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Powered Device for Pushing a Manual Wheelchair

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Powered Device for Pushing a Manual Wheelchair

A Major Qualifying Project Proposal

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

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Abstract

Attendants who push manual wheelchairs face difficulties travelling long distances, up slopes, over uneven terrain, and over rough surfaces. It is evident that the strain caused by pushing a wheelchair can lead to fatigue and injury. A device which aids in the pushing of a wheelchair could reduce this strain and prevent strain-induced injury.

The primary goal of this project was to address this need and develop a product which would satisfy both institutional and personal use requirements while remaining a cost-effective solution. Existing product research and original ideas led to preliminary designs. Components of the device such as locomotion, braking, steering, power source, attachment, and user interface were designed. After analysis of preliminary designs, a final design was chosen. The device locks around a crossbar underneath the wheelchair and uses a battery-powered motor with a drive wheel and a manually controlled front wheel to steer.

Testing was conducted to evaluate how well the device complied with the design specifications. Static and dynamic stability, physical characteristics, and safety were all tested. In addition to these tests, five volunteers operated the device to determine the functionality and intuitiveness. The device was functional and performed well overall. Users found it to be easy and intuitive to operate but there were some minor issues with steering and traversing uneven terrain. Recommendations are made for future development of the design to better meet design specifications.

Acknowledgements

The Pushers project team would first like to thank Professor Allen Hoffman and Professor Holly Ault for their guidance throughout the entire project. We would also like to thank Neil Whitehouse for his help with machining. His work and advice on the manufacturing end of our project was greatly appreciated. We'd like to thank Barbara Furhman for her help with purchasing our parts. Finally, we'd like to thank Tom Mercier from the Kelley Assistive Technology Center of the Massachusetts Department of Developmental Services in Hathorne, MA. His help in understanding the need for our device was extremely useful. His donation of two old electric wheelchairs also provided us with a driving wheel and motor for our device.

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Introduction

In 2005 an estimated 54.4 million Americans suffered from some type of disability (Brault, 2008). Of these 54.4 million people, an estimated 1.6 million used wheelchairs outside institutions (Kaye, Kang, & LaPlante, 2002). Wheelchairs are used for a variety of reasons. Wheelchairs are typically used by people with limited leg mobility or who tire easily when walking (Wheelchairs-Manual, 2009). Spinal cord injury, spina bifida, early stages of multiple sclerosis, arthritis, stroke, lower limb amputations and old age are all conditions which could result in a need for a wheelchair (Cooper, 2006). These conditions often leave individuals with the inability to walk and can restrict them to using wheelchairs for mobility.

The benefits of manual wheelchairs when compared with other assisted mobility devices include, lighter weight, easier transportation in cars or vans, access to more areas, lower cost, lower maintenance, and easier maneuverability (The Medical Supply Guide, 2008; Wheelchairs-Manual, 2009). Though there are many benefits of manual wheelchairs, some wheelchair users do not have the upper body strength necessary to propel themselves. Typically these individuals use powered wheelchairs, but some occupants are incapable of operating powered devices due to cognitive and/or physical disabilities and therefore need an attendant to push their wheelchair.

An attendant may be a spouse or other family member, a nurse or health care assistant, or a paid employee who assists the occupant in moving around. Pushing a wheelchair as an attendant may appear to be an easy task, but attendants still face the same difficulties that wheelchair users do while interacting with the environment. Also, pushing a wheelchair over a long distance for a long period of time can be very tiring as it is difficult to push wheelchairs up long slopes, over uneven terrain, or over rough surfaces (International Standards Organization, 2009). Even ramps that comply with standards established by the Americans with Disabilities

Act (ADA) can be difficult to climb for wheelchair pushers of any strength. It is evident that the strain caused by pushing a wheelchair can lead to fatigue and injury.

Nurses, psychiatric and home health aides are occupations that consistently suffer a large number of workplace injuries with nearly 800,000 injuries and illnesses reported between 1995 and 2004 (Hoskins, 2006). In 2004, it was determined that 54 percent of nursing injuries were musculoskeletal disorders (MSD). MSD is a condition where a part of the musculoskeletal system is injured over time and is often caused by overexertion, repetitive motion and repetitive action. Pushing a wheelchair could cause overexertion and lead to injury. Not only nurses suffer from strain, but also assisting family members can face overexertion. Products which alleviate the strain associated with pushing a wheelchair could prevent injuries and improve the lives of attendants who are nurses, and family members of wheelchair users.

A wheelchair mobility aid can be used to help an attendant in difficult situations and prevent strain or injury due to overexertion. There are a few products that address these needs, however, they are very expensive and can take away from the benefits of a manual wheelchair as they are large and cumbersome. A majority of wheelchair users have a family income of under $10,000, while a very small percentage of the population makes more than $25,000 (Kaye, Kang & LaPlante, 2009). The average family cannot afford existing products, so it is important for a retrofit mobility aid to be affordable and still maintain the advantages of a manual wheelchair.

This establishes the need for a cost-effective product to aid attendants in pushing wheelchairs during challenging tasks such as up and down slopes and over rough surfaces. The goal of this project was to design and prototype a cost-effective wheelchair pusher that is easy to use, transportable, and satisfies the requirements of both institutional and personal use.

Background

The background section examines important areas of interest to provide a foundation for the design process. Existing products and related patents are examined to determine important design specifications along with ideas for propulsion and overall design. Next, the different types of manual wheelchairs are studied to gain a better idea of the types of wheelchairs that a device pushing a wheelchair might be interfacing with. Safety standards and testing procedures are reviewed in order to ensure compliance of a new design and identify testing procedures that can be utilized to test the new design. Lastly, research was performed on the market for a pusher device including investigating the user base, the environment of product use, and the human factors to be considered.

Existing Products

The Existing Products section describes four different products that are on the market and are designed to assist the attendant in pushing a wheelchair. These products have many similarities and fall into two categories: those that are designed for use in an institution, which are typically much larger and heavier, and those that are intended to be used privately and are more lightweight and transportable.

ERGOtug Patient Transport System

The ERGOtug Company develops products to help employees work safely. The ERGOtug Patient Transport System claims to fit most adult and bariatric wheelchairs and can push a combined weight of 1200 pounds (wheelchair and patient), Figure 1. The ERGOtug can steer over 180 degrees and has an adjustable handle height with a maximum of 47 inches, which can accommodate people of different sizes. The ERGOtug is driven into the back of a wheelchair and two C-shaped clamps attach to the horizontal bar on either side between the back post extensions and the wheelchair's wheel. The system weighs 220 pounds, includes brakes, a safety emergency stop button, and can travel at a maximum speed of 3.2 miles per hour. This product costs $5795 and is intended for use in an institution, not in the home. It cannot reasonably be transported in a car because of its weight and size (ERGOtug Patient Transport System, 2008). Its capability of pushing a load of 1200 pounds is high, but it is not necessary for a typical wheelchair pusher in an institution. Also, the motor and battery required to push 1200 pounds increase the weight, size, and cost of the product, and limit the product by making it not transportable.

Figure 1: ERGOtug Patient Transport System (ERGOtug Patient Transport System, 2008)

Dane Technologies Wheelchair Mover

The Dane Technologies Wheelchair Mover, Figure 2, has a hitching system that attaches to the bottom frame of a wheelchair. The product has an automatic brake for safety as well as throttle acceleration and user control of the system speed. The system is approximately the same width and length as the ERGOtug, but has a shorter height, with 42 inch handles, compared to the ERGOtug's maximum adjustable handle height of 47 inches. Like the ERGOtug, this product is mostly marketed to institutions such as hospitals and clinics (The Wheelchair Mover, 2009). Since it weighs 334 pounds, it would be very difficult to transport outside of the building and therefore would not be appropriate for a user who also wanted to use the pusher in other locations.

Figure 2: Dane Technologies Wheel Chair Mover (The Wheelchair Mover, 2009)

Viamobil

Viamobil, Figure 3, is another similar product intended to make pushing a wheelchair easier and is marketed mainly for personal use. The device comes with a supplemental attachment that clips onto the back post extensions of the wheelchair and supports itself on the wheelchair frame. When activated, the Viamobil device lowers its center powering wheel to the ground and moves at the speed set on its hand controller. It weighs a little over 50 pounds and the maximum push capacity is rated for a person of 285 pounds, not including the wheelchair. It can push and brake while going up and down hills, is capable of reversing, has a safety switch, and a long battery life, traveling about 16 miles on one charge. It also claims that it can be detached from the wheelchair by releasing the locks on the frame and can then be stored in the trunk of a car along with a folded wheelchair (Viamobil, n.d.). This feature is essential for many wheelchair users and makes the device use/capabilities more flexible. This product costs $5,720 which is outside of the average wheelchair user's budget.

Figure 3: Viamobil (Viamobil, n.d.)

The existing products on the market today have some key components that could be incorporated into a better new design. Speed control, braking, and an emergency stop are all important features. Adjustable handle height is also a useful feature that will be considered in the design process.

Though these products are all sufficient in assisting an attendant in pushing a wheelchair, they are not affordable. The family of the average wheelchair user cannot afford such expensive products as the cost of these products is almost half of these users' yearly incomes. Some smaller clinics or institutions may not be able to afford this amount either and some of these products either require the user to buy a new wheelchair or do not fit every style of wheelchair. Since most of these products were intended for use in institutions, ease of transport may not have been considered in the design.

Power Assist Patents

There are several patents that relate to assisting the propulsion of a wheeled device which provide ideas that can be related to a new wheelchair pushing device. Three of the patents discussed in this report are classified as power assists for manual wheelchairs. Other patents mentioned contain different types of drive mechanisms that could be applied to assisting a manual wheelchair.

Power Assist Device for a Wheelchair (Patent 5,222,567)

Patent 5,222,567, the Power Assist Device for a Wheelchair, is a device designed to be mounted to the lower side rails of a manual wheelchair, Figure 4. Mounted between the rails are a chassis (7) that holds two electric motors, a drive wheel (9), and the electronics and mechanisms required for operating the device. One of the motors powers the drive wheel and the other controls the elevation of the drive wheel. Being able to raise and lower the drive wheel gives the operator the ability to engage and disengage the device from the surface the wheelchair is riding on. When the first motor is lowered and the device is engaged, the second motor will power the drive wheel, which will in turn provide a force that will assist the operator in pushing the wheelchair. Advantages of this design are that it can be mounted to ordinary manual wheelchairs, can be engaged and disengaged, and also operates in forward and reverse.

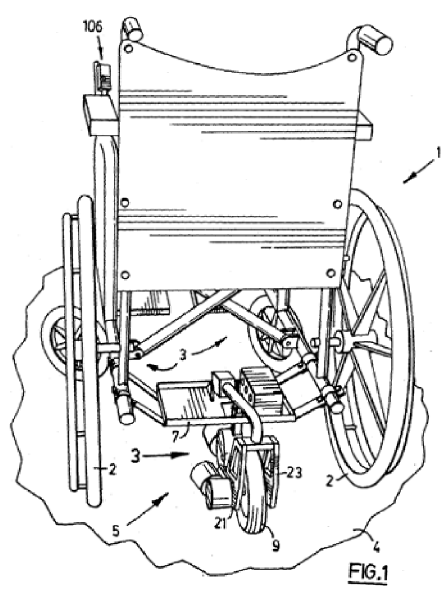

Figure 4: Patent 5,222,567

This design enables the drive wheel to maintain adequate contact with the surface beneath the wheelchair, making it possible for the device to act as both a driving and braking force. The weight of the wheelchair, the device, and the occupant of the chair provide the normal force necessary for the drive wheel to push the chair. This design also can be removed from the wheelchair by detaching it from the lower side rails. A disadvantage of this device is that it is not quickly attached and detached from the device so it would not be ideal for institutional use. Also, there is altered steering while the drive wheel is engaged with the floor. Steering of the wheelchair will be altered because the wheelchair must rotate around the driving wheel rather than the point between the wheelchair's main wheels. Another disadvantage is that the control for the device does not control steering. Operating the speed of the device while simultaneously steering the wheelchair by the push-rims may require a level of skill not obtainable by the typical wheelchair user. While this patent is designed to be operated by the occupant of the chair, it could be adapted for an assistant to engage and disengage the device (Broadhead, Douglas G. & Blaine M. Hobson, 1991).

Power-Assisted Wheelchair (Patent 5,234,066)

Patent, 5,234,066, the Power-Assisted Wheelchair, Figure 5, is the design of a manual wheelchair that has an electric power assist. The battery and motors are enclosed in a detachable unit, shown in Figure 6. The large wheels of the wheelchair are powered by independent electric motors (50). These motors are activated when the controller senses the occupant's input into the wheelchair's push-rims. The motors transmit their power through a gear train (47, 48) to the wheel's axle (71). Having the bulk of the device in a removable case (49) allows for the wheelchair to be folded for storage and transportation.

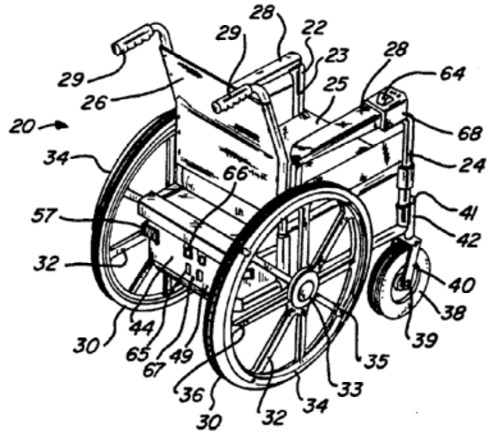

Figure 5: Patent 5,234,066

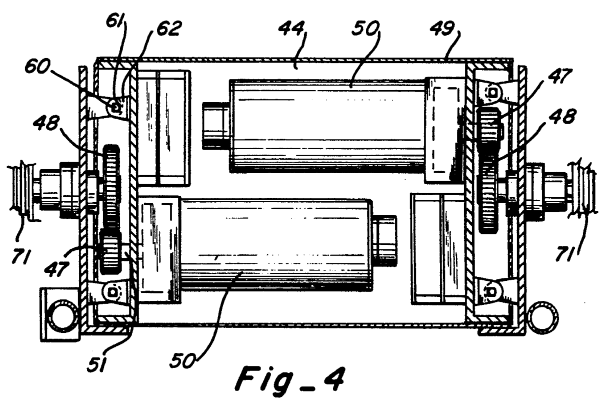

Figure 6: Patent 5,234,066 Chassis

One major disadvantage of this design is that it cannot be applied to common manual wheelchairs. Instead the chair must be custom built to properly receive the power and motor unit. Also, this device is only designed for occupants requiring a wheelchair who are capable of operating the push-rims of a standard manual wheelchair (Ahsin, Hopping, Owen, & Stenehjem, 1993).

Precision Direct Drive Mechanism (Patent 5,934,401)

Patent 5,934,401, the Precision Direct Drive Mechanism for a Power Assist Apparatus for a Bicycle, is not designed to be a power assist for a wheelchair; however, the drive mechanism could be adapted to function on a wheelchair. In this device, an electric motor (104) is mounted to the frame of the bicycle (116), as shown in Figure 7. The motor engages with a drive gear (110), pulley, or sprocket that is mounted to the rear wheel (32). A battery pack (92) is then mounted elsewhere on the bicycle frame and provides power to the electric motor. All parts of the device are designed to be removed easily and the bike can be converted from manual to electric-assisted in less than three minutes.

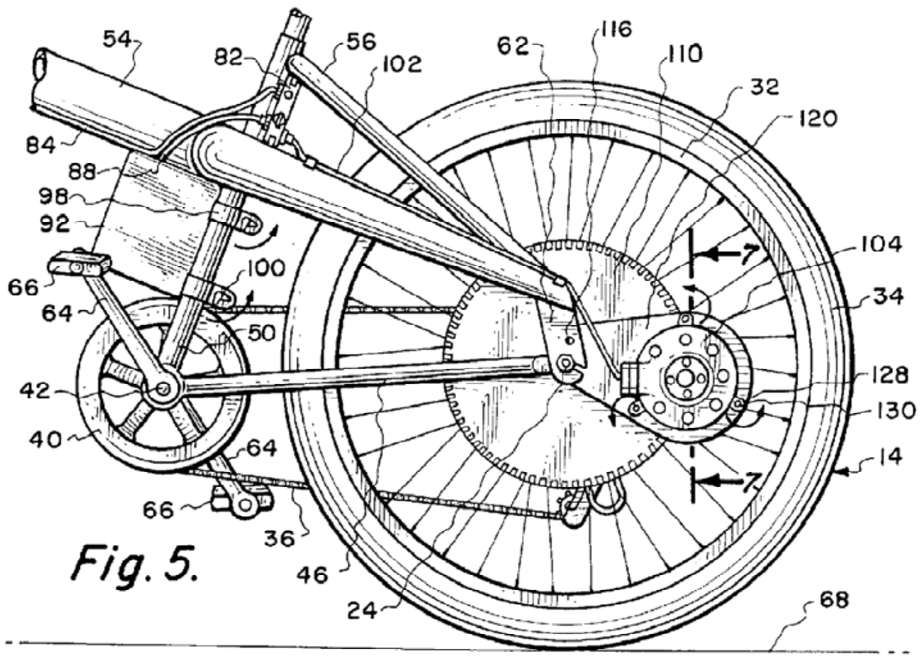

Figure 7: Patent 5,934,401

This design could be adapted to use on a wheelchair by mounting a separate motor and drive system to each rear wheel of a manual wheelchair. The wheelchair would be steered by varying the speeds of each motor similar to a tank or a skid steer. This would be an effective way of powering the wheelchair, however a disadvantage of this concept is that using a gear, pulley, or sprocket system would make disengaging the device more difficult. The authors of the patent suggest adding a clutching mechanism that would engage and disengage the electric motor and allow the wheel to be driven manually without having to remove the motor from the frame (Mayar & Currie, 1999).

Power Assist Apparatus for a Manually Operated Vehicle (Patent 5,816,355)

Patent 5,816,355, Figure 8, is a power assist device that can either be turned on when needed or can be the sole source of power. The device is currently configured to a bicycle but could be operational with other manually operated devices. For a bicycle, the apparatus is attached to the rear support wheel of the bike (22). After installation the device is permanently attached to the bike. The electrical power used to drive the motor assembly is supplied by batteries (66), and a switch is used to turn the device on or off. The electric motor has a knurled pinion (80) that is forced against the surface of the bicycle tire, which then drives the bicycle with friction. In addition, a handle (120) can be placed in three positions: a primary position where the drive wheel of the device is separated from the support wheel of the bicycle, a second "initial engaging" position that is to be used in dry weather, and a third more secure position to be used in wet weather. The objective was to provide a transportation device that did not add smog to the environment (Battlogg & Mayar, 1998).

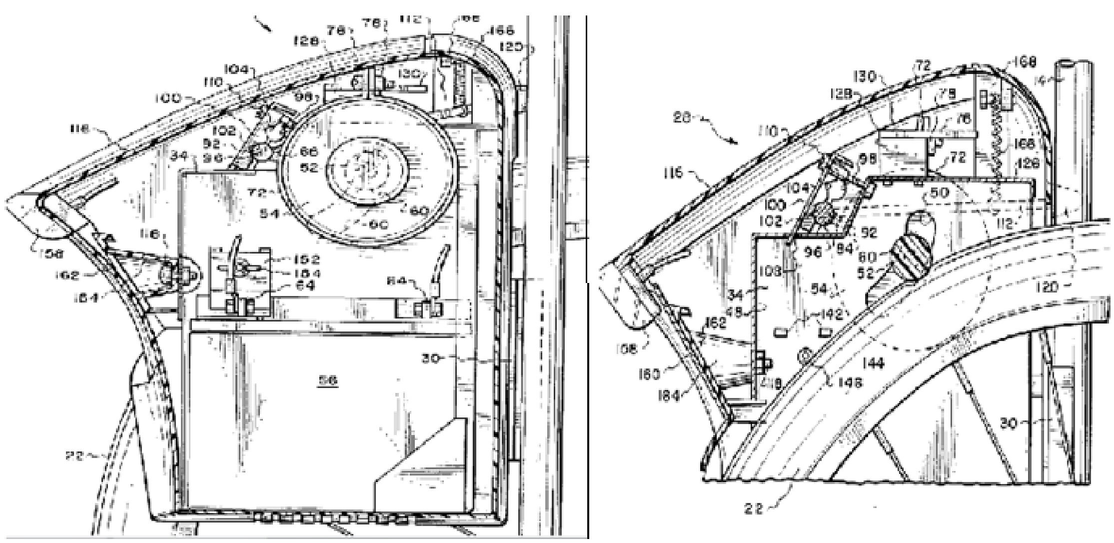

Figure 8: Patent 5,816,355

Self Propelled Lawn Mower (Patent 5,442,901)

Patent 5,442,901 is a self propelled lawn mower. The mower is powered by a battery/DC drive motor assembly that is connected to the wheels and the speed of the mower varies depending on how much force the user applies to push the mower. Figure 9 is a perspective view of the drive system. The drive motor (24) is attached to a drive motor gear (38) which drives the input gear (40) which is attached to the driveshaft (42). The driveshaft extends through the sleeve (54) of the "Trailing arm assembly" (50) which also includes a stub axle (48) and an arm plate (52). The sleeve is mounted to the chassis of the mower by the clamp (58) and a rotary bearing (60), which allows the trailing arm assembly to move around the chassis without interference. A switch (30) is connected in series to both the drive motor (24) and speed control (28). The speed control regulates the amount of energy going to the motor which is determined by the amount of power supplied to the motor, the amount of force the user applies to the handles, and the amount of resistance received from the terrain (Niemela, Morikawa, & Demarco, 1995).

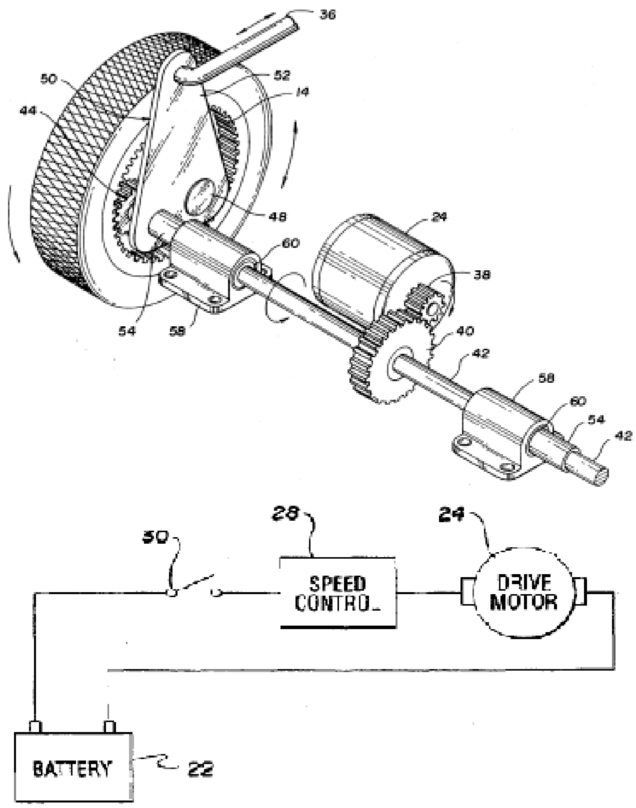

Figure 9: Patent 5,422,901

These patents mainly suggest ways to propel an assistive device. All of the patents discussed involve the use of an electric motor and batteries to power the driving force. The drives in these patents include a gear drive, a sprocket drive, a belt drive, and a friction drive. While some electric drives are incorporated into the device's wheels, other designs have a separate drive device that is independent of the device it is mounted to. Having the electric drive incorporated into the device's wheels has both advantages and disadvantages. For a wheelchair, this type of design allows for a more compact unit and minimizes moving parts making it a simpler design. Disadvantages of this design are that it is more integrated into the wheelchair's design and can interfere with the manual operation of the chair. Also, it would be more difficult for these designs to be adapted to a wide variety of manual wheelchairs, and in institutions where more than one wheelchair will be pushed in a short period of time, quick removal is important.

Independent drive systems do not operate through the wheelchair's existing system. These devices attach to the chair's frame and push it through means other than the wheelchair's wheels. Advantages to this design are that it can be more adaptive and can fit a variety of wheelchairs. Also, not having the drive train incorporated into the wheelchair allows for less modification (if any) of the wheelchair to fit the device. Disadvantages of this type of design are that it alters the movement of the wheelchair because the device moves independently from the wheelchair's wheels, thus changing the steering mechanics of the chair.

Other items that have to be taken into consideration are how the device will alter the physical characteristics of the wheelchair. Adding anything to the chair will change its overall mass and center of gravity. These changes will affect how the wheelchair steers, stops, tips, and handles. Testing and evaluation will need to be done to ensure that the device will not endanger the operator of the device or occupant of the wheelchair.

The existing product and patent research was very useful. It helped to give an idea of what has already been designed. By identifying the positive aspects of all products and patents, desirable features can be determined. By identifying the negative aspects, any problems the products face can be avoided. The new device will aim to be available for personal use for people who may want to travel with their pusher. In order to complete this goal the device must be transportable, lightweight, and compact. The design should also be affordable and retrofit to most wheelchairs in order to accommodate the maximum number of users. It also should be marketed to both institutions and individuals in order to be available to a larger market.

Different Types of Wheelchairs

The wheelchair pusher device needs to be compatible with as many different wheelchair types as possible in order for it to target the largest market. Therefore, it is necessary to understand all of the different types of wheelchairs that the user base will be using. This will include a wide range of chairs, from the popular lightweight chair, to the less common tilt models, to models custom made to suit an individual's needs. Because an electric wheelchair negates the need for the device, these chairs will not be considered.

Rigid Chairs

Rigid wheelchairs, Figure 10, are the lightest chairs available because they have fewer parts and use lighter material and therefore have more frame flexion. Because of their light weight and larger rear wheels, they are easy to propel. Rigid chairs are stronger than folding chairs, are very durable, and are very responsive to the user inputs. Although rigid chairs have many benefits, they also have some disadvantages. Not only do they require good balance by the user, but they can be very expensive, ranging from $2,500 - $8,500 (Stewart, Rigid Wheelchairs, 2009).

Figure 10: Rigid Wheelchair (Product Details, 2003-2009)

Folding Chairs

Folding chairs, Figure 11, are the best option for a user that is often transported by a vehicle and are the most commonly used chairs today. A folding chair has the ability to fold up and take up less space in a vehicle unlike rigid or lightweight chairs. Although convenient, folding chairs are heavy compared to lightweight or rigid chairs and are harder to push. They have lower durability than lightweight or rigid chairs because parts are not secure and may become loose or break. Due to this, they are not strong enough for all activities and could collapse (Oeser, 2008).

Figure 11: A Folding Wheelchair (London Wheelchair Rental, 2009)

Tilt Chairs

Tilt wheelchairs, Figure 12, allow the user to recline and change positions. Not only does this reduce the chances for the user to develop pressure sores, but users that have a forward curve in their spine are able to sit in a more natural position. Tilt wheelchairs also reduce the need for supports to stop the user from falling out, and are known to be very comfortable. Tilt wheelchair users are usually pushed by an attendant since these chairs are heavy and difficult to propel (Stewart, Tilt Wheelchairs, 2009).

Figure 12: Tilt Wheelchair (Tilt In Space Reclining Wheelchairs, 2009)

Institution Chairs

The least expensive type of chair is an Institution chair, Figure 13. Institutions include hospitals, nursing homes, and dayhab centers. Institution chairs are designed to transport a patient quickly and they are not intended for extended use or for anyone who requires independent movement. It is fitted for a wide range of users making comfort a low priority (Halverson & Belknap, 1994).

Figure 13: Institution Wheelchair (Hospital Equipment, 2007)

Custom Chairs

Since some users have needs that regular wheelchairs do not meet, custom chairs are used. Some chairs are lower to the floor in order for users to use their own leg strength. One arm drive manual chairs are created for people with paralysis on one side of the body. There are chairs made to accommodate overweight users, as well as chairs made "friendly looking" to encourage children to develop socially. There are even chairs that allow the user to assume a standing position in order to aid those who need to stand at their jobs (Halverson & Belknap, 1994). An example of a custom chair is shown in Figure 14. A new device designed to accommodate the most number of wheelchairs possible should consider custom chairs.

Figure 14: An Example Custom Wheelchair (Bologh, 2008)

Wheelchair Standards

When designing a pusher it is important to be aware of wheelchair standards because a device which interacts with a wheelchair should follow the same standards to ensure safety and maneuverability. The American National Standards Institute (ANSI) along with the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) have developed a set of standards used to define the safety, durability and performance of wheelchairs. They have set these standards to be very similar to those of the International Standards

Organization (ISO), so that these specifications will be standard across the world. The group that forms these standards is the ANSI Technical Advisory Group (TAG), which includes “users, manufacturers, engineers, testing authorities, therapists and distributors” (McLaurin & Axleson, 1992). The variety of professions represented in this group provides for many opinions and helps to make sure that the standards address most needs. While these standards are very important, companies are not required to meet them. However, complying with these standards and having the ANSI label is advantageous in the wheelchair market (McLaurin & Axleson, 1992). Safety is the main goal of the ANSI wheelchair standards and a wheelchair pusher should comply with applicable standards to maintain the safety of both the wheelchair occupant and attendant.

The standards list outlines tests and analysis that can be performed to assure that a wheelchair meets a certain level of safety and performance. Taken from McLaurin & Axleson, (1992) these include tests and analysis of:

- Overall dimensions
- Static stability
- Dynamic stability of electric wheelchairs
- Efficiency of brakes

These standards will be taken into consideration when creating the design specifications and testing plan for the device.

Dimensions

Section 5 of the ANSI Wheelchair Standards focuses on wheelchair dimensions (Rentschler, 1995). Specifications of the overall dimensions describe the dimensions of the chair, including the dimensions after folding and after the removal of parts such as footrests. The standards define that the overall dimensions should be no larger than 28 inches wide, 51 inches long, and 43 inches high in order to be able to navigate wheelchair accessible areas (McLaurin & Axleson, 1992). Since the new device must not hinder the functions of the actual wheelchair in any way, it must comply with the same size standards in order to navigate all wheelchair accessible areas.

Stability

Section 1 of the ANSI/RESNA standards is the "Determination of Static Stability" (Rentschler, 1995). To test the static stability of a wheelchair, the chair is placed facing forwards, backwards, and sideways on an incline, Figure 15, with a 220 pound test dummy in the chair. The chair is tested in both the "most-stable" and "least-stable" configurations for each orientation as well. For example, the most-stable downhill configuration was determined to be when the seat was adjusted back, reclined, and as low as possible. In this configuration, the rear-wheel was also in its furthest back position. The least-stable downhill configuration was the complete opposite (Rentschler et. al, 2004). To perform the test, the incline is raised "until an ordinary piece of paper can just pass under the rear wheels without them turning" (Cooper, 1995). Most wheelchairs are stable on slopes up to 20 degrees (Cooper, 1998).

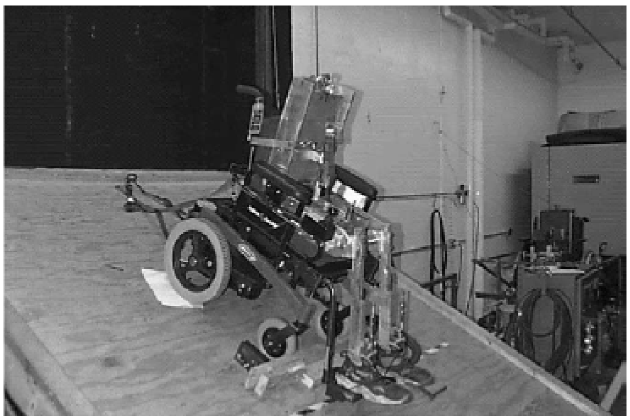

Figure 15: Static Stability Test (Rentschler et. al, 2004)

Section 2 of the standard is the "Determination of Dynamic Stability of Electric Wheelchairs." The standards for dynamic stability of an electric wheelchair are important to consider because a wheelchair pusher behaves similarly to an electric wheelchair and should meet the same safety standards. In this test, wheelchairs are driven up and down inclines of different slopes with a 220 pound test dummy seated in the wheelchair. The performance of the wheelchair is given a grade of 1, 2, 3 or 4. The chair receives a grade of 4 if none of the wheels leave the surface, a grade of 3 if the uphill wheels leave the surface, a grade of 2 if uphill wheels lose "contact and the anti-tip device contacted the surface," and a grade of 1 if the wheelchair "rested on the anti-tip device," or if the wheelchair tipped over (Rentschler et. al, 2004).

Brakes

Section 3 of the ANSI/RESNA standards is the "Test Methods and Requirements for the Effectiveness of Brakes" (Rentschler, 1995). To test the effectiveness of brakes, wheelchairs are driven on level ground and up and down an inclines of 5 degrees with a 220 pound test dummy in the wheelchair. To perform this test, the wheelchair is driven at maximum speed down an incline and braking is initiated by releasing the joystick for a set of trials, by reversing the direction of the joystick for another set of trails, and by turning off power to the controller during another set (Rentschler et. al, 2004). This test is performed in both the forward and backward directions. The average stopping distance of three trials was taken for each wheelchair. In this test, a person drove with weight added to the wheelchair to add up to 220 pounds (Rentschler et. al, 2004).

Market Research

This section intends to define the market for the project. Research was performed to learn more about the users and to understand their needs.

User Base

In 2002, the Disability Statistics Center determined that 897,000 people over the age of 65 used wheelchairs, and of them, 864,000 used manual wheelchairs (Kaye, Kang, & LaPlante, 2002). Since women are historically known to live longer than men (Austad, 2006) and are more likely to be healthier than their spouses, women are often responsible for pushing their husbands. For this reason, the targeted user base is an elderly spouse, and is more likely to be a woman, so the device must be operable by a female over the age of 65. In other families, children, teens, or adults may be the wheelchair occupants and in those cases, an adult would be the wheelchair attendant. Therefore, the device must be operable by this age group as well. Finally, in institutions, nurses are responsible for transporting patients in wheelchairs and must be able to operate the product as well.

Product Use in Institutions

In institutions such as hospitals and rehab centers, nurses are responsible for transporting patients around the facility. Sometimes, this includes up and down inclines, elevators, and in and around tight hallways and rooms. They must be able to maneuver in tight spaces such as small doorways and crowded hallways. The pusher and wheelchair system must also be able to fit in these spaces and must maneuver through the obstacles as easily as a single wheelchair would. With so many patients to transport, the pusher must also a long duty time without the need for recharging of the batteries.

Personal Product Use

In 2002, one point six million people used wheelchairs outside of institutions and this number is increasing (Kaye, Kang & LaPlante, 2002). Private wheelchair owners face many obstacles when navigating homes and neighborhoods. Many homes are not handicap accessible and the price to make these important changes to the home is too high for many wheelchair users. Additionally, the environment outdoors provides some rough terrain for wheelchair users. In 2000, one third of wheelchair users said that that they encountered obstacles outside the home. Different terrain such as grass, cobblestone, curbs and speed bumps also present obstacles to wheelchair users (Wheelchair Park Lets Patients Practice Overcoming Obstacles, 2009). The pusher should not inhibit the motion of the wheelchair through doorways, hallways or thresholds. It should not limit the wheelchair's original operation and should not hinder the movement around the environment in any way.

Transportation of manual wheelchairs is another task to consider. Manual wheelchairs are often chosen because of their flexibility to be folded and transported in a car. Most manual wheelchairs are able to be folded up and placed in the trunk of a sedan, as well as larger vehicles. Wheelchair pushers are not necessarily as easy to place into a trunk because one would have to transport both the pusher and the wheelchair; but the pusher should be designed to be able to fit into the trunk. The challenge of transportation is one that must be considered when designing manual wheelchairs and wheelchair accessories.

Human Factors

Human factors science is about understanding human capabilities while human factors engineering is about applying that understanding to design. Human factors science is closely related to ergonomics, which is the study of the relationship between a person and their workplace or environment, considering the "anatomic, physiologic, and mechanical principles affecting the efficient use of human energy (Inverarity, 2004)." Ergonomics is also concerned with safety and reducing the risk for injury due to improper form while performing a task, which is also a key concern of human factors engineering.

When considering the design of a product, it is important to examine the human factors associated with the use of the product. Examining these factors will reduce the risk of injury, reduce the possibility of error, and design a simple and effective user interface. When considering the "human element" in human factors engineering, interfaces should be designed to meet the needs of the user with the lowest skills and should keep in mind abilities under stressful or distracted environments (Fries, 2006). Analysis of the skill set of the user should consider physical strength, mental ability, range of motion, memory, and targeting abilities. The environment in which a device will be used is also important to consider including any obstacles such as surface area, lighting, or noise. Doing this will hopefully limit potential problems (Fries, 2006). Additionally, the device should not have noises or movements which might distract the user and put them or others in danger. The "hardware element" in human factors engineering considers the "size limitations, the location of controls, compatibility with other equipment, the potential need for portability, and possibly user training (Fries, 2006)." Often, the hardware element is affected by the human element because of the skills of the user. These are all important considerations for a design and affect design goals and specifications.

Understanding human factors engineering will assist in designing the interface of the product and will make it desirable in the market. Safety and usability are essential for a successful product and design specifications based on human factors will be included. Additionally, the possibility of using kill switches, safety locks, and automatic shut-downs will be considered in order to account for possible problems while using the device. For example, if an automatic brake was activated when the handles were released, it would help to prevent collision if the operator were to be startled or distracted while pushing the wheelchair and released the handles.

Design Specifications

After gaining a full understanding of the scope of the project, the team developed a list of design specifications for the device. The design specifications are divided into five categories: function, physical characteristics, user interface, maintenance and other. These specifications will be the guide for designing, building and testing the device.

Function

1. The product will be able to push a combined weight of 300 pounds up an incline of 5 degrees on dry smooth surfaces.

   The average weight of an American male is 190 pounds (*Body Measurements*, 2009) with 95 percent weighing 254 pounds or less (Halls & Hanson, 2008), rounded down to 250 pounds. The majority of manual wheelchairs weigh less than 50 pounds, when this is added to 250 pounds the total is 300 pounds. The maximum male weight is used as a reference point in order for the product to apply to a larger market including institutions and personal use.

2. The attachment mechanism of the device must be able to withstand the maximum force (40 pounds) with a safety factor of three. The ability to withstand 120 pounds of force, pulling and pushing, would prove it is securely fastened to the wheelchair, with no risk of the wheelchair detaching.

   This is a safety concern that Tom Mercier has already encountered problems with. Unintentional detaching of the device can cause dangerous situations where occupants, attendants, or bystanders could be injured and property could be damaged.

3. The product must not limit the wheelchair's functionality.

The device must not impede a wheelchair user or attendant from performing normal activities, for example, doorways or hallways in an institutional setting.

4. The product must have parking brakes when the device is at rest.

   When the wheelchair is at rest or not attended by assistant, the brakes will be engaged.

5. The product will have automatic emergency brakes in the unexpected event of the attendant releasing the device.

   If the device is being used and the operator suddenly releases the control, the brakes will automatically be engaged.

6. Once the brakes are engaged, the device will come to rest within 10 feet.
7. The device must be statically and dynamically stable at an incline of at least 10 degrees.

   Five degrees is the angle of incline of the steepest ramps that meet ADA requirements, however users in an institution or users in the home could come across an incline of more than five degrees since the outdoor environment contains many cases, and not all institutions need to meet ADA standards.

8. The product will charge with the use of a charger that plugs into a standard wall outlet.
9. The product's duty time should be at least four hours between charges.

   A duty time of four hours will allow the users to perform daily activities that require power assistance.

Physical Characteristics

1. The device will not endanger those around it.

The geometry of the device will not include sharp edges, protrusions pinch points, exposed electrical components, or dangerous moving parts.

2. The attachment mechanism of the product will fit between the frames of the smallest compatible wheelchairs (14 inches) while still being functional with larger wheelchairs (up to 30 inches)
3. The product will attach to and detach from the wheelchair without the necessity of tools.

   If the device can be easily and quickly (less than 30 seconds) detached from the wheelchair, it will be more convenient to use.
4. If the device weighs more than 30 pounds then the device must be easily broken into sections, individually weighing no more than 30 pounds.

   Attendants who plan to transport the wheelchair and pusher should be capable of lifting at least 30 to 50 pounds (the weight of a standard lightweight wheelchair) for short distances. It is assumed that the attendant would be able to lift a pusher of 30 pounds. This is important for targeting a market for personal use.
5. The overall dimensions of wheelchair and device system should be no larger than 28 inches wide, 51 inches long and 43 inches high, based on the ANSI standard that allows mobility devices to navigate wheelchair accessible areas.
6. The device must be small enough to fit in the confines of an average car's trunk.
   a. An average car's trunk dimensions are: Depth: 38.5in, width: 31 in, height: 17 in (Subaru Impreza trunk measurements). In order for the device to be transportable, it must fit inside a trunk of this size.

User Interface

1. The product must be able to be operated by a single attendant.
2. The device must be easy to learn and intuitive so that an adult with average cognitive abilities could learn to control the pusher without training.
3. The product will have brakes that can be engaged by the operator.
4. The operator will be able to turn the product on and off with a “switch”.

   Having the product turn off will preserve battery charge and is a good safety precaution.

Maintenance

1. The design must be able to be maintained by an attendant such as hospital staff or family member with basic mechanical knowledge.

   This makes the device more convenient because the user will not have to obtain outside help and will not incur further inconvenience or future service charges.
2. The product should not require minor maintenance more than every 4 weeks.

   General cleaning and lubrication are examples of minor maintenance that should not need to be performed more than once every four weeks.
3. The product should not require major maintenance more than once every year.

   Changing the battery, replacing brake pads, or motor inspection should not need to be performed more than once a year.

Other

1. The prototype must not exceed the allocated budget ($600).

This is the assumed budget available from the ME department.

2. The product must be commercially available for less than 2,000 to 4,000 dollars.

   Tom Mercier says that 4,000 dollars is an appropriate cost for an institutional pushing device. The average price for existing institutional and private products is approximately 6,600 dollars. Undercutting this would make the product more desirable and competitive in both the industry and personal use markets. A device marketed for private use should cost even less, in the range of 2,000 to 3,000 dollars.

Preliminary Design Concepts

The preliminary design concepts section discusses the five main components of the device: propulsion and steering, braking, user interface and control, attachment and detachment, and safety stop. Each component was researched in detail to establish current electric wheelchair technology as well as new and different ideas for each element of the design.

Locomotion

Propulsion and steering are two of the most important aspects of the pusher design. The two elements of propulsion are the driving force and the drive train. Many different drive force and drive train options were examined on a variety of different types of devices including existing powered wheelchair products. Steering is also critical in the wheelchair pusher device design, and depends on the type of propulsion as well as the wheel and wheel rotation capabilities.

A new wheelchair pushing device will likely be powered by a DC motor, and is therefore very analogous to modern electric wheelchairs and mobile robotics. Mobile robots often derive their power from a battery powering an electric motor. The motor then transmits the power to the locomotive mechanism through a drive train, such as a gear box or chain drive. In order to apply this to a wheelchair assistive device it is important to understand two basic concepts of locomotion, wheels and tracks.

Wheels

All manual and electric wheelchairs use wheels for mobility. In manual wheelchairs, these wheels are not powered and provide no power assistance in propelling the chair. For a wheelchair pushing device, it would be possible to power the existing wheels on the wheelchair like electric wheelchairs do. If the device were to provide power to the manual wheelchair's wheels it would assist in propelling the chair. Another option for a wheel-based locomotion system would be to provide a device that has its own driven wheel or wheels that are separate from the wheelchair that would attach to and propel the wheelchair. Such locomotion is achieved in products such as the Viamobil and ERGOtug.

When choosing the type of wheels to utilize in the wheelchair pusher, one must consider size and type based on where the device will be used, what type of weather it will be used in, and in what way the device will be used. Current electric wheelchair designs typically use pneumatic, semi-pneumatic, or solid tires (Wheelchair-guide, 2009). A device like this could incorporate wheels with diameters from a few inches to over a foot. Thickness and tread of the tire are also important features that will provide certain advantages and disadvantages in different situations. If the wheelchair pusher has a separate drive wheel, it is necessary to have tread that will allow it to travel on smooth surfaces for institutional use and on rough outdoor surfaces for private use. The best tread for wheelchairs in outdoor use is a medium, knobby tread with a wider wheel (Koontz, 2009). Indoor use treads are typically smoother and lightly treaded, with a skinnier tire, which increases mobility (Koontz, 2009). The wheelchair mover from Dane Technologies and other existing devices, have three small solid rubber tires (The Wheelchair Mover, 2009). A newly developed wheelchair pusher will most likely have pneumatic tires if it is intended to travel outdoors because it will need to have a degree of shock absorption. If the device is intended to travel solely indoors and on smooth surfaces, then having solid rubber tires would be beneficial because this would eliminate the chance of a flat tire.

Tracks

Another type of locomotion commonly used in outdoor applications is the use of tracks. Commonly associated with tanks, track locomotion operates by rotating treads around a set of rollers that keep the tread in place while allowing it to turn. It is most common for there to be a track on either side of the device. The track is usually as long as the device; however there are many different designs for the shape of the track. The track propels the device much like the wheel locomotion, but due to the shape of the track there is much more contact between the tread and the surface being driven on. This increase in contact surface gives great advantages in traction. Choice of the right tread material can provide excellent traction in many different environments.

