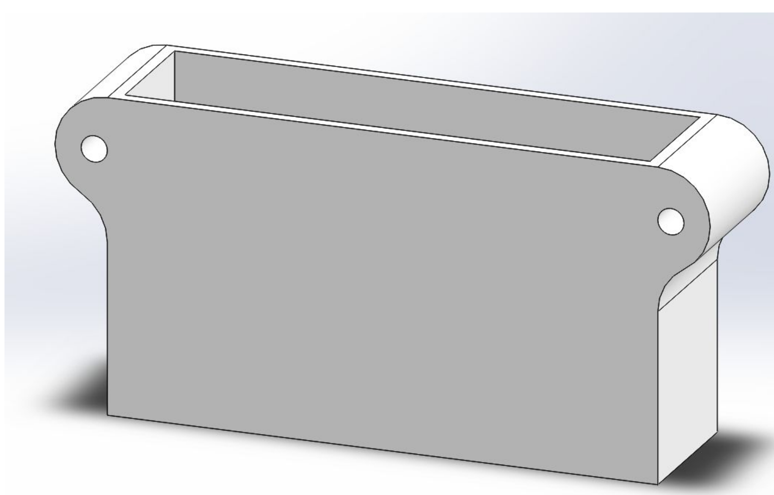
(16) Axle



(17) Tire



(18) Cross Beam



(19) Battery Holder