The disadvantage of the track is its reduced steering ability. Due to the length of the track, any rotation will require the track to slip or skid on the ground. Most track-propelled devices operate through skid steering, where one track rotates at a different speed or direction than the other. For example, if one tread were to go twice as fast as the other in the same direction the device would drive in a circular path. If the two treads were to rotate in opposite directions, one clockwise and one counter clockwise, the device would spin. This results in a rotational force that must overcome the friction of the tread in order for the device to turn. The amount of friction between the tread and the surface can greatly affect the device's turning abilities.

The tread concept would be beneficial for a wheelchair pushing device because it would be able to run on a variety of surfaces, making the device more versatile. Skid steering could be very difficult for a person to control though, especially if it depended on the user physically overcoming the friction of the treads and the ground to turn. Having a controller turn the two treads at variable speeds would allow the operator to turn the device without the use of manual force. Another disadvantage of treads is that it may be damaging to the surfaces being driven on. Due to the skid steering, it could mar up floors or tear up loose surfaces like dirt or gravel.

Compared to wheels, the tread system involves more components, including treads and rollers. More components require more maintenance and may also take up more space; this could interfere with the wheelchair's function and reduce compatibility.

Driving Force

All electric wheelchairs and wheelchair pushers involve a driving force required for propulsion. Electric motors are the most commonly used power generators for indoor and outdoor electric wheelchairs. There are two major classifications of electric motors; AC and DC. An AC motor and inverter are beyond the budget available for our design, and are not typically used in electric wheelchairs. DC motors are direct current motors and can be either brushed or brushless motors. Brushed motors are the most commonly used motor in electric wheelchairs.

DC Brushed Motors

A simple brushed motor can be seen in Figure 16. The electricity from the battery enters the motor through two leads and charges the brushes. These brushes make contact with the commutator ring. The current then runs through the wire coiled around the armature, this electric coil creates a magnetic field around the armature. The armature then rotates to align with the field magnet's magnetic field. At a certain point in the rotation the commutator switches the polarity of the armature. This switch continues the rotation and the cycle continues. The armature is attached to the axle of the motor which is the same axle that protrudes from the motor (Brain, 2000).

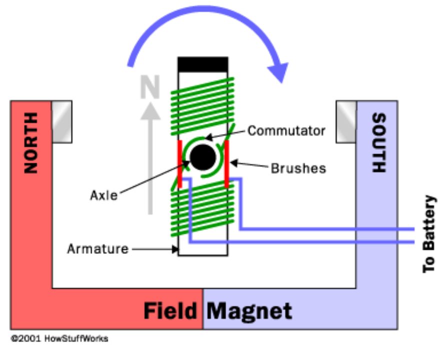

Figure 16: Simple Electric Motor (Brain, 2000)

Advantages of brushed motors are that they are relatively low cost compared to other types of electric motors. Brushed motors also make it very easy to control the speed and have a linear torque to speed curve. Disadvantages of the brushed motor are that the brushes are constantly scratching the commutator, creating friction and wear. This increases the maintenance of the motor and reduces the efficiency to levels of 75 to 80 % (Levy, 2007).

Electric wheelchair motors are most commonly DC brushed motors and run off of a 24V battery. They are available for purchase, however they are specialty motors and are very expensive. This is due to the unique requirements demanded by an electric wheelchair. Electric wheelchair motors must provide sufficient power, minimum maintenance, and long life (Bayne, 1999). The motor is attached to a gear box that transmits the power of the motor to the wheel. If possible, a wheelchair motor and gearbox would be a desirable component of a new design; however, due to cost an electric wheelchair motor would need to be donated to the group if used.

DC Brushless Motors

A brushless motor operates on the same principles of electromagnetism that the brushed motor does. However the internal design of the motor is different. In a brushless motor the electromagnetic coils are stationary and the field magnet is replaced by many permanent magnets attached to the rotor. The coils are positioned and get charged in sequence such that the permanent magnets are forced to rotate. A brushless motor controller is required to control the charging of the coils (Brain, 2009). Brushless motors are highly advantageous because they do not have the friction or wear created by the brushes in a brushed motor. This makes them 85 to 90% efficient and requires much less maintenance than brushed motors. Brushless motors are more expensive than brushed motors but can be cost effective over the long run due to their efficiencies (Levy, 2007). The first generation prototype will be made based on cost effectiveness, but longer lasting, more efficient motors would be recommended for future generations.

Batteries

Batteries are a challenge of electric wheelchair design because of their large weight and size. Batteries need to be accounted for in the physical design and there is a great need for adequate power and life (DiGiovine, 2009). There is a similar challenge present in designing a wheelchair pusher. It is necessary to understand the requirements the pusher will be demanding from the motor so that a suitable battery can be chosen. This will allow the motor to perform efficiently and effectively (Norton, 2008).

Electric wheelchairs use deep-cycle, sealed, lead-acid, rechargeable batteries. They are available in different sizes and power or ampere-hour ratings. They are typically 24V batteries that are available in 30 to 90 ampere-hour capacities (DiGiovine, 2009). These batteries are very heavy, for example, a 90 ampere-hour, 12 volt battery weighs 66 pounds and costs 173 dollars at BatteryWeb.com (Wheelchair Batteries, 2009).

Drive Trains

The drive train and motor are chosen simultaneously, the combination of motor and drive train must provide sufficient power to the driving device. It is necessary to decide how the rotary force of the motor's drive shaft will be applied to the mechanism. Very common methods of applying this power are through gear, belt, chain, and friction drives. Torques and speeds of each type can easily be calculated by comparing the sizes and speeds of the parts in the drive train. The torque ratio can be calculated by dividing the output radius by the input radius while the velocity ratio is calculated by dividing the input radius by the output radius. This means the torque output is inversely proportional to the velocity output. Torque is maximized at the expense of speed and conversely, speed is maximized at the expense of torque. Existing electric wheelchairs and wheelchair pushing products often use a gear drive due to unique advantages.

Gear Drives

Gear drives consist of two or more gears that transmit the power from the drive gear to the driven gear or gears. Gears require direct contact between each other for the power to be transmitted. The first gear, called the drive gear, is connected to the power source, and transmits power to the other gears called driven gears. Gear drives have high efficiencies when transmitting power and are very durable (Intro to Mechanical Systems, 2009). Due to their ability to transmit power efficiently and in a compact area they are very suitable to a wheelchair pusher. These advantages are the reason that gears are most often used in existing electric wheelchair drives.

Belt and Chain drives

Belt and chain drives operate through the use of belts and pulleys or chains and sprockets. Unlike gear drives, when designing a belt or chain drive the pulleys or sprockets do not mesh with one another. Instead, belt and chain drives transmit power from one pulley or sprocket to another through the tension of a belt or chain. Another difference is that all pulleys and sprockets rotate in the same direction unless a belt or chain is twisted. Belt and chain drives are convenient because the speed can be changed by changing the size of the pulleys and sprockets. In addition, belt drives operate quietly, require no lubrication, are easy to maintain. Chain drives, on the other hand, require lubrication and can be louder than belt drives. Pulleys or sprockets do not come into contact with one another and so two pulleys or sprockets can be located further apart than two gears of the same dimension (Beardmore, 2008). This can be beneficial if the wheelchair pusher's motor and driven wheels are further apart than a gear drive could accomodate.

Friction Drives

As shown in Figure 17, a friction drive commonly consists of a driving spindle that is pressed against the tire to be driven. Depending on the torque curve of the motor and the diameter of the tire it is very common for the spindle to be directly attached to the output shaft of the motor. These devices are commonly used with small engines in order to power manual two-wheeled scooters and bicycles. This is due to the simplicity of having the motor or engine's output shaft directly drive the tire of the bicycle. The drive operates by transferring the power of the motor to the wheel through the friction between the drive spindle and the tire. A friction drive requires minimal maintenance because it has no gears, pulleys, or sprockets that need lubrication or cleaning.

Figure 17: Friction Drive (Spindle Drive, 2009).

The amount of driving power available is directly related to the friction between the spindle and the tire. This is a disadvantage because more friction will cause more wear. Both spindles and tires have to be replaced as the wear will reduce the amount of friction between components and therefore make the spindle drive less efficient. The amount of wear is dependent on the type of tire and spindle used. Also, the normal force between the spindle and tire has to be great enough so that the friction between the two is able to drive the device. Low profile, or minimal tread, tires will have more surface contact with the spindle, better distributing the drive force and improving traction; however, they may not be adequate for all terrain where a higher profile tire is required. Another disadvantage is that if the tire gets any liquid or material on it that reduces the friction between it and the spindle it will reduce the power transferrable to the tire. This is a problem for outdoor applications where the ground might be damp or have puddles. Lastly, since the frictional force is dependent of the normal force, a large enough force has to press the spindle into the tire for it to transfer power efficiently. This pressure can bend or break the spindle or motor output over time (Spindle Drive, 2009).

Steering Mechanisms

This section describes four different steering mechanisms to control a device with two wheels in line with each other, one driven and one steered, where the front wheel is the wheel which is steered. The four steering mechanisms which are discussed are Push-Pull, Pull-Pull, Bevel Gear, and Belt.

Cable Controlled

The two methods examined were push-pull steering and pull-pull steering where the front wheel is controlled by control cables. A control cable primarily consists of two components; a cable and a hollow tube. The two ends of the tube are rigidly fastened and the cable runs through the tube. The cable is then attached to the controlling device and the device being operated. The cable is pushed and pulled at the controlling end and this action transmits the force to other end. The distance the cable is able to move is called the stroke. If the tube was not present the cable would just go slack when pushed and could contort when pulled. The purpose of the tube is to contain the cable and prevent it from changing its shape. One of the major benefits of a control cable is that it allows for translational force to be transmitted from one point to another through a complex path. The cable also allows for movement between the two cable ends. Control cables are commonly found in many automotive applications including throttle control and trunk and hood releases. The push-pull and pull-pull methods of steering both operate with control cables.

Push-Pull

The push-pull method involves the use of only one control cable. The steering mechanism would work by converting the rotation of the handlebars into a translational force using a lever. One end of the cable would be attached to the lever. The other end of the cable would be attached to a lever on the front wheel. An example diagram is shown below in Figure 18.

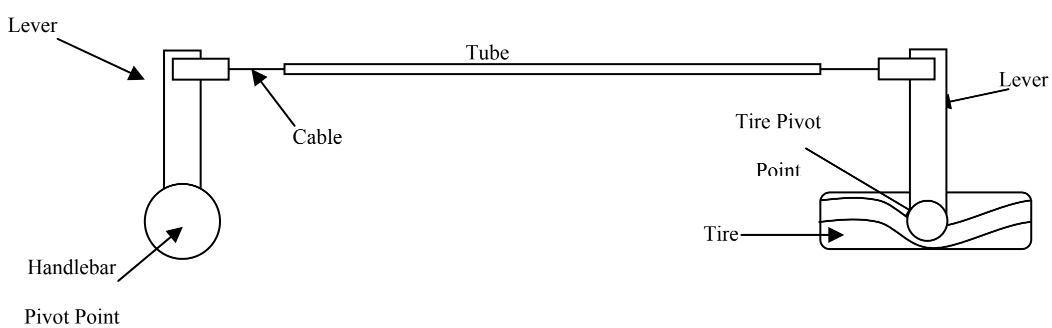

Figure 18: Push-Pull Steering (Top View)

In the case of this diagram, when the handles are turned counterclockwise the cable is pulled, thereby pulling the lever on the wheel and turning it counterclockwise. When the handles are turned clockwise the cable is pushed and the lever on the wheel rotates the wheel clockwise. When using one cable in this way the cable is effectively pushing or pulling the lever, giving it the name of push-pull steering. A major limitation of this method is that cables are problematic during pushing. The compression of the cable can cause it to buckle when it is not within the tube. Minimizing the distance the cable moves, or the stroke, and decreasing flexibility of the cable increases the pushing performance, but reduces the overall performance of cable.

Pull-Pull

Pull-pull steering involves using two control cables. An example of this method is shown below in Figure 20

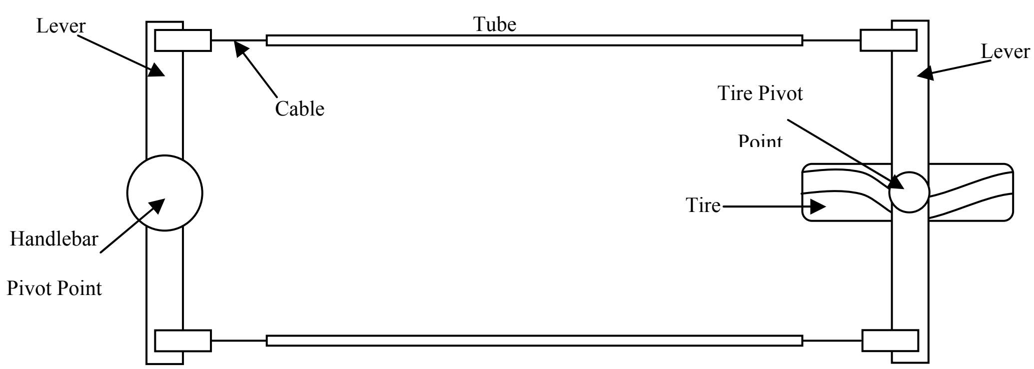

Figure 19: Pull-Pull Steering (Top View)

As shown, the cables are on either side of both the handlebar and the wheel's center of rotation. As one cable is pulled by the handlebars the other cable is pushed. Having both push and pull simultaneously reduces the problems faced when pushing a push-pull cable because each push is accompanied by a pull. Using longer strokes and lighter cables are possible with this system. A disadvantage of the pull-pull method is that there are two cables which increase the complexity of the design.

Bevel Gear

This steering method involves four bevel gears set up at two separate locations, Figure 20. The concept is to transfer the intuitive motion of turning handlebars into turning the front wheel of the pusher design. This is a mechanical connection and it would need to be supported by a frame and would need some degree of precision.

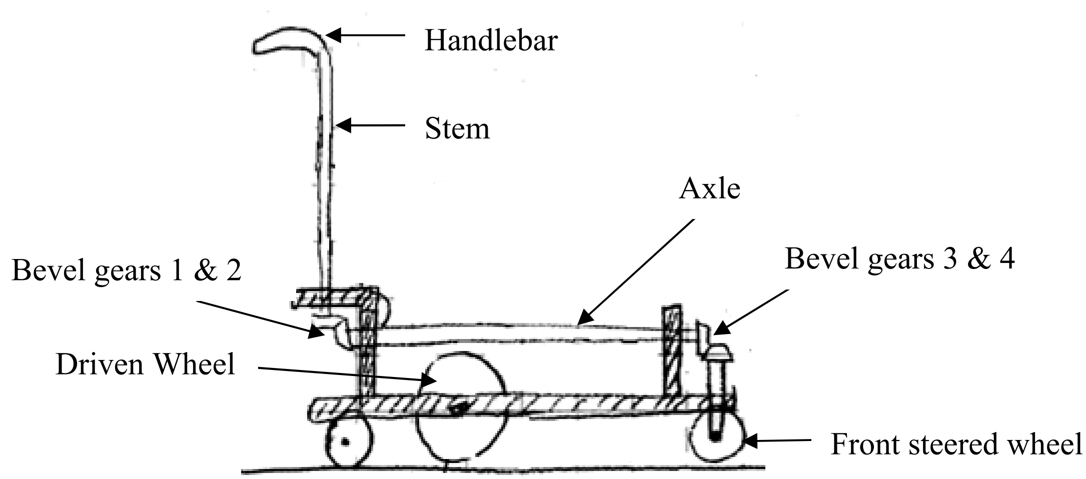

Figure 20: Side View, Bevel Steering Design

When the handlebar is turned clockwise around the stem, the stem will rotate, turning the bevel gears 1 and 2. Assuming a 1:1 gear ratio the axle will rotate at the same angular velocity as the stem, thereby rotating bevel gears 3 and 4. Bevel gears 3 and 4 transfer the rotation 90 degrees again (into the original vertical axis direction) and turn the front steered wheel, Figure 21.

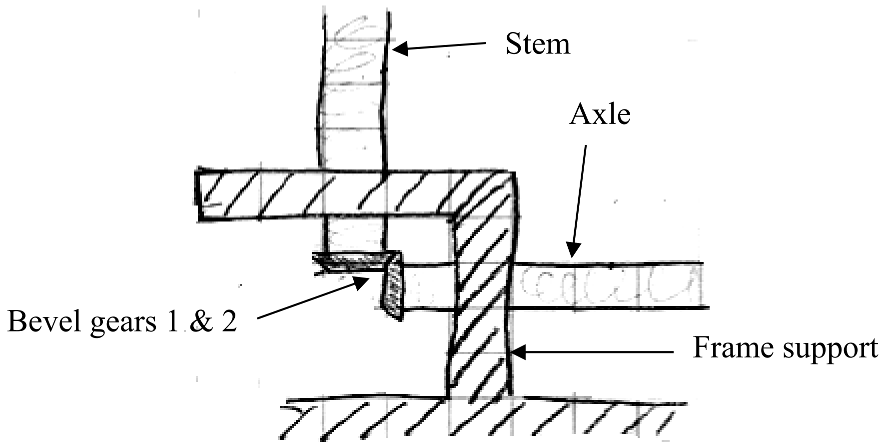

Figure 21: Close-Up Side View of Bevel Steering Design

Bevel gears are common parts and would be easy to obtain. With this bevel gear design, there would be little chance of slipping or sliding between the gears and the rotation of the handle bars is directly proportional to the rotation of the steered wheel in front. This direct proportionality makes the device intuitive to use. A set-back of this device is that four bevel gears are required for this design and each bevel gear costs between 30 to 60 dollars depending on size, pitch, and material. Also, there is very little leeway or forgiveness in the design if it is not assembled correctly or if the device is under a certain stress which causes it to bend slightly, such as when moving from flat ground to travelling up a ramp. Additionally, it might not be possible to design it so that the device could collapse. It will be important to make the device collapsible so that it can easily fit into a car. Lastly, there is very little room underneath the wheelchair to fit a bevel gear system, so it might be difficult to include in the design.

Belt and Pulley

In this belt steering system, pictured in Figure 22, the belt will be looped over two pulleys and will rotate the pulleys in the same direction. The belt system transmits rotating motion between the two shafts that aren't axially in line. When the handlebars are turned clockwise, the shaft will rotate, and the pulley at the end of the shaft will also rotate at the same rate. The pulley will cause the belt to move, therefore rotating the other pulley clockwise, which is fixed to the shaft of the steered wheel in the front of the device.

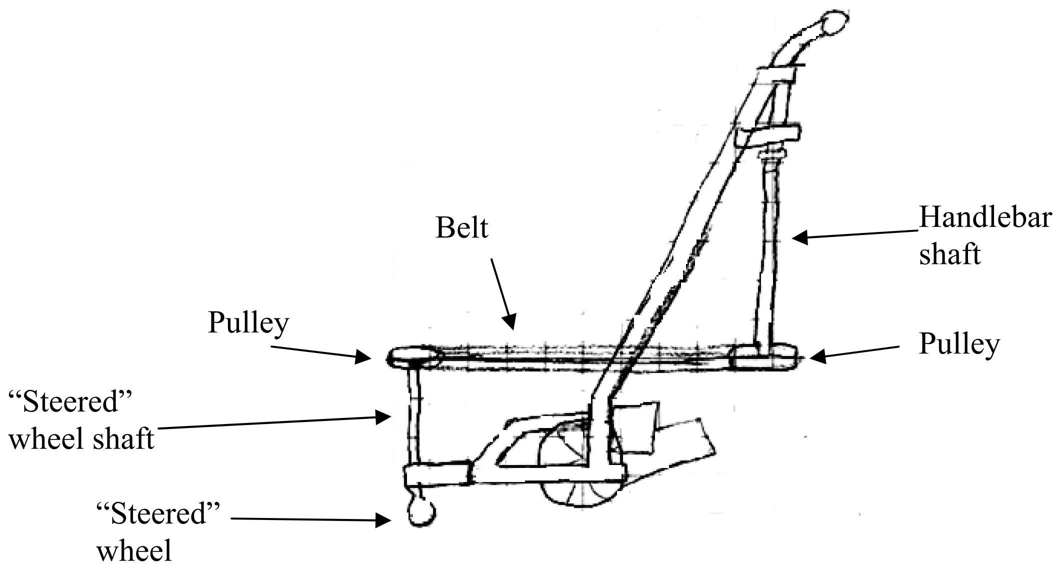

Figure 22: Side View Belt Steering Design

If the pulleys, Figure 23, are the same diameter, the front steered wheel will rotate the same amount as the handlebars. If the front wheel was slightly smaller, the wheel would turn slightly more than the handlebars. In our device, we would want the wheel and handlebar to turn either the same amount, or we would want the wheel to turn a bit more than the handlebars. This would require the user not to have to turn the handlebars very much, making it a less awkward motion when pushing a wheelchair.

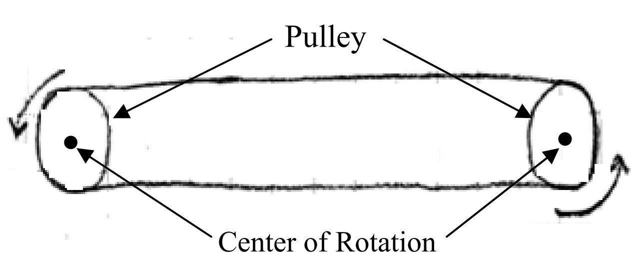

Figure 23: Top View of a Belt Drive

Belt drives need very minimal maintenance and are very efficient. In order for the belt to work efficiently, a spring loaded tensioner could be used, which would keep the belt tight against the pulleys. Also, toothed belts can be used to decrease any chance of slipping. A chain/gear system can also be used with the same concept, but needs lubrication so maintenance required is different between the two concepts. The benefit of this design is that a belt drive provides some leeway when assembling and building. It does not need to be perfectly aligned to work well and when the pusher is under a bending stress, like when travelling from a flat surface to going up a ramp, the belt will continue to work correctly assuming very small bending. A possible disadvantage of this design is that it might not be able to be designed to fold up. Also, there is very little room underneath the wheelchair to fit a pulley system, so it might be difficult to include in the design.

Braking

Braking can be achieved through several different methods. Common braking systems are disc brakes, drum brakes, and caliper brakes. Another option is regenerative braking.

Disc Brakes

With disc brakes (Figure 24), a rotor is attached to the wheel that needs to be braked. Controlling the speed of the rotor will in turn control the speed of the wheel. Brake pads are then positioned on either side of the rotor and a caliper holds them in place. Commonly through the use of a piston, the brake pads are then pushed together so that they squeeze the rotor. Other variations include calipers that compress the brake pads. These pads apply a friction force to the rotor which converts the kinetic energy into heat and slows the rotor down (Nice, 2000). Disc brakes would be a possible option for a wheelchair pushing device, but the attachment of rotors to the wheels would be an additional requirement. Also, the calipers must be well-aligned with the rotors and might require technical maintenance.

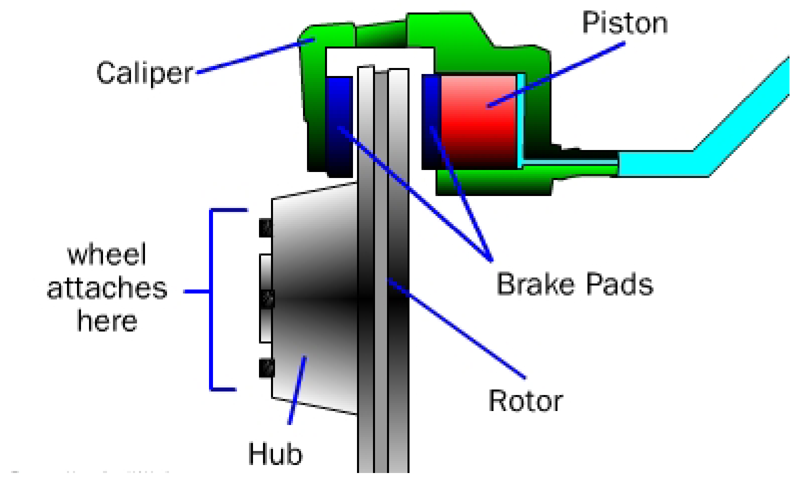

Figure 24: How a Disc Brake Works (Nice, 2000)

Drum Brakes

Drum brakes (Figure 25) operate similarly to disc brakes, however instead of a rotor, a drum is attached to the wheel. Inside the drum there are two pads that are controlled by a piston. When the brakes are engaged, the piston forces the pads outwards and against the inside wall of the drum. The friction between the pads and the drum applies a force that slows the drum and wheel (Nice, 2000). This is another feasible option for braking a wheelchair pusher; the drum would be attached to the pusher's driving wheel. The advantage of the drum brake is that it is self- contained and protected from the environment. The disadvantage of having enclosed brakes is that the drum must be disassembled for maintenance and would require higher technical skill.

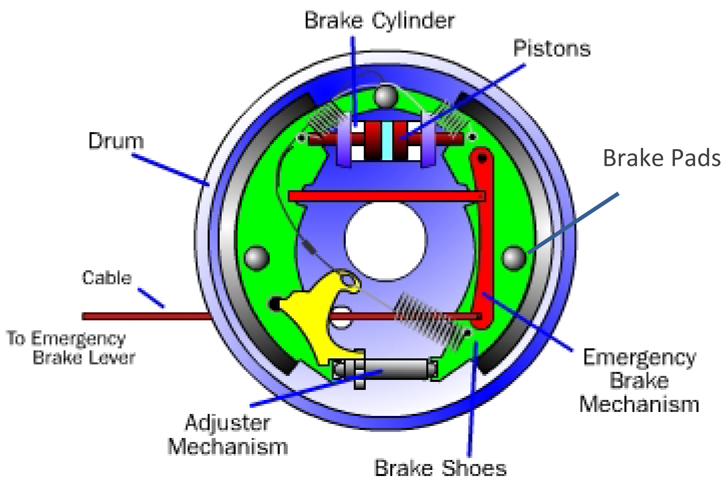

Figure 25: How a Drum Brake Works (Nice, 2000).

Caliper Brakes

Caliper brakes (Figure 26) are commonly used and seen on bicycles. These brakes operate through the use of calipers. With a bicycle, the calipers are controlled by a cable. As the cable is tightened the calipers pinch the two brake shoes against either side of the tire, once again applying friction and slowing down the tire (Nice, 2000). The caliper brake design is a simpler design than the disc and drum brakes because the pads contact the tire directly. Maintenance of caliper brakes is also simpler and requires only basic technical skills. These brakes are not as effective as other brakes because the contact area of the pads is smaller.

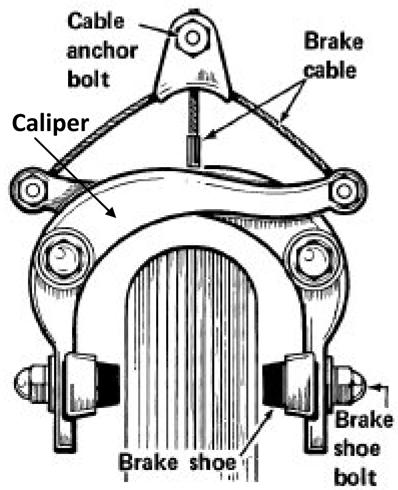

Figure 26: How a Caliper Brake Works (Nice, 2000).

Disc, drum, and caliper brakes all apply friction and generate heat. This heat must be managed to prolong brake life. Fins and other methods of cooling are often used to prevent overheating when necessary. Another concern is pad wear. Due to the friction forces, pads are continuously being worn down when used and need to be replaced accordingly. Maintenance is a concern when choosing a brake design. It is important for brakes to be easily maintained so that they function properly and ensure the safety of the wheelchair occupant.

Regenerative Braking

An alternative type of braking is regenerative braking. Regenerative braking is possible when an electric motor is involved in powering the device. Regenerative braking can be explained using the example of an electric car. During acceleration and constant speed driving, the electric motor is being used to propel the car. It gets its power from the batteries and converts it to mechanical energy which is then sent to the wheels through the drive train. However, when the car is braking, the electric motor is not being used and traditional friction braking would waste the energy in the form of heat. The basis behind regenerative braking is that an electric motor can also be used as a generator. Therefore, instead of braking with friction, the electric motor is turned off and the car's spinning wheels drive the motor. The motor is then able to act as a generator and convert the mechanical force from the wheels to electricity that recharges the batteries powering the car. This is a much more efficient system because the energy that would be wasted as heat in a traditional braking system is converted to electricity to charge the batteries in the car (Lampton, 2009). If the pushing device were to incorporate regenerative braking it would greatly increase the efficiency and increase the time and distance the device could be used between battery charges. Any time the device is used for active braking it would charge the battery, this would include down hills and stopping. In order for the regenerated energy to charge the battery the circuitry becomes more complex. Analysis of how beneficial the regenerative properties are will depend on the regenerative properties of the motor and the types of loads the motor will be subject to. This analysis will determine if the regeneration is worth the expense of installation and purchase of necessary electronics.

User Interface

When designing the user interface, the main goal is to make it easy to use and intuitive for the final user of the device. This means the designer must know the user's goals, skills, experience, and needs. With this information, the user interface can be designed to reflect the user and operation can be more instinctive and logical. It is also important to understand the user because the user interface should be made so that the user's existing skills can be applied in the operation (Joiner, 1998).

Existing Product Concepts

The focus on an intuitive device which will be more easily accepted by the user is why the existing wheelchair products typically add a controller onto the handles which are already located on the back of the wheelchair, or include separate handles next to the existing wheelchair handles. For example, the Viamobil by Frank Mobility has handles which are directly attached to the wheelchair handles themselves, Figure 27. Viamobil handles also have the option of separate handles which are located behind the wheelchairs handles and have an adjustable height. The option of adjustable height allows the device to be flexible for users of different heights (Viamobil, n.d.). The controls are located on the Viamobil handles and include an LCD display, variable speed, direction of travel switch, an on/off switch, and a driving lever to control speed.

Figure 27: Viamobil Hand Grips (Viamobil, n.d.).

Dane Technologies' Wheelchair Mover has separate handles that are attached to the device itself, Figure 28. The handles are solely for resting the attendants' hands and all the controls are located on the device in-between the hands, at hand level. The throttle controller is a thumb-controlled lever with a rabbit and turtle switch to control the speed level. The product also includes user controlled brakes.

Figure 28: The Wheelchair Mover's Controls and Handles (The Wheelchair Mover, 2009)

The ERGOtug has handles that also point perpendicular to the direction of travel, Figure 29. The controller is within thumb-reach of the hand grips and has the capability of being driven one-handed, unlike the other two. The ERGOtug also has adjustable handles.

Figure 29: ERGOtug Controller (ERGOtug Patient Transport System, 2008).

The newly designed wheelchair pusher will need controls which are intuitive and also ensure safety of the user and others. The mechanically operated device should include safety stops and an intuitive shut down procedure in case anything goes wrong while operating the device. It also should contain controls which steer the device left, right, forward and backward. The most important parts of designing a user interface will be ergonomic comfort, safety, convenience, and a device which is intuitive and therefore easy to learn and use.

Joystick Control

A joystick is a typical user interface for electric wheelchair users. A joystick connected to a device works by moving the device in the direction of where the joystick is pushed and at a proportional speed to how far the joystick is pushed from the neutral position. This control is great for electric wheelchair occupants to control their motion, but would not be ideal for a wheelchair pusher attendant. One reason is that the attendant would usually grip the back of the wheelchair handles to push the wheelchair and gripping a joystick would not be a similar hand position or location to usual wheelchair use, therefore making the joystick control less intuitive.

Having the assistive device operate similarly to a manual wheelchair would be beneficial because the attendant already has the skills necessary to operate a manual wheelchair and the adjustment to using a wheelchair pusher would be simpler. Functions of the device must be obvious to the user and the faster the attendant learns to use the pusher, the more beneficial the pusher will be and the chance for injury or accidents related to mishandling will be avoided.

Attachment and Detachment

Existing products and new concepts for attaching and detaching the device to a wheelchair were researched and developed.

Existing Product Concepts

The ERGOtug Patient Transport system has an automatic hitch that slightly lifts the wheelchair from underneath, this attachment secures the wheelchair and the device transports the wheelchair with minimal effort exerted by the user (ERGOtug Patient Transport System, 2008). The ERGOtug is comparable to a pallet mover in that it lifts a load straight up, but in this case it is only a slight lift so that the front and rear wheels still remain in contact with the ground. A disadvantage of this mechanism is that exerting an upward force on the wheelchair may reduce the stability of the chair depending on the center of gravity of the chair and occupant, and the magnitude of the force.

Dane Technologies Wheelchair Mover uses a push down hand lever that when activated secures an attaching mechanism to the frame of the wheelchair (The Wheelchair Mover, 2009). This design is more secure than ERGOtug's system since the attachment is wrapped around the frame of the wheelchair as opposed to only lifting it. A major disadvantage of the current Dane

Technologies device is the small number of wheelchairs it is compatible with. Currently, the mechanism is only configured to fit standard wheelchairs.

Viamobil created a smaller device that attaches to a bracket installed on each side of the wheelchair frame (Viamobil, n.d.). This allows for quick attachment and detachment of the device without the use of tools. Due to the brackets being permanently mounted to the wheelchair they provide a very secure attachment for the device. However, several disadvantages arise from permanently attaching brackets to the wheelchair. Viamobil requires the brackets to be attached by a trained professional; this means the customer cannot assemble the device. This also means the customer must have a technician complete the installation on any other chairs the customer would like to use the Viamobil on in the future. If an institution were to purchase this device they would be required to install the brackets on every wheelchair that they plan on using with the device.

New Attachment Designs

New attachment designs were created after research on latches, clamps and locks.

Retracting Carabiner

The concept of the retracting carabiner is that the device would be wheeled up to the chair; the user would have to reach down to clip two carabiners onto the frame of the wheelchair at suggested locations. Then the cables attached to the carabiners would retract around a spring loaded dowel or pulley, activated by a lever or switch. The device would also include a bumper piece is on its front which would act as a contact point where the device would push against the wheelchair as it's being driven. This design can attach to many different types of wheelchairs and is versatile. Ideally, this attachment could clip onto many different types of wheelchairs and would not require any attachment to the wheelchair or any modification of the wheelchair for the device to work with it. A setback of this device is that the user would have to bend over to both attach and detach the device from the wheelchair. It also is not intuitive to use and the user will have to be taught how and where it can be attached. Also, the cable will have to be locked in place to keep the wheelchair stably attached. When the device and wheelchair are going downhill, this cable clipping system will not be sufficient to ensure the safety of the occupant or the attachment of the device.

Fence Latch

The fence latch attachment was very similar to a pool gate lock, Figure 30. When the top button is pushed down, the latch of the mechanism is no longer locked, and the gate is free to turn. Once the latch returns to its original position the button pops back up to its original position by a spring and the latch is relocked. Implemented in the pushing device, the mechanism would be driven up to the wheelchair with the latch in a disengaged position. A horizontal bar attached to the chair would then come into contact with the latch and force it closed and into the locked position. This attachment would be ideal in situations where speed of attachment is important, however, the latch does not fully constrain the wheelchair's bar in place. Over rough terrain the wheelchair may be able to bump up and out of the latch, releasing the wheelchair from the pushing device.

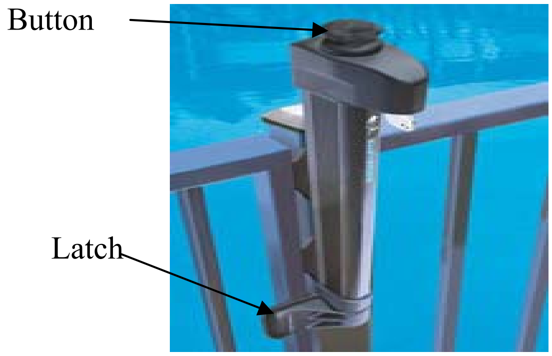

Figure 30: Pool Gate Lock (Gate Latches and Locks From D&D Technologies, n.d.)

Caliper Clamp

These caliper clamps work similarly to caliper brakes, however, with this design, the back piece will be rigidly attached to the frame of the pusher and the front piece will rotate around point "P". There is a cable attached to the top of the rotating piece that will thread through the rigid piece and exit from the top of the rigid piece. A spring will be attached around the cable to keep these pieces constantly in the "open" position shown in Figure 31.

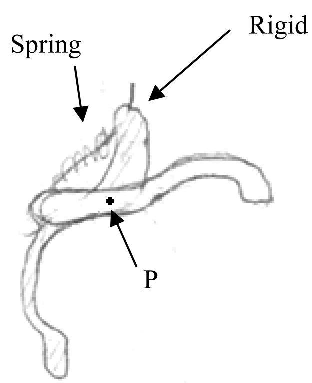

Figure 31: Detailed View of a Caliper Clamp

The cable from the top of these clamps will be threaded through the frame of the device and will be threaded out through the track cut out in the back of the frame, Figure 32. The cable from the attachments will fit through this track. There will be a handle at the end of the cable that will not fit through the track and therefore will rest against the frame without being pulled into the frame when the cables are in tension. The user will pull the handle to bring the cable through the track. When the handle is at the bottom of the track, the cable will not be in tension and the clamp will be open. When the handle is pulled to the top of the track, the clamp will be in tension and the clamp will lock securely.

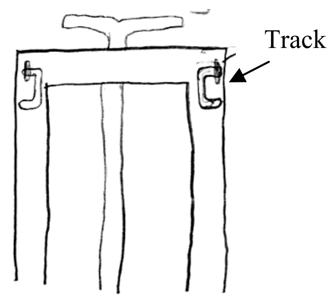

Figure 32: Back View of Caliper Clamp Design

Cable Latch

The cable latch attachment design operates on the same concept as the caliper clamp attachment; however the shapes of the receiver and hook pieces are different. As shown in Figure 33 the hook lifts and allows the horizontal bar to enter the receiver. The hook is then closed around the bar. An advantage of this design is that once engaged, the bar would be locked into place. The cable would need to be pulled in order to release the bar. A disadvantage of this design is that the engagement between the bar and the attachment has little room for error potentially making engagement difficult. Also, the operator must somehow keep the cable in tension while trying to engage the device with the wheelchair. There is a possibility that this device may jam if there are forces applied to the hook by the wheelchair.

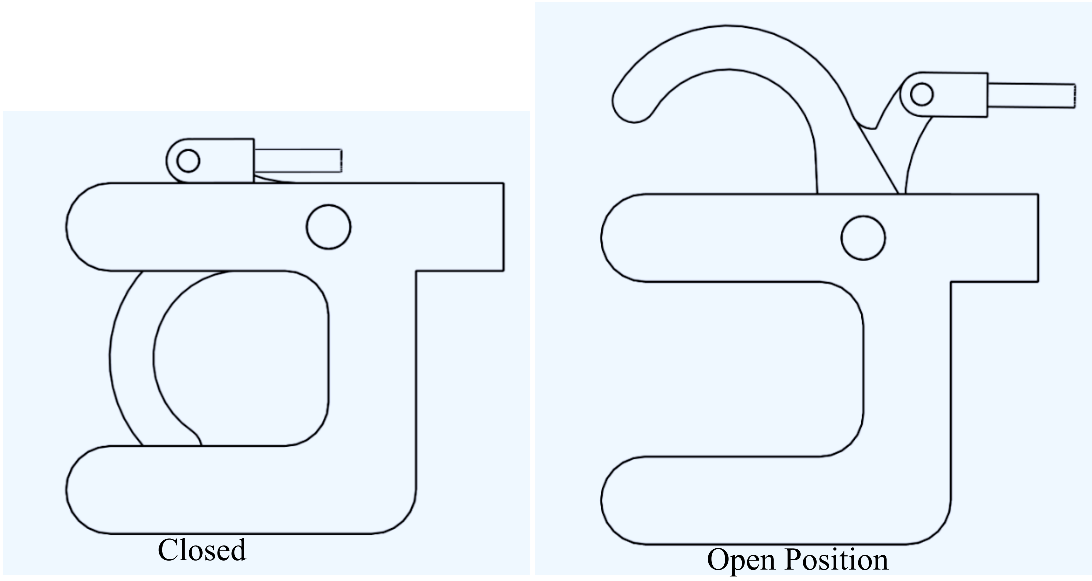

Figure 33: Cable Latch

Safety Stop

Safety of both the attendant and occupant is extremely important. One way to keep the design safe is to incorporate an emergency stop into the design. With the main power cut off, the device would come to a stop. Below are two patents that have incorporated safety stops into well known devices.

Treadmill Emergency Shut-off

United States patent 4,426,075 is an emergency shut-off switch for an exercise machine. When the user thrusts down on the handles, shown as numbers 18 and 20, Figure 34, the drive motor is immediately shut off. When the user thrusts the handles down, they free the switch actuating lever, creating an open circuit which deactivates the main power relay and thus shuts off the power to the drive motor. This allows the user to avoid dangerous situations in cases where they quickly become tired, begin to fall, etc. Handles travel a small distance in order to activate the emergency stop and the force required to thrust the handles down is adjustable in order to accommodate users of different strengths (Otte, 1979). This emergency stop motion is not intuitive, however, since when you fall on a treadmill your hands do not necessarily move down, they move away. A similar idea could be incorporated into the pusher device. Like this mechanism, a certain movement of the handles could deactivate the power by opening a circuit.

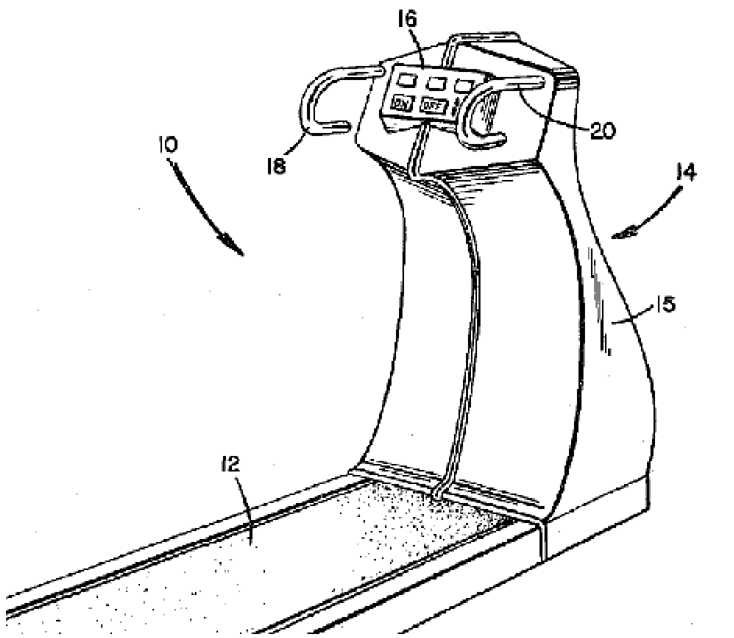

Figure 34: United States Patent 4,426,075

Industrial Robot Emergency Shut-off

United States Patent 5,903,123 is an emergency shut-off button for an industrial robot. Two emergency stop buttons are placed on the robot assembly, Figure 35. The first one is placed on the teach pendant (4) or controller. The teach pendant is what the operator uses to move the robot-arm through different positions. A button is installed here because the teach pendant is in the operator's hands whenever the robot is moving, making sure that at least one button is in range of the operator at all times. The second button is placed on the external control board (6). The external control board is where the main power for the robot is turned on and off. The external control panel receives an emergency stop button because it is the second most likely place for an operator to be. Also, in the case where the operator is in danger, it is the easiest location for a second person to access. When either switch is pushed the electrical circuit becomes open, shutting off power to the robot (Shimogama, 1999). The pusher device could also have an emergency stop button available to the operator which would open the circuit and shut off the power to the device.

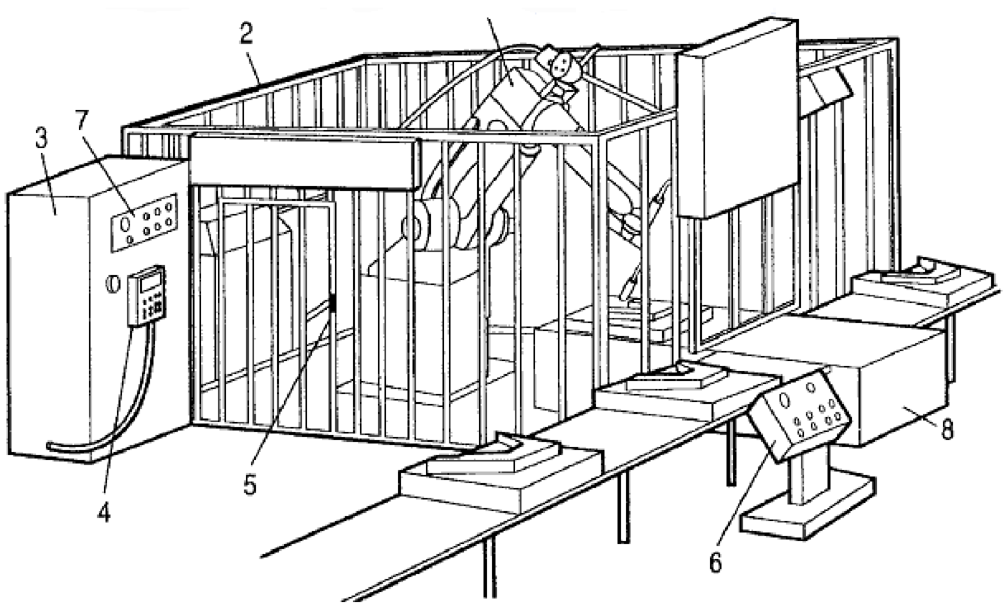

Figure 35: United States Patent 5,903,123

Preliminary Design Descriptions

The preliminary designs cover a broad range of design concepts which were researched in the design concepts section. Each preliminary design is explained and discussed in the following sections.

Design A

The back view of design A, Figure 36, shows the general orientation of the components of this design.

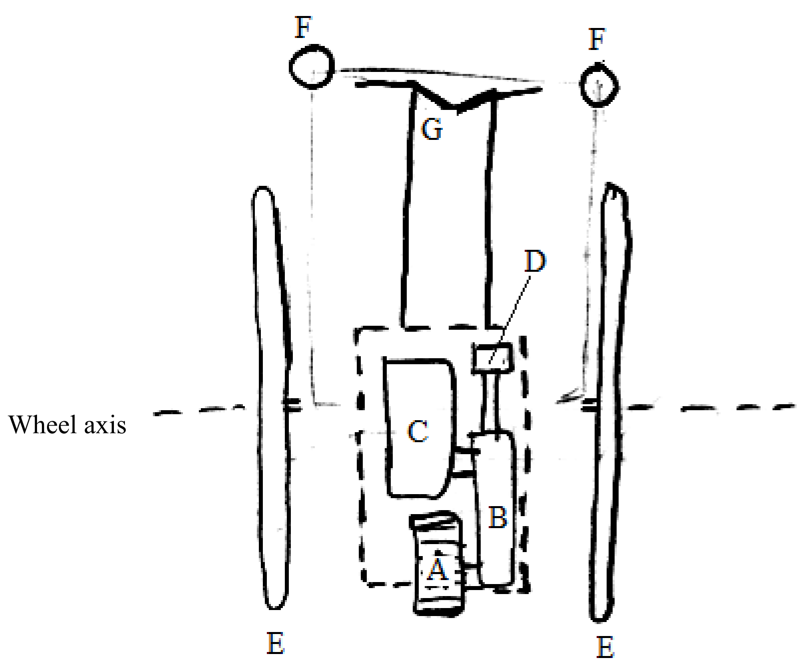

Figure 36: Back View of Design A

- A- Wheel (single, driven)
- B- Motor
- C- Battery
- D- Microcontroller
- E- Wheelchair Wheels (large, back)

F- Wheelchair handlebars

G- Handles/controllers

The handles and controller of this design are in an ergonomic shape, similar to a bike handle, Figure 37. The controller will be mounted to these handlebars in a way that is ergonomically comfortable and convenient, and will be as intuitive as possible. The handles will be able to retract into the base of the device for easy storage, and the two supporting bars would be sturdier than one when turning the device (which is done by force, similarly to how a manual wheelchair is turned by an attendant). This is a similar method of turning as the Viamobil (Viamobil, n.d.).

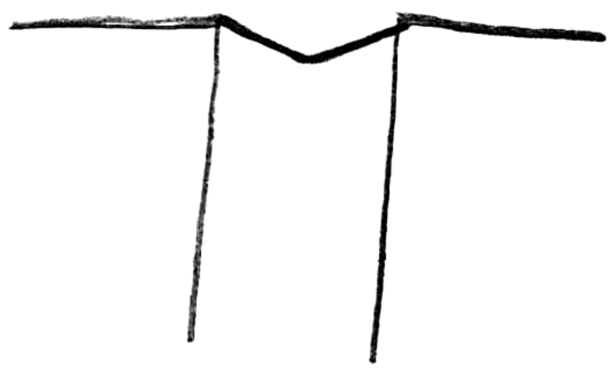

Figure 37: Handles/Handlebars of Design A

The braking method on this design involves three braking mechanisms: motor braking, manual braking, and park braking. The motor can be used as a brake for the majority of situations, when the device and wheelchair need to slow down gradually. In a situation where the wheelchair must be slowed down at a faster rate the manual brakes can be utilized. These could also provide an additional degree of comfort for the operator since he or she will be able to choose whether or not to use it. If the operator needs to stop the wheelchair quickly, the motor will begin braking and manual brakes can also help slow the wheelchair down faster. The wheelchair's manual brake system is shown in Figure 38. These brakes are activated similarly to how a bicycle's manual brakes are actuated, by squeezing levers on the handlebars. When the levers are squeezed, cables attached to them are tightened, pulling up on the cable and causing the caliper brake to press against the sides of the wheel and slow it down. This design is meant to have the caliper brake on the single driven wheel of the device. An important aspect of the design is that it does not matter what angle the handles are at, the caliper brake works the same because the cable passes through the pivot point of the handle bars. This is important because this design includes a parking brake which depends on the angle of the handlebars.

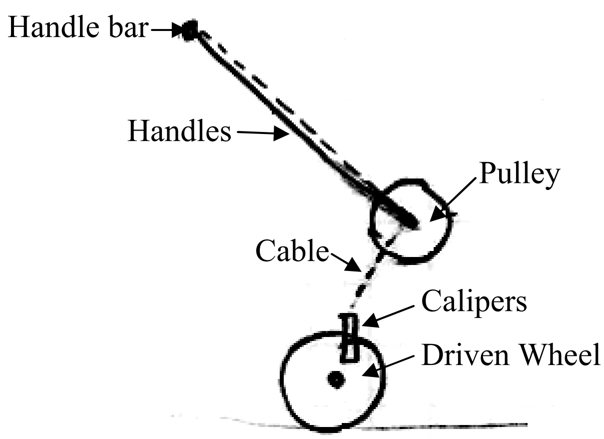

Figure 38: Side View of Manual Brake System for Design A

The parking brake concept is shown in Figure 39. This brake is actuated when the handlebars are in the upright position (intended when the wheelchair and device are not in use, or are parked).

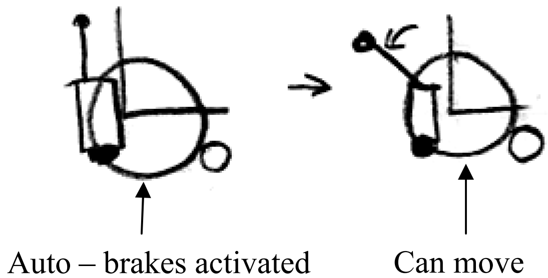

Figure 39: Handle Position of Design A and Motion

When the handlebars are pulled towards the user, a cable which is attached at a point on the handlebars is slackened and a caliper brake (which is separate from the one described in the manual brake section) is loosened, Figure 40.

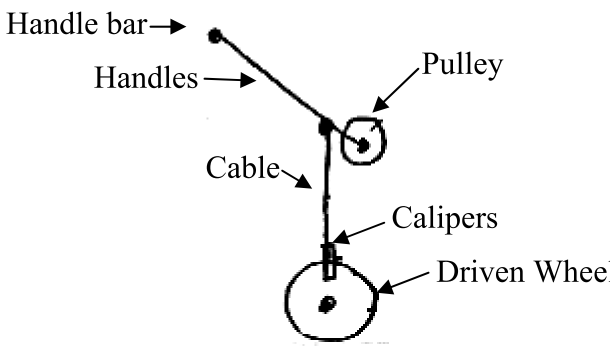

Figure 40: Parking Brake of Design A in Non-Activated Position

When the handlebars are brought into an upright position, Figure 41, the cable tightens and is pulled around a pulley at the pivot point of the handlebar. This pulls the caliber brake so that the calipers squeeze together and there is friction with the driven wheel. The wheelchair cannot move until the handlebars are lowered again, Figure 39. This design is intended as a parking brake and is a safety precaution so that if the wheelchair is left unattended, it will not be able to roll off.

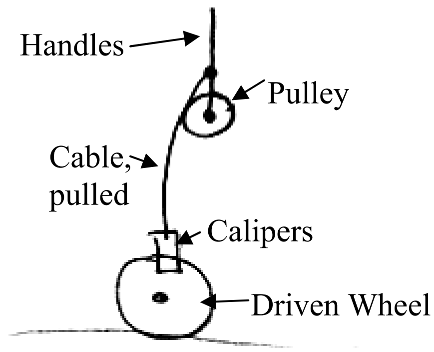

Figure 41: Parking Brake of Design A in Activated Position

A second alternative parking brake design, Figure 42, uses a friction brake that is pressed against the large wheel of the manual wheelchair by a spring. This design is intended to work so that it is automatically engaged when a lever is released on the controller. When the lever is squeezed, the brake is released by tensioning a cable, and the device can then be pushed manually or by the device. This brake is automatic and is also intended to increase the safety of the manual wheelchair.

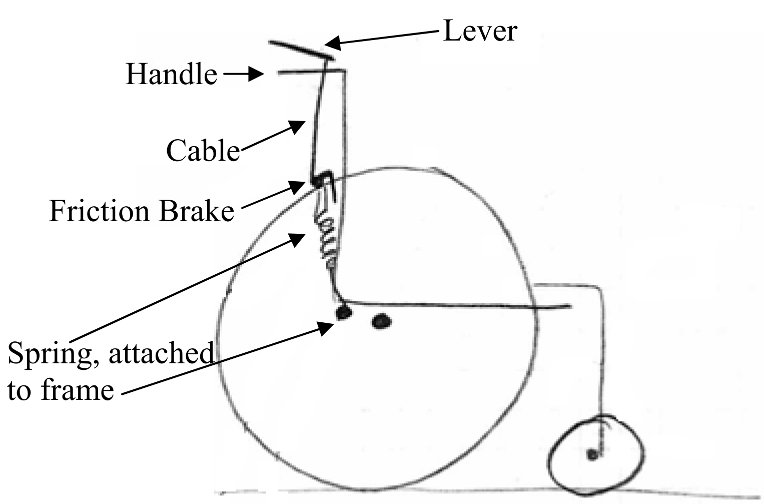

Figure 42: Automatic Brake Design of Design A

Many manual wheelchairs already have parking brakes, but typically these existing brakes require the attendant to bend over. The concept in Design A makes it more convenient for the attendant. The other benefit of a parking brake is that it is automatic.

Propulsion could be incorporated with these braking concepts by setting the speed of the device depending on the angle of the handles. If the handles are at an upright 90 degrees with the ground, then the automatic parking brakes are engaged and the motor is in neutral or off. When the handles are lowered, the parking brake is disengaged, the motor begins to accelerate and the device picks up speed until it reaches a set speed. It might be possible to connect a goniometer or other device to the handles in order to measure their angle. Then, the microcontroller could be programmed to relate speed to the angle of the handles.

The device is attached to the wheelchair using a clamp lock concept, Figure 43. The device would be driven up to the wheelchair and would clamp onto a horizontal bar, previously installed at the correct height. The lock of the clamp would be engaged when it was driven into the bar. To release, a mechanical lever could lift up the retractable wire.

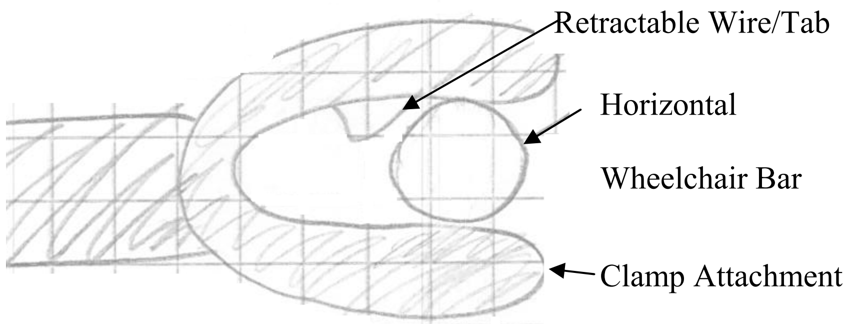

Figure 43: Clamp Attachment of Design A

This design has advantages in terms of size and portability. It is small enough to fit into a car, in the trunk and in the backseat. This design also has convenient manual brakes, which can be used to slow the device and wheelchair in the event of an emergency or when the attendant needs the chair to slow down at a faster rate than the motor is capable of braking. This device also includes a parking brake which is automatically activated when the device is not being used by the attendant. This might be an overdesign because a motor which is shut off with the wheel still in contact with the ground could provide sufficient braking force. This design also controls the speed and the brake with the same motion. When the handles are upright the motor does not drive the wheel and the automatic parking brake is activated. When the handlebars are at an angle toward the user, the parking brake will be disengaged and the motor will drive the wheel. The speed of the device is dependent on the angle between the handle and the vertical axis. To turn this device, there is slip steering. This is a problem if the handles bend towards the attendant because turning could be awkward for the user.

This concept is good for the user but is overcomplicated to design since there are simpler and more intuitive methods of controlling speed. Lastly, the attachment is not a strong idea because the release mechanism is not clearly defined and the attachment would need to be manufactured instead of purchased.

Design B

Design B is shown in Figure 44 and uses two clamps, a bumper, and the horizontal bar of a wheelchair as an attachment device.

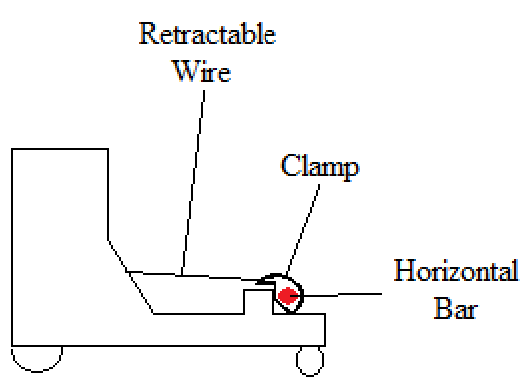

Figure 44: Side View of Design B

Both clamps would be attached to a wind up cable (Figure 45) so the attendant could pull the cables out, attach them to the wheelchair, and then remove as much slack as possible. The attachment is described above as the Retracting Carabiner in the New Attachment Design section.

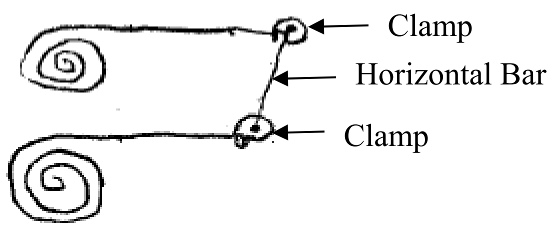

Figure 45: Clamp Attachment Mechanism of Design B

When going downhill the clamp attachments and cables must be strong enough so that they won't detach from the wheelchair, but this could be challenging to find. A front view of the horizontal bar, clamps and bumper is shown in Figure 46.

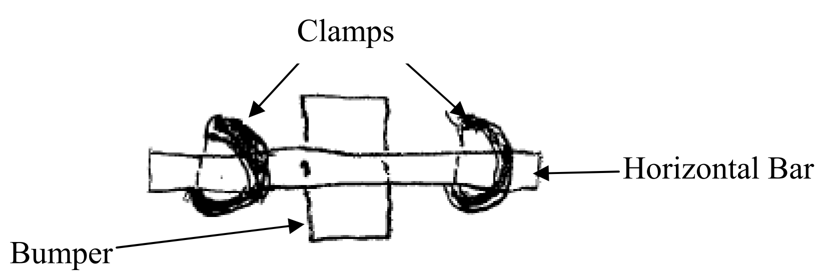

Figure 46: Front View of Design B Attachment Mechanism

The device will have one rear drive wheel, one front turning wheel directly in front of the drive wheel, and will utilize two caster wheels for balance (Figure 47). Having this wheel setup allows the device to rotate about the rear driven wheel and avoids skid steering.

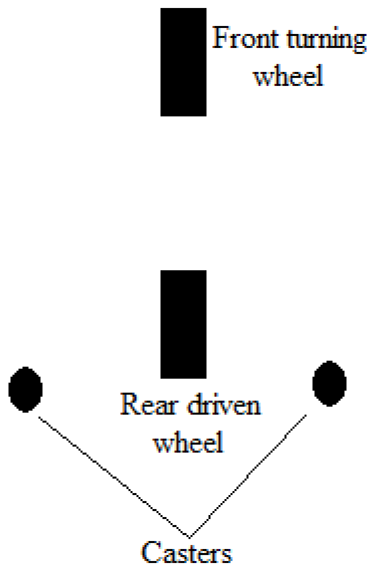

Figure 47: Top View of Design B Wheel Layout

An electric wheelchair motor (containing a gear box) and battery will be used as the drive system of the device. They will be hooked up to a microcontroller which will allow the user to control the speed of the device. The drive system is pictured in Figure 48.

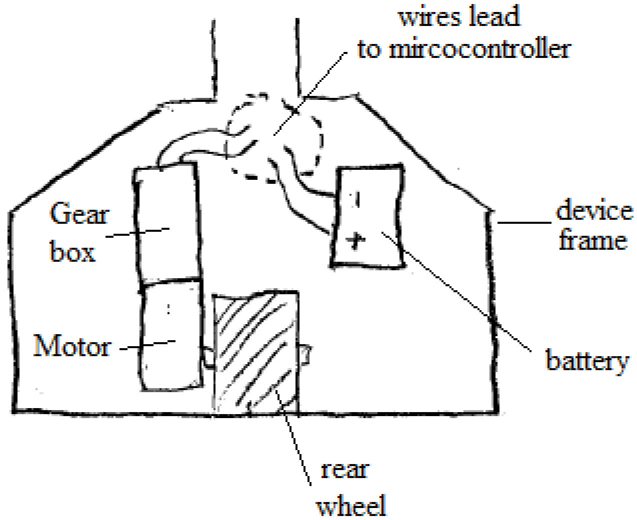

Figure 48: Drive System Inside Design B

The user interface for steering will be fabricated bicycle handles (Figure 49). The handles will be connected to the front turning wheel and will allow the user to turn the device left or right. Ideas include mechanical mechanisms, pull-pull steering, and push-pull steering, discussed in the Steering section.

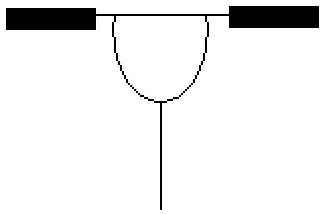

Figure 49: Handlebar Idea for Design B

The wheel layout allows the device to have a turning radius close to the wheelchair's own. Although the attachment mechanism of this design would work with the widest range of wheelchairs, it may be uncomfortable for the user as they would need to apply force, and need to bend over to attach and detach the device.

Design C

The third preliminary design utilizes two motorized triangles, Figure 50. The design consists of two machined triangles that hook onto each wheelchair wheel. Each triangle has two small castor wheels that are in contact with the ground to stabilize the device.

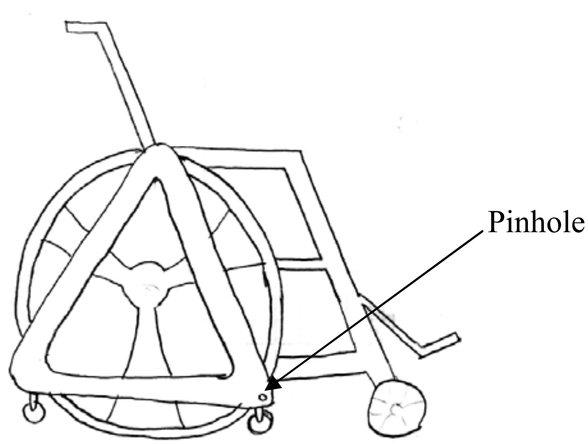

Figure 50: Side View of Design C

The top corner and the back corner of the triangles hook around the wheel while the front corner has a pinhole, labeled in Figure 50. With these features, the triangle can be rolled up to the chair and hooked on to the wheels. To secure the triangle, a pin is placed through the pinhole on the right corner of the triangle. This pin would also be a bearing so that the wheel could still move freely. There would also be bearings at each of the other two corners of the triangle, again so that the wheel could move freely, Figure 51.

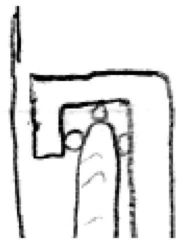

Figure 51: Detailed Rear View of Bearings for Design C

Figure 52 is a rear view of the design. This is where the battery and motor controller would be placed. A basket would be connected under the seat of the wheelchair with the two components placed inside.

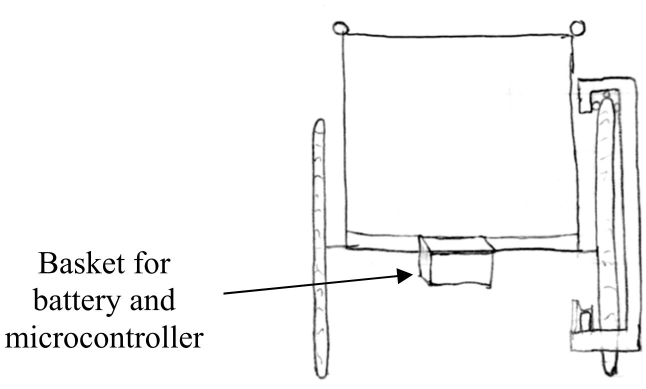

Figure 52: Back View of Design C

Figure 53 shows how the motor would be connected. There would be an additional piece attached to the triangle that hooks around the wheel. Here, the motor would be attached.

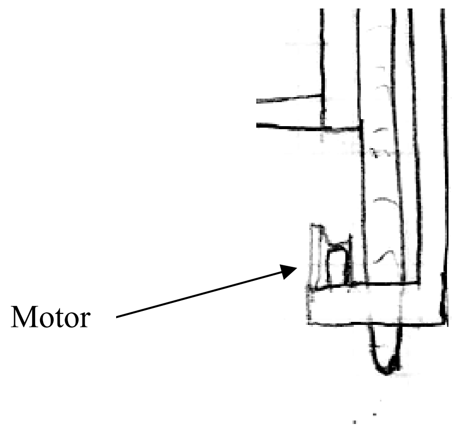

Figure 53: Rear View of Design C Motor Connection

Also, to contain the battery and microcontroller, a basket is belted around the back of the chair, Figure 52. These components would then be wired to the motor and the controller which would be located on the handlebars.

In this design, two motors are utilized for the friction drive system. Each motor has a knurled piece at the end of its output shaft which will rotate with the output shaft, Figure 54. This knurled piece would rotate at the same speed as the drive shaft and would be in contact with the wheelchair wheel and therefore cause the wheel to rotate, Figure 55. There will be a spring component which would put pressure on the driving knurled piece and provide constant pressure and enough friction to drive the wheelchair wheel.   A lever will be added in order to provide a way to release this contact and keep the motor locked in a disengaged position. This would allow for free movement of the wheelchair wheels when the device is not in use.

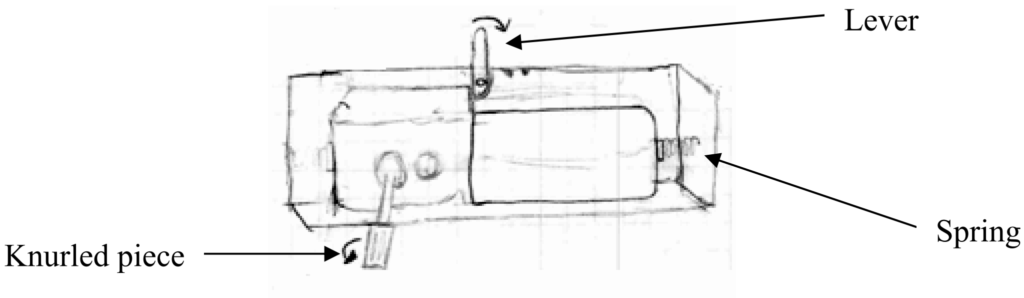

Figure 54: Detailed Side View of Motor for Design C

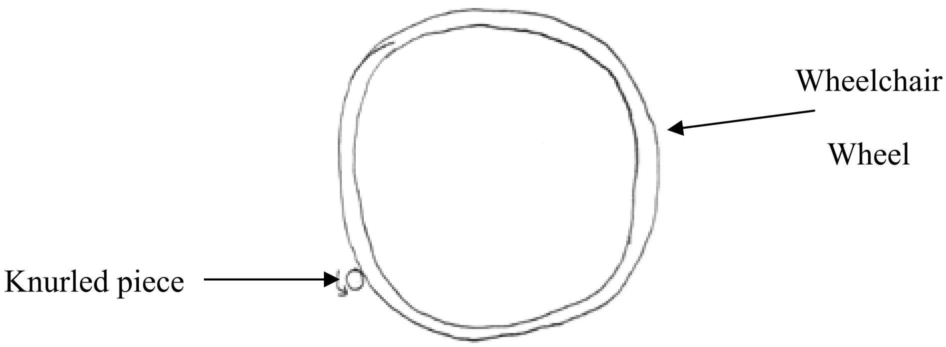

Figure 55: Side View of Contact Between Motor Shaft and Wheel of Design C

The controller, Figure 56, will be clamped on to the wheelchair's existing handlebar. This controller will have an on/off switch to turn on the motors, three speed settings, and a "GO" button to start the motors. The left and right arrow buttons will control each motor individually to turn the wheelchair. The braking of this design will be performed by the braking of the motors. The motor will be stopped by pressing the stop button on the controller and this will stop the entire device by braking the motor.

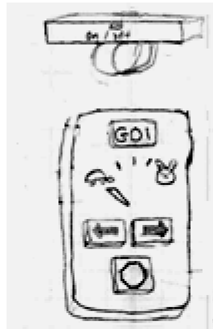

Figure 56: Controller of Design C

The driving method of this device allows for control of both of the wheels and will allow for a tight turning radius. Though the driving method and performance are very efficient in this design, the device is also not practical for a number of reasons. This design has three separate large pieces and therefore would be difficult to carry around. Also, the triangle shape will only fit wheels of a specific diameter and therefore the design is not versatile. Since there are three different components, the attachment/detachment method is not a quick process. The idea of having two motors, driving each wheel separately, is a very efficient way to drive the system as it works in the same fashion that someone pushing themselves in a wheelchair would, however, the rest of this design is not practical because of its three large components.

Design D

This preliminary design was created with most development focused on the device's engagement with the wheelchair. All manual wheelchairs have two large diameter rear wheels. This commonality was used as an advantage to the design. A side view of the device can be seen in Figure 57. Motorcycle wheel chocks inspired the design of this device. It operates by cradling the manual wheelchair's large real wheels and lifting them off the ground. It achieves this by first loading the wheelchair into the wheel chocks shown in Figure 57. The wheels are locked into the chocks at point 'a' and the attendant rotates the chocks and wheels around point ‘b’. This rotation will lift the rear wheels of the wheelchair off the ground and bring the wheels above the frame of the device as shown in Figure 58.

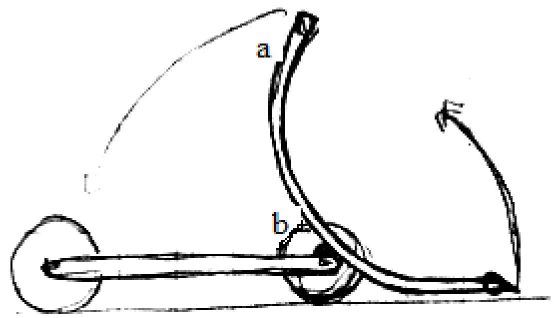

Figure 57: Design D Carriage Loading Unloading Position

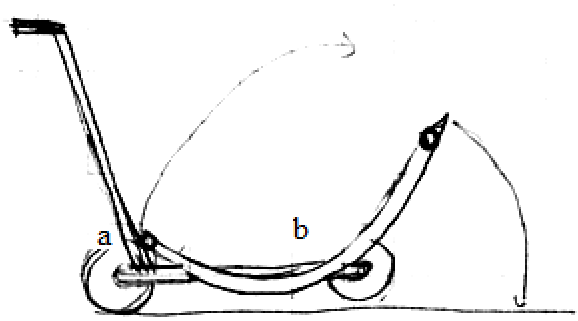

Figure 58: Design D Carriage Occupied Position

Figure 59 shows the preliminary layout of the electronics in the device. The center rear wheel is powered by the electric motor equipped with a friction drive (e). The friction drive allows for the motor to be easily disengaged from the device. The drive wheel would power the wheelchair forwards and backwards. The attendant would turn the device by physically rotating the device in the direction desired.

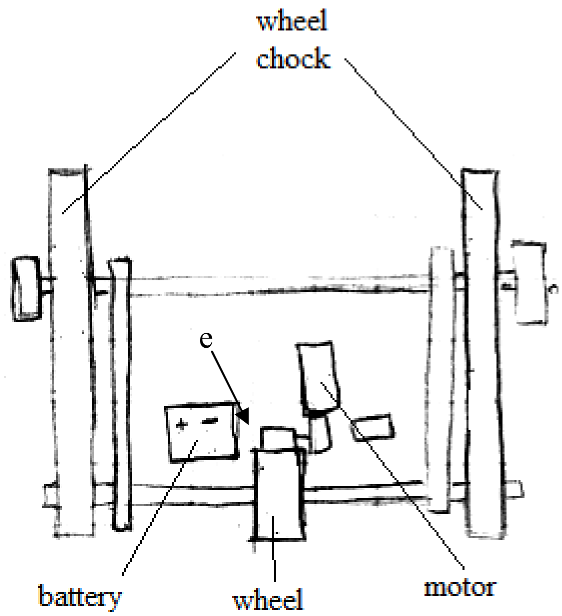

Figure 59: Carriage Layout of Design D

A throttle would be attached to the handlebars on the device. This would allow for the attendant to control speed while also steering the device. The handlebars can be seen in the rear view, Figure 60.

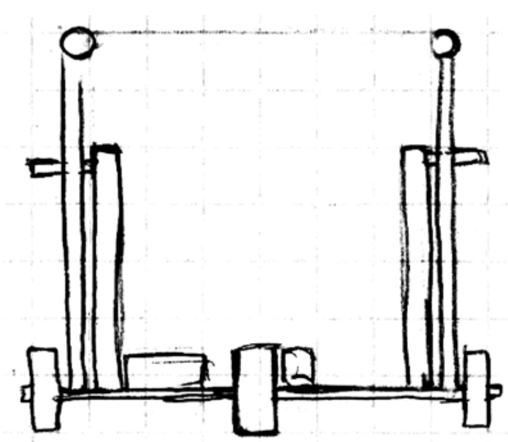

Figure 60: Rear View of Design D Carriage

Due to the fact that most manual wheelchairs have large diameter rear wheels, this design could be compatible with most wheelchairs. However, this would not be compatible with stroller type wheelchairs. Also, the diameter and other dimensions of the tire may affect the compatibility of the design. One dimension of major concern is the distance between the two rear wheels. Having the device be adaptable to different wheelbases would improve its compatibility with more wheelchairs. At first review, it is obvious that this design is larger than other options. This makes the device less conveniently portable; either because of its size, or because it would require more assembly and disassembly for transporting. Also the front wheels of the wheelchair remain on the ground and would cause the chair to be tilted forwards slightly. The tilt will be inversely proportional to the ground clearance of the device. A balance must be found between comfort and practical ground clearance.

Design E

Design E, shown in Figure 61, combines the layout idea from Design A and a modified attachment mechanism of the Design D. In addition, a steering system was added.

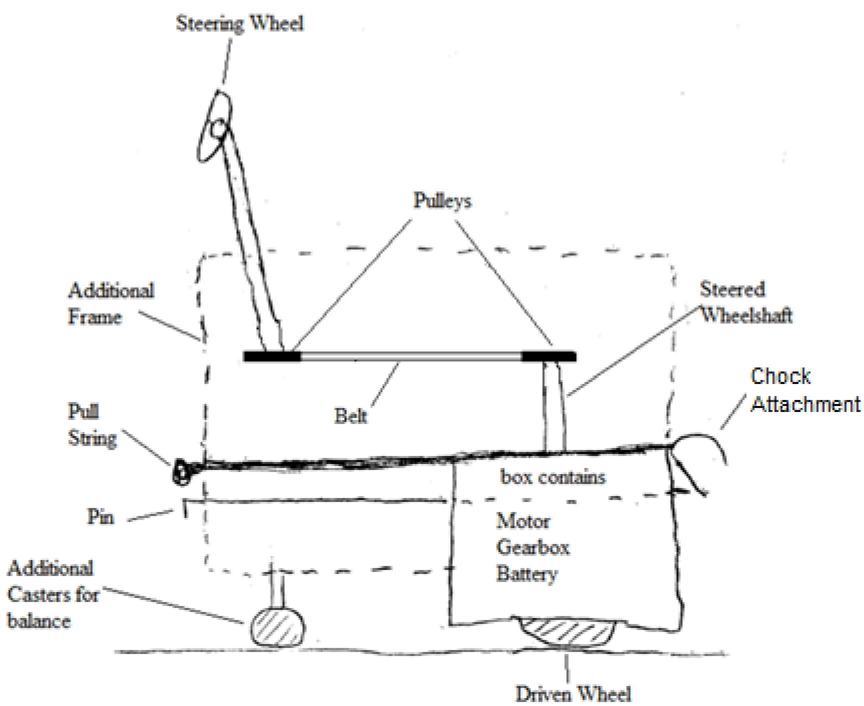

Figure 61: Design E

The “Box” of Design E, shown in Figure 62, is taken from Design A in its entirety.

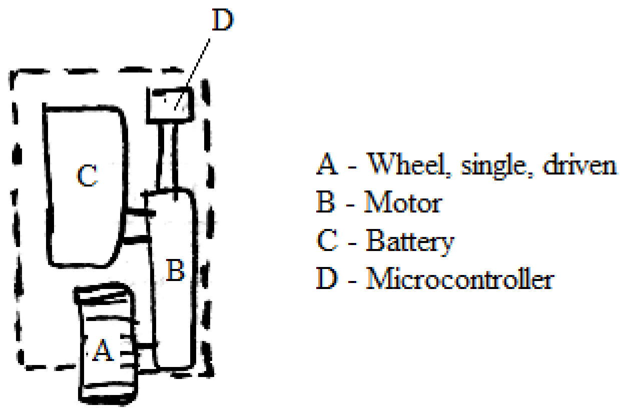

Figure 62: "Box" of Design E

However, a steering mechanism, Figure 63, was added. This was in order to eliminate the force that the user would need to exert in order to turn the device. The steering system chosen was a belt drive with a steering wheel. A steering wheel was chosen over handlebars because the drive wheel is being turned and requires more force to turn than simply a front castor wheel. With correct pulley ratios, the steering wheel will have to rotate multiple times to achieve the minimal turning radius, but will require much less force from the user.

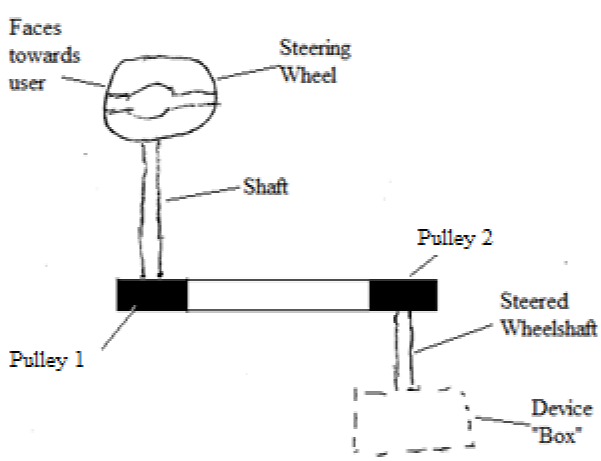

Figure 63: Steering Mechanism of Design E

An attachment like the Carriage device could be used in a smaller scale. The attachment, Figure 64, uses small chocks that are pushed into position by the horizontal bar of the wheelchair. They rotate around a pivot point and then lock by placing a pin between the two holes. Also, around the location of the pivot point, a pull string would be attached to the chock in order to pull the attachment back off of the horizontal bar. The attachment of the device would fit with many chairs, but depending on the manufacturing quality and materials used, the wheelchair may be able to detach from the device.

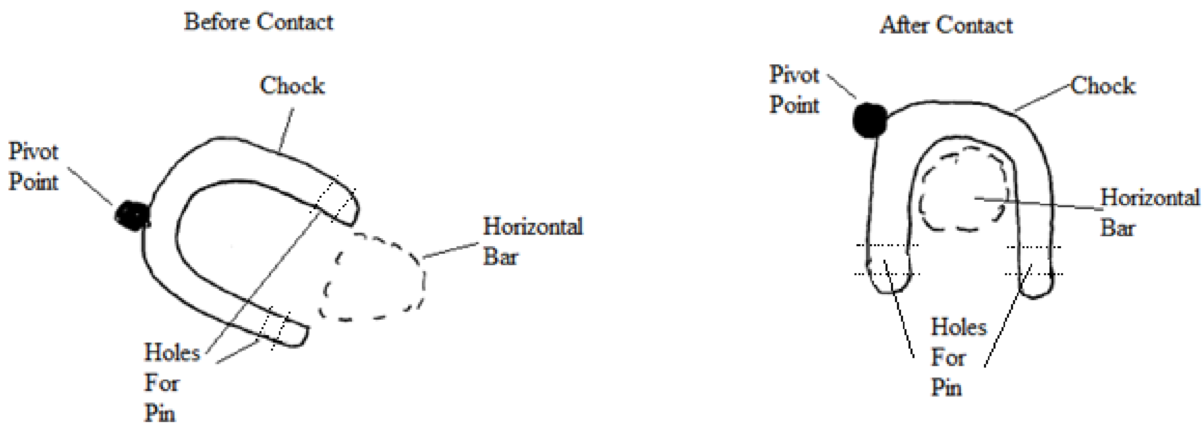

Figure 64: Attachment of Design E

A disadvantage of the device is that the drive wheel also acts as the turning wheel. Because of this, turning the drive wheel requires much more force. Pull-pull and push-pull steering would not be feasible for this device. Belt and bevel gear steering are more feasible, but the user will still need to apply excess force if handlebars were used. As described above, a steering wheel combined with a pulley system could fix this problem if there was favorable gear ratio of the pulley diameters.

Design F

This design is a modification of design B, and also uses the two wheel/two castor set-up. This design is different in its steering method, its location of the two castor wheels, and its attachment. Figure 65, Figure 66 and Figure 67 show various views of the device with the following parts labeled:

A. Motor
B. Back driven wheel
C. Castor wheel
D. Battery
E. Handles
F. Lever steering
G. Large wheelchair wheels
H. Front, steered wheel
I. Pulley system

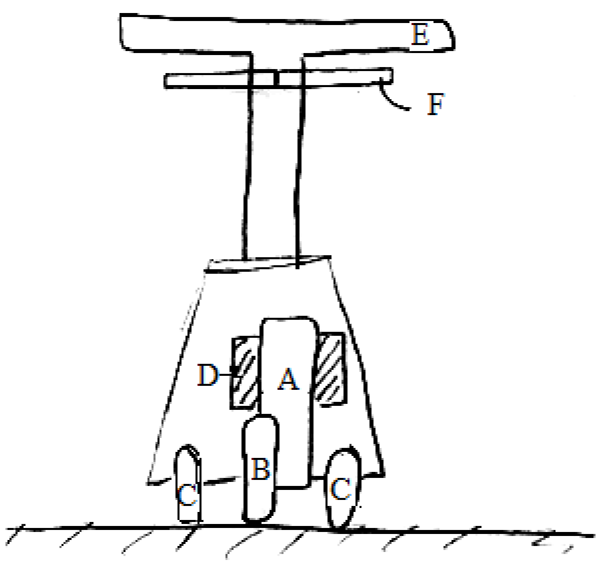

Figure 65: Back View of Design F

The castor wheels of this device have been moved forward, Figure 66, in line with the back driven wheel. This is so that there isn't the risk of losing contact with the ground when the device is transferring from a flat surface to a ramp. If the castor wheels are in line, Figure 67, then this will not be an issue.

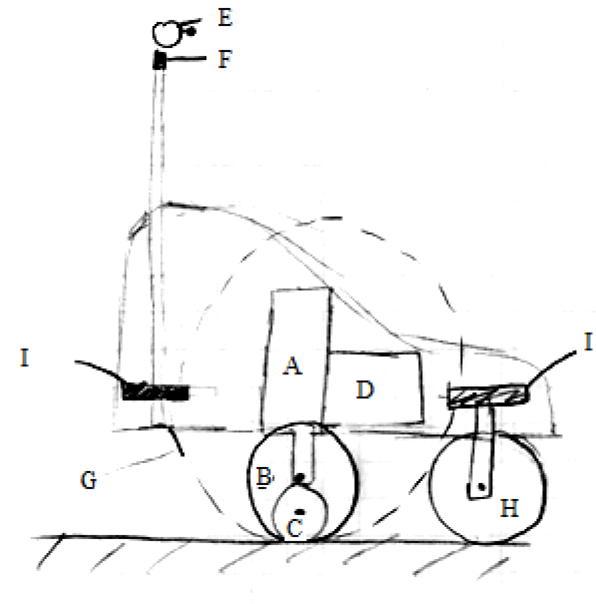

Figure 66: Side View of Design F

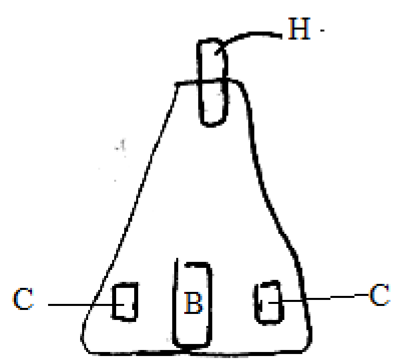

Figure 67: Top View of Design F

This design utilizes the belt pulley system of steering, described above, Figure 68. A thumb lever is used, Figure 69, to steer. By changing ratio of the diameters of the two pulleys, pushing the thumb lever could be made easier. The friction of the wheel with the ground would be difficult to overcome but providing a mechanical advantage will make it easier for the thumb to turn the device. It is also possible to flip the design and use a finger throttle. The diameter ratios can also be changed to make it so that a small rotation of the thumb or fingers will result in a larger rotation of the front wheel. This will most likely be necessary because the thumb and fingers do not have much freedom to move with this design. Unfortunately, both of these advantages require opposite pulley ratios. Where mechanical advantage requires the front pulley to be larger, turning advantage requires the front pulley to be smaller.

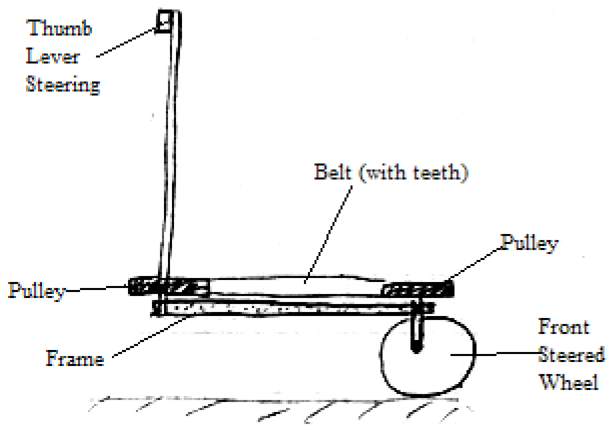

Figure 68: Side View of Design F Pulley Steering Mechanism

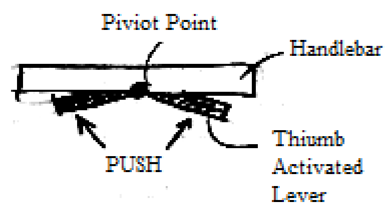

Figure 69: Top View of Design F Handlebars

The attachment utilizes a latch concept. When the device is driven up to the wheelchair, Figure 70, the horizontal bar which is either already on the wheelchair or used as a supplemental attachment, will push against the side of the mouth, causing the mouth to rotate about its pivot point, Figure 71. Once in the position shown in Figure 71, a pin that is spring loaded will poke out of the bar and into a hole in the mouth which lines up the bar and the mouth in this position.

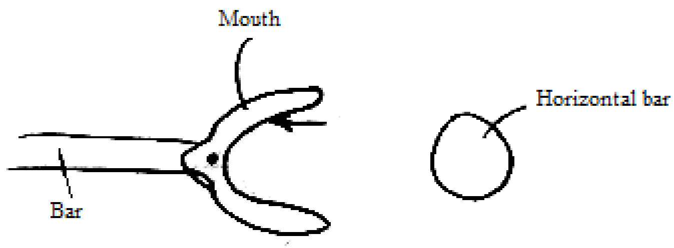

Figure 70: Side View of Design F Attachment

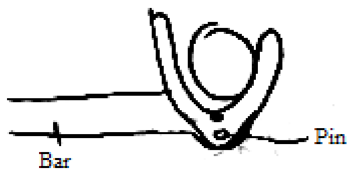

Figure 71: Side View of Design F Attachment When Actuated

The pin will be disengaged by a lever on the side of the handles, Figure 72, which is attached to the attachment by a cable. Moving the lever down will pull the cable up and disengage the pin.

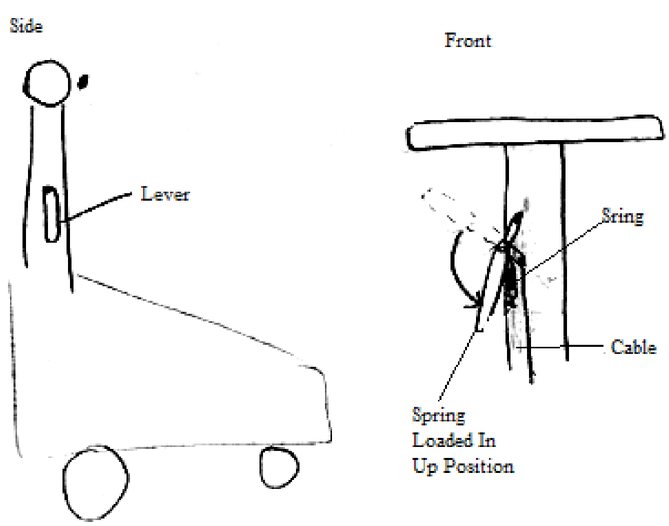

Figure 72: Side View of Attachment/Detachment Hand Mechanism of Design F

The pin will be disengaged when the cable is pulled by pulling a small piece located inside the bar. This will allow the pins to move inward and separate from the mouth piece (Figure 73).

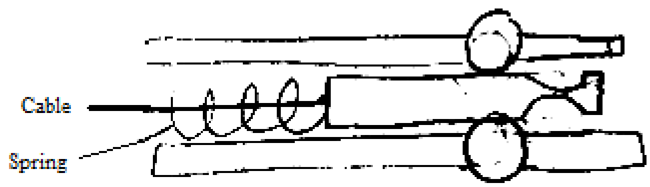

Figure 73: Pin Disengagement of Design F

A problem with this device is that although the driven wheel will not lose contact with the ground when moving from a flat surface to a ramp because of the castor wheel location, it might still lose contact when moving at an angle up a ramp, or over a curb. Also there is the problem with the need for pulley diameter ratios mentioned earlier. Lastly, the attachment locking mechanism is not a reliable design for a device expected to experience forces higher than a few pounds. The pins could be too feeble and release at dangerous or bad times. This design incorporates new ideas for the pusher device, but they do not all work well together.

Design G

Design G combines some of the features of previous designs A-D while incorporating some improvements to problems that were identified with these designs. Design G incorporates a similar frame to the frame that was used in Design B. It has a steering wheel at the front and the driven wheel in the back labeled “A” in Figure 74.

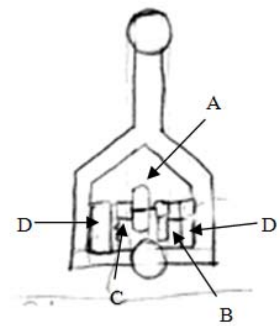

Figure 74: Top View of Design G

In the figure, “B” is the motor, “C” is the battery, and “D” is the attachment arms. These attachment arms are shown more clearly in Figure 75. The attachment arms will hold two attachment clamps which will clamp on to the horizontal bar of the wheelchair. These attachment arms are hinged at the point shown and will lower and lock down on the horizontal bar. There will be a seatbelt incorporated into this design which will wrap around the back seat of the wheelchair to add an additional attachment feature. Also, the “hinged rod” shown in Figure 75 is the shaft for the front pulley of the pulley steering system. This rod will have the ability to bend so that a belt can be attached or replaced.   After the belt is attached, the rod will be placed and locked upright.

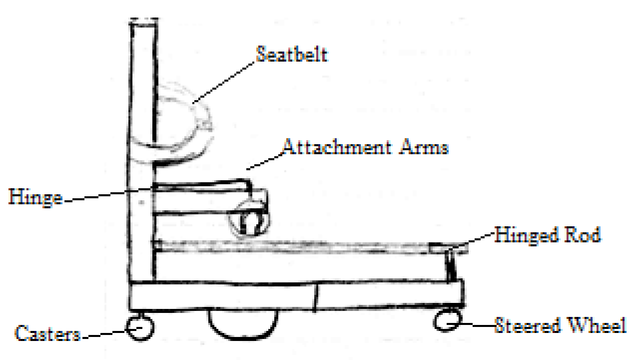

Figure 75: Side View of Design G

The attachment for this device is the Caliper Clamp design mentioned above in New Attachment Designs.

Figure 76 shows an isometric view of Design G. With this view, the handlebars are most clear. One of the problems with previous designs that used the pulley steering system was with the rigidity of the pulley shafts. If these shafts aren't completely rigid, the system can shift and misalign. To fix this problem, there will be an additional part added to the frame that will support the handlebar shaft. This addition will have bearings so that the handlebars will still rotate freely.

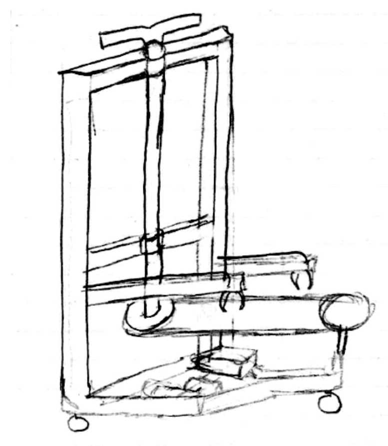

Figure 76: Isometric View of Design G

This design combines many components from previous designs and improves on some of the components and concepts. The steering method used in this design is a pulley steering system. Unlike bevel gears, the pulley steering system would not bind up with small movements. However, there are some space requirements associated with the pulley steering system. The pulleys and belt must be raised a few inches above the bottom of the frame. Also, with this design, the handlebars would be supported in two places and therefore, the handlebar shaft would be stable enough to support one pulley of the pulley steering system. The attachment mechanism in this design is unique because it clamps from above. The method to lock this clamp is simple and would not require the user to bend over.

Design H

This design, Figure 77, is based on previous design concepts with other modified components. This design consists of a drive wheel, a steering front wheel, two trailing casters, pull-pull steering, a hinged motor mount, and a cable operated attachment mechanism. The device is turned using handlebars, which control the front wheel though a pull-pull system further explained in the steering methods section. The attachment mechanism is operated by the attendant through means of a lever. Once the wheelchair is engaged a thumb throttle attached to the handlebars is used to control the speed of the device.

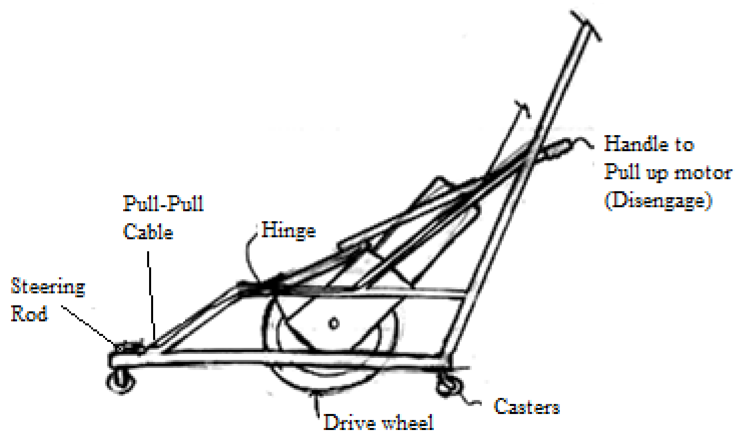

Figure 77: Design H Side View

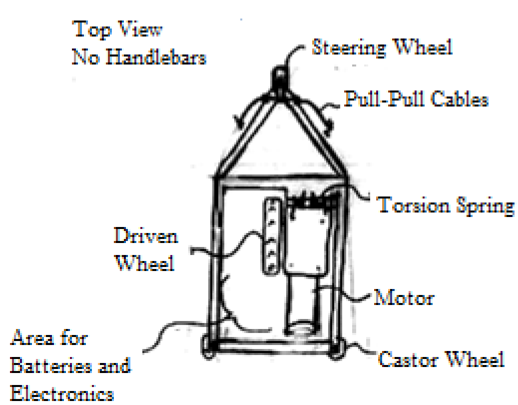

Figure 78: Design H Layout

One unique feature of this design is the modified motor mount. This motor mount is hinged so that the motor rotates around point A in Figure 79. This will allow for the motor to maintain contact with the ground when the device is on varying terrains. Another feature of this motor mount is that it has a preloaded torsion spring that applies a constant rotational force. This forces the drive wheel against the ground, providing a normal force needed for propulsion. Having the motor on a hinge would also allow for the motor to be disengaged from the ground if the torsion spring was overcome. A problem with this design is that the normal force on the motor could never be more than what the spring can apply, making it necessary to have a very stiff spring. Having high preloaded forces in the design can be dangerous and results in higher stresses on the device. If the operator were to want to disengage the motor from the ground, he or she would have to overcome the torsion spring, which may not be possible for the entire target market.

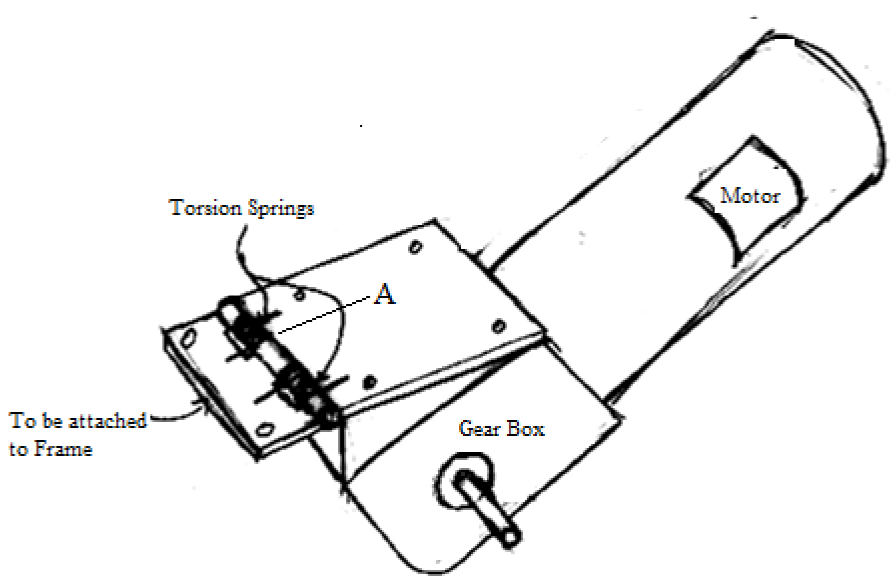

Figure 79: Motor Mount for Design H

Design Selection

Once four preliminary designs were sketched and discussed, a design selection matrix was used to set the best designs apart from the rest. Each main aspect of designs A through D were rated and placed in the decision matrix. From there, the best aspects of each design were identified and then combined to create new hybrid designs of the first four; these are designs E through H. Creating these hybrid designs allowed the analysis of the original 4 designs to determine which components were the best and most compatible.

First Decision Matrix

A pair-wise comparison chart, shown in Appendix A, was used to rank the major design goals of the project. The design goals were compared side by side and consequently ranked by importance. The ranked goals were assigned different weighting factors based on the values obtained in the pair-wise comparison chart. This is displayed in a weighing factor chart in Appendix B. These weighting factors are used as the multiplying values in the decision matrix.

In order to appropriately score each design, a list of parameters were developed that each design should ideally meet. The design selection criteria were determined based on the design specifications. Each design would have received the same score for some design specifications. Because of this, some specifications were left out of the selection criteria for simplicity. Other selection criteria were added when needed to distinguish important differences between the designs.

The following parameters listed in terms of category are:

Safety

1. The device cannot be unintentionally detached.
2. The wheelchair occupant cannot be thrown from their chair.

3. No one can be harmed by the device.
4. The device stops in less than 10 feet (as stated by design specs).
5. The wheelchair remains in place when not in use (parking brake).
6. The device is statically and dynamically stable at an incline of 5 degrees.

Performance

1. The turning radius of the device, when attached to the wheelchair, meets ADA standards.
2. This device has a near zero degree turning radius when attached to the wheelchair.
3. The steering method is intuitive to use.
4. The device can travel in forward and reverse.
5. The device does not impede the wheelchair's functionality (i.e. going through doorways, maneuvering through the environment).
6. The device can go into neutral by disengaging the motor without any back driving of gears.
7. The steering method of the device does not include slip steering.

Ease of Use

1. The device is useable by a single attendant.
2. It is easy to learn how to use the device.
3. The device is intuitive to use.
4. The device does not need tools to attach/detach.
5. The user doesn't have to exert a high force (greater than 25 lbs) at any point of operation.
6. The user will not have to bend over to attach, detach, or use the device.

Compatibility

1. The attachment mechanism fits under the smallest chairs (12 inches wide, 9 inches high).

2. The device works the same way with all types of chairs.
3. The device does need a supplemental attachment in order to fit certain wheelchairs.

Weight

1. The device does not need to be disassembled to meet the weight requirement.
2. No single disassembled part of the device weighs more than 30 pounds.

Portability

1. The device fits in a 4-door car.
2. The device fits into the trunk of the car.

A binary selection matrix was created based on these parameters and for every parameter, each design was given a score of one or zero. A score of one indicated that the design met the parameter and a score of zero indicated that the design did not meet the parameter. The scores of each category were added up and placed in a scoring matrix, shown in Table 1, in the yellow rows. The weakness of a binary rating scale is that it can be difficult to distinguish which designs achieve certain standards *better* than others. For this reason, the designs which met each individual parameter best were observed.

Table 1: Binary Selection Matrix for Designs A - D

	Design A	Design B	Design C	Design D
Safety				
1	1	1	1	0
2	0	1	0	0
3	1	1	0	0
4	1	1	1	1
5	1	1	0	0
6	1	1	1	0
Total	**5/6**	**6/6**	**3/6**	**1/6**
Performance				
1	1	1	1	1
2	0	0	1	0
3	1	1	0	1
4	1	1	1	1
5	1	1	0	0
6	0	0	1	0
7	0	1	1	0
Total	**4/7**	**5/7**	**5/7**	**3/7**
Ease of Use				
1	1	1	1	0
2	1	1	1	1
3	1	1	0	1
4	1	1	1	1
5	0	1	1	0
6	1	0	0	1
Total	**5/6**	**5/6**	**4/6**	**4/6**
Compatibility				
1	1	1	0	0
2	1	1	0	0
3	0	0	1	1
Total	**2/3**	**2/3**	**1/3**	**1/3**
Weight				
1	1	1	0	1
2	1	1	1	0
Total	**2/2**	**2/2**	**1/2**	**1/2**
Portability				
1	1	1	1	1
2	1	0	1	0
Total	**2/2**	**1/2**	**2/2**	**1/2**

Each score in the binary selection matrix was multiplied by 10, and placed in the decision matrix shown in Table 2. The decision matrix displays the weighing factor for each major design goal, and the score of each category of the binary selection matrix. The weighting factor of each design goal was multiplied by the binary matrix score received in that section by each design. The total grade received by each design is displayed in the right hand column.

Table 2: Decision Matrix for Designs A -D

	Safety x 10	**Performance x 7**	**Ease of Use x 6**	**Compatibility X4**	**Portability x 2**	**Weight x 1**	**Total**
Design A	8.34	5.714	8.34	6.67	10	10	**230**
Design B	10	7.142	8.34	6.67	5	10	**247**
Design C	5	7.142	6.67	3.34	10	5	**178**
Design D	1.67	4.285	6.67	3.34	5	5	**115**

The design which was rated the highest was Design B, followed closely by Design A. Both designs received much higher grades than Designs C and D. When comparing Designs A and B, it was observed that Design B scored higher in all criteria except in portability. Design A fits both in the trunk of a car and in the back seat of a car, while Design B only fit in the backseat of a car. Design A was much smaller which is why it would fit in a car trunk so the team had to consider how to make Design B more portable. Making Design B collapsible would make it more portable.

The team also looked at the binary decision matrix to analyze where Design B received a score of zero. If another design received a score of one under a parameter, the team had to determine if the same concept could be incorporated into Design B to improve it. For example, with Design B, the user would have to bend over to attach, detach, or use the device. The attachment methods which did not require bending over were explored to see if they were compatible with Design B. Also, Design B cannot go into neutral without back driving the motor gears. Design C could go into neutral because the motor could be removed from the wheels so that the wheelchair could move freely when the device wasn't in use. Possibly, a component could be designed to remove the driven wheel from the ground, essentially bringing the device to neutral.

From the decision matrix, it was deduced that an independent/separate device with one wheel, two wheels, or three wheels is better for the basic drive system, as opposed to a device which drives the wheelchair wheels, or lifts all or part of the wheelchair off of the ground. This is because of space limitations, complexity of design, and user comfort. It was also concluded that the device needs to be attached to the wheelchair in more than one way. A belt from the device around the chair in addition to the attachment would ensure that even if the attachment failed, the device and the wheelchair would remain connected. This will require additional steps for the user, but might be essential in ensuring the safety of the wheelchair occupant.

Second Decision Matrix

Once Designs A through D were sketched, discussed, and rated based on design criteria, it became apparent that another round of invention was necessary to create better designs to choose from for the final. Four additional designs, E through H, are based on the highest rated concepts from designs A through D and steering and attachment design ideas which were researched and brainstormed. These four additional designs were placed in a second decision matrix with the same criteria as were used to rate the first four designs. The scoring matrix for designs E-H is in Table 3 and; the decision matrix is in Table 4.

Table 3: Binary Selection Matrix for Designs E-H

	Design E	Design F	Design G	Design H
Safety				
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	0	0	0	0
6	1	1	1	1
Total	**5/6**	**5/6**	**5/6**	**5/6**
Performance				
1	0	1	1	1
2	0	0	0	0
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1
6	0	0	0	1
7	1	1	1	1
Total	**5/7**	**5/7**	**5/7**	**5/7**
Ease of Use				
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	0	1
6	1	1	1	1
Total	**6/6**	**6/6**	**5/6**	**6/6**
Compatibility				
1	0	0	0	1
2	1	1	1	1
3	0	0	0	0
Total	**2/3**	**2/3**	**1/3**	**2/3**
Weight				
1	1	1	1	1
2	1	1	1	1
Total	**2/2**	**2/2**	**2/2**	**2/2**
Portability				
1	1	1	1	1
2	0	1	0	1
Total	**1/2**	**2/2**	**1/2**	**2/2**

These totals were placed into the same decision matrix shown in Table 4.

Table 4: Decision Matrix for Designs E-H

	Safety x 10	Performance x 7	Ease of Use x 6	Compatibility X4	Weight x 2	Portability x 1	Total
Design E	8.34	7.142	10	3.34	10	5	**232**
Design F	8.34	7.142	10	3.34	10	10	**237**
Design G	8.34	7.142	8.34	3.34	10	5	**222**
Design H	8.34	7.142	10	6.67	10	10	**237**

The highest scoring designs were F and H. Design F scored lower than H in compatibility because Design F utilized a pulley steering mechanism and this method most likely would exceed the minimum nine inches to fit underneath a wheelchair. Design H incorporated a pull-pull steering mechanism and this would more easily meet the space requirement. Since each design scored nearly the same, there was a discussion of what concepts in each design were the best. It was concluded that the best wheel set-up for the design would be a 2 wheel setup with two castor wheels for support. From here, the steering mechanism and attachment mechanism concepts were examined further to determine which was the best for the two-wheel design.

Steering and Attachment Mechanisms

A design was finalized based on the components that were most beneficial in the existing designs, including a single drive wheel and a single turning wheel. When looking at the best steering mechanism and attachment mechanism, it was important that the components were compatible with each other, and it was decided that the attachment and steering still needed to be examined. The different designs for attachments and for steering were put into a binary decision matrix. The design selection criteria again were based on the design specifications.

The following 4 parameters were taken into consideration when analyzing steering.

1. The steering is intuitive (turn handlebar right, move right; push button on right side, move right).
2. The steering mechanism can fit easily into the space constraints of the device (most likely needs to fit underneath the wheelchair, in a 14in wide, 9 in high space).
3. The steering mechanism will continue to work correctly even when the device in under a high load scenario, such as when the wheelchair is changing from a flat surface to a slanted one.
4. The steering mechanism cannot get stuck or break under normal conditions.

The following 8 criteria were used in analyzing attachment mechanisms.

1. The attachment mechanism will continue to work correctly in all circumstances (even in such cases as when the wheelchair is changing from a flat surface to a slanted one).
2. The attachment mechanism can fit into the space constraints of the device (most likely needing to fit underneath the wheelchair, in a 14in wide, 9 in high space).
3. The attachment will be intuitive to use.
4. The attachment engages automatically (pin placement not necessary, or to switch a lever, etc when attaching it to the chair).
5. The attachment will not require bending over to attach.
6. The attachment will not require bending over to detach.
7. The attachment works the same way with all types of chairs.
8. The attachment does need a supplemental wheelchair attachment (such as horizontal bar) in order to fit certain wheelchairs.

Each of the four designs for steering: push-pull, pull-pull, bevel gear, and belt, and each of the four designs for attachments: retracting carabiner, caliper clamp, fence latch, and cable lock were rated on a binary scale. On this scale, a score of 1 was given to a design which met the criterion and a score of 0 was given to a design that did not meet the criterion. The scores of each category were added up and are shown in Table 5 in the yellow rows. The designs with the highest scores had the best compliance with the design criteria.

Table 5: Steering and Attachment Decision Matrix

Steering	Push-Pull	Pull-Pull	Bevel Gear	Belt
1	1	1	1	1
2	1	1	0	0
3	0	1	0	1
4	0	1	0	1
Total	**2/4**	**4/4**	**1/4**	**3/4**
Attachment	Retracting Carabiner	Cable Lock	Fence Latch	Caliper Clamp
1	0	1	1	0
2	1	1	1	1
3	0	1	1	1
4	0	0	1	0
5	0	1	1	1
6	0	1	0	1
7	1	1	1	1
8	0	0	0	0
Total	**2/8**	**6/8**	**6/8**	**5/8**

The results of the decision matrix show that the best steering method is pull-pull steering. Push-pull steering works in the same way as pull-pull steering, and requires fewer parts and less space in the design, but received a lower score because some cable types may bind under high loads. If push-pull cables can be found which would not load under the forces expected in this device then these may also be used. These cable designs are intuitive, would fit the best under most chairs, would not bind up or develop problems if there were small changes in alignment of the device, and would most likely be able to be folded or transported.

Due to the safety issue regarding the possibility of the device detaching with the fence latch attachment the decision was left to the fence latch and the cable lock. The cable lock attachment is superior because it will easily fit into the small confinement of the device, and it has a degree of freedom where the device does not have to line up perfectly with the horizontal back.

After exploring the cable lock attachment further, it was determined that this device would work well attaching and detaching and would work well when the device was pushing uphill, however, the cable system may not hold well pushing downhill since the cables would receive the full weight of the wheelchair and user. The team deduced that a clamp, rather than a cable, would work best. After further research, an attachment mechanism that would support both directions of movement was a toggle clamp. This method would be sturdy enough to support the force both going up and downhill and could be adapted to device in a way that would attach and detach easily.

The attachment mechanism must be able to withstand the force both when the wheelchair is moving up and down a hill. Toggle clamps are often activated by lifting or lowering a lever which will open the clamp. The clamp is closed and locked by lowering this lever. A toggle clamp could easily be incorporated into our design and the action of lowering the lever could be activated by the foot so that the user would not need to bend down to attach or detach the device. The horizontal toggle clamp in Figure 80 could be attached to the design at the height of the horizontal bar located underneath the wheelchair. Many wheelchairs have this horizontal bar underneath the seat of the wheelchair between the axles of the wheels. The spindle on the front could be replaced with either a C-shaped attachment or angle iron. When the wheelchair was driven up to the device, this clamp would be in the open position. The lever would then be pushed down to close the device and clamp around the horizontal bar.

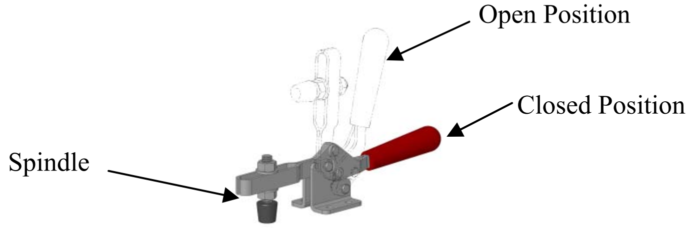

Figure 80: Toggle Clamp (Toggle-clamp manual horizontal 3D closed outline, 2007)

Final Design Description

Based on evaluation of preliminary designs the final design was developed and is shown in Figure 81.

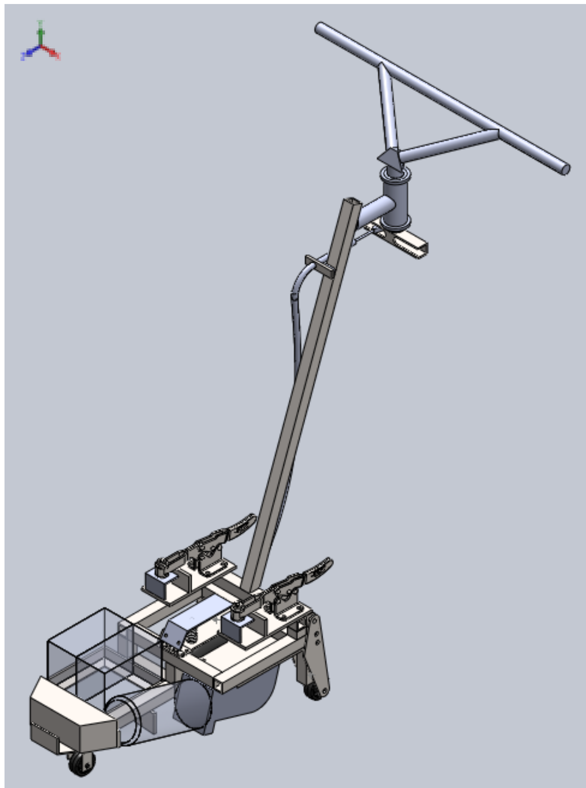

Figure 81: Device Assembly Model

The frame of the device is made completely of 1" steel tubing welded together. The battery tray, motor mount, and attachment mounts are also welded to the frame. The battery tray, Figure 82, is made from 1" angle iron welded together.

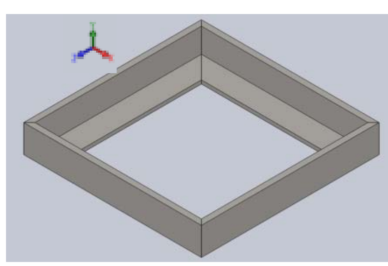

Figure 82: Battery Tray Model

The motor mount, Figure 83, is made from a plate of ¼” steel. Holes are drilled through the plate to match the bolt pattern of the electric motor. The motor mount is welded to the frame of the device and the motor is mounted using 4 bolts.

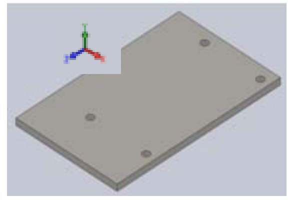

Figure 83: Motor Mount Model

The attachment mounts are also made from ¼” steel with a vertical piece welded on and holes drilled to attach the horizontal toggle clamps. The toggle clamps, which were modified to include a piece of $^{1}/_{8}$” angle iron bolted at the end, are bolted to each of the attachment mounts, Figure 84.

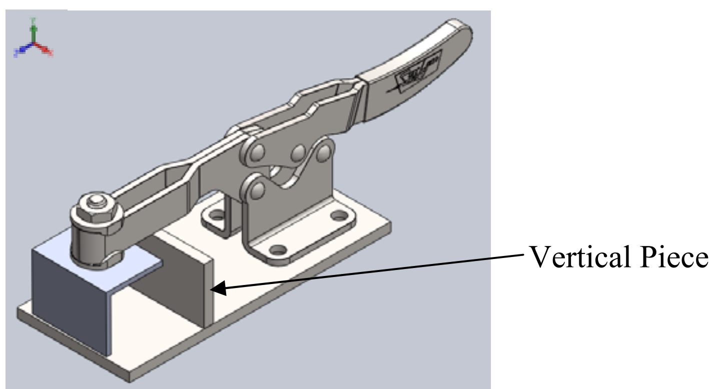

Figure 84: Toggle Clamp and Attachment Mount Model

The device attaches to the horizontal bar, aligned vertically with the axis of the wheelchairs rear wheels. A supplemental horizontal bar attachment will be installed in wheelchairs that do not already have a horizontal bar, Figure 85 and Figure 86.

Figure 85: Wheelchair with Installed Horizontal Bar

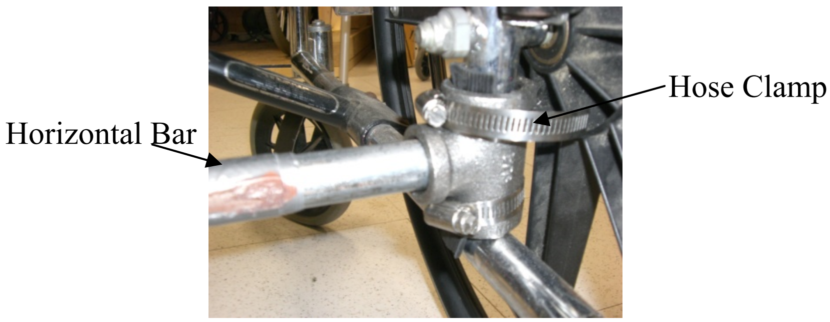

Figure 86: Horizontal Bar

For the prototype design, a steel 1” and ¾” pipe T was cut in half at an angle and the sides were sanded down, Figure 87. ¾” inch conduit was cut to fit in between the back post extensions of the wheelchair. To install, the conduit was placed in the center tube of the T. The T’s were also lined with rubber so that they would not slide up and down the back post extensions as easily. Each half of the T was placed around the back post extensions of the wheelchair and was clamped with hose clamps, Figure 86.

Figure 87: Pipe T

The vertical piece of the attachment mounts act as a “bumper” for the horizontal bar (Figure 84). The angle iron of the toggle clamps locks around the front of the horizontal bar to secure the device. The attachment mounts are welded to the frame so that the horizontal bar of the wheelchair will be positioned. To attach the device to the wheelchair, the toggle clamps are open, Figure 88, and the device is driven up to the back of the wheelchair. The clamps close around the horizontal bar to secure the device, Figure 89.

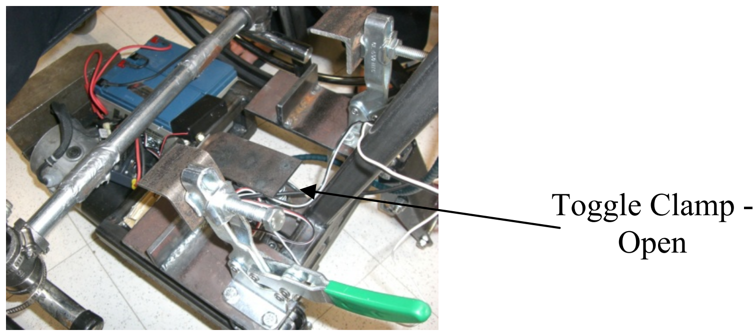

Figure 88: Device Before Attachment

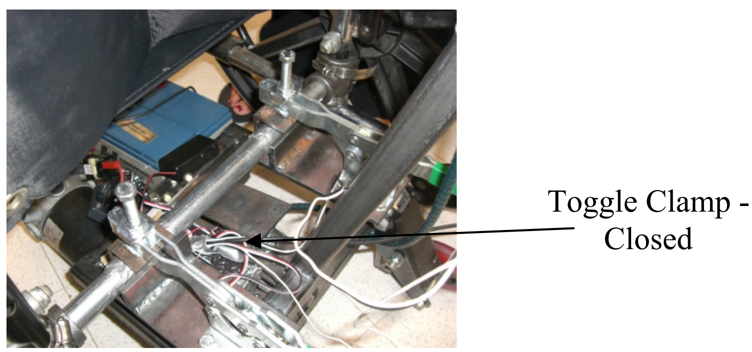

Figure 89: Device Attached

The device, Figure 90, is powered by an Invacare electric wheelchair motor that is bolted to the motor mount. A 6” wheel is attached to the motor’s axle. The axle of the driven wheel is in line with the axle of the rear wheelchair wheels in order to best accommodate turning. The motor runs on two 12-volt batteries located at the front of the device in the battery tray.

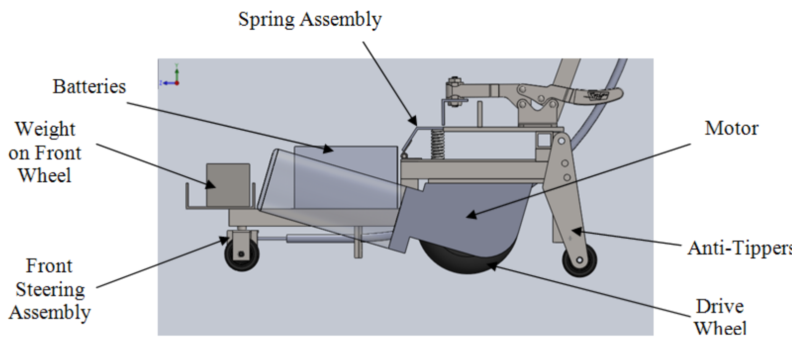

Figure 90: Right Side View of Device Model

The device is steered by a push-pull cable. The cable is attached on one end to the handlebars and on the other end to the front steered wheel. An arm, Figure 91, is welded to the bottom of the handlebars and tie-rods are bolted in. The cable threads into the tie-rod to allow for a full range of motion when steering.

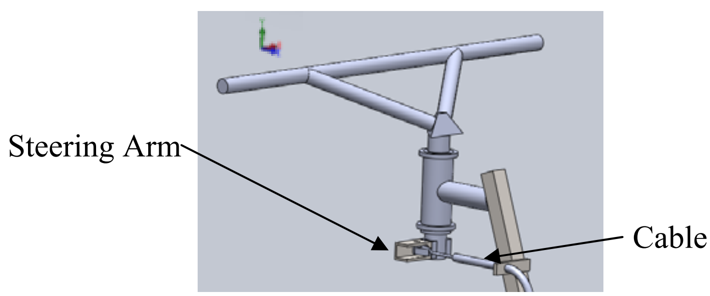

Figure 91: Steering Assembly Model

The front steered wheel, Figure 92, has a vertical post that bolts to the front of the frame to allow for rotation of the front wheel. There is also weight added to the front wheel to create more normal force and better traction. A weight tray, Figure 93, was made out of steel and this piece was bolted on to the vertical post of the front steered wheel. A steel block is placed in this tray to add the necessary weight to the front wheel. There are thrust bearings on either side of the weight tray to allow for smoother rotation of the wheel.

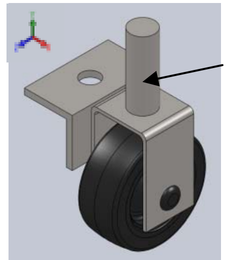

Figure 92: Front Steered Wheel Model

A piece of angle iron was bolted to the front steered wheel and a tie-rod was bolted to this angle iron with a shoulder bolt. The cable end threads into this tie-rod. When the user turns the handlebars, the movement of the cables will cause the steered wheel to turn simultaneously, Figure 93.

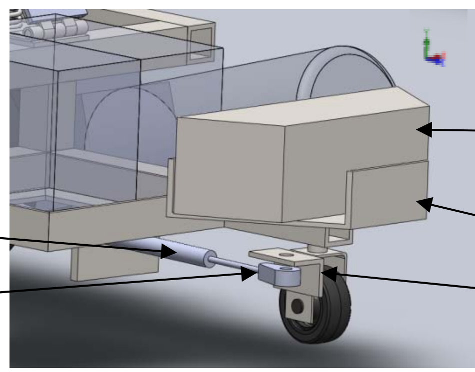

Figure 93: Front Steering Assembly Model

The device contains two casters on the back for stability, Figure 94. The part of the anti-tipper assembly of an electric wheelchair that includes the castor wheel was used in this device subassembly. A piece of steel tubing was cut and drilled to mate with the anti-tipper piece. A spring was then connected to both the anti-tipper piece and the steel tubing to complete the assembly. This anti-tipper subassembly acts similar to that of an electric wheelchair and keeps the casters on the ground when driving the device from flat to up and down hill. This will keep the device stable as well. Springs and anti-tippers from an electric wheelchair were modified to be used in this subassembly.

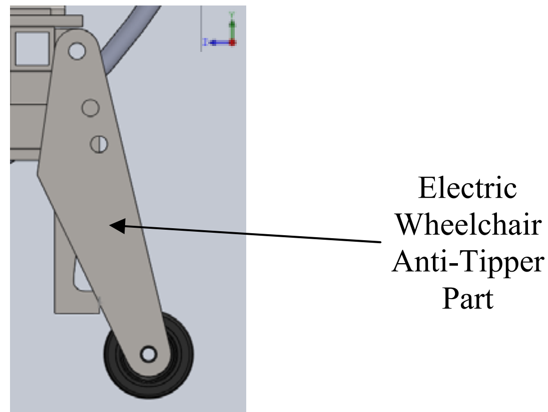

Figure 94: Back Caster Wheel Model

The spring assembly shown in Figure 95 was added so that the device could take some of the weight of the wheelchair. The assembly does this through the use of a compression spring. The four main parts of the spring assembly: the ramp, hinge, spring, and base, can be seen in Figure 96.

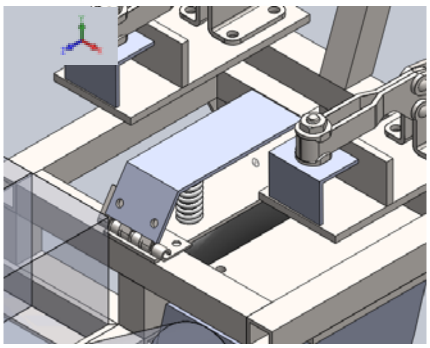

Figure 95: Installed Spring Assembly Model

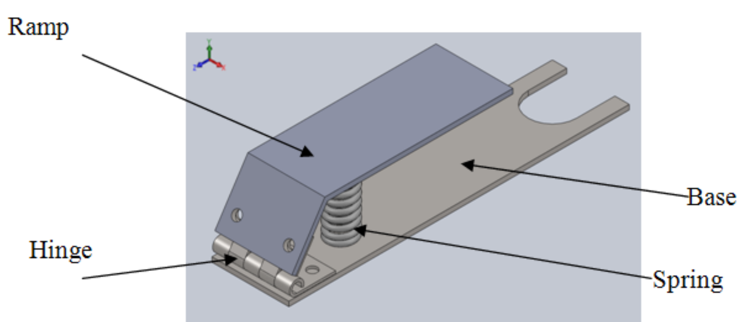

Figure 96: Spring Assembly Model

The spring assembly is located between the two clamp bases. When there is no chair attached to the device, the spring is at rest and the ramp is above the level of the clamp bases. When the device begins to engage with the wheelchair, the horizontal bar pushes down on the ramp and compresses the spring (Figure 97). The location of the spring and spring constant determine the force that gets applied from the horizontal bar to the device. Due to the location of the spring assembly, the force applied by the wheelchair is directly above the axle of the device's drive wheel. This force increases the normal force between the drive wheel and the ground. Increasing the normal force increases the friction force and allows the device to operate with more traction on more slippery surfaces.

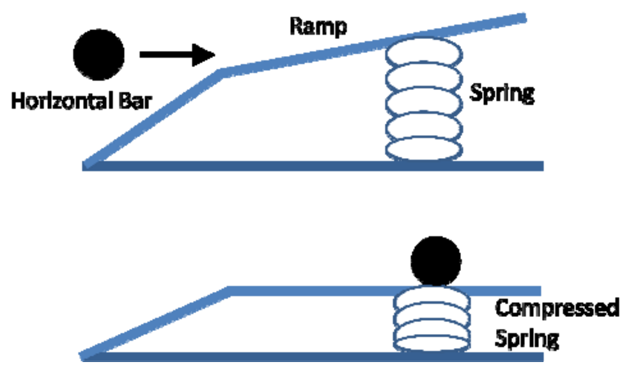

Figure 97: Spring Subassembly in Both Positions

The motor is controlled by the operator through the use of a thumb operated throttle. The throttle is mounted to the handlebars allowing the operator to both steer and control speed simultaneously. The equipment required to control the motor includes; a motor controller, a microcontroller, and a thumb throttle. These are connected as shown in Figure 98.

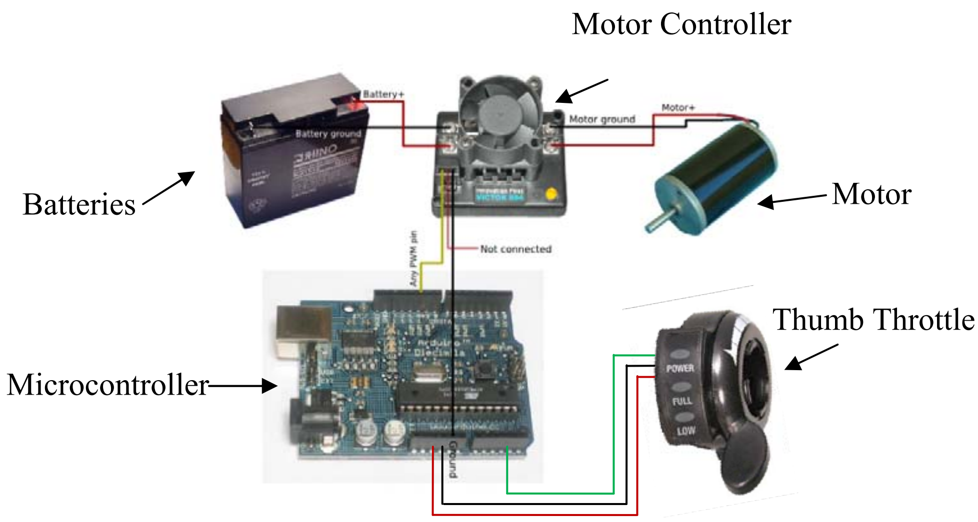

Figure 98: Electronics (Modified from http://img185.imageshack.us/img185/961/victormc4.png)

The microcontroller receives the information from the operator through the thumb throttle, and then signals commands to the motor controller. The motor controller then controls the amount of power available to the motor, thereby controlling the speed. Inside of the throttle there is a Hall Effect Sensor. This sensor detects the position of a magnet that is moved as the throttle is twisted. The Hall Effect sensor is modeled as a voltage divider in the design. The microcontroller supplies the sensor with 5 volts. As the throttle is twisted, the voltage of the signal wire (green) changes. The microcontroller then reads the analog change in voltage and converts it to a digital Pulse Width Modulation (PWM) signal. This PWM signal is then sent to the pre-programmed motor control. The motor controller then controls the speed of the motor (from stopped to full speed). A battery level indicator is included on the throttle and gives the operator visual feedback on the voltage level of the battery. The motor controller also includes calibration and motor braking. The motor controller, microcontroller and thumb throttle allow the operator smooth and intuitive control over the device.

Failure Analysis

Failure analysis was required before purchasing parts and manufacturing the device. Ensuring the correct normal forces on the wheels as well as the affect of external forces on the device was crucial to designing a fully operational prototype. For example, the drive wheel required a certain normal force from the ground so that the wheel would not lose traction and leave the device stationary. The forces applied on the device from the wheelchair and from the user were also considered in the analysis. The program MathCAD was used throughout the analysis to evaluate the static and stress equations. ANSYS was used to perform Finite Element Analysis.

Center of Gravity

The center of gravity of a wheelchair with a person sitting in it was calculated so that the effect of the device on the wheelchair could be determined. The device must not negatively affect the stability of the wheelchair during its use. A study from the Journal of Rehabilitation Research and Development included a test to find the center of gravity for a wheelchair (Lemaire et al., 1991). By recreating a modified version of this test, the center of gravity was found for two scenarios, both with the same wheelchair, but with one heavier and one lighter person in the wheelchair.

A balance platform was created using a sheet of plywood and with two short 2x4 inch boards on opposite edges attached underneath. The platform and support setup has a known center of gravity in the middle, assuming that the plywood has homogeneous density and the supports are approximately the same. By placing the balance platform on a scale and a stable object of equal height, the scale reading can be recorded and used in the provided equation. See Appendix C for complete calculations.

Equation 1

$$R_{rwx} := \left[r_{1x} - \left(\frac{r_{1x} \cdot w_{scx} - r_{2x} \cdot w_{bpx}}{w_{wsx}} \right) \right] - r_{rwx}$$

Where:

w_{sc} = Weight reading from scale

w_{bp} = Weight of balance platform

w_{ws} = Weight of the wheelchair + weight of the occupant

r_1 = distance between the two pivot points

r_2 = distance from the pivot point to the balance platform's center of gravity

R_{rw} = distance from the rear wheel axle to the occupant-wheelchair center of gravity

r_{rw} = distance from the scale to the rear wheel axle

The only unknown in the equation is R_{rw}. All other values were measured prior to the experiment, with two different values of w_{ws} (107 and 235 pounds) depending on the occupant. These values were substituted into Equation 1 and the distances are shown in Table 6. Figure 99 illustrates the axes of reference. It is assumed that the center of gravity of a 235 pound person on a 33 pound manual wheelchair is similar enough to the center of gravity of a 300 pound person wheelchair combination, which is the maximum wheelchair and occupant weight expected.

Table 6: Center of Gravity Measurements

Horizontal Center of Gravity	Weight of person + wheelchair	Scale reading	Distance of COG from front wheel (X Direction)
107lb Subject	140 lbf	90 lbf	**11.4 in**
235lb Subject	268 lbf	146.5 lbf	**9.6 in**

Vertical Center of Gravity	Weight of person + wheelchair	Scale reading weight	Distance of COG from front wheel (Y Direction)
107lb Subject	140 lbf	89.5 lbf	**13.3 in**
235lb Subject	268 lbf	177.5 lbf	**9.3 in**

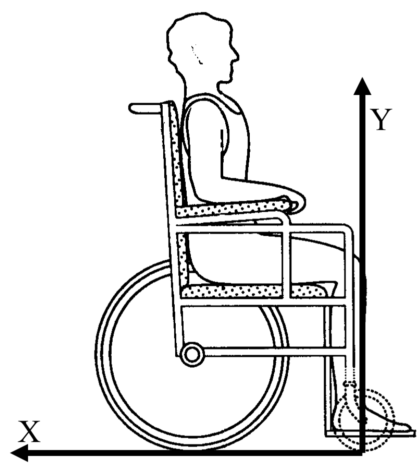

Figure 99: Wheelchair and Occupant COG ("Choosing an Attendant-Propelled Wheelchair")

Static Analysis of Wheelchair

Static analysis of the wheelchair was performed to determine the effect the device has on the wheelchair under certain circumstances. Both rear wheels of the wheelchair must stay in contact with the ground at all times while accelerating on a flat surface, uphill (5 degrees), and downhill (5 degrees). Figure 100 shows the external forces acting on the wheelchair:

Where:

F_{w1}, F_{w2} = The normal force acting on the two wheels from the ground

F_{sx}, F_{sy} = The force on wheelchair from the pusher device

m_{ch} = The weight of the wheelchair and the occupant at the center of gravity location (determined above)

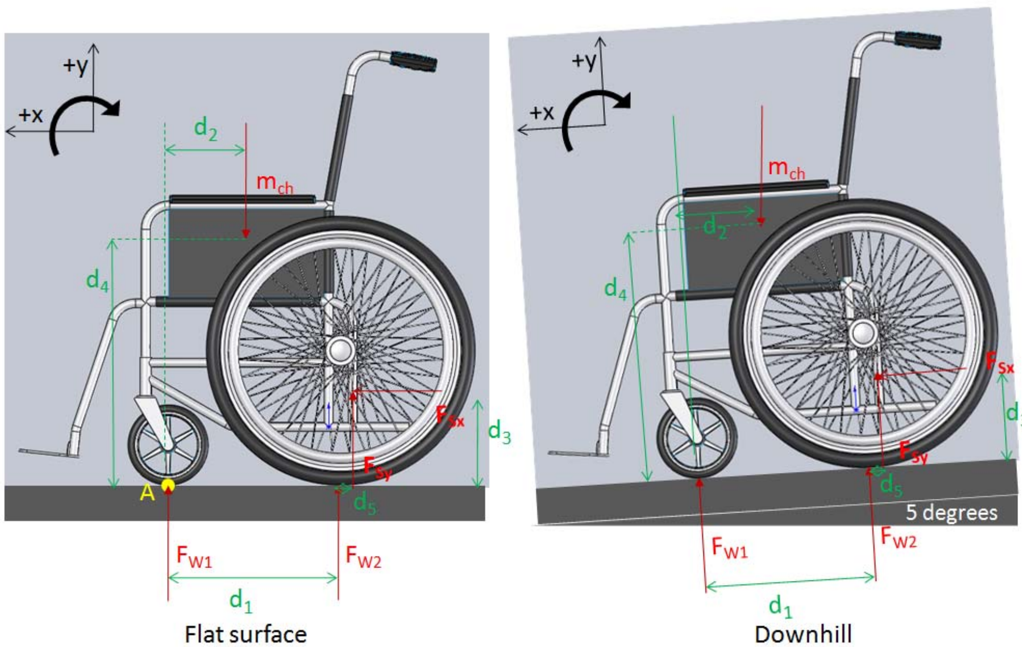

Figure 100: Effect of Spring Force (*F_{sy}*) on Wheelchair on a Flat Surface and Going Downhill 5 Degrees

With the wheelchair accelerating from zero to four miles per hour in four seconds, the force exerted on the device was determined using Newton's second law, force = (mass) x (acceleration). The mass was set to be either 140 lbs or 300 lbs to account for situations of both lighter and heavier occupants, respectively. At normal operation on level ground, this equation was used to determine the force acting on the attachment mounts. Table 7 shows the total force on the wheelchair from the device, shown in Figure 100 as F_{sx}, with a constant acceleration of 1.5 ft/s^2 (zero to four mph in four seconds).

Table 7: Horizontal Force From Device on Wheelchair

	Force (lbf) for 140lb wheelchair and occupant	Force (lbf) for 300lb wheelchair and occupant
Flat surface	6	14
Uphill 5 degrees	19	40
Downhill 5 degrees	-6	-12

Table 7 also shows the results of the wheelchair travelling uphill at 5 degrees, and uses Equation 2 to determine the force acting on the wheelchair by the toggle clamps and attachment mounts. In this equation, *a* is the constant acceleration uphill, W_{ch} is the weight of the wheelchair and occupant, and *g* is the force of gravity. Travelling downhill at 5 degrees, the same equation was used, except the force due to the weight (the second term) is subtracted. When going downhill and decelerating from four to zero mph in four seconds, the force on both toggle clamps of the device would be the same as the force calculated in the uphill scenario; however, the force would be acting on the toggle clamps in the positive x direction, rather than on the attachment mounts in the negative *x* direction.

Equation 2

$$F_{c2} := \frac{W_{ch}}{g} \cdot a + W_{ch} \cdot \cos(85\deg)$$

These calculations determined the horizontal forces applied to the wheelchair at the location where the horizontal attachment bar will be fastened. The device will also apply an upward vertical force on the wheelchair from the spring mechanism which pushes up on the horizontal attachment bar, F_{sy}.

Analysis of the wheelchair was performed for weights of both 140lbf and 300lbf, and the horizontal force applied by the device as well as the center of gravity location are dependent on these factors. The results of this analysis are shown in Table 8. When at rest, the normal force acting on the rear wheels is important. If this value is known, the vertical force the device can safely apply to the wheelchair can be determined. It is assumed that if the wheelchair is stable while going downhill and on a flat surface, it will also be stable going uphill. This is because the normal forces on the rear wheels would be even greater when travelling uphill.

Table 8: Normal Force on Each Rear Wheelchair Wheel While Accelerating

	Force (lbf) for 140lb wheelchair and occupant	Force (lbf) for 300lb wheelchair and occupant
Flat surface	90.5	162.2
5 degree decline	87.1	161.1

With a safety factor of 2, the device will not be able to tip over the wheelchair or make it unstable if a vertical force of 40lbf is applied from the spring assembly; even in the downhill worst case scenario (See Appendix D for MathCAD calculations). Table 9 shows the normal force acting on the rear wheel when a 40 lbf upward vertical force is acting on the wheelchair.

Table 9: Normal Force on Rear Wheelchair Wheel with a 40 lb Upward Vertical Force from Device

	Force (lbf) for 140lb wheelchair and occupant	Force (lbf) for 300lb wheelchair and occupant
Flat surface	47.7	119.4
5 degree decline	44.3	118.3

Static Analysis of Device

Static analysis was performed to determine the external forces acting on the device as well as the internal forces within the device.

Force on Toggle Clamps

The forces required to push the wheelchair alone on level ground, pushing uphill, and braking downhill were all calculated. It was assumed that there was no friction in the wheelchair bearings and no drag on the chair.

Forces on each attachment in the x-direction were determined by Newton's second law described above in the wheelchair analysis section and is the same value but acting in the opposite direction, according to Newton's first law. At normal operation with a constant acceleration of 1.5 ft/s^2 (zero to four mph in four seconds), the total force acting on each toggle clamp is shown in Table 10 and depends on the weight of the wheelchair and occupant and the surface incline which it is on. This is one half of the force calculated for the attachment mounts shown in Table 7 since the force is assumed to be distributed equally between both attachments .

Table 10: Force on Each Attachment Clamp Acting in the X-Direction Depending on the Weight of Wheelchair and Occupant

	Force (lbf) on each clamp base (140lb wheelchair and occupant)	Force (lbf) on each clamp base (300lb wheelchair and occupant)
Flat Surface-Accelerating	3	7
Uphill-Accelerating	9.5	20
Downhill-Accelerating	-3	-6
Downhill-Decelerating	-9.5	-20

Normal Force on Wheels

Calculating the normal force on the front steered wheel and the drive wheel was completed using the diagram in Figure 101 (see Appendix E for calculations). Summing the moments about two points, *A* and *B*, gives two equations with two unknowns: Force on the front wheel (F_{w1y}) and the drive wheel (F_{dwy}) (Equation 3). For these equations, the acceleration is assumed to be zero in both the x and y direction to simplify the equation. The force on the attachment mount is set to the force determined for an accelerating condition shown in Table 7 since this is the maximum force scenario.

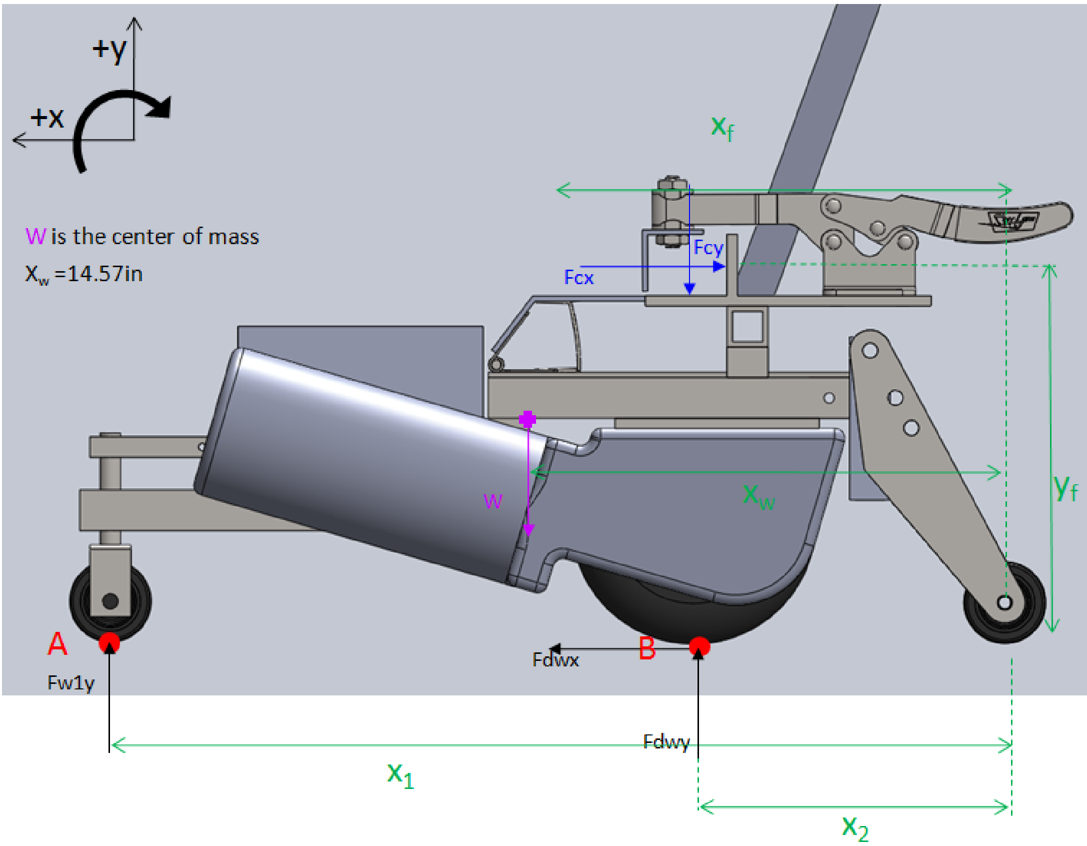

Figure 101: Free Body Diagram of Device

Equation 3

Sum of the moments about point A:

$$-F_{dwy}\cdot(x_1 - x_2) + W\cdot(x_1 - x_w) + F_{cy}\cdot(x_1 - x_f) + F_{cx}\cdot y_f = 0$$

Sum of the moments about point B:

$$F_{w1y}\cdot(x_1 - x_2) - W\cdot(x_w - x_2) + F_{cx}\cdot y_f - F_{cy}\cdot(x_f - x_2) - F_w\cdot(x_1 - x_2) = 0$$

Where:

W = Weight of device

F_{dwy}= Normal force on drive wheel axle

F_{w1y}= Normal force on front wheel

F_{cx}= Force at clamp base in x direction

F_{cy}= Force from spring in y direction

x_1 = Length of the device

x_2 = Length from rear wheel axle to drive wheel

x_w = Length from rear wheel axle to center of mass

x_f = Length from rear wheel to spring

y_f = Height of contact with wheelchair

Using the known values for these variables, obtained from the CAD model and the calculations of the forces on the attachment mount, the values of F_{dwy} and F_{w1y} were determined and are summarized in Table 11.

Table 11: Normal Forces on Steered Wheel and Drive Wheel

	Normal Force (lbf)	
	140 lb wheelchair and occupant	300 lb wheelchair and occupant
Flat surface- Steered wheel	15.7	10.3
Flat surface- Drive wheel	92.3	97.7
Uphill surface- Steered wheel	7.0	-7.0
Uphill surface- Drive wheel	101.0	115.0
Downhill surface- Steered wheel	23.7	27.7
Downhill surface- Drive wheel	84.3	80.3

The normal force on the steered wheel for a 300 pound person and wheelchair has a value of -7.0 lbf. This means that there is no steering in this situation. To resolve this issue, a 15 pound weight was added directly above the steered wheel. Additionally, users will be recommended to turn at slow speeds and avoid tight turns.

Maximum Pushing Force from Drive Wheel

The drive wheel can apply a maximum force based on the normal force acting between it and the ground and the coefficient of friction between the ground and the drive wheel tire. This maximum force is the force which the motor can apply between the rotating wheel and the ground before it begins to slip. The maximum forward force of the drive wheel was determined by multiplying the normal force on the drive wheel under each scenario, shown in Table 11, by two different friction coefficients. Friction coefficients of 0.5 and 0.25 were used; 0.25 is expected to be the minimum coefficient of friction that the device might face (approximate coefficient of rubber and wet linoleum) and 0.5 is expected to be the friction coefficient of a typical surface over which the device would run (for example, dry concrete). All other dry conditions, such as asphalt, carpet, and linoleum, are expected to be at least 0.25. Negative values in these tables indicate that the device requires no forward force to accelerate it and the wheelchair when travelling downhill. These negative situations mean that the device must be holding the wheelchair, preventing it from rolling downhill. The negative values are the forces required to hold back the chair as the device accelerates downhill. Table 12 and Table 13 show the maximum force which the device can apply to the wheelchair before it begins to slip and loose traction with the ground. This means that the force on the attachment mounts cannot exceed this value or the device's wheels may slip. Negative values in these tables indicate that the device requires no forward force to accelerate it and the wheelchair when travelling downhill. These negative situations mean that the device must be holding the wheelchair, preventing it from rolling downhill. The negative values are the forces required to hold back the chair as the device accelerates downhill.

Table 12: Maximum Pushing Force and Required Pushing Force to Accelerate on a Surface with 0.25 Friction Coefficient

		Maximum pushing force (lbf)	Force required to accelerate (lbf)
140 lbf person and wheelchair	Flat surface	23	6
	Uphill surface	25	19
	Downhill surface	21	-6
300 lbf person and wheelchair	Flat surface	24	14
	Uphill surface	29	40
	Downhill surface	20	-12

Table 13: Maximum Pushing Force and Required Pushing Force to Accelerate on a Surface with 0.5 Friction Coefficient

		Maximum pushing force (lbf)	Force required to accelerate (lbf)
140 lb person and wheelchair	Flat surface	47	6
	Uphill surface	51	19
	Downhill surface	42	-6
300 lb person and wheelchair	Flat surface	49	14
	Uphill surface	58	40
	Downhill surface	40	-12

Twice the force on each toggle clamp base (listed in Table 10) was used for the "force required to accelerate" values. The maximum pushing force which the wheel is capable of pushing while maintaining traction always exceeds the force required to accelerate the device and wheelchair in each scenario, except one. In the situation of a 300 pound person and wheelchair, the force required to accelerate the device up a five degree incline from zero to four miles per hour in four seconds is 40 pounds force. The wheel can only push with 29 pounds force on a surface with a coefficient of friction of 0.25. The possible solutions to this problem are to increase the traction of the drive wheel or to lower the force required by accelerating at a slower rate. Traction can be increased by raising the coefficient of friction or the normal force. Avoiding situations of low coefficients of friction could be recommended; also a device with a stiffer spring assembly would increase the normal force on the drive wheel. However, this stiffer device would only be useable with heavier occupants due to the dangers of tipping the chair forward. Accelerating more slowly would also prevent the wheel from slipping in situations such as this.

Turning Radius Analysis

To determine the maximum turning radius of the device, a simplified free body diagram of the wheel from the top view was used, shown in Figure 102, which did not consider slipping.

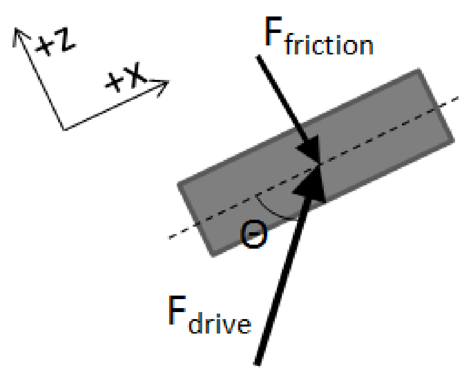

Figure 102: Free Body Diagram of the Top View of Turning the Front Wheel

Forces acting on the front wheel in this diagram are F_{drive} and $F_{friction}$. The force on the steered wheel from the rear drive wheel, F_{drive}, acts in the direction in which the drive wheel points. This drive force is determined from the analysis performed to determine the force on the toggle clamps when the device is accelerating. The force of friction, $F_{friction}$, acts along the axis perpendicular to the direction of roll (*z* axis), this is determined by the normal force due to the weight multiplied by the friction coefficient (either 0.25 or 0.5).

Assuming that there is constant velocity and summing the forces in the *z* direction, Equation 4 is derived. The maximum turning angle is denoted as Θ. (See Appendix F for calculation).

Equation 4

$$\theta := \operatorname{asin}\left[\frac{(F_{friction})}{F_{drive}}\right]$$

This can be solved for the maximum turning angle based on the weight of the occupant and whether the device and wheelchair are accelerating on a flat surface, uphill, or downhill. The normal force on the steered wheel was determined above. In order for the normal force on the front wheel to be positive in all circumstances, a weight of at least ten pounds must be added to the front steered wheel. For this reason the normal forces used in the steering calculation are ten pounds more than was calculated above. The results are shown in Table 14.

Table 14: Maximum Turning Angle of Steered Wheel

	When μ=0.25	When μ=0.5
Flat (140lb)	~90 deg	~90 deg
Flat (300lb)	21 deg	45 deg
Uphill (140lb)	13 deg	27 deg
Uphill (300lb)	1 deg	2 deg
Downhill (140lb)	~90 deg	~90 deg
Downhill (300lb)	36 deg	~90 deg

For the wheelchair to be able to make a turn with a radius of 60 inches, the wheelchair would need to turn its steered wheel at least 16 degrees from straight. As Table 14 shows, almost every situation allows the wheelchair to turn its front wheel at least 16 degrees. The exception is for the 140 pound wheelchair and occupant going uphill on a surface with a coefficient of friction being 0.25, and the 300 pound wheelchair and occupant going uphill on 0.25 and 0.5 coefficients of friction. In order to obtain optimal results, more than 10 pounds will need to be added at the front wheel. If 15 pounds is added, the 140 pound wheelchair and occupant will have a steering angle of 16 degrees rather than 13 and the 300 pound would have a steering angle of 3 degrees on the slippery slope and 6 degrees on the typical slope. Adding 25 pounds would double the turning angle, however, adding 25 pounds is undesirable. Therefore, 15 pounds will be added so that the 140 pound occupant and wheelchair will have a steering angle of 16 degrees in all situations.

It is noted that these calculations do not take into account the slip angle which the wheel experiences when turning and rolling, but this should not be more than 1 to 2 degrees and therefore those values which are well above 16 degrees will still not experience a problem turning the device on a path of radius 60 inches.

Stress Analysis of Device

Once static analysis of the device was complete, stress analysis was performed to determine which locations on the device could fail during use. Manual calculations were performed on locations which were a concern for failure or permanent deflection. Finite Element Analysis (FEA) was also performed on the SolidWorks model to confirm the conclusions of the manual calculations.

Manual Calculations

Two locations on the device were of particular concern and were chosen to determine the stresses and whether the steel or welds would be able to sustain the forces. These models were simplified in order to determine rough estimates of the forces and were then confirmed by FEA analysis. Internal force analysis and then stress analysis was performed.

Battery Tray

The battery tray part of the design is a component which is square, holds two batteries within the "tray," and is welded to the frame on two of its four sides. The battery tray was simplified from a three-dimensional problem to a two-dimensional problem, Figure 103. Since the tray is supported on two adjacent sides, simplifying it to being supported on one side is an overestimation of the forces and stresses acting on the tray and therefore this is a conservative model. Figure 103 shows the free body diagram of the battery tray. Summing the forces in the *x* direction, where the acceleration is zero, gives a normal internal force, *N*, equal to zero.

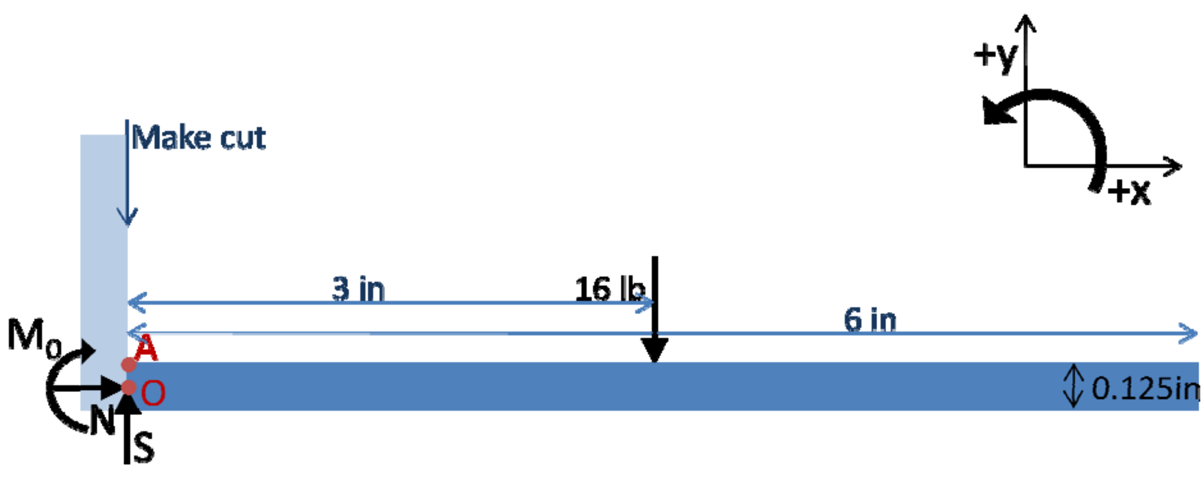

Figure 103: Battery Tray Free Body Diagram

Summing the forces in the *y* direction, where the acceleration is also zero, gives a reaction force, *S*, of 16 lbs. Summing the moments around point *O* gives a resultant moment M_O

equal to 48 lbs*in. The second moment of area is found to be 9.77 x 10^4 in^4 and from this the bending stress at point *A* is found to be 3072 lbs/in^2 tension. The shear stress is found to be zero lbs/in^2 at point *A* and 21 lbs/in^2 at point *O*. Both of these values are significantly less than the yield strength of steel, which is 36,000 lbs/in^2. See Appendix G for MathCAD file.

Handlebar Stem

The handlebar stem is a critical piece of the device. A FBD of the handlebar stem is provided in Figure 104. Three different forces and torques are applied: Pushing Force (*F)* (which creates reaction moment M1), Torsion (*T*), and Compression (*P*). F, P, and T are three different types of forces that the user could apply to the handlebar stem. The forces and torques were given the values of 30lbf, 1300 lbf*in, and 30lbf, respectively. These values represent an assumed large force. It was assumed that calculating all three forces together at high values would not only be the maximum force that could be applied, but also would account for forces caused when a user may try to pull down on the handlebar. In order to simplify the problem, compression was assumed to act in the direction of the bar. Stress analysis was used to find the maximum stress acting on the bar. The complete stress analysis for the horizontal stem can be found in Appendix H.

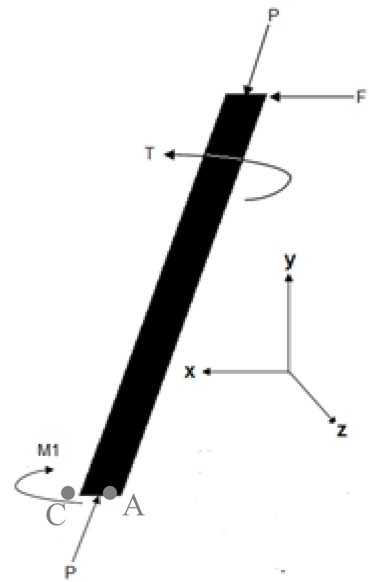

Figure 104: FBD of Handlebar Stem

It was found that the most critical point of the stem was at the bottom weld at points *A* and *C* (Figure 105) where *A* is the side facing the user, and *C* its opposite side. This is due to the fact that points *A* and *C* are greatly influenced by the moment created by pushing force *F* since they are the positions where the handlebar stem would experience the most reaction force. When the analysis was completed, the stresses at points *A* and *C* were equal. The stress analysis for point A is shown here; see Appendix H for point C calculations.

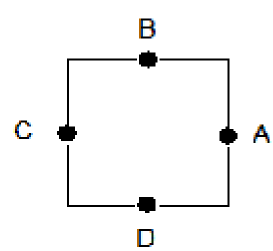

Figure 105: Critical Points of the Handlebar Stem

The principal stresses as well as the Von Mises stresses were calculated using the following Equation 5 and Equation 6. (Note that in this case $\sigma_2 = 0$):

Equation 5

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{(\frac{\sigma_x + \sigma_y}{2})^2 + {\tau_{xy}}^2}$$

Equation 6

$$\sigma` = \sqrt{\sigma_1^2 - \sigma_1\sigma_3 + \sigma_3^2)}$$

Where: $\sigma_{1,3}$ = principal stresses, and $\sigma`$ = Von Mises stress with:

$\tau_{xy} = T \times \frac{c}{J}$ and:

T = Torsion

c =distance from the center to the outside of the hollow tube

J = second polar moment of area

In addition:

$$\sigma_x := \frac{P}{A_{cross}}$$

Where:

A_{cross} = Cross sectional area

P = compression Force, and

$$\sigma_y := M_{max} \cdot \frac{c}{I_{square}}$$

Where:

M_{max} = Max Moment force

I_{square} = Second moment of area for the square tubing

With σ_x and σ_y substituted into Equation 5, the calculated values obtained are:

$$\sigma_1 = 11.614 kpsi$$

$$\sigma_3 = -2.313kpsi$$

Then, substituting σ_1 and σ_2 into Equation 6, the calculated Von Mises stress is:

$$\sigma` = 12.927kpsi$$

Since $\sigma`$ was the largest stress value, it was chosen to calculate the safety factors at the two critical points. Our steel is rated to approximately 36kpsi. Therefore, our safety factor is $\frac{36}{12.927} = 2.80$ which is suitable for the purposes of our device.

FEA Analysis

ANSYS Workbench was used to perform finite element analysis (FEA) on the frame of the device. Before importing the device into ANSYS, some of the components were simplified to reduce the computational time required to solve the FEA. With a simplified model, three scenarios were modeled to find the internal stresses and deflections. In all three scenarios considered, forces were applied as if the device was pushing a wheelchair uphill. This is modeled by applying 20 lbf to each attachment mount to simulate the pusher pushing a wheelchair. An additional 40 lbs is applied where the spring assembly would be transferring the force from the wheelchair to the compressed spring. Also, a force of gravity was applied to the entire model for the device on level ground. The model was constrained in two places. First the model is fully constrained at the drive wheel shaft with the assumption that the drive wheel does not slip in any direction. The second constraint was made at the front steered wheel axle. This constraint is used to solve for the stresses related to the weight applied to the front wheel. The force applied to the handlebars from the user changes between FEA scenarios. In the first scenario (FEA Scenario 1), the user is applying 50 pounds straight down towards the floor. The force layout can be seen in Figure 106.

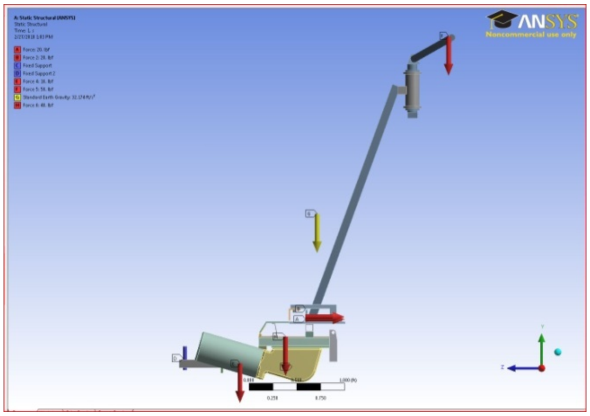

Figure 106: FEA Scenario 1 (50 Pounds Down on Handlebars)

In the second scenario, the user is pushing forwards with the same force of 50 lbs. The forces for scenario two are shown in Figure 107.

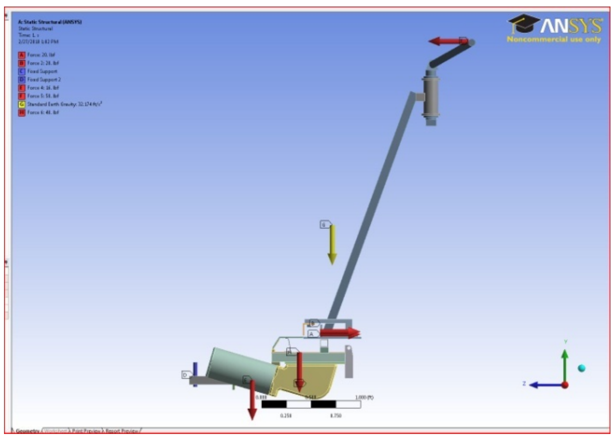

Figure 107: FEA Scenario 2 (50 Pounds Forward on Handlebars)

In the final scenario, the user is pulling back on the handlebars with a force of 50 lbs, shown in Figure 108.

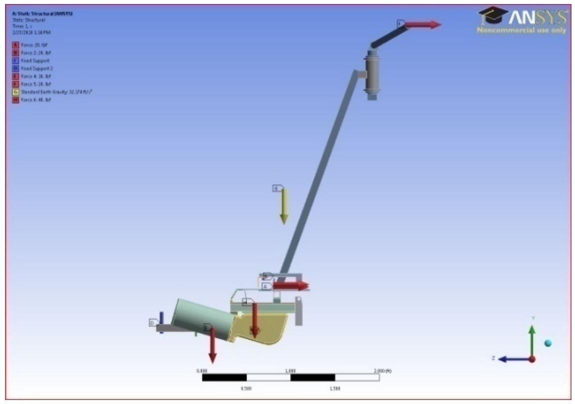

Figure 108: FEA Scenario 3 (50 Pounds Backwards on Handlebars)

Each scenario was solved to find the maximum stress and the total deflection within the model. The maximum stresses for each scenario are summarized in

Table 15.

Table 15: Maximum Stresses

Scenario	Maximum Stress (psi)
1	1.707×10^4
2	1.689×10^4
3	1.450×10^4

Comparing these values to the yield strength of steel 250 MPa or 3.626×10^6 psi, the safety factor of the current frame can be determined. The comparison is shown in Table 16.

Table 16: Safety Factors

Scenario	Safety Factor
1	2.21
2	2.15
3	2.09

The point of maximum stress for the first scenario can be seen in Figure 109. This maximum is on the back of the post supporting the toggle clamp bases. It should be noted that this point is in compression. The frame will not fail here; instead it will fail at an area of high tension. However, because the maximum stress is in compression, it is safe to assume all tensile stresses will be below the maximum stress found by the FEA. Since the maximum stress (compression) was found to have a safety factor of 2.214, it can be assumed that all tensile stresses would have a safety factor of at least 2.214.

The same analysis was done for the other two scenarios and can be seen in the respective figures; Figure 110 and Figure 111. The analysis establishes that there is a safety factor of at least two with the entire device. A safety factor of two is somewhat lower than desirable; therefore, to compensate for this the device will be constructed as designed and structural bracing will be recommended to increase the safety factor.

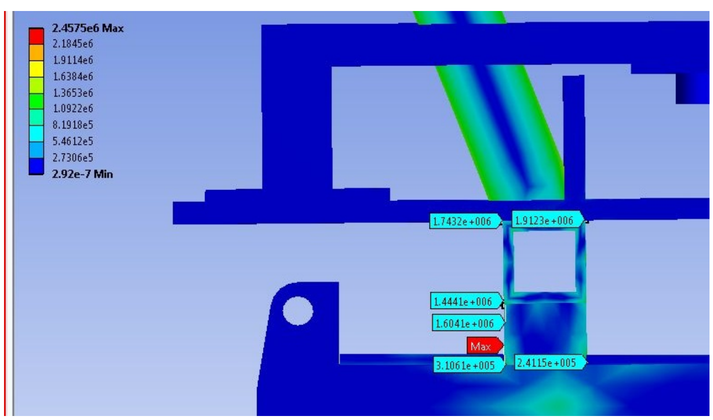

Figure 109: FEA Scenario 1 Close-up

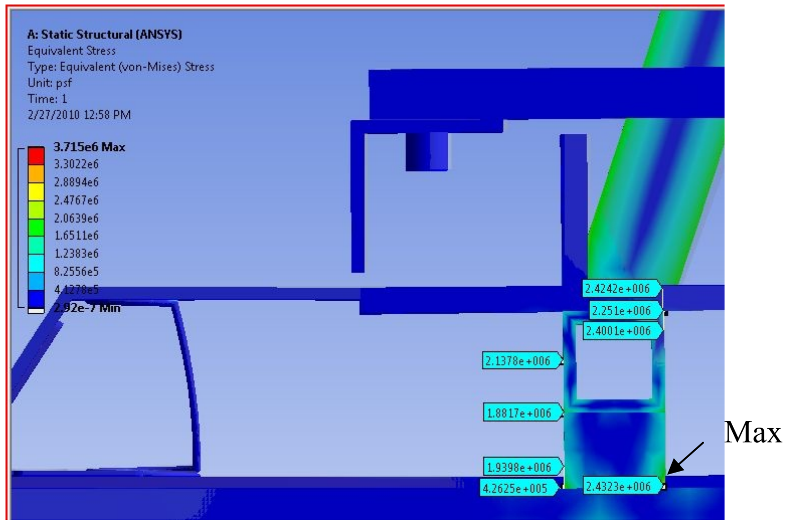

Figure 110: FEA Scenario 2 Close-up

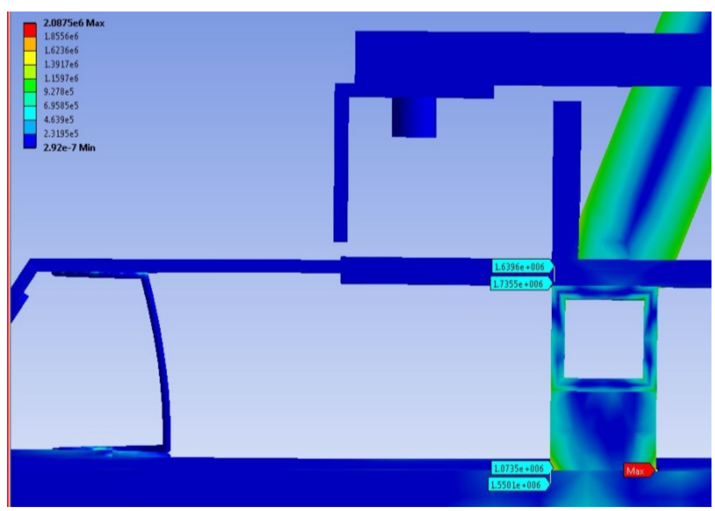

Figure 111: FEA Scenario 3 Close-up

Manufacturing

The following section describes the procedure by which the device was manufactured and assembled. The device contains components that were both machined and purchased. After obtaining all the components, the device was assembled.

Machined Parts

Some of the device components were custom-made by the group. These parts were modeled in CAD and were machined in the shop in Higgins Laboratories. Please see Appendix I: CAD Drawings for full CAD drawings.

Frame assembly

The frame assembly, Figure 112, is made of several 1"diameter steel tubing members that are welded together. The steel was cut to the dimensions called out in the CAD drawings. Some of the steel tubing also required holes to be drilled into them. The handlebar stem is made of a 33" long section of tubing. The bottom end is cut at an angle so that the stem could be inclined towards the user.

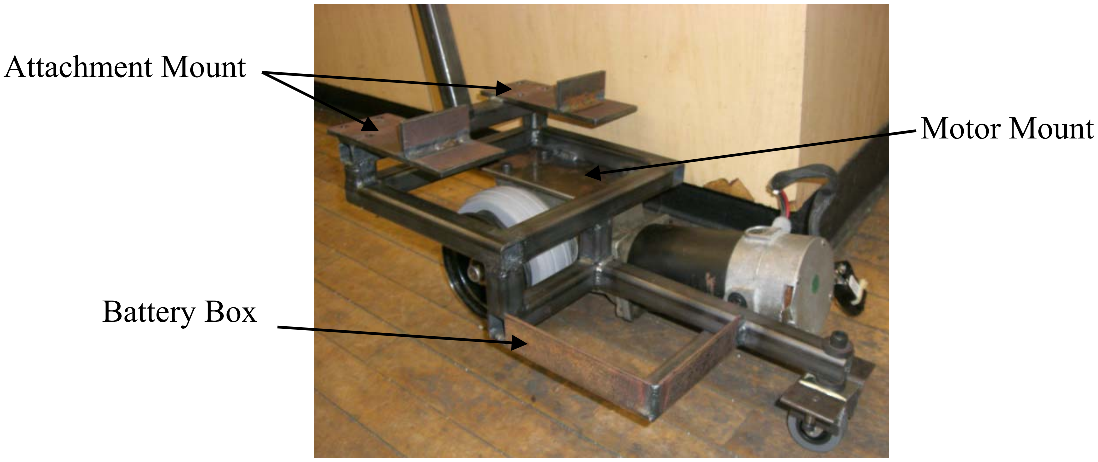

Figure 112: Frame

Motor mount

The motor mount is a ¼" piece of sheet metal with four holes drilled to match the bolt pattern on the motor.

Battery tray

The battery tray is fabricated from four 6 inch pieces of angle iron. Each end of the angle iron pieces were cut at 45 degree angles. These four pieces were then welded together to form the tray.

Attachment Mount

The attachment mount is made from a piece of ¼" sheet metal with four holes drilled to match the bolt pattern on the toggle clamps. A vertical ¼" piece of sheet metal is welded to this piece. The attachment mount holds the toggle clamps which clamp over the wheelchair's horizontal bar.

Toggle Clamp Modification

Horizontal toggle clamps, Figure 113, were purchased and an additional part was machined and combined with the clamp to accommodate the needs of the device.

Figure 113: Toggle Clamps

A 2" x 1.5" x 1.5" piece of angle iron was used. The angle iron has a hole drilled through the center of one side. The existing toggle clamp has a screw and bolt at the end which allows the piece of angle iron to be mounted on to the screw. The screw was then threaded through this hole and a bolt was added to secure it onto the end of the screw.

Steering Subassembly

The steering is controlled by a push-pull cable attached to a set of bicycle handlebars. The bike handlebars were cut at an angle and welded to the handlebar stem so that they were parallel to the ground. At the top of the device, Figure 114, the cable was attached to either side of the handlebar arm which was welded to the bike's handlebars. The sheath of the control cable was fixed to the cable support, and the end of the cable was threaded to a machined aluminum tie-rod. The tie-rod bolts to the handlebar arm and allows for full rotation of the handlebars. When the user turns the handlebar, the cable is pushed or pulled.

The cable support is fabricated out of ¼" steel with a hole drilled through it. Because the handlebar stem is at an angle and the cable support needed to be perpendicular to the ground, a wedged piece made of steel was welded to the handlebar stem and the cable support was then welded to this piece.

Figure 114: Steering Assembly

Front Steered Wheel Subassembly

At the front of the device, there is a similar subassembly where the cable runs through another cable support and threads into a tie-rod of the steered wheel arm that is bolted to the front steered wheel. The steered wheel arm is a piece of 1” angle iron. A castor wheel was purchased for the front steered wheel, Figure 115. The action of turning the handlebars pushes/pulls the cable, which turns the steered wheel.

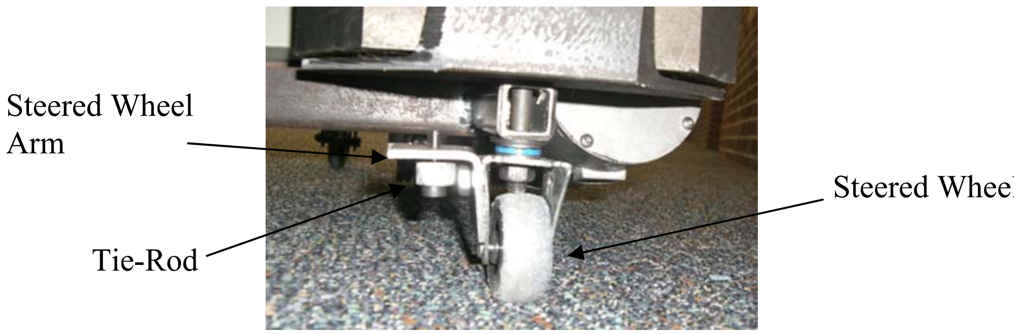

Figure 115: Front Steered Wheel Assembly

Spring Subassembly

The spring subassembly (Figure 116) consists of four main components: the ramp, the base, the spring, and the hinge. The base and the ramp were cut from $^{1}/_{8}$” steel. Retaining rings made of steel tubing were welded to the base of the spring assembly to prevent the springs from buckling. Both the ramp and the base were predrilled at one end to attach to the hinge. Once the holes were drilled in the ramp, it was bent (Figure 116) and assembled with the rest of the components. The spring was placed in the retaining rings. With the spring assembly completed it was bolted to the frame at the front end of the base where it comes in contact with the frame.

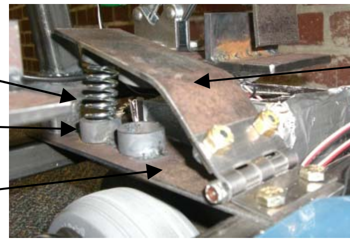

Figure 116: Spring Assembly

Purchased Parts

Many of the device components were purchased from various vendors. Some needed slight modification after purchasing, which was performed in the Higgins Lab Machine Shop.

Table 17: Purchased Parts

Name	Source	Part Number	Description
Toggle Clamps	Carr Lane	HTC-550	Horizontal Toggle Clamp
Motor Control	IFI Robotics	Victor 883	Speed Control
Battery (2)	Batterymart.com	SLA-12 V10-F2	12 V 10Ah Sealed Lead Acid Battery
Control Cable	McMaster	1407K57	Push/Pull Cable
Drive Wheel	MobilityDirect	060200-lg	6” drive wheel
Steel	Peterson Steel	N/A	1” square tubing
Springs	McMaster	N/A	Compression and tension springs
Front Castor Wheel	Grainger	1UHL8	Rigid 2” Castor
Hinge	Grainger	3HTW5	2” x 2” Hinge

Reused Parts

Tom Mercier of Kelley Assistive Technology generously donated two Invacare electric wheelchairs to the project. A motor from one of these wheelchairs was used in the device. This motor comes with a preinstalled gearbox with a universal axle mount. Part of the anti-tipper assembly was also used from these chairs. The wheels and springs from this system were used to create a modified anti-tipper subassembly for the device. The drive wheel was also taken from the electric wheelchair.

Professor Hoffman donated a microcontroller to the project. The microcontroller that is controlling the motor controller is an Arduino Microcontroller. The code used is modified from public code available on Arduino's website. An IFI Robotics motor controller was obtained from the Robotics team. The electronics are placed in a secure and safe position on the frame of the device. The thumb throttle is attached to the handlebars next to the grip so that the person can easily operate it.

A used bike was purchased from a seller on craigslist. The handlebar and stems were cut from the front of the bike to use in the device. The handlebar assembly was welded to the handlebar stem.

Assembly Process

The frame was created first. After the steel was cut to length, the pieces were welded together according to the CAD model. The motor mount and battery box were welded to the frame. The attachment mounts were then welded to the frame. The spring assembly was assembled and then bolted to the frame. The handlebar arm was fitted with the tie-rods and this was welded to the handlebars. The handlebar system was then welded to the frame. The steered wheel subassembly was attached to the front of the frame. The anti-tipper subassembly was then added to the back of the frame. The motor was bolted onto the motor mount of the frame. After the cable supports were welded to the frame, the steering subassemblies were attached and the control cables were installed. The toggle clamps were bolted onto the attachment mounts of the frame. The batteries were placed into the battery box and finally, the electronics were installed into the system. The electronics included attaching the throttle control to the handlebars and securing the motor controller and microcontroller.

Testing Procedures and Results

To evaluate the device, the team conducted a series of tests that analyzed how well the device complies with the design specifications. Each design specification is broken up into two types of tests. The first type of test is pass/fail (ex. The device weighs less than 30 lbs). Any specification that is not qualified as pass/fail undergoes a performance test. For this type of test the device was evaluated by receiving a performance rating. Multiple trials were needed in order to perform this type of test properly. After completing all tests, the results were analyzed to determine what aspects of the device could be reworked and improved, thereby better satisfying the design specifications.

For tests which required volunteers, the volunteers were told what the device is used for, and that they were assisting in testing an MQP project. Volunteers were college-aged males and females. They were trained on how to use the device until they felt comfortable operating it. They learned how to turn the device on, how to use the thumb throttle to accelerate and brake, and also how to steer the device. They were also told typical ways in which the device might be used incorrectly and how to avoid those instances. The volunteers then drove the device and wheelchair inside a building to become comfortable using it. The proctor timed how long each training loop took and asked the volunteer after each trial whether or not they felt comfortable. It was recorded if the volunteer had any problems or bumped into anything during training. Once the training was complete and the testing began, the test proctors did not direct the volunteers in how to operate the device unless safety was a risk, or the volunteer had a specific question for the proctor.

Function Testing

1. The product will be able to push a combined weight of 300 pounds up an incline of 5 degrees with a length of 30 feet.

    To test this specification, the pusher was loaded with weight so that the wheelchair and load was 300 pounds. The wheelchair was then pushed by the device up a 5 degree, 30 foot incline (ramp at the WPI fitness center). This was repeated 5 times. This test was rated pass or fail and the time it took to make it up the hill was recorded. If the device failed then the distance that the device and wheelchair made it up the ramp before failing was measured and recorded.

    Results: The device was able to push 300 pounds of weight (wheelchair and occupant) 30 feet each time. The time taken to complete this is shown in Table 18. The average time taken was 5.21 seconds. To cover 30 feet at the designed speed of 4mph takes 5.113 seconds. Since the average and calculated times are close, it can be concluded that the device was also able to travel at maximum speed when completing this test. Therefore the device satisfies the design specification Function 1.

Table 18: Time Taken to Travel 30 Feet

Trial #	Time Taken (s)
1	5.25
2	5.15
3	5.2
4	5.3
5	5.15

2. The attachment mechanism of the device must be able to withstand the maximum force (40 pounds) with a safety factor of three, therefore 120 lbs of force on each clamp.

To perform this test a toggle clamp was bolted to a piece of scrap steel ¼ inch thick and 6 inches long (orange outline in Figure 117). This was then placed in a vice with a dial indicator placed in compression above the angle iron where the weights were hung from (red dot). By first zeroing the dial indicator, then adding weights, the dial indicator read any linear displacement. Finally, a laser pointer was taped to the bottom of the angle iron (green rectangle) aimed at a sheet of graph paper, which measured any angular deflection. Weight was hung around the angle iron (at the red dot in Figure 117) by twine, in increments of 20 pounds, until 120 pounds was reached. In between increments of weight, any angular and linear deflection was recorded.

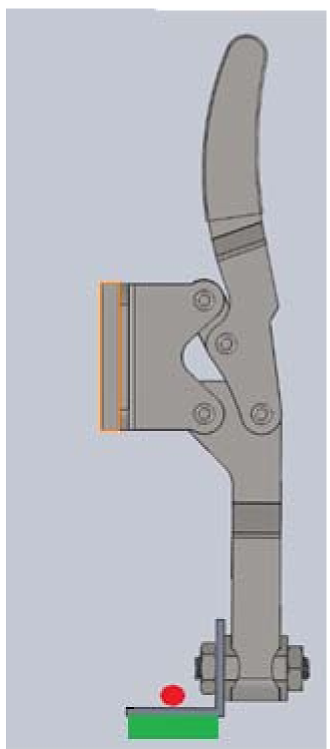

Figure 117: Toggle Clamp Test Set-Up

Results: At 120 pounds, angular deflection was negligible and linear deflection was 0.034 inches. This experimental test shows that the purchased toggle clamps will be able to withstand normal operation. This is calculated by dividing the weight the clamp was tested at by the maximum force expected on the clamp. Although the clamp was not tested to failure, this is a conservative safety factor and establishes that the clamp will not fail under the devices operating conditions. This satisfies design specification Function 2.

3. The product must not limit the wheelchair's functionality.

The product and wheelchair were tested by five volunteers in a variety of common situations to ensure that the pusher did not hinder the wheelchair's functionality. A normal wheelchair can maneuver around a building, through doorways, in elevators, and around corners. When attached to a wheelchair, the pusher and wheelchair are expected to maneuver through the same environment. This test was performed in a building that meets ADA specifications. The five volunteers turned on the device and connected it to the wheelchair (with an occupant in it), then traveled in Higgins Labs from the rehab lab, past the bathroom, around the corner to the ME department, into the elevator, down to the first floor, exit, then back up into the rehab lab where they disconnected the wheelchair and turned off the device, Figure 118.

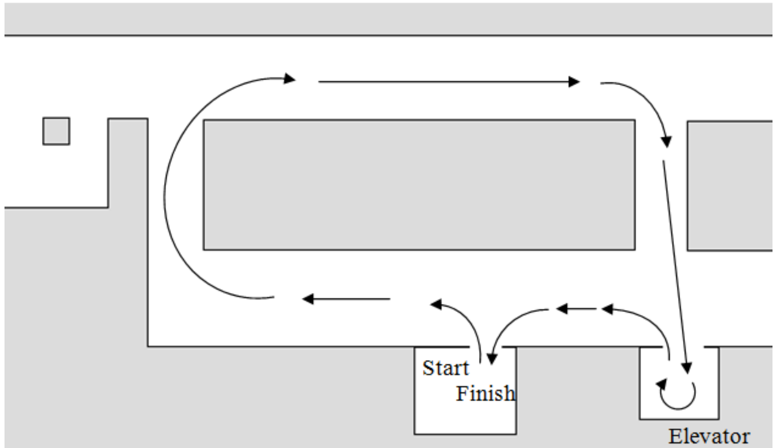

Figure 118: Testing Course (Aerial View of Higgins 1st Floor)

The volunteers were told where they should drive the device. Each volunteer's run received a score based on the number of collisions and steering problems on a 5 point scale. The ratings were given by the design team based on the volunteers' performance. The scoring criteria are listed below.

1-The device was very difficult to move or control, unintentionally ran into or nearly ran into stationary objects often, and did not move in the direction it was turned, making the device unusable.

2- The device was difficult to move or control some of the time, unintentionally ran into or nearly ran into stationary objects more than three times, and did not move in the direction it was turned more than three times.

3- The device was rarely difficult to move or control (two or three times), it never unintentionally ran into or nearly ran into stationary objects, and always moved in the direction it was turned (two or three times).

4- The device was easy to move or control, it very rarely (1 or fewer times) unintentionally ran into or nearly ran into stationary objects, and always moved in the direction it was turned.

5- The device was very easy to move or control, it always turned and stopped when directed to, and it made maneuvering a wheelchair easier than without the pusher.

Results: The results of the test are shown in Table 19. Overall, the device received positive feedback from the volunteers. Subject 1 had no problems, while subjects 2, 3, and 5 had very few problems, mostly from turning when the device was at too high a speed. Subject 4 had the most trouble using the device. Problems occurred when the handlebars were pulled backwards. Additional problems included a loss of traction between the drive or steered wheel and the ground, problems turning while at high speeds, and trouble entering and exiting the elevator due to the steered wheel falling into the door gap. Problems were most noticeable when the volunteer was traveling high speeds. Four out of five volunteers were able to easily maneuver the device, thereby satisfying design specification Function 3.

Table 19: Device Functionality Scores

Subject #	Device + Wheelchair Functionality (1 - 5)
1	5
2	4
3	4
4	2
5	4

4. The product will remain stationary when the device is turned on but at rest on a level surface and on an incline.

This test was performed when the device was on a level surface, facing up an incline, facing down an incline, and was performed one time. The ramp was built by the design team from plywood. The ramp was raised gradually until the device tipped or slid off the ramp. The angle at which the device tipped or began to slide was recorded.

Results: The device passed the test on a level surface since it was able to remain stationary at rest. Based on our test results (Table 20), if the device is not in use by an attendant it should not be left alone on anything but a level surface. This test satisfies design specification Function 4.

Table 20: Angle Until Failure Occurs

	Level surface	Angle until failure, Facing Up	Angle until failure, Facing Down
Device alone	Passes	Slides at 5 degrees	Slides at 5 degrees

5. The product will come to a stop in the unexpected event of the attendant releasing the device.

   To test this specification, the device was set in motion at full speed while attached to a wheelchair with an occupant. The control was then released to test that the brakes of the motor automatically engaged. This test was performed once and was either pass/fail depending on whether the brakes engaged or not.

   Results: The device passed this test since releasing the thumb throttle activates the brakes of the motor, satisfying design specification Function 5.

6. Once the motor brakes are active, the device will come to rest within 10 feet.

   To test this specification, the wheelchair and device were driven at maximum speed down a 5 degree incline with a weight combination of 300 lbs. Once maximum speed was achieved the motor brake was engaged. The stopping distance was measured from the point when the brake was engaged to the point where the device made a complete stop. This test was repeated five times. The distance required to stop was recorded and if all five distances were below 10 feet the device passed this test.

Results: Table 21 shows the results of this test. The average distance travelled was 17.4 feet the standard deviation of the data was 2.8 feet. The device fails this test and fails to meet design specification Function 6.

Table 21: Stopping Distances

Trial #	Distance required to stop when going downhill at 5 degrees
1	18’ 6”
2	13’ 10”
3	19’ 10”
4	15’ 1”
5	19’ 9”

7. The device must be statically and dynamically stable at an incline of at least 10 degrees.

To test for static stability the device was placed (without an attached wheelchair) facing up, down and sideways on a 10 degree ramp created by the design team from plywood. The ramp angle was then increased until an angle was reached where either a piece paper could slide underneath the higher wheels (tip angle), or the device began to slide. The maximum angle was recorded. This test was repeated for the device attached to the wheelchair, with the wheelchair’s parking brakes engaged.

To test for dynamic stability, the device was accelerated and decelerated up and down an incline of 10 degrees when connected to an empty wheelchair. The device was observed during motion and if all of the wheelchair’s wheels remain on the ground, and if the device's driven and steered wheel remain on the ground for the entire motion, the device passed the test.

Results: Table 22 shows the results of the static stability testing. The device alone passed the static stability test when it was placed sideways with the motor facing down the ramp. The device and wheelchair were all stable up to 10 degrees but the device and wheelchair did begin to tip or slide when facing up and downhill at 10 degrees. The dynamic stability test showed that the wheelchair was stable on a ramp of at least 10 degrees while accelerating and decelerating. Overall the design specification Function 7 was not satisfied.

Table 22: Maximum Angle for Static Stability

	Max Angle Up Ramp	**Max Angle Down Ramp**	**Max Angle Sideways (Motor Uphill)**	**Max Angle Sideways (Motor Downhill)**
Device Alone	Slides at 5 degrees	Slides at 5 degrees	Tips at 5 degrees	Slides at 10 degrees
Device and Wheelchair	Tips at 10 degrees	Slides at 10 degrees	Slides at 18 degrees	Slides at 27 degrees

8. The product will charge with the use of a charger that plugs into a standard wall outlet.

This is a pass/fail specification and passes if the batteries can be charged with a battery charger that is plugged into a standard wall outlet.

Results: The device can be charged using a standard 24 volt battery charger and thereby satisfies design specification Function 8.

Physical Characteristics Testing

1. The device will not endanger those around it.

   Five volunteers evaluated the device, noting sharp corners, obtrusions, and pinch points, on a scale of 1-5. Score criteria are listed below.

   1- The device has more than 6 sharp corners, pinch points or obtrusions.

   2- The device has 4-6 sharp corners, pinch points or obtrusions.

   3- The device has 2-4 sharp corners, pinch points or obtrusions.

   4- The device has 1 sharp corner, pinch point or obtrusion.

   5- The device has no sharp corners, pinch points or obtrusions.

   Results: Results of this test are shown in Table 23. The device fails this test for multiple reasons. There are many sharp corners, and the toggle clamps have pinch points. Also there is no "guard" to protect someone from accidentally hitting the reverse button. Design specification Physical Characteristics (PC) 1 is not satisfied.

   Table 23: Safety Evaluation Scores

Subject #	Safety Rating (1-5)
1	1
2	2
3	1
4	2
5	2

2. The attachment mechanism of the product will fit between the frames of the smallest compatible wheelchairs (14 inches wide) and the largest compatible wheelchairs (up to 30 inches).

This specification is pass/fail. If the device was able to fit between wheelchair frames of 14 inches, it was also be able to fit between chairs of larger width.

Results: The device passed this test because body of the device, excluding the handlebars, is less than 14 inches wide. It was measured to be 12 inches wide and satisfies design specification PC 2.

3. The product will attach to and detach from the wheelchair without the necessity of tools.

    This specification is pass/fail.

    Results: The device passes this test because no tools are necessary to attach or detach the device to and from a wheelchair. The user simply needs to lift and lower the toggle clamps in order to engage and disengage the device. Design specification PC 3 is satisfied.

4. If the device weighs more than 30 pounds then the device must be easily broken into sections, individually weighing no more than 30 pounds.

    This test is pass/fail. To test this specification, the device was weighed on a scale. If the device weighed more than 30 pounds, it must disassemble into separate parts with the use of only the basic tools provided in order to pass this specification. These individual parts would be weighed to assure each part is no more than 30 pounds. In order for the device to be easily portable, it will need to meet this specification.

    Results: The device failed this test because it weighed 90 pounds and was unable to be broken down into sections, failing to satisfy design specification PC 4.

5. The overall dimensions of wheelchair and device system should be no larger than 28 inches wide, 51 inches long and 43 inches high, which are the recommended maximum dimensions for mobility devices (McLaurin & Axleson, 1992).

   This specification is pass/fail.

   Results: The device currently fails the design specification PC 5 because it has dimensions of 26 ¾ inches wide, 36 inches long and 45 ¾ inches high. The height of the device is 2 ¾ inches higher than the recommended height of mobility devices, however no volunteers complained about the height of the device. The height specification of the device should be based on the height of the user and anthropometric comfort.

6. The device must be small enough to fit in the confines of an average car's trunk. Depth: 38.5in, width: 31 in, height: 17 in (Subaru Impreza trunk measurements).

   This test is pass/fail. To test this specification, the dimensions of the device were compared with the dimensions of a typical car trunk.

   Results: The device fails design specification PC 6 because it cannot fit in the trunk of a car, however, it should be noted that the device could fit in the backseat of the car. A Mercedes W220S class vehicle would be able to hold the device; it has trunk dimensions of: 52" wide, 36" deep, and 18.5" high.

User Interface Testing

1. The product must be able to be operated by a single attendant.

   To test this specification, the team required 5 volunteers to turn the device on, attach the device to a wheelchair, use the brakes, park the device, detach the device, and turn the device off. After completion of this test, it was recorded whether or not the volunteer could successfully operate the device alone. If all five volunteers could operate it alone, the device passed this test.

Results: All volunteers were able to use the device alone and therefore it passes this test and satisfies design specification User Interface (UI) 1.

2. The device must be easy to learn and intuitive.

If all of the volunteers were able to learn how to use the device in the 5 minute training session before use and remembered how to use it during all tests, then the device passed this test.

Results: All volunteers were able to learn how to use the device in the 5 minute training session; therefore, the device passes this test and satisfies design specification UI 2.

3. The product will have brakes that can be engaged by the operator.

If the product has brakes that can be engaged by the operator then it passed this test.

Results: The current design incorporates braking into the thumb throttle. By releasing the throttle, the motor brake is activated and therefore satisfies design specification UI 3.

4. Brake engagement must be intuitive and easily learned.

If the brake was able to be engaged automatically, the device passed this test.

Results: The current design incorporates the braking into the thumb throttle; therefore this specification is passed with successful use of the throttle.

5. The operator will be able to turn the device on and off with a “switch”.

This is a pass/fail specification. If the device had a working switch then it passed this specification.

Results: The device presently fails this test because there is not one single, easily accessible switch to turn on/off the device. The device had to be turned on by bending over and flipping a switch near the motor and connecting the battery to the motor controller.

Discussion

Overall, the prototype met the main design criteria and was able to attach and detach to a wheelchair, be operated by a single attendant, move forward and backward, stop, move through doorways, turn, and travel up and down hill acceptably. Testing was able to confirm these accomplishments and highlight areas for improvement.

The test participants had little trouble turning the device on and off and attaching and detaching it to the wheelchair. One test participant commented after attaching it that turning it on and attaching was "pretty quick." However, the toggle clamps were a little stiff and were somewhat difficult to lock fully. They also required the operator to bend over, which did not satisfy a design specification.

The thumb throttle also was not a problem for any of the testers and appeared to be easy to use. The device also proved to be intuitive to use because all test participants were able to learn how to use the device in less than 5 minutes and four of the five were able to perform the test runs easily the first time. The fifth participant took a little longer to master turning the device, taking two test runs to feel comfortable using it. This was partly due to operating issues of the device, such as turning problems when accelerating too quickly around corners. These were known problems which hindered the easy learning of the device.

The braking of the device was sufficient when tested travelling at full speed on flat surface carpet with all weight ranges up to a 220 pound occupant. The device came to a stop in at most five feet and was reliable. Braking was, however, not as reliable when tested outside on a smooth cement ramp travelling downhill (5 degrees) full speed and with a 265 pound occupant. This showed that the device's motor brake was not sufficient during the worst-case scenario testing and needs to be improved. This may also be due to the low friction between the drive wheel and the ground, a tire with a higher coefficient of friction would improve breaking distances. It also may be beneficial to add a parking brake to the device for situations when the device may be parked on an incline.

The device also did not remain stationary and when facing up or down a ramp of more than 5 degrees. This could be a problem with the motor controller programming since electric wheelchairs that use the same motors do not have this problem.

The steering mechanism worked well and was reliable overall. There were few steering problems faced during testing once each tester was comfortable using the device and had learned the best way to steer, but there is room for improvement. Traction on the steered wheel proved to be a problem. When the steered wheel was turned too far to either side, the wheel would begin to skid and would not turn the device in the direction desired. One tester turned the handlebars too far which locked the steered wheel at its extreme, making steering difficult. Lastly, the steering did not work when the steered wheel was lifted off of the ground. This tended to occur when the operator accelerated and pulled back slightly on the handlebars as the device moved forward. When the handlebars were pulled back or pushed down, the front wheel was lifted off of the ground, making the steering system obsolete. The weight which is located on the front of the device allows the steered wheel an increased normal force from the ground but only works when the device is not being pulled backwards on the handlebars and the steered wheel is on the ground. The weight provides little resistance to pulling the handlebars so another means of resisting this motion should be implemented.

Reversing the device using a button was effective and easy to learn. The reverse button had only one speed, which was set to the comfort level of the programmer, but one of the test participants found this reverse speed to be a little too fast. Also, one of the participants accidentally touched the reverse button while bending over to attach the device and it rolled backwards towards her. This is a safety problem which should be corrected.

Other observations showed that the spring attachment did not work as intended when it was designed. The compression distance is not as large as had been designed, therefore the springs do not compress as much and not as much force is applied to the device as was called for in the design (40 pounds). This is because when it was built, manufacturing limitations required the design to be changed to fit on the frame better and this changed the ramp angle. Therefore, the springs are not compressed as much as anticipated.

Another problem was that the device had difficulty travelling over the gap between the elevator and the floor. This was corrected by the operator pushing forward on the device, but this is not ideal. The device also had a problem of becoming off-center with the wheelchair, making it difficult to steer. It also failed the specifications of weight (it weighed over 30 pounds and could not be broken down into lighter subsections), height (it was nearly 3 inches taller than the specification), and portability (it did not fit in the trunk of a car).

The ride was observed to be a little jerky for the wheelchair occupant. This is also not ideal because it should be comfortable for the occupant. Lastly, the device has some sharp corners and areas which protrude and could pose a safety issue. A finished product should address these issues so that there are no risks of injury.

Recommendations

Braking was a concern with all test subjects and needs to be improved. This may be corrected by changing the motor controller program so that the motor would resist turning more when the throttle is released. The motor should work effectively as a break because of its current use on electric wheelchairs, therefore a new system of applying a breaking force should programmed into the motor controller. Another improvement would be a different drive wheel which has a larger coefficient of friction with smooth surfaces, such as rubber tire with treads. This would create more friction with the ground and would bring the wheelchair to a stop faster. Manual or other brakes in addition to the motor brake are recommended so that the user has better and more reliable control over stopping the device. To correct the problem of the device rolling when on ramps greater than 5 degrees, research could be done on the motor controller programming of electric wheelchairs and could determine whether or not an adjusted motor controller program could fix the problem. Manual parking brakes are recommended if this does not correct the problem since it is important that the device not roll away unattended.

It is recommended to find a better steered wheel which has more traction to avoid slipping. A different material (such as rubber) or a wheel with treads would improve the steering of the device. Also having a stop on the handlebar's steering would effectively prevent the operator from turning the handlebars too far and creating a toggle position in the control cables.

A resistance to pulling the handlebars and lifting the front wheel needs to be implemented. Adding a second connection to the wheelchair in the front such as a compression spring would resist the motion of lifting the front wheel. If a weight is still included in future generations, a smaller one is recommended so as not to obstruct the wheelchair's front wheels.

Despite the simplicity of turning the device on and off, it is not ideal because the operator must bend over and connect the power cable between the batteries and the motor controller. Adding an on/off switch to the system would be beneficial. To correct the issue of the difficulty using the toggle clamps, other toggle clamps which require less force could be substituted. Another solution would be to connect the two toggle clamps by a bar thereby simplifying attachment and creating a mechanism to lift and lower the toggle clamp by using the operator's foot. Since people have stronger legs, this could make attaching easier and would also satisfy the design criteria, which states that the operator must not need to bend over to attach the device.

The reverse function needs to be modified so that the device is more comfortable to use and is also safer. Changing it so that either the reverse speed is slower, or depends on the position of the thumb throttle is recommended. In addition, a cover over the button would make it so that it cannot be accidentally pushed, but would also make reversing more difficult. It could also be changed so that two buttons must be pressed simultaneously to reverse. Another option would be to change the programming of the microcontroller so that the button activates reverse, but the device does not move unless the thumb throttle is also activated. Another improvement would to require the device to be at a complete stop before being able to change from forward to reverse. This would eliminate the possibility of the device going from full speed forward to reverse if the reverse button was accidently activated.

The spring assembly design should be reexamined and either the actual mechanism corrected, redesigned, or another method of applying some of the weight of the wheelchair to the device could be designed. A new design would be more effective at using the weight of the wheelchair and occupant and applying it to the driven and steered wheel for improved traction.

A larger drive and steered wheel could improve the performance of the device moving over the elevator gap because the current wheel is falling slightly in this gap. A wheel with more traction, as mentioned earlier, might also correct this problem by creating enough friction to move the device out of the dip. Changing the microcontroller programming could smooth out the ride for the occupant and make it less jerky. This could be accomplished by making the dead band shorter on the throttle so that it is less sensitive to user input and therefore won't jerk when starting to move forward or backward.

The device would be improved if it were able to come apart in sections which weighed less than 30 pounds. This would make it more portable and would make it fit into the trunk of a car. Another recommendation is to implement adjustable handlebars which can accommodate users of different heights comfortably. Lastly, it is important that a final product address the dangerous sharp corners and the protrusion of the steering arm located below the handlebars. Covering the corners with thin rubber or plastic would eliminate the risk of scratching.

It was important that design would be able to attach to more than one type of wheelchair so that it may be used in an institution. This criterion was met by designing a horizontal bar which would attach to wheelchairs in the specified location and the device would then attach to that bar. This worked well on the test wheelchair, however the horizontal bar may not fit all wheelchairs and the design of the horizontal bar could be improved. Also, if a wheelchair already has a horizontal bar but it is not at the specific height required by the device, the device will not be able to adjust to the required height because the attachment mounts are permanently fixed to the frame of the device. It is recommended that the attachment of this device be thoroughly examined and modified so that it would be adaptable to more wheelchairs, possibly without a supplemental horizontal bar, or that it may fit to more than one height horizontal bar.

Conclusions

The goal of this project was to design and prototype a cost-effective wheelchair pusher that is easy to use, transportable, and satisfies the requirements of both institutional and personal use. The prototype satisfies the ease of use and intuitive requirements as shown through volunteer testing. Though this prototype could not be transported in the trunk of a car, it could be transported in the back seat of a car or in a van. Besides transportability, the device meets most of the criteria of personal use and institutional use. Improvements for institutional use would be to increase the compatibility with varying wheelchair types.

Overall, the primary goal was achieved for this first generation prototype. A successful device was completed that will assist an attendant in pushing a manual wheelchair up an incline or over rough terrain. Though there are some flaws in the device, the team is confident that with the recommendations provided, a second generation prototype could meet all the design criteria.

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Appendix A: Pair-Wise Comparison of Design Goals

Table 17: Pair-Wise Comparison Chart

	Performance	Ease of use	Portability	Safety	Weight	Compatibility	Total
Performance	–	1/2	1	0	1	1	3.5
Ease of use	1/2	–	1	0	1	1/2	3
Portability	0	0	–	0	1/2	1/2	1
Safety	1	1	1	–	1	1	5
Weight	0	0	1/2	0	--	0	1/2
Compatibility	0	1/2	1/2	0	1	--	2

Appendix B: Weighting Factors of Design Goals

Table 18: Weighting Factor Chart

	100	Safety
Critical	90	
	80	
	70	Performance
Important	60	Ease of Use
	50	
	40	Compatibility
	30	
Optional	20	Portability
	10	Weight

Appendix C: Center of Gravity for a Wheelchair

Equations obtained from the Journal of Rehabilitation Research and Development (Lemaire, E. D., Lamontagne, M., Barclay, H. W., John, T., & Martel, G.)

Below is a picture of the Journal of Rehabilitation Research and Development's testing supplies in order to find the center of gravity. A balance platform is constructed to to be level when resting on the scale (left) and supporting surface (right). The balance platform has a known center of gravity, and the scale and supporting surface have minimal contact with the balance platform, providing known piviot points.

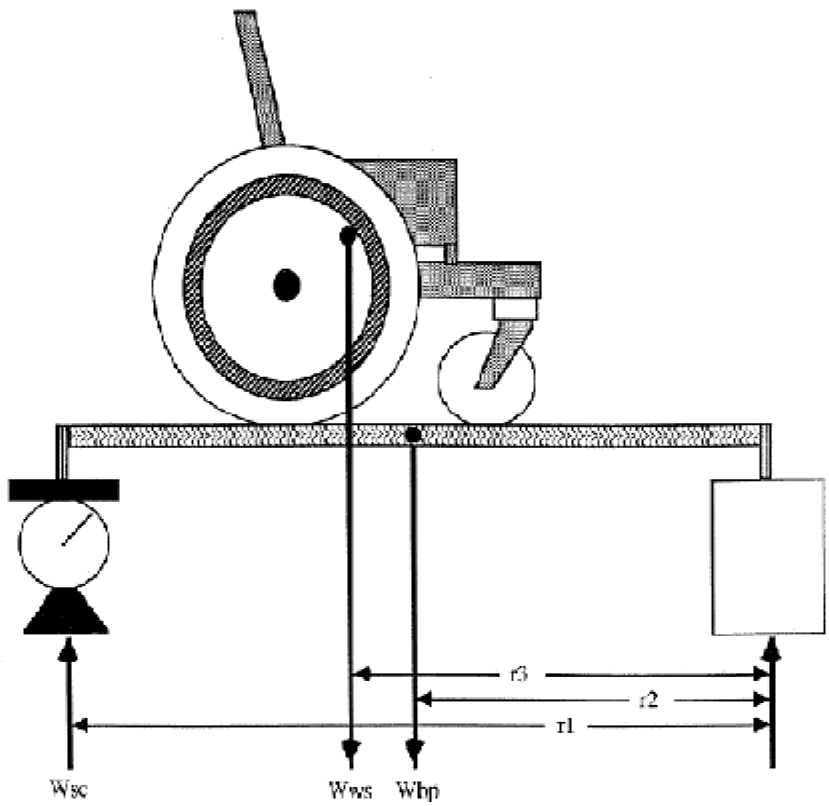


Figure 119: Example Picture of Center of Gravity Experiment (Lemaire et.al., 1991)

w_{sc} = Weight reading from scale
w_{bp} = Weight of balance platform
w_{ws} = Weight of the wheelchair + weight of the patient
r_1 = distance between the two piviot points
r_2 = distance from the piviot point to the balance platform's center of gravity
r_3 = distance from the piviot point to the patient-wheelchair center of gravity
R_{rw} = distance from the rear wheel axle to the patient-wheelchair center of gravity
r_{rw} = distance from the scale to the rear wheel axel

X direction

Subject 1

$w_{scx} := 90lbf$ $r_{1x} := 4ft$ $r_{rwx} := 17.5in$

$w_{bpx} := 35lbf$ $r_{2x} := 2ft$

$w_{wsx} := 140lbf$

$(r_{3x} * w_{wsx}) + (r_{2x} * w_{bpx}) - (r_{1x} * w_{scx}) = 0$

$$r_{3x} := \frac{(r_{1x} \cdot w_{scx}) - (r_{2x} \cdot w_{bpx})}{w_{wsx}} = 24.857 \cdot in$$

By solving for the distance from the scale to the patient-wheelchair center of gravity and subtracting the distance from the scale pivot point to the rear axle, the distance from the rear wheel axle to the patient wheelchair center of gravity can be obtained.

$$R_{rwx} := \left[r_{1x} - \left(\frac{r_{1x} \cdot w_{scx} - r_{2x} \cdot w_{bpx}}{w_{wsx}} \right) \right] - r_{rwx} = 5.643 \cdot in$$

distance of center of gravity from front wheel is

$17in - R_{rwx} = 11.357 \cdot in$

17 is the distance between the 2 wheel axles

Subject 2

$w_{scx} := 146.5lbf$ $r_{1x} := 4ft$

$w_{bpx} := 35lbf$ $r_{2x} := 2ft$ $r_{rwx} := 17.5in$

$w_{wsx} := 268lbf$

$(r_{3x} * w_{wsx}) + (r_{2x} * w_{bpx}) - (r_{1x} * w_{scx}) = 0$

$$R_{rwx} := \left[r_{1x} - \left(\frac{r_{1x} \cdot w_{scx} - r_{2x} \cdot w_{bpx}}{w_{wsx}} \right) \right] - r_{rwx} = 7.396 \cdot in$$

distance of center of gravity from front wheel is

$17in - R_{rwx} = 9.604 \cdot in$

Y direction

Subject 1

$w_{scy} := 89.5lbf$ $r_{1y} := 4ft$

$w_{bpy} := 35lbf$ $r_{2y} := 2ft$ $r_{rwy} := 10in$

$w_{wsy} := 140lbf$

$(r_{3y} * w_{wsy}) + (r_{2y} * w_{bpy}) - (r_{1y} * w_{scy}) = 0$

$$R_{rwy} := \left[r_{1y} - \left(\frac{r_{1y} \cdot w_{scy} - r_{2y} \cdot w_{bpy}}{w_{wsy}} \right) \right] - r_{rwy} = 13.314 \cdot in$$

distance of center of gravity from the ground is

$R_{rwy} = 13.314 \cdot in$

Subject 2

$w_{scy} := 177.5lbf$ $r_{1y} := 4ft$

$w_{bpy} := 35lbf$ $r_{2y} := 2ft$ $r_{rwy} := 10in$

$w_{wsy} := 268lbf$

$(r_{3y} * w_{wsy}) + (r_{2y} * w_{bpy}) - (r_{1y} * w_{scy}) = 0$

$$R_{rwy} := \left[r_{1y} - \left(\frac{r_{1y} \cdot w_{scy} - r_{2y} \cdot w_{bpy}}{w_{wsy}} \right) \right] - r_{rwy} = 9.343 \cdot in$$

distance of center of gravity from the ground is

$R_{rwy} = 9.343 \cdot in$

Appendix: D Static Analysis of a Wheelchair

Effect of spring force on wheelchair

Flat surface, accelerating 0 to 4mph in 4 seconds

$d_1 := 17\text{in}$

$d_2 := 9.604\text{in}$

$d_3 := 9\text{in}$

$F_{sy} := 0\text{lbf}$

$d_4 := 9.343\text{in}$

$d_5 := 1.18\text{in}$

$m_{ch1} := 300\text{lb}$

$a_1 := 4\dfrac{\text{mph}}{4\text{sec}} = 1.467\cdot\dfrac{\text{ft}}{\text{s}^2}$

Guess

$F_{w1} := 20\text{lbf}$

$F_{w2} := 20\text{lbf}$

in x direction, sum forces

$F_{sx} := m_{ch1}\cdot a_1 = 13.676\cdot\text{lbf}$

Given

in y direction, sum forces

$F_{w1} + F_{w2} + F_{sy} - m_{ch1}\cdot g = 0$

Sum moments around point A

$-F_{w2}\cdot d_1 - F_{sy}\cdot(d_1 + d_5) - F_{sx}\cdot d_3 + m_{ch1}\cdot g\cdot d_2 = 0$

$\text{Find}(F_{w1}, F_{w2}) = \begin{pmatrix} 137.758 \\ 162.242 \end{pmatrix}\cdot\text{lbf}$

Appendix E: Static Analysis of Device

Calculated External Forces

Finding the Normal force at each wheel

F_{w2y} = Normal force on rear wheel
F_{dwy} = Normal force on drive wheel
F_{w1y} = Normal force on front wheel

x_1 = Length of the device
x_2 = Length from rear wheel to drive wheel
x_f = Length from rear wheel to spring
x_w = Length from rear wheel to center of mass
y_f = Height of contact with wheelchair

F = Force of spring
W = Weight of device

Plug in correct Numbers here:

$F_{cx} := 33lbf$

$F_{cy} := 40lbf$

$W := 68lbf$

$x_1 := 21.09in$

$x_2 := 7.62in$

$x_f := 7.62in$

$x_w := 11.52in$

$y_f := 9in$

Force values are guesses (do not change)

$F_{dwy} := 10lbf$

$F_{w1y} := 10lbf$

$F_w := .0lbf$

sum forces around point: Given

B $$F_{w1y}\cdot(x_1 - x_2) - W\cdot(x_w - x_2) + F_{cx}\cdot y_f - F_{cy}\cdot(x_f - x_2) - F_w\cdot(x_1 - x_2) = 0$$

A $$-F_{dwy}\cdot(x_1 - x_2) + W\cdot(x_1 - x_w) + F_{cy}\cdot(x_1 - x_f) + F_{cx}\cdot y_f = 0$$

$$\text{Find}(F_{dwy}, F_{w1y}) = \begin{pmatrix} 110.361 \\ -2.361 \end{pmatrix}\cdot lbf$$

Appendix F: Turning Radius Analysis

$N := 20lbf$

$\mu := .25$

$F_{friction} := N \cdot \mu = 22.241N$

$m := 68lb$

$$a := 4\frac{mph}{4sec} = 1.467\frac{ft}{s^2}$$

$F_{drive} := 12lbf$

$$\theta := asin\left[\frac{(F_{friction})}{F_{drive}}\right] = 24.624deg$$

For a 60 inch turning radius the turning angle needs to be 16 degrees.

This calculation does not account for slip angle; however slip angle is accounted for in remained or the report

Appendix G: Battery Tray Stress Analysis

Sum forces in x dir: (acceleration is 0)

$$N := 0$$

Sum forces in y dir: (acceleration is 0)

$$S := 16lb$$

Sum moments about O

$$M_O := 16lb \cdot 3in = 48\,lb \cdot in$$

Cross sectional area of beam:

$$w := 6in \qquad h := .125in$$

$$A := w \cdot h = 4.839 \times 10^{-4}\,m^2$$

Moment of Area of beam

$$I := w \cdot \frac{h^3}{12} = 9.766 \times 10^{-4}\,in^4$$

Bending stress at A:

$$c := \frac{.125}{2}\,in = 0.063\,in$$ distance from point O to A

$$\sigma_b := M_O \cdot \frac{c}{I} = 3.072 \times 10^3\,\frac{lb}{in^2}$$

Sheer stress at point O:

$$\tau_O := \frac{S}{A} = 21.333\,\frac{lb}{in^2}$$

Appendix H: Horizontal Stem Calculations

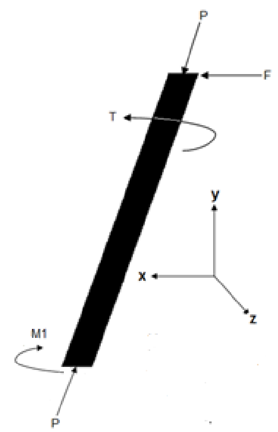


Figure 120: FBD of Handlebar Stem

Critical Points Are A, B, C, and D

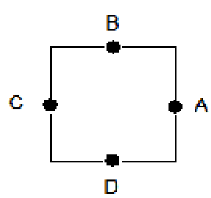


Figure 121: Critical Points of the Horizontal Stem

Define

Tube Length	$L := 33in$	$L = 0.838\,m$
	$B := 1in$	$b := .75in$
	$B = 0.025\,m$	$b = 0.019\,m$
Tube Dimensions	$H := 1in$	$h := .75in$
	$H = 0.025\,m$	$h = 0.019\,m$
Tube Area	$A := B \cdot H - b \cdot h$	$A = 0.438 \cdot in^2$
		$A = 2.823 \times 10^{-4}\,m^2$
Cross Sectional Area	$A_{cross} := \pi \cdot \left(\frac{B - b}{2}\right)^2$	$A_{cross} = 3.167 \times 10^{-5}\,m^2$

Distance from center to outside of tube	$c := 2.5in$	$c = 0.064\,m$
Moment of Area Inertia	$I_{zzsquare} := \dfrac{B \cdot H^3 - b \cdot h^3}{12}$	$I_{zzsquare} = 2.371 \times 10^{-8}\,m^4$
Polar moment of inertia	$J := 2 \cdot I_{zzsquare}$	$J = 4.742 \times 10^{-8}\,m^4$
Applied force	$F := 10 \cdot N$	
Torque Force	$T := 10N \cdot m$	
Compression or Tension force	$P := 10N$	

$q(x) = M1\langle x - 0\rangle^{-2} - F\langle x - L\rangle^{-1}$

$V(x) = M1\langle x - 0\rangle^{1} - F\langle x - L\rangle^{0}$

$M(x) = M1\langle x - 0\rangle^{0} - F\langle x - L\rangle^{1}$

BC (2)

$V(L^{+}) = M1 - F = 0$

$M(L^{+}) = M1(L) = 0$

$M_1 := F \cdot L = 8.382\,J$

Shear and Moment Equations

$S(x,z) := \text{if}(x \geq z, 1, 0)$ $\qquad x := 0, 0.005 \cdot L .. L$

$V(x) := F \cdot S(x,L)$

$M(x) := M_1 \cdot S(x,0m) - F \cdot S(x,L) \cdot (x - L)$

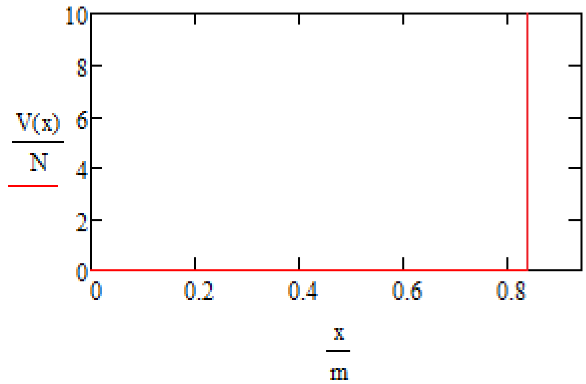


Figure 122: Graph of Shear Force Across Horizontal Stem

Max Shear is at x = a, so

$V_{max} := |V(L)| = 10\,N$

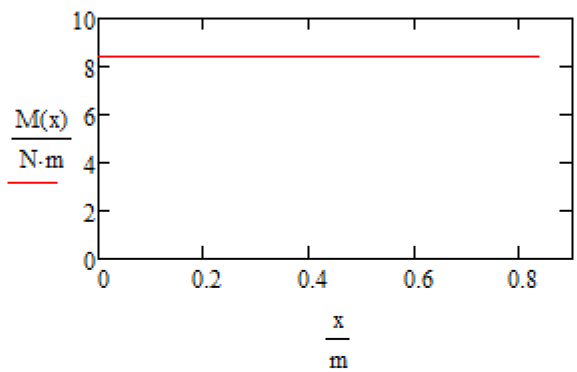


Figure 123: Graph of Moment Across Horizontal Stem

Max Moment is at any point so

$M_{max} := |M(L)| = 8.382\,J$

Max Moment is at any point so

$M_{max} := |M(L)| = 8.382\,J$

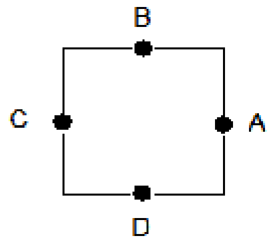


Figure 124: Critical Points of the Horizontal Stem

Stress

$$I_{zzsquare} = 2.371 \times 10^{-8}\,m^4$$

$$\sigma_{xa} := M_{max} \cdot \frac{c}{I_{zzsquare}} = 22.448 \cdot MPa$$

$$\sigma_x := \frac{P}{A_{cross}} = 3.158 \times 10^5\,Pa$$

Torsion

$$\sigma_z := 0$$

$$J = 4.742 \times 10^{-8}\,m^4$$

$$\tau_{torsion} := T \cdot \frac{c}{J} = 1.339 \times 10^7\,Pa$$

Bending

$$\tau_{bending} := \frac{4 \cdot V_{max}}{3 \cdot A_{cross}} = 0.421 \cdot MPa$$

TOTAL

$$\sigma_{total} := (\sigma_{xa} + \sigma_x) = 2.276 \times 10^7\,Pa$$

$$\tau_{total} := \tau_{bending} + \tau_{torsion} = 13.811 \cdot MPa$$

Point A:

$$\sigma_{total} = 22.763 \cdot MPa$$

$$\tau_{pointA1} := \sqrt{\frac{(\sigma_{total} - \sigma_z)^2}{4} + \tau_{torsion}^{\ 2}} = 17.574 \cdot MPa$$

Principal Stresses / Mohr's Circle

$$\sigma_{pointA1} := \frac{(\sigma_{total})}{2} + \sqrt{\frac{(\sigma_{total})^2}{4} + \tau_{torsion}^{\ 2}} = 28.956 \cdot MPa$$ point 1

$$\sigma_{pointA3} := \frac{(\sigma_{total})}{2} - \sqrt{\frac{(\sigma_{total})^2}{4} + \tau_{torsion}^{\ 2}} = -6.192 \cdot MPa$$ point 2

$$\sigma'_{pointA} := \sqrt{\sigma_{pointA1}^{\ 2} + \sigma_{pointA3}^{\ 2} - \sigma_{pointA1} \cdot \sigma_{pointA3}} = 32.497 \cdot MPa$$ von mises

$$\tau_{pointA13} := \frac{\sigma_{pointA1} - \sigma_{pointA3}}{2} = 17.574 \cdot MPa$$ T max

Point B:

T.tot=T.bending+T.torsion

$$\tau_{total} = 13.811 \cdot MPa \qquad \sigma_{xpointB} := -\sigma_x$$

Principal Stresses / Mohr's Circle

$$\sigma_{pointB1} := \frac{(\sigma_{xpointB})}{2} + \sqrt{\frac{(\sigma_{xpointB})^2}{4} + \tau_{total}^{\ 2}} = 13.654 \cdot MPa$$ point 1

$$\sigma_{pointB3} := \frac{(\sigma_{xpointB})}{2} - \sqrt{\frac{(\sigma_{xpointB})^2}{4} + \tau_{total}^{\ 2}} = -13.97 \cdot MPa$$ point 2

$$\sigma'_{pointB} := \sqrt{\sigma_{pointB1}^{\ 2} + \sigma_{pointB3}^{\ 2} - \sigma_{pointB1} \cdot \sigma_{pointB3}} = 23.924 \cdot MPa$$ von mises

$$\tau_{pointB13} := \frac{\sigma_{pointB1} + \sigma_{pointB3}}{2} = -0.158 \cdot MPa$$ T max

Point C:

$\sigma_{total} = 22.763 \cdot MPa$

$$\tau_{pointCmax} := \sqrt{\frac{(\sigma_{total})^2}{4} + \tau_{torsion}^{\ 2}} = 17.574 \cdot MPa$$

Principal Stresses / Mohr's Circle

$$\sigma_{pointC1} := \frac{(-\sigma_{total})}{2} + \sqrt{\frac{(\sigma_{total})^2}{4} + \tau_{torsion}^{\ 2}} = 6.192 \cdot MPa$$ point 1

$$\sigma_{pointC3} := \frac{(-\sigma_{total})}{2} - \sqrt{\frac{(\sigma_{total})^2}{4} + \tau_{torsion}^{\ 2}} = -28.956 \cdot MPa$$ point 2

$$\sigma'_{pointC} := \sqrt{\sigma_{pointC1}^{\ 2} + \sigma_{pointC3}^{\ 2} - \sigma_{pointC1} \cdot \sigma_{pointC3}} = 32.497 \cdot MPa$$ von mises

$$\tau_{pointC13} := \frac{\sigma_{pointC1} - \sigma_{pointC3}}{2} = 17.574 \cdot MPa$$ T max

Point D:

T.tot=T.bending+T.torsion

$\tau_{total.} := \tau_{torsion} - \tau_{bending} = 12.969 \cdot MPa$

Principal Stresses / Mohr's Circle $\sigma_{xpointD} := -\sigma_x$

$$\sigma_{pointD1} := \frac{(\sigma_{xpointD})}{2} + \sqrt{\frac{\sigma_{xpointD}^{\ 2}}{4} + \tau_{total.}^{\ 2}} = 12.812 \cdot MPa$$ point 1

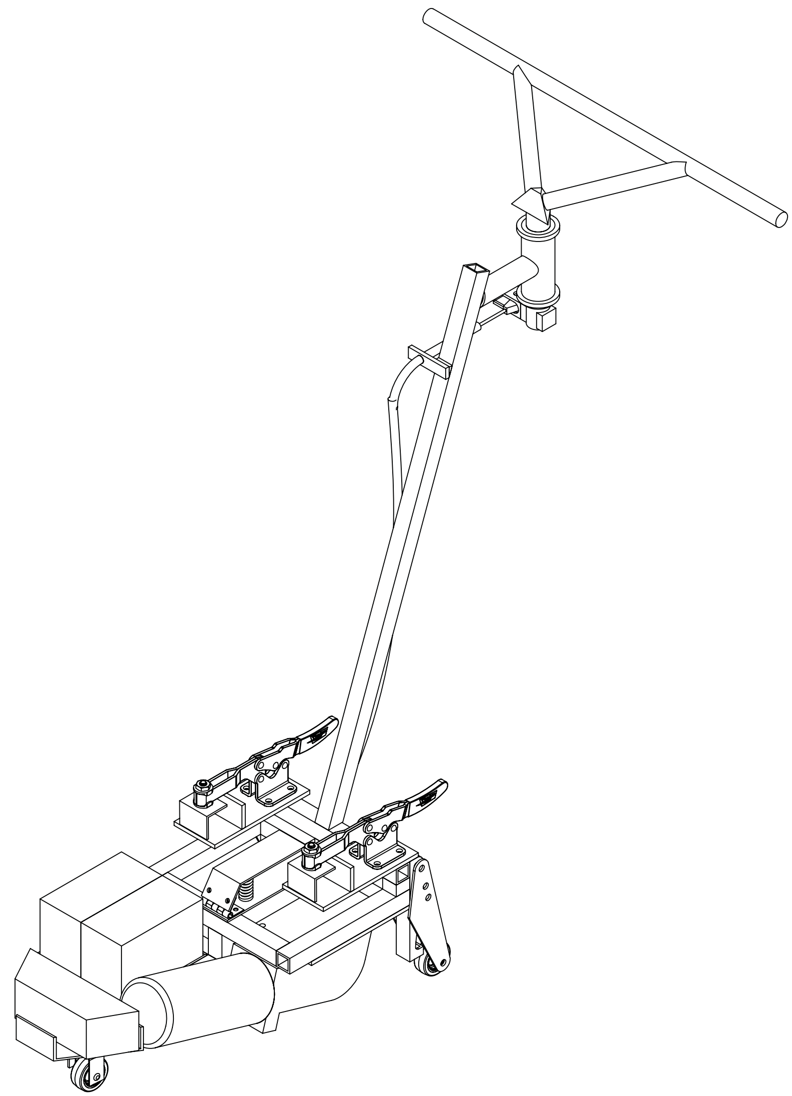
$$\sigma_{pointD3} := \frac{(\sigma_{xpointD})}{2} - \sqrt{\frac{(\sigma_{xpointD})^2}{4} + \tau_{total.}^{\ 2}} = -13.128 \cdot MPa$$ point 2

$$\sigma'_{pointD} := \sqrt{\sigma_{pointD1}^{\ 2} + \sigma_{pointD3}^{\ 2} - \sigma_{pointD1} \cdot \sigma_{pointD3}} = 22.466 \cdot MPa$$ von mises

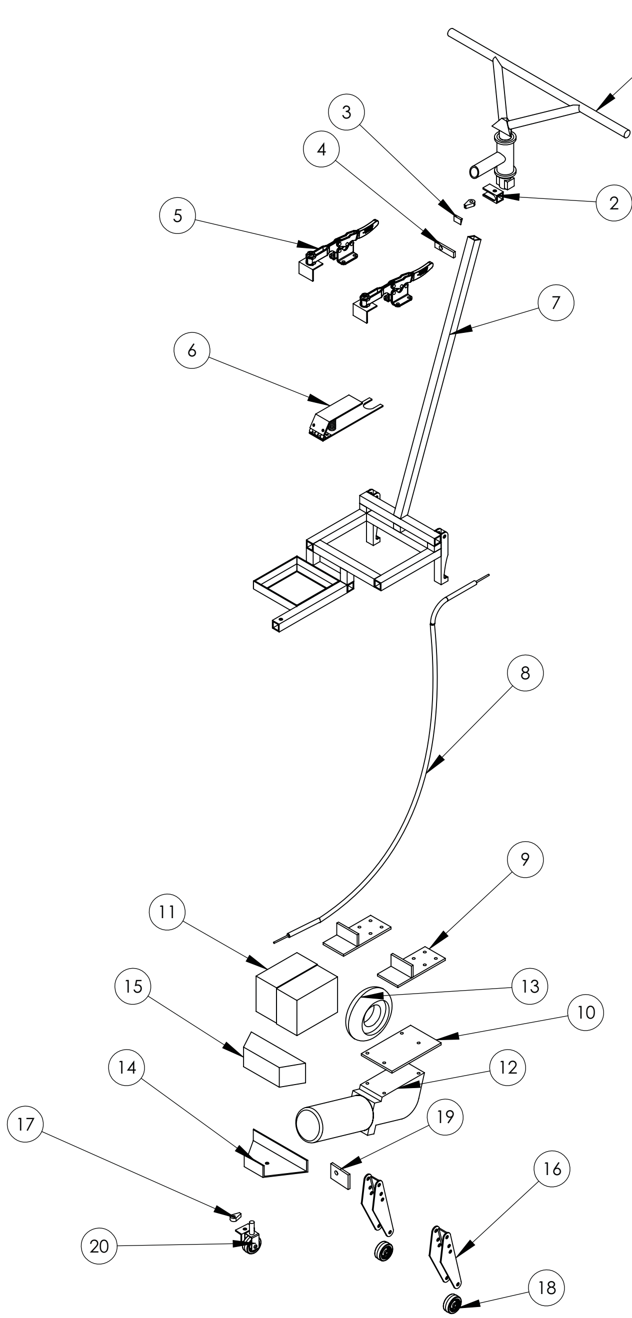
$$\tau_{pointD13} := \frac{\sigma_{pointD1} - \sigma_{pointD3}}{2} = 12.97 \cdot MPa$$ T max

Appendix I: CAD Drawings

CAD drawings start on the next page.



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/15/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	Device Assembly
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:10 WEIGHT: SHEET 1 OF 30



ITEM NO.	PART	QTY.
1	Bike Handlebars	1
2	Stembar Arm	1
3	Wedged Peice	1
4	Cable Support for Stembar	1
5	Toggle Clamp	2
6	Spring Assembly	1
7	Frame Assembly	1
8	Cable	2
9	Attachment Mount Assembly	2
10	Motor Mount	1
11	Battery	2
12	Motor	1
13	Driven Wheel	1
14	Weight Tray	2
15	Weight	1
16	Antitipper	2
17	Tie-rod	2
18	Back Caster Wheel	2
19	Cable Support for Front Wheel	1
20	FWA	1

NOTE: THE ENTIRE ASSEMBLY WILL BE MANUFACTURED IN HIGGINS LABORATORY.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

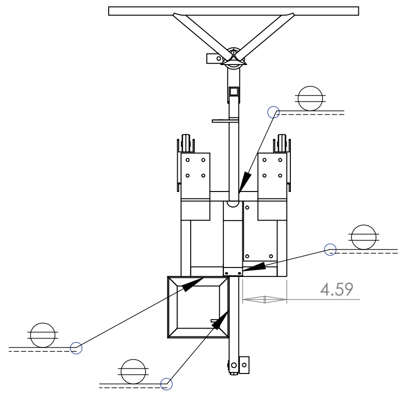
	NAME	DATE
DRAWN		
CHECKED	LM	2/15/10
ENG APPR.	GVR	4/16/10
MFG APPR.		
Q.A.		
COMMENTS:		

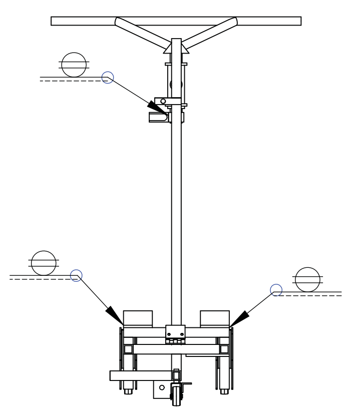
Worcester Polytechnic Institute

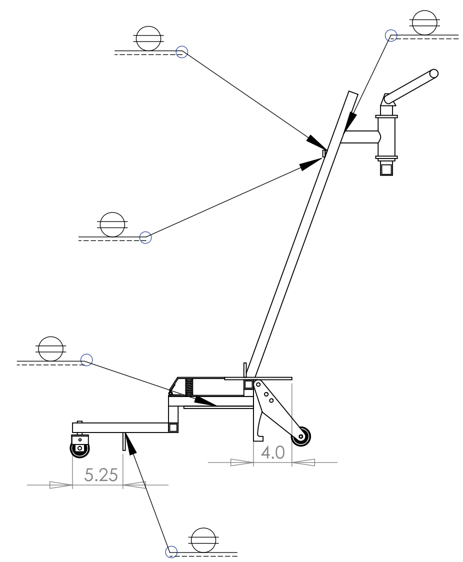
TITLE:
Exploded Device Assembly

SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:20 WEIGHT: SHEET 2 OF 30







NOTE:
ALL WELDS MUST BE +/- .1 UNLESS CRITICAL
ASSURE ALL WELDS ARE STRAIGHT AND SQUARE
WELD .25" AROUND ALL SURFACES IN 12 SPOTS INDICATED

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED	LM	2/15/10
ENG APPR.	GVR	4/16/10
MFG APPR.		
Q.A.		
COMMENTS:		

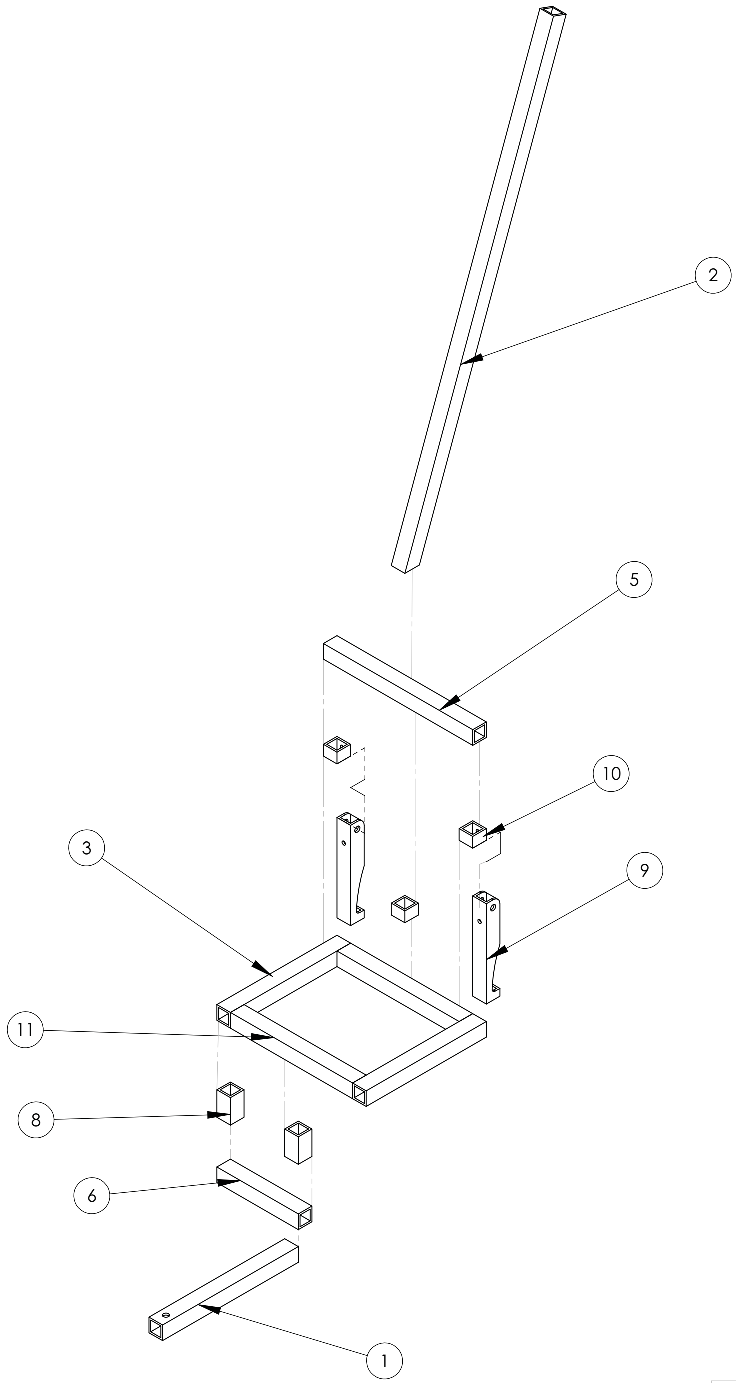
Worcester Polytechnic Institute

TITLE:
Exploded Device Assembly

SIZE C | DWG. NO. Pusher Device | REV 2

SCALE: 1:10 | WEIGHT: |

ITEM NO.	PART	QTY.
1	10 inch bar	1
2	Handlebar Stem	1
3	8.85 inch bar	2
4	9 inch bar	1
5	11 inch bar	1
6	6 inch bar	1
7	.75 inch bar	1
8	1.75 inch bar	2
9	Tipper Support	2
10	.75 bar with hole	2
11	9in bar with holes	1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

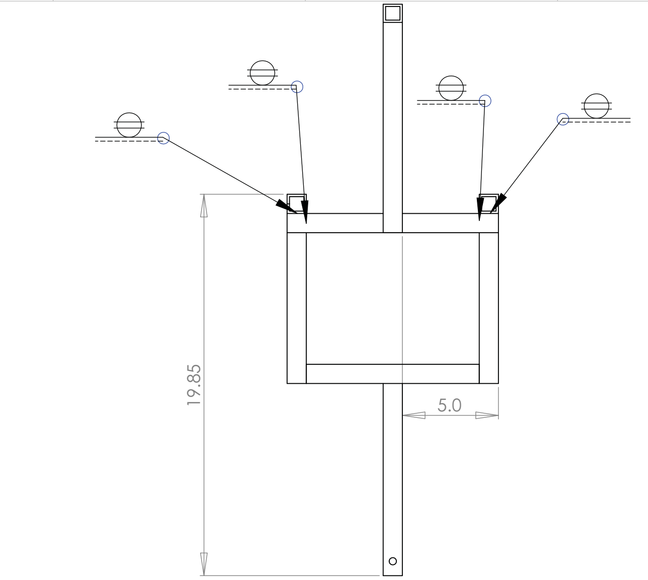
Worcester Polytechnic Institute

TITLE:

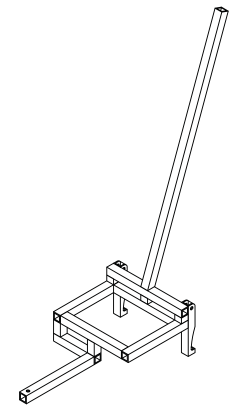
Exploded Frame Assembly

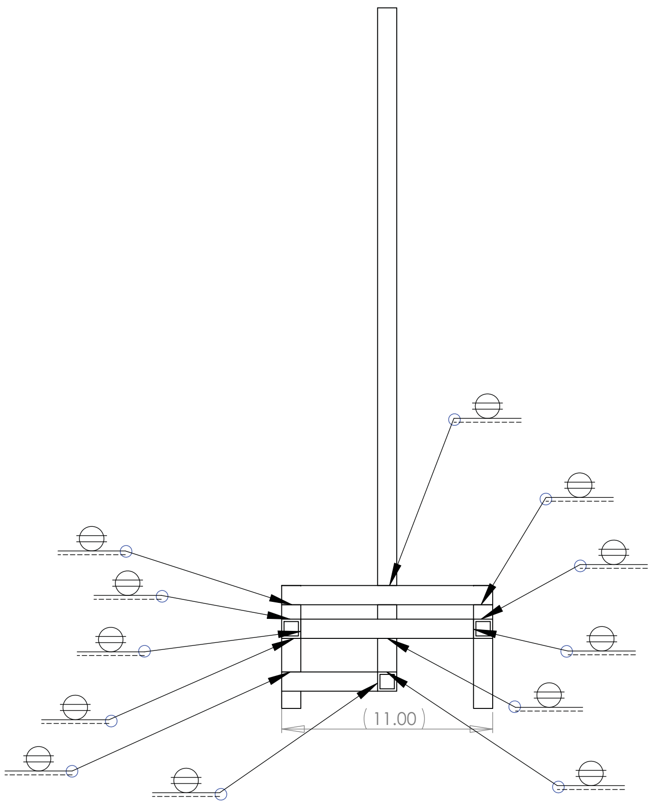
SIZE C DWG. NO. Pusher Device REV 2

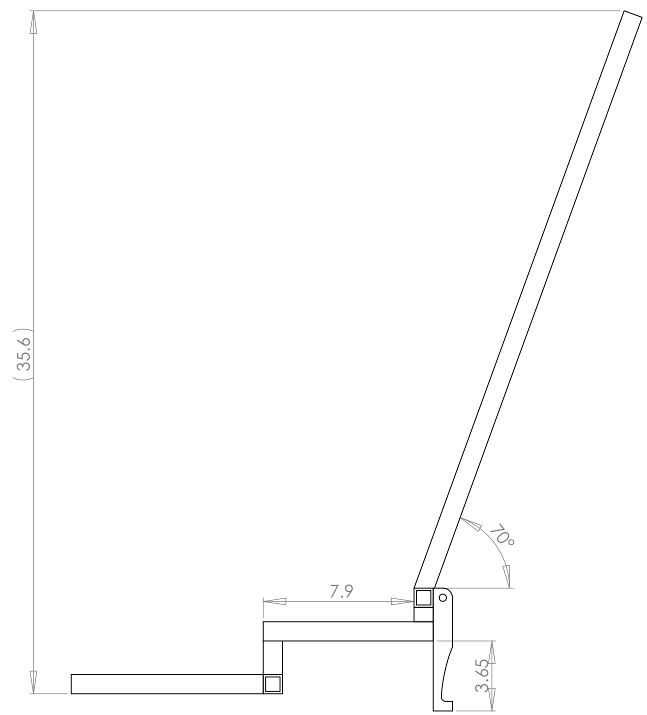
SCALE: 1:20 WEIGHT: SHEET 4 OF 30



NOTE:
ALL WELDS MUST BE +/- .1 UNLESS CRITICAL
ASSURE ALL WELDS ARE STRAIGHT AND SQUARE
WELD .25" AROUND ALL SURFACES IN 16 SPOTS INDICATED







UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Worcester Polytechnic Institute

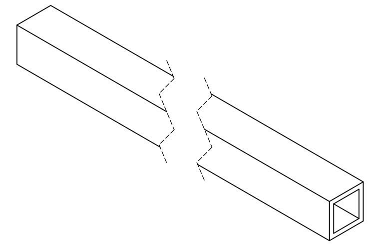
TITLE:

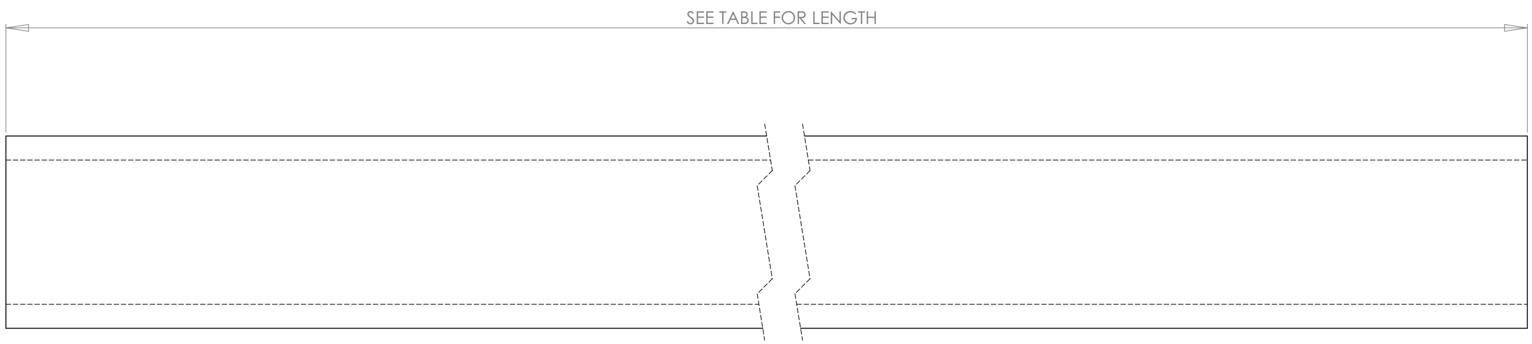
Frame Assembly

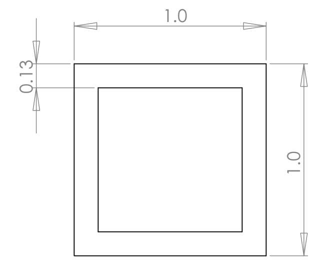
SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:10 WEIGHT: SHEET 5 OF 30

PART	LENGTH
10 inch bar	10.0"
8.85 inch bar	8.85"
9 inch bar	9.0"
6 inch bar	6.0"
.75 inch bar	.75"
1.75 inch bar	1.75"







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	2/25/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

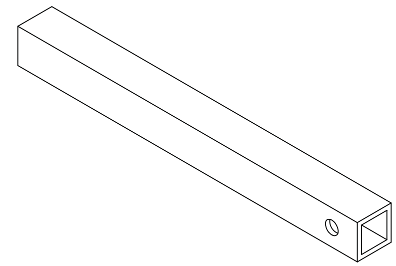
Worcester Polytechnic Institute

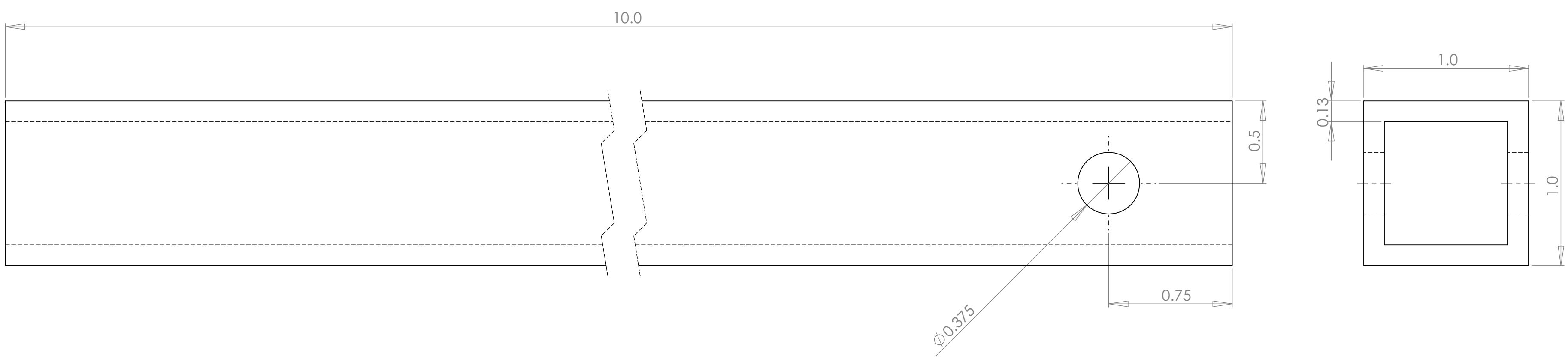
TITLE:

Bars in Frame Assembly

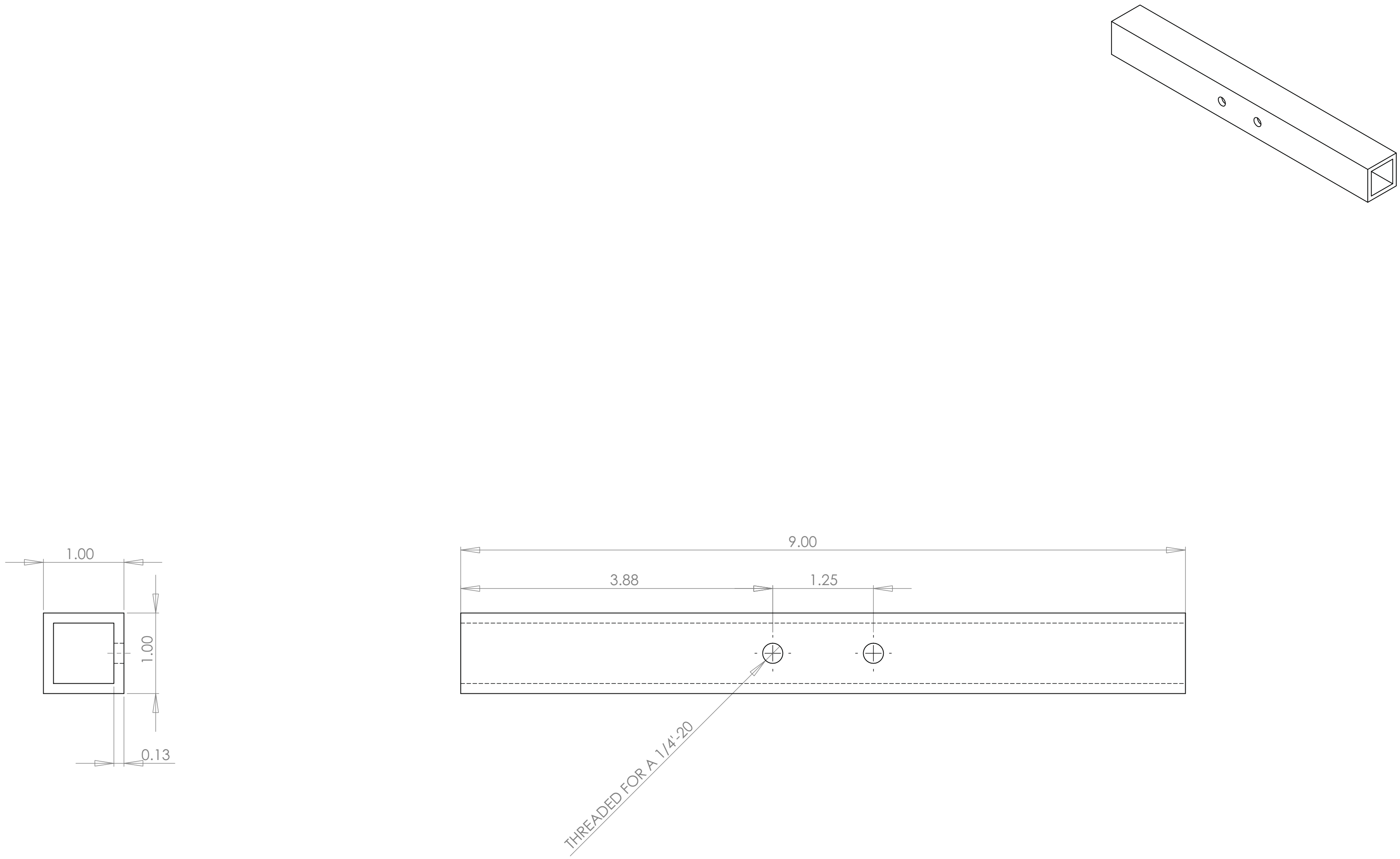
SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:2 WEIGHT: SHEET 6 OF 30

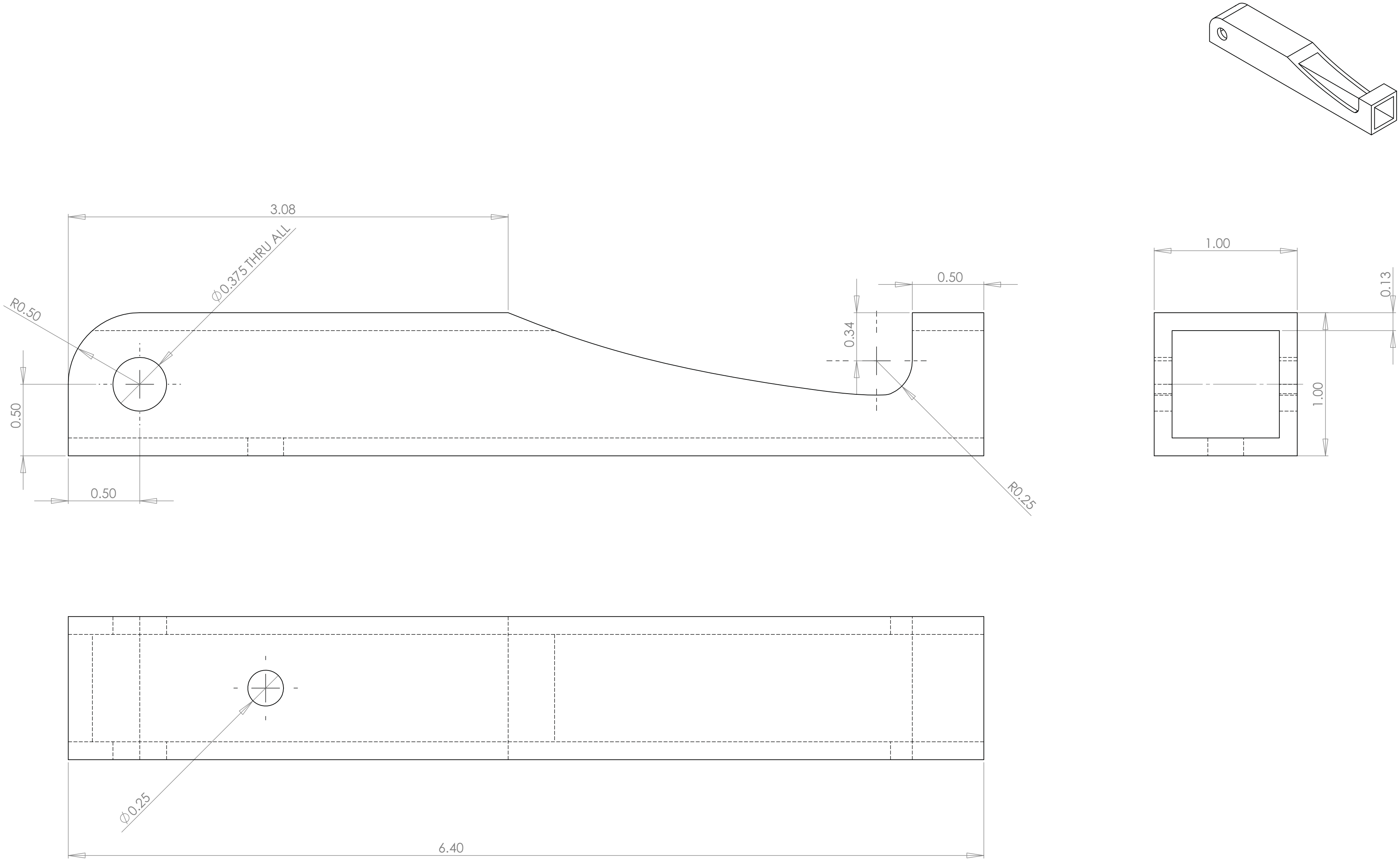




UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	10 inch bar
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 7 OF 30



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	9 inch bar for Spring Assem
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 8 OF 30



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DIMENSIONS ARE IN INCHES

TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.05
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	2/25/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

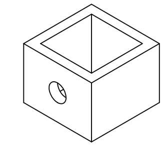
Worcester Polytechnic Institute

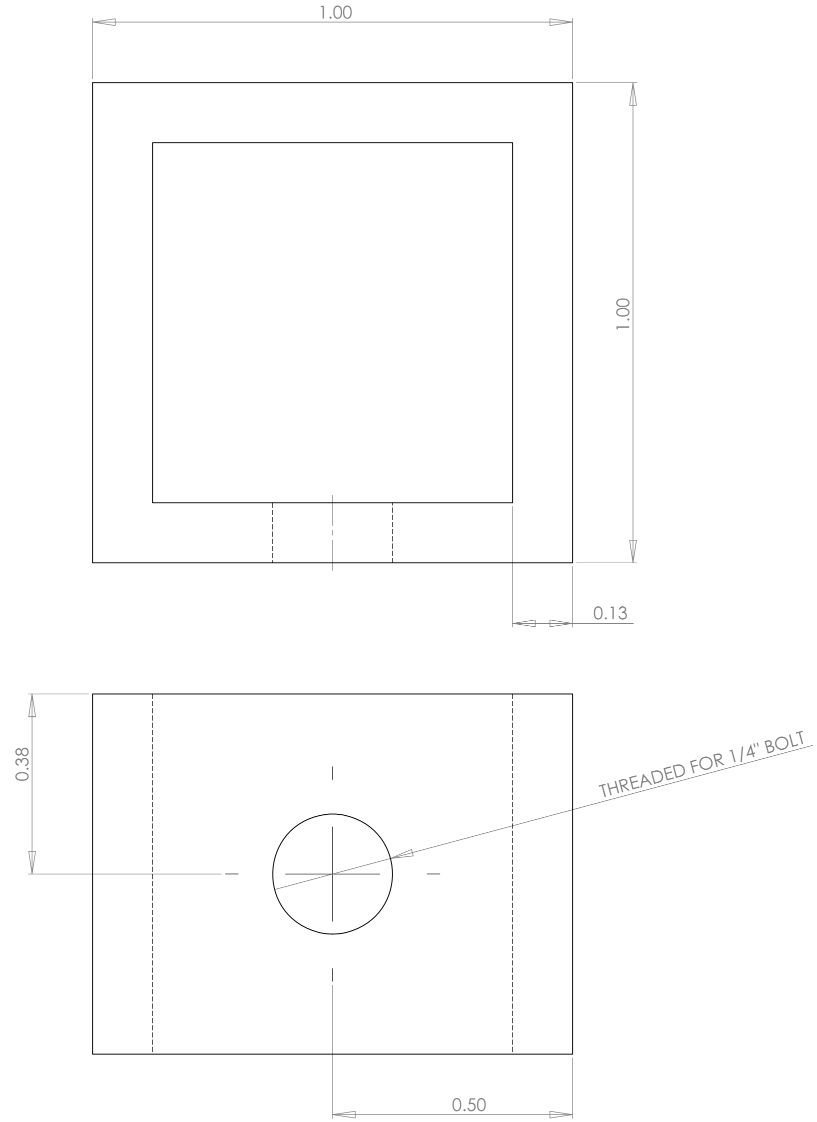
TITLE:

Tipper Support

SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:1 WEIGHT: SHEET 9 OF 30





UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.05 THREE PLACE DECIMAL ±.005	CHECKED	GVR	4/16/10
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

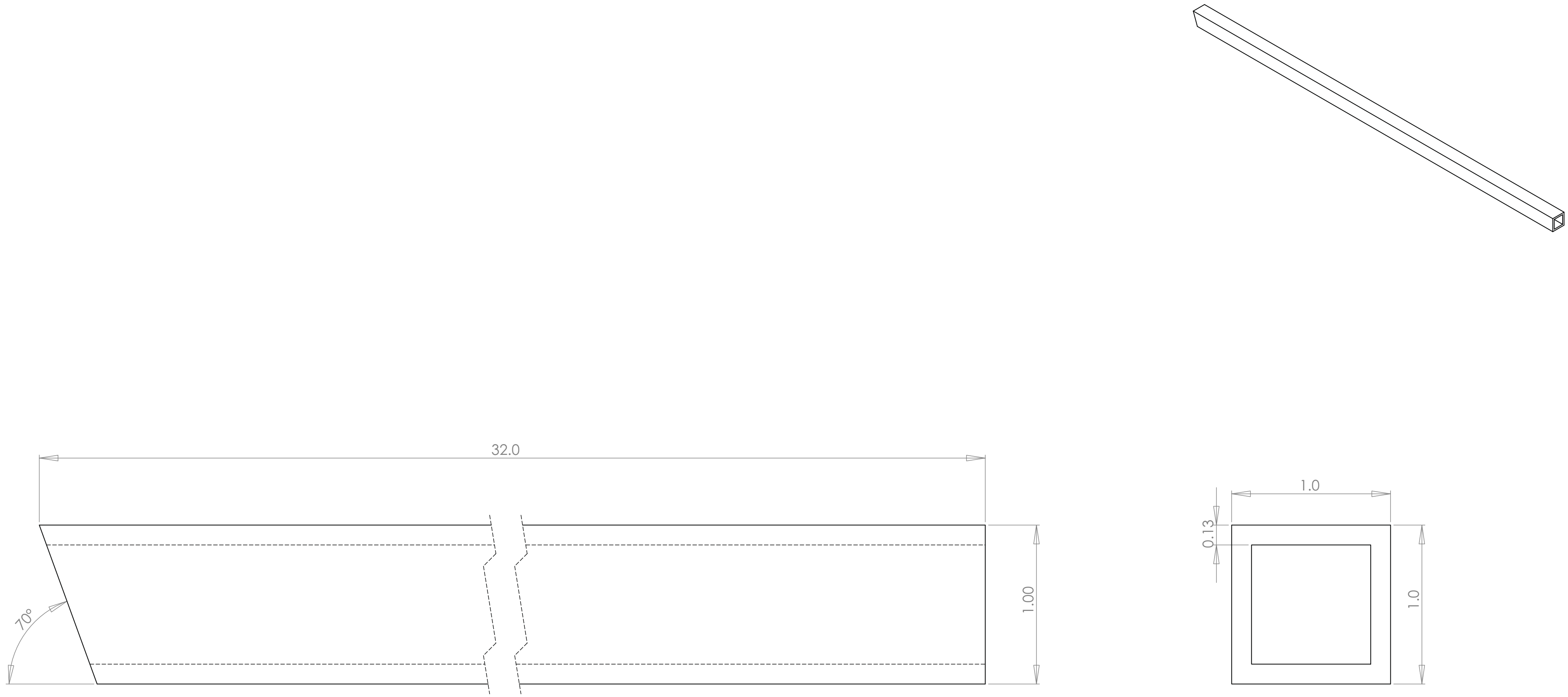
Worcester Polytechnic Institute

TITLE:

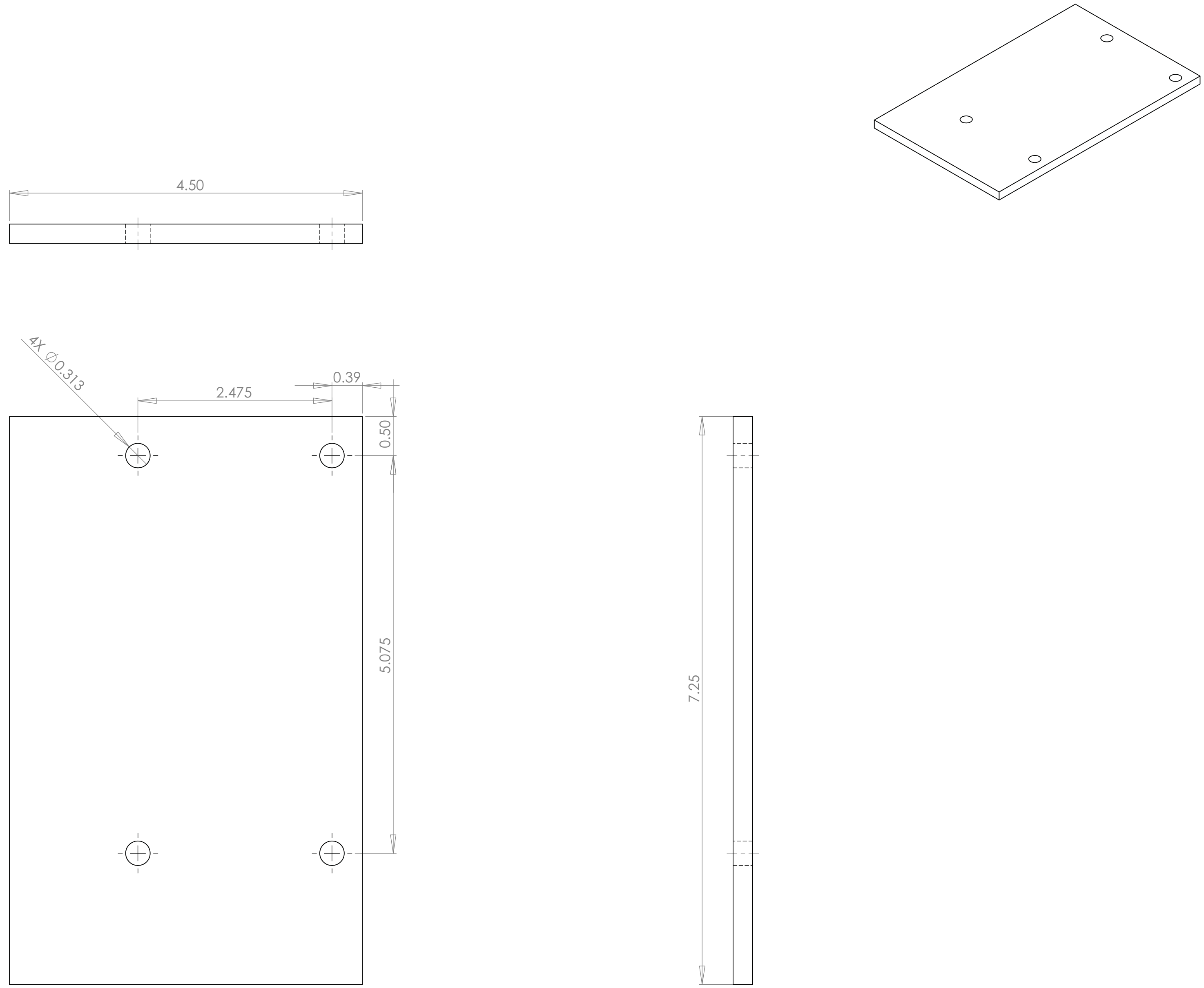
.75 bar with hole

SIZE C | DWG. NO. Pusher Device | REV 2

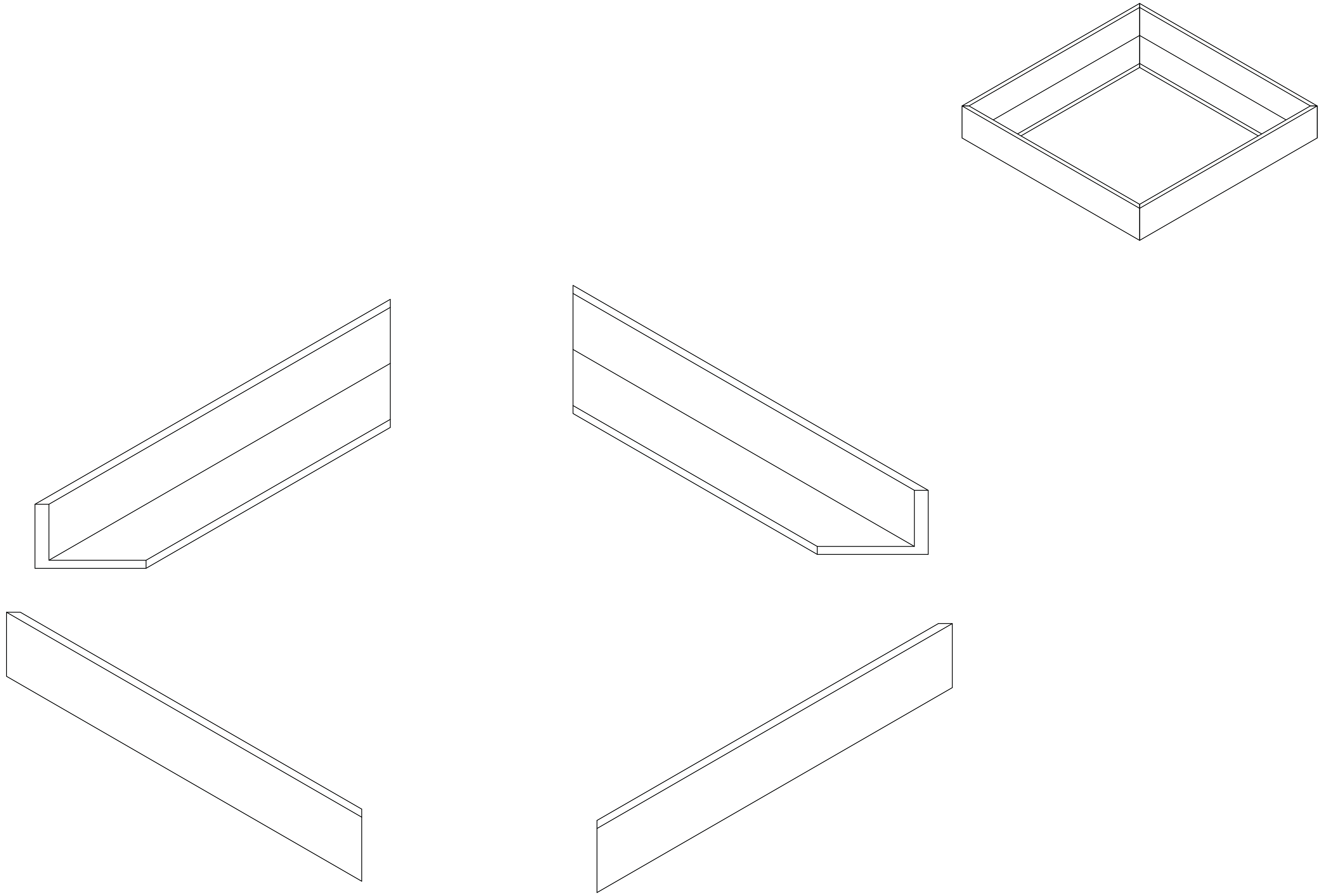
SCALE: 5:1 | WEIGHT: | SHEET 10 OF 30



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	Handlebar Stem
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:5 WEIGHT: SHEET 11 OF 30



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	Motor Mount
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 12 OF 30



NOTE:
ALL EDGES WELDED TO CREATE SQUARE TRAY

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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

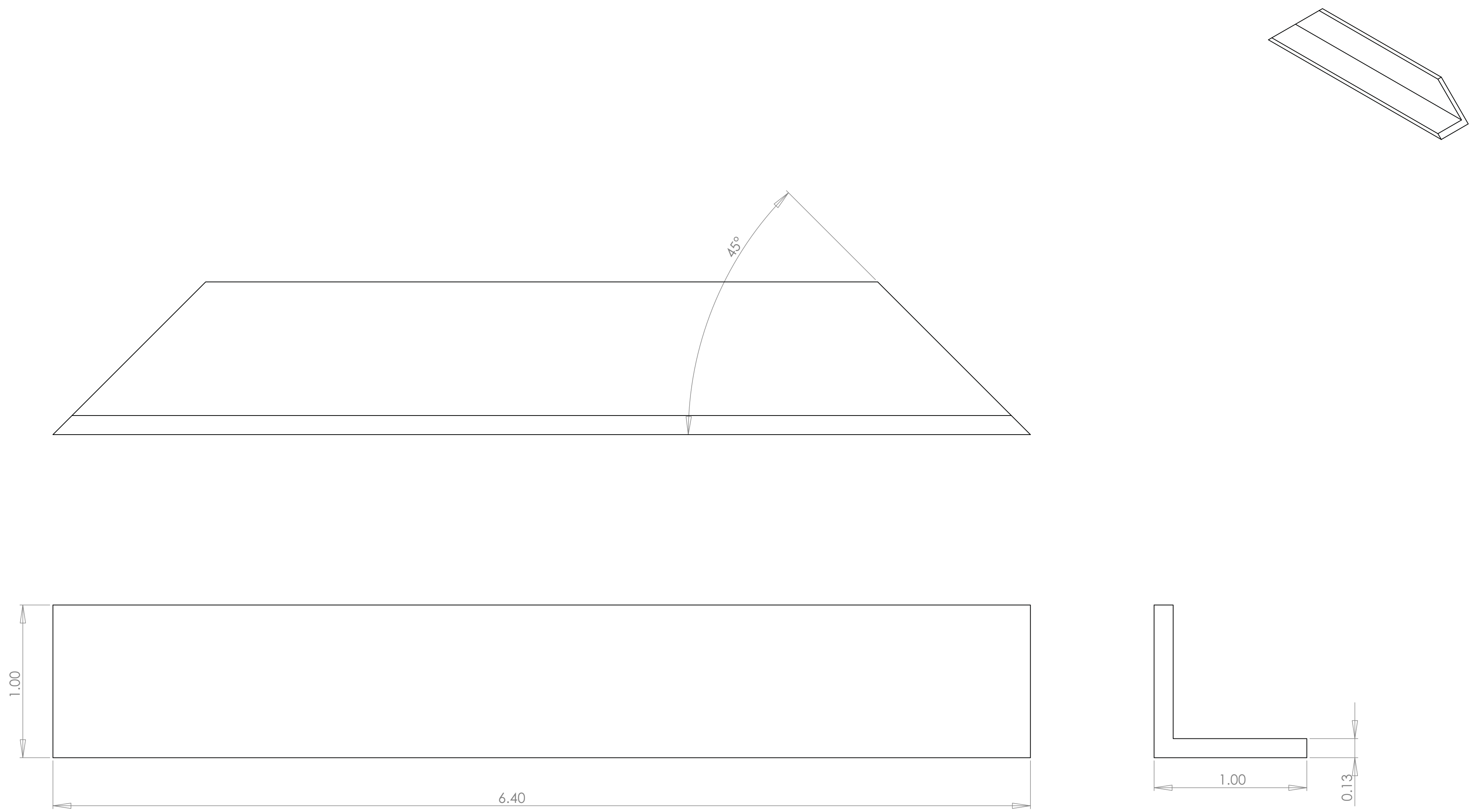
	NAME	DATE
DRAWN	LM	4/12/10
CHECKED	KP	3/4/10
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

Worcester Polytechnic Institute

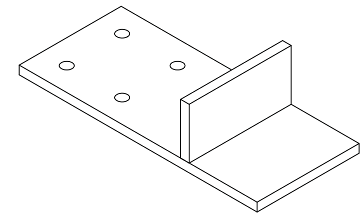
TITLE:
Battery Tray Assembly

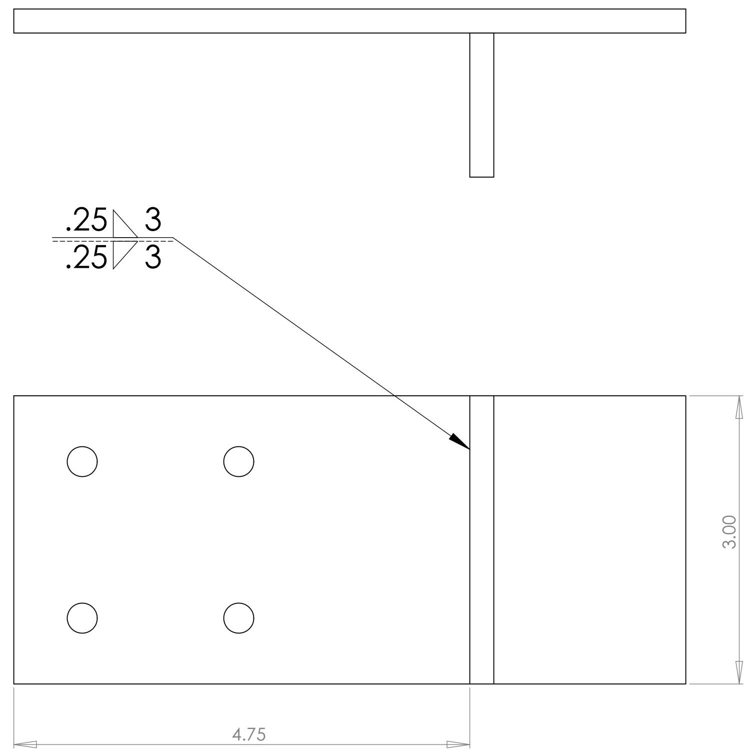
SIZE C DWG. NO. Pusher Device REV 1

SCALE: 1:2 WEIGHT: SHEET 13 OF 30

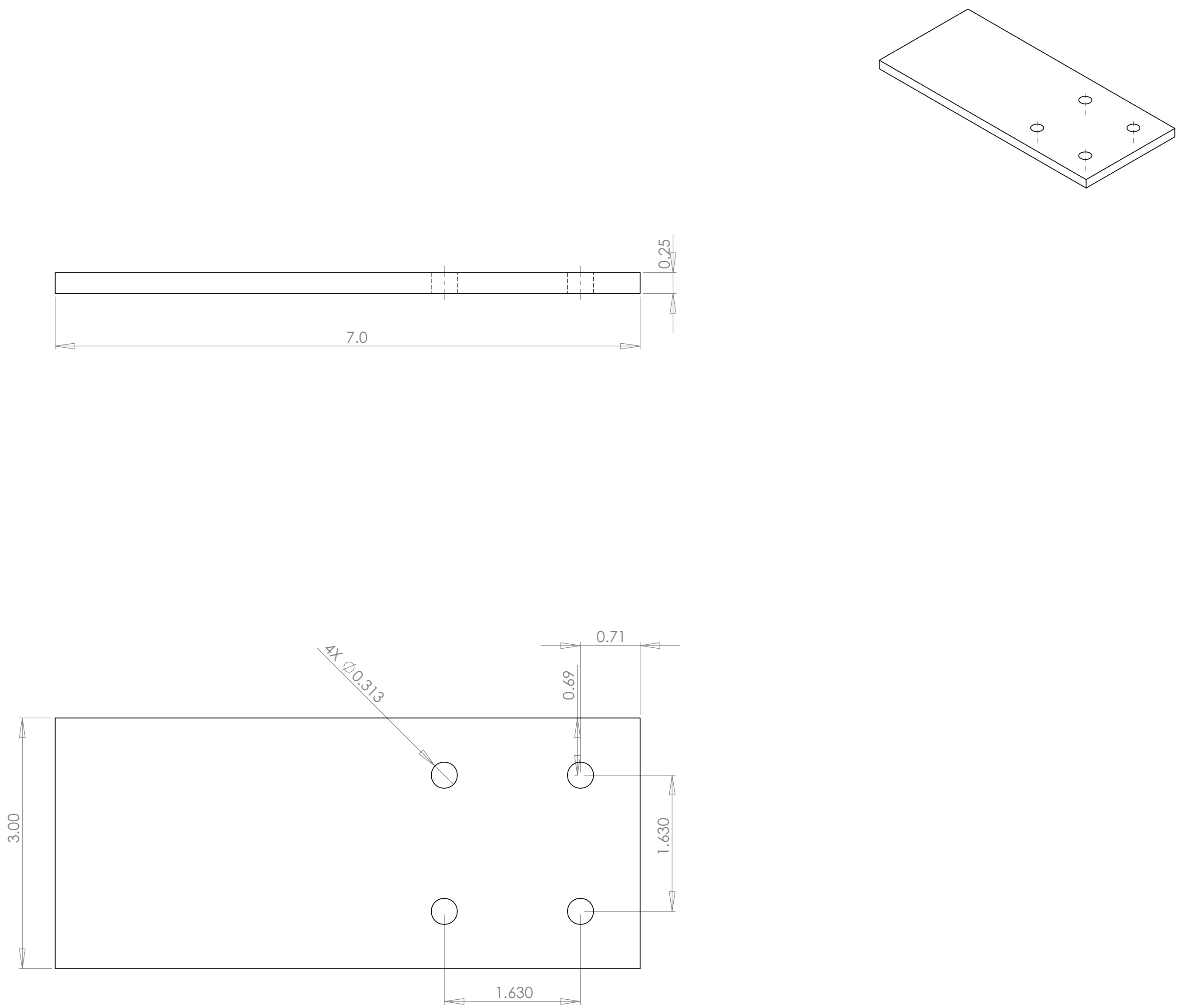


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	4/12/10	
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	TITLE: Battery Tray Peice
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 1
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 14 OF 30

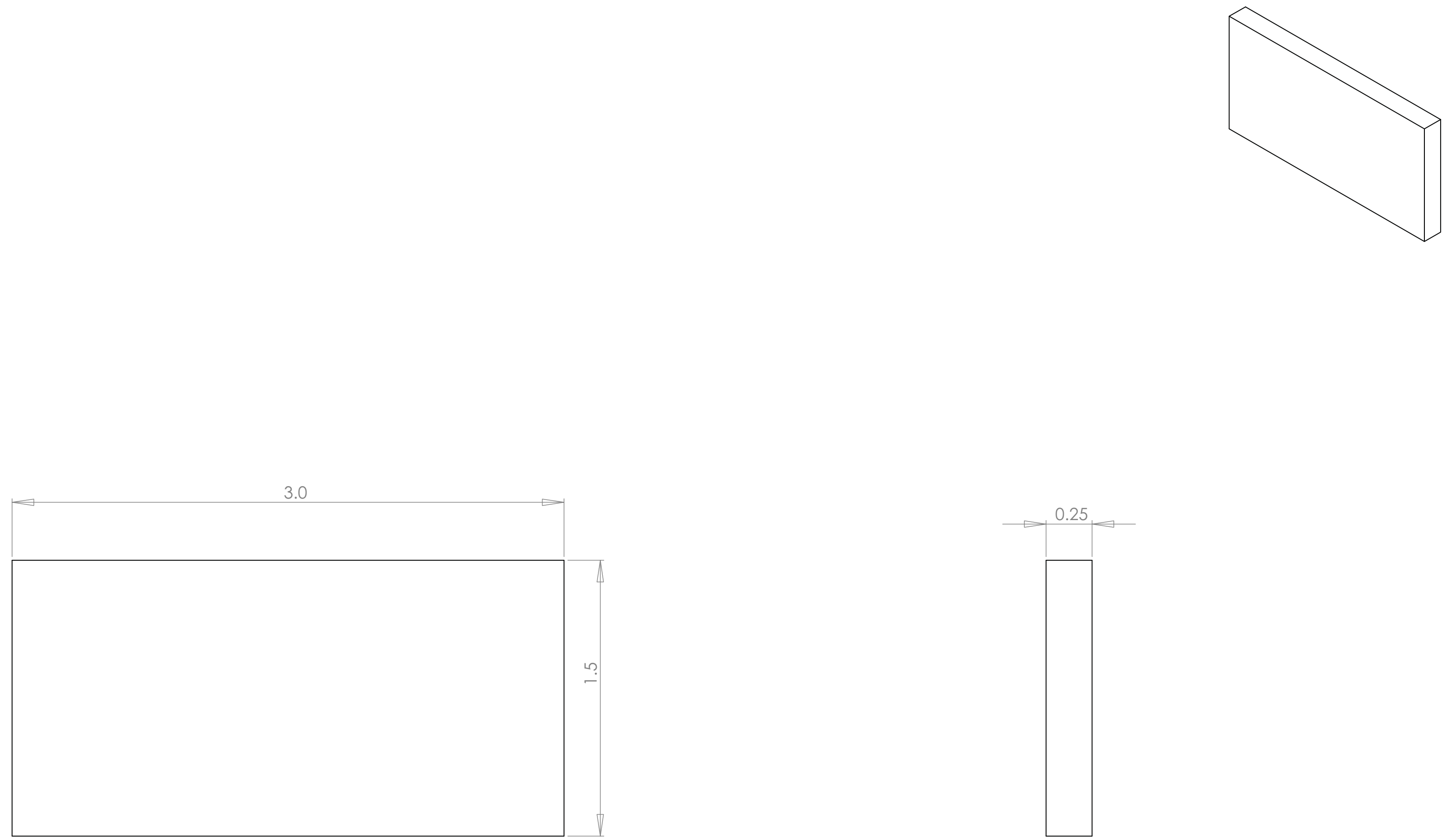




UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	Attachment Mount Assembly
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 15 OF 30

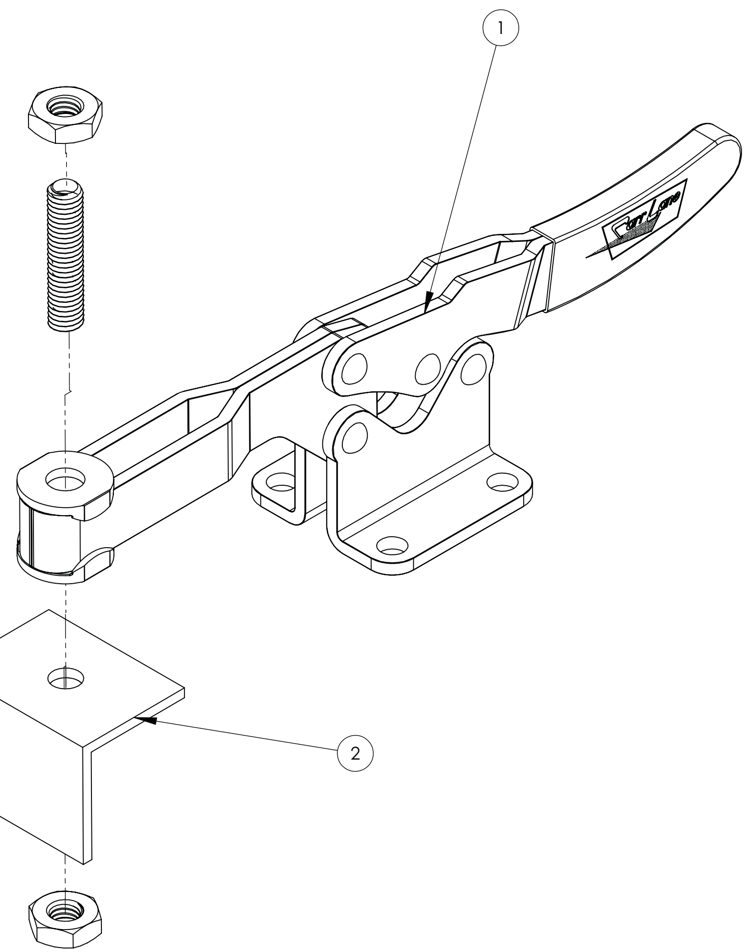


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.05 THREE PLACE DECIMAL ±.005	CHECKED	GVR	4/16/10	Attachment Base
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 16 OF 30



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.05 THREE PLACE DECIMAL ±.005	CHECKED	GVR	4/16/10	TITLE: Vertical Peice
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 2:1 WEIGHT: SHEET 17 OF 30

ITEM NO.	PART	QTY.
1	Toggle Clamp	1
2	AngleIron	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES

TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	2/25/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		

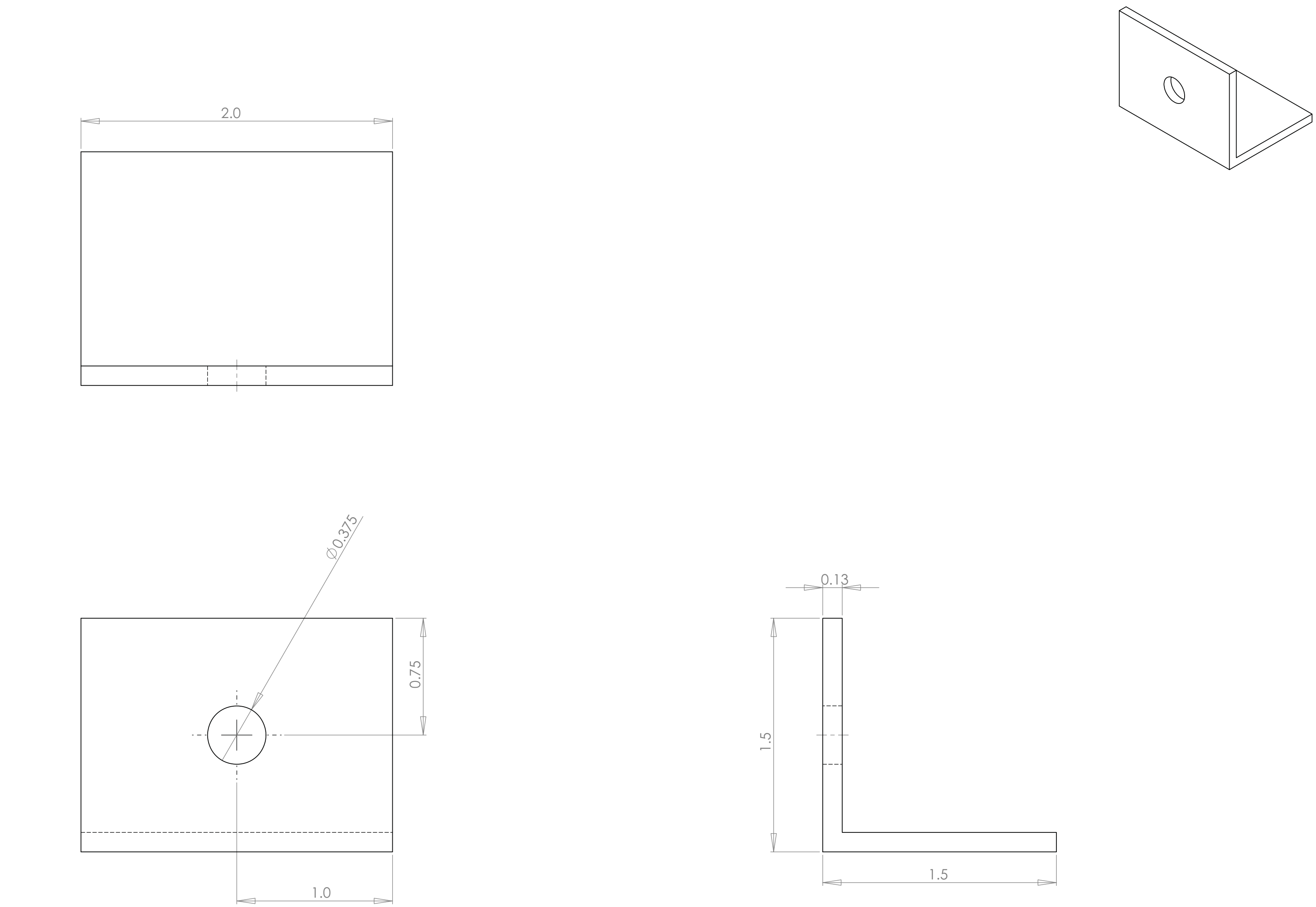
COMMENTS:

Worcester Polytechnic Institute

TITLE: Toggle Clamp Assembly

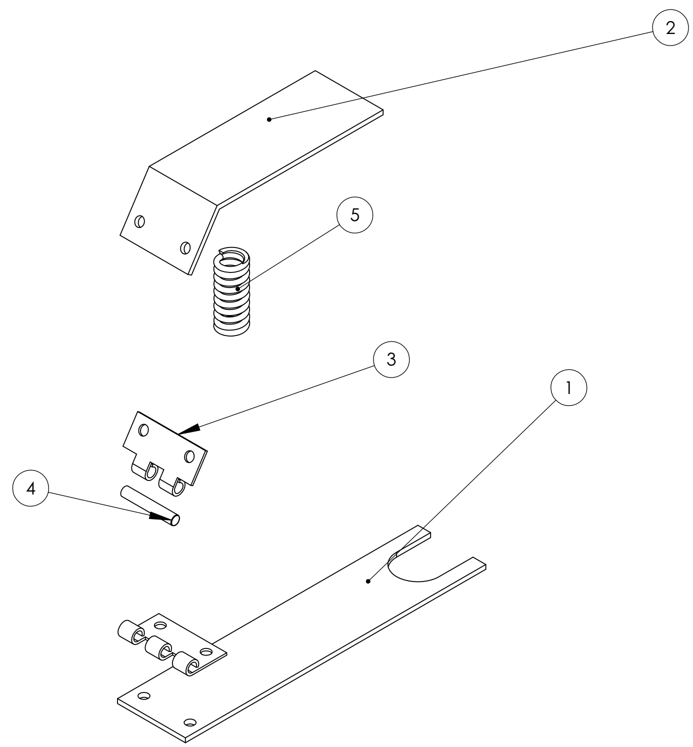
SIZE C | DWG. NO. Pusher Device | REV 2

SCALE: 1:5 WEIGHT: SHEET 18 OF 30



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	Angle Iron
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C · DWG. NO. Pusher Device · REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 2:1 · WEIGHT: · SHEET 19 OF 30

ITEM NO.	PART NUMBER	QTY.
1	SpringBase	1
2	Ramp	1
3	Hinge	1
4	Hinge Pin	1
5	Spring	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	2/15/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

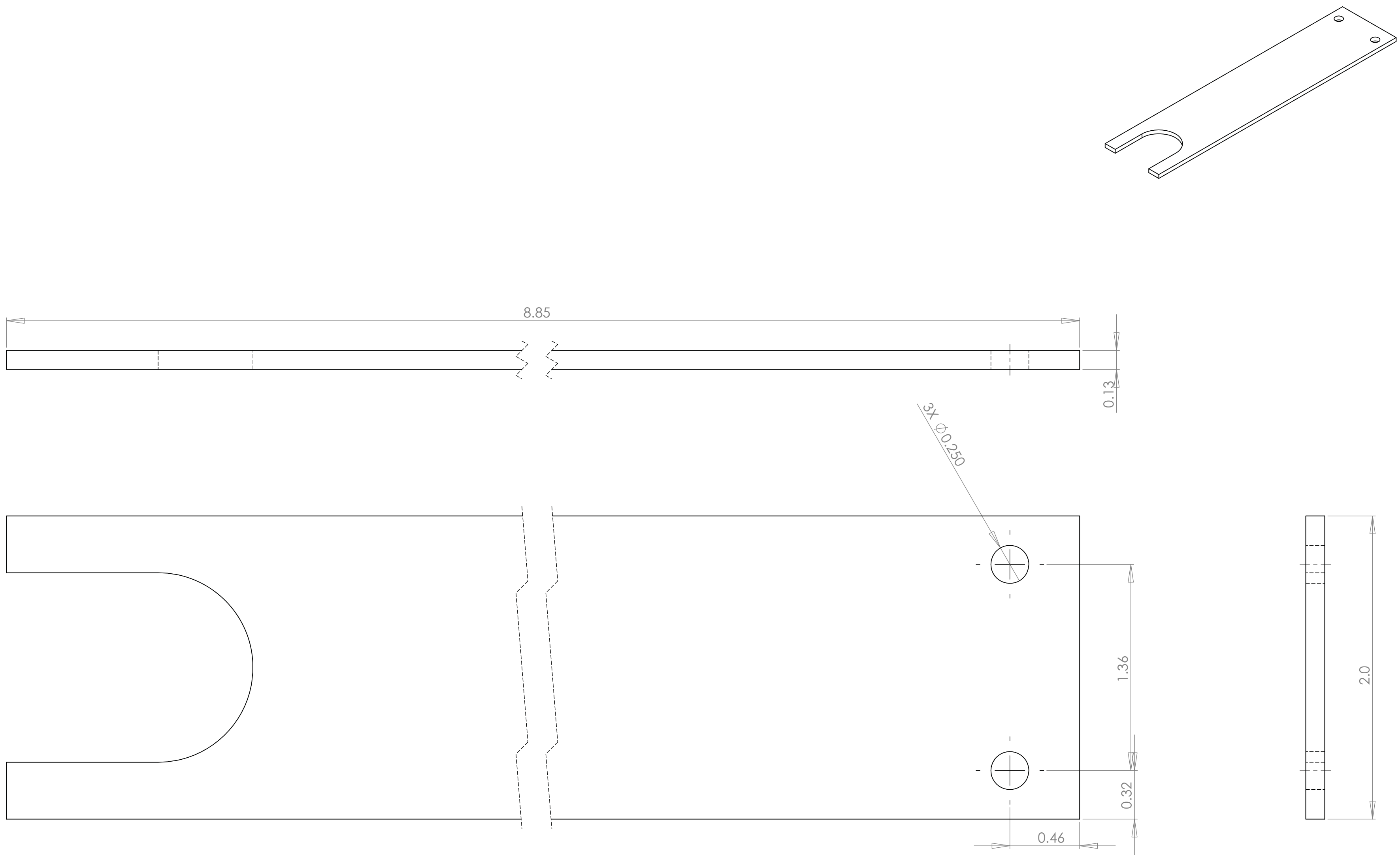
Worcester Polytechnic Institute

TITLE:

Exploded Spring Subassembly

SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:5 WEIGHT: SHEET 20 OF 30



PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES

TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.05
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	2/15/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

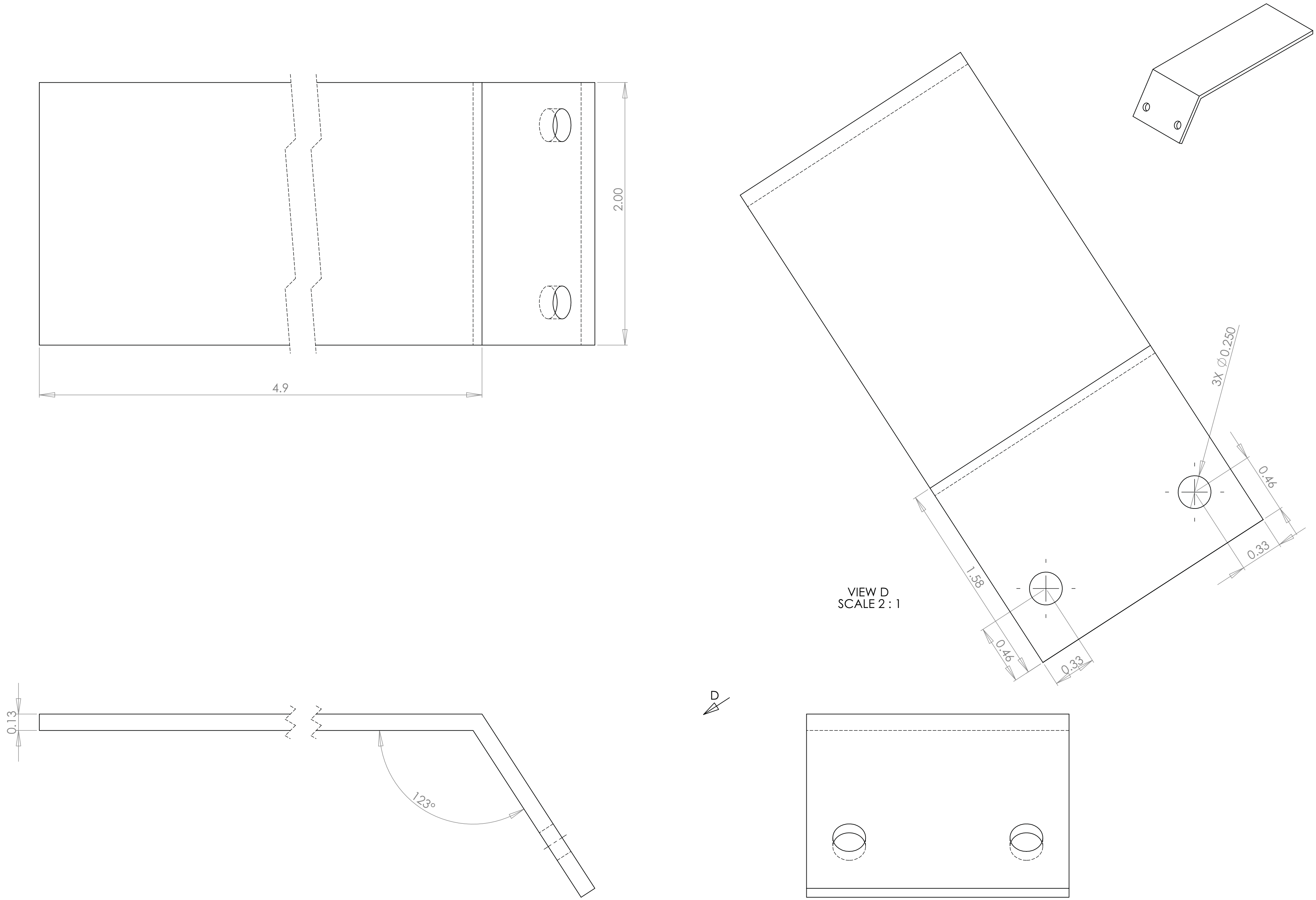
Worcester Polytechnic Institute

TITLE:

Spring Base

SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:1 WEIGHT: SHEET 21 OF 30



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TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	2/15/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

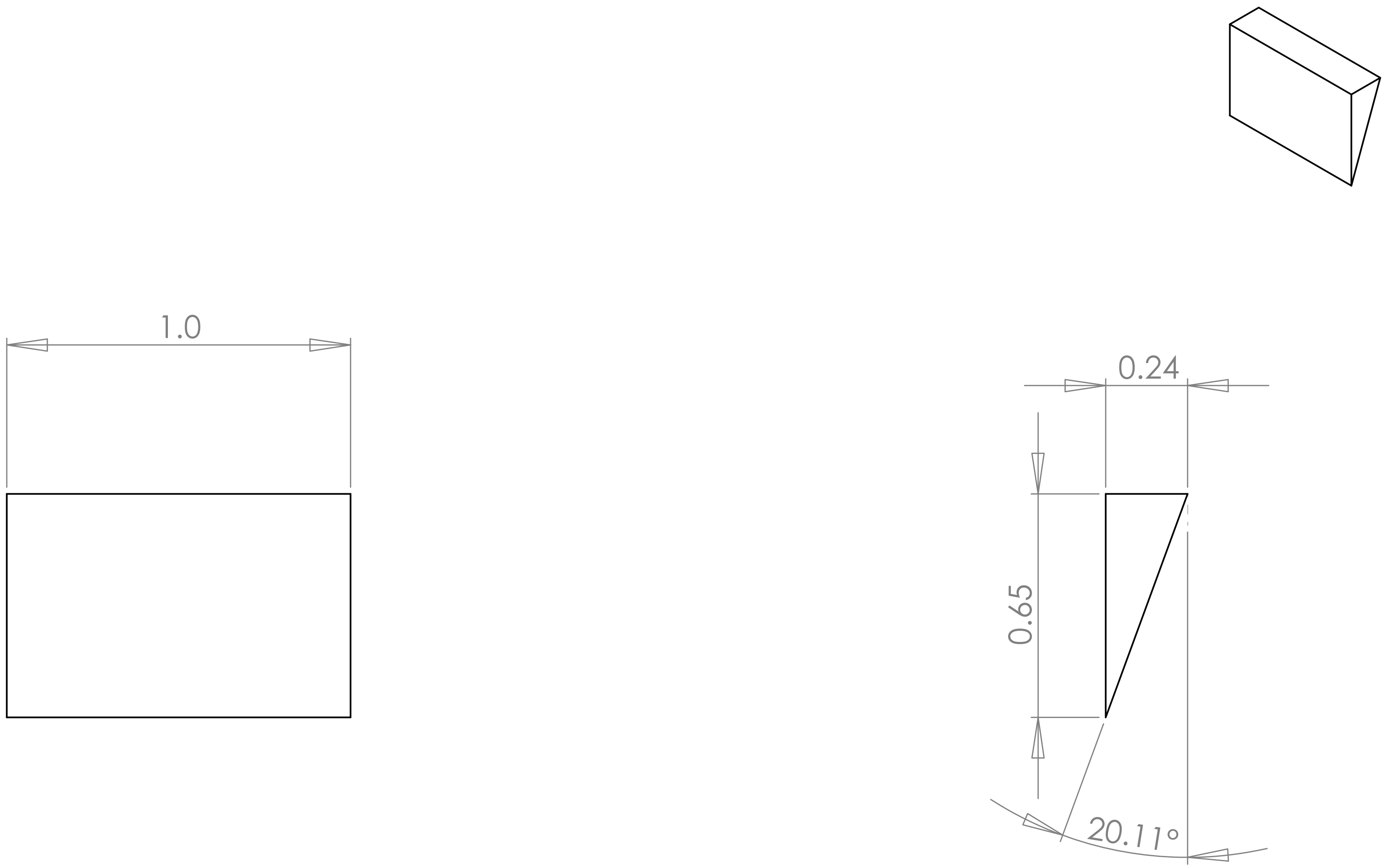
Worcester Polytechnic Institute

TITLE:

Spring Ramp

SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:1 WEIGHT: SHEET 22 OF 30



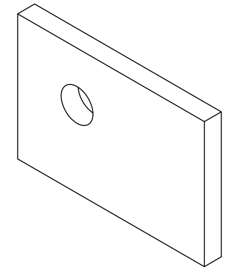
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/30/10
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

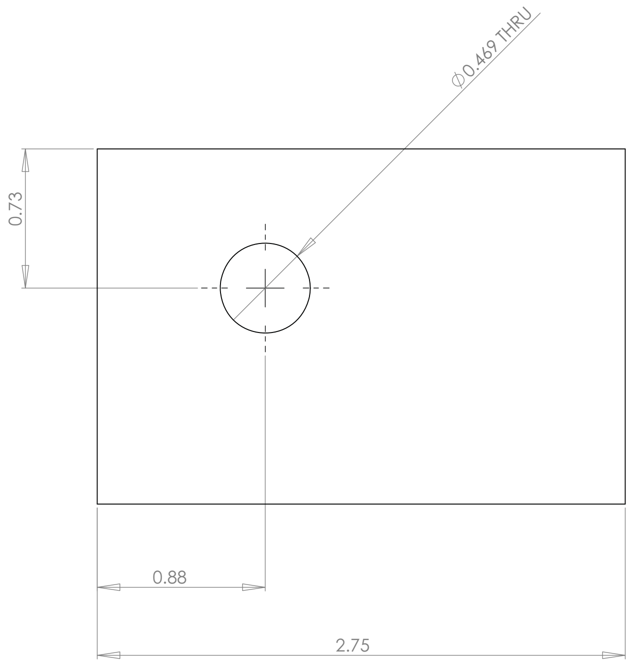
TITLE:

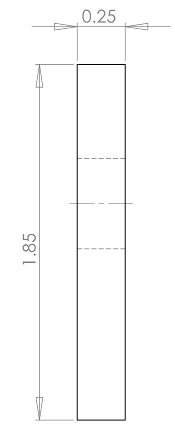
Spring Ramp

SIZE	DWG. NO.	REV
A	Pusher Device	2
SCALE: 5:1	WEIGHT:	SHEET 23 OF 30

5 4 3 2 1







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DIMENSIONS ARE IN INCHES

TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	2/25/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

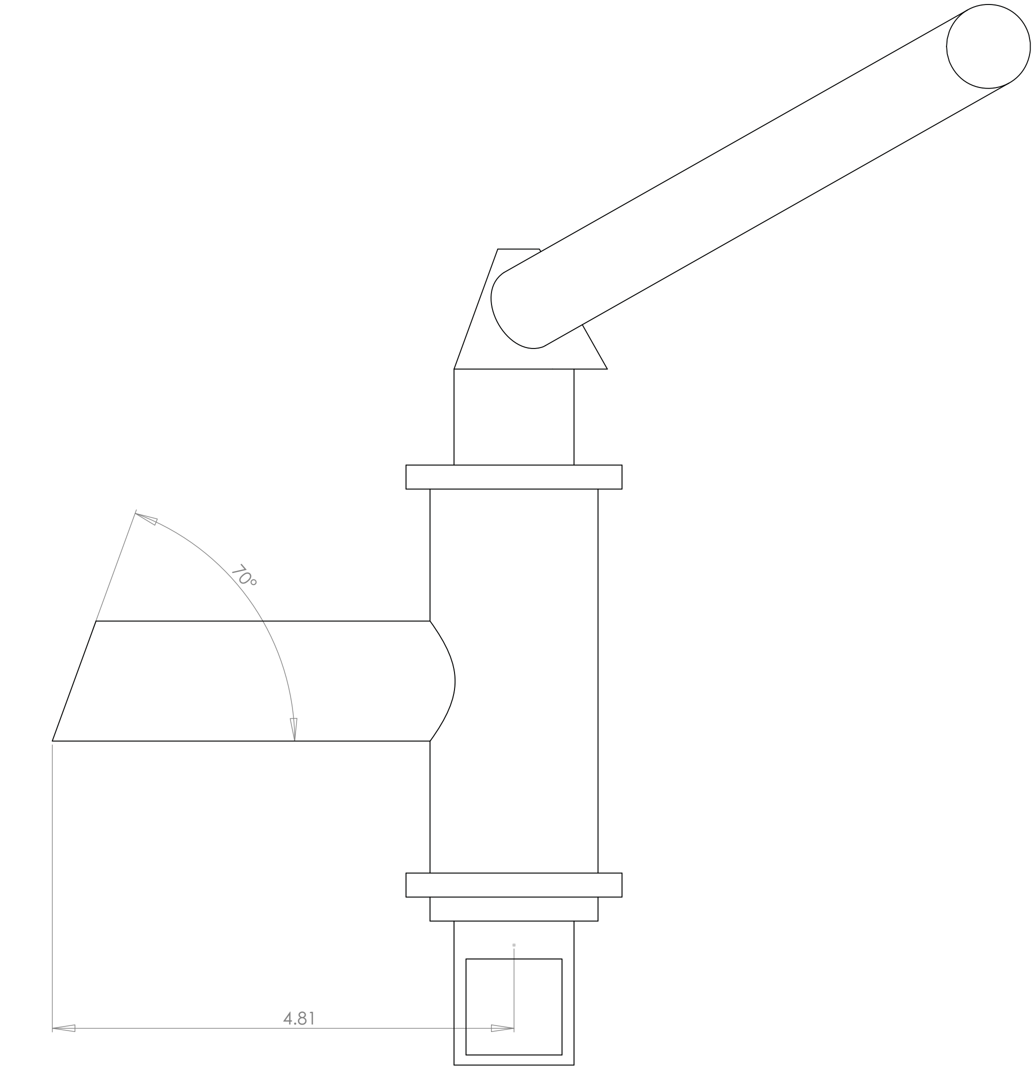
Worcester Polytechnic Institute

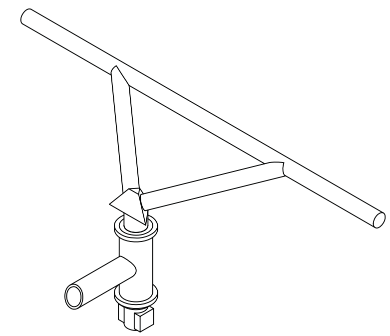
TITLE:

Cable Support

SIZE C | DWG. NO. Pusher Device | REV 2

SCALE: 2:1 | WEIGHT: | SHEET 24 OF 30





NOTE: BIKE BAR MUST BE CUT 4.81 INCHES FROM THE CENTER OF THE STEM

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

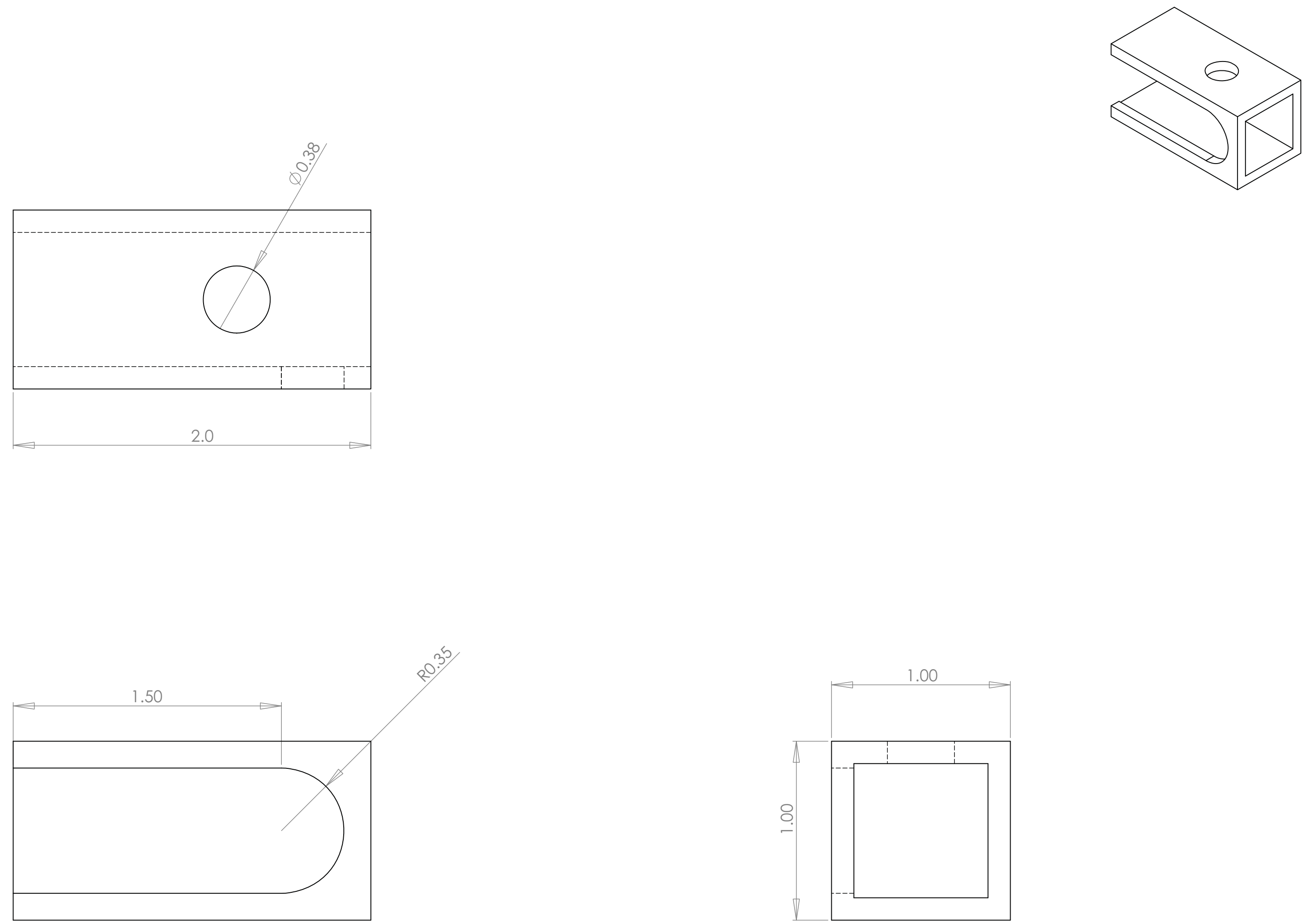
	NAME	DATE
DRAWN	LM	2/25/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

Worcester Polytechnic Institute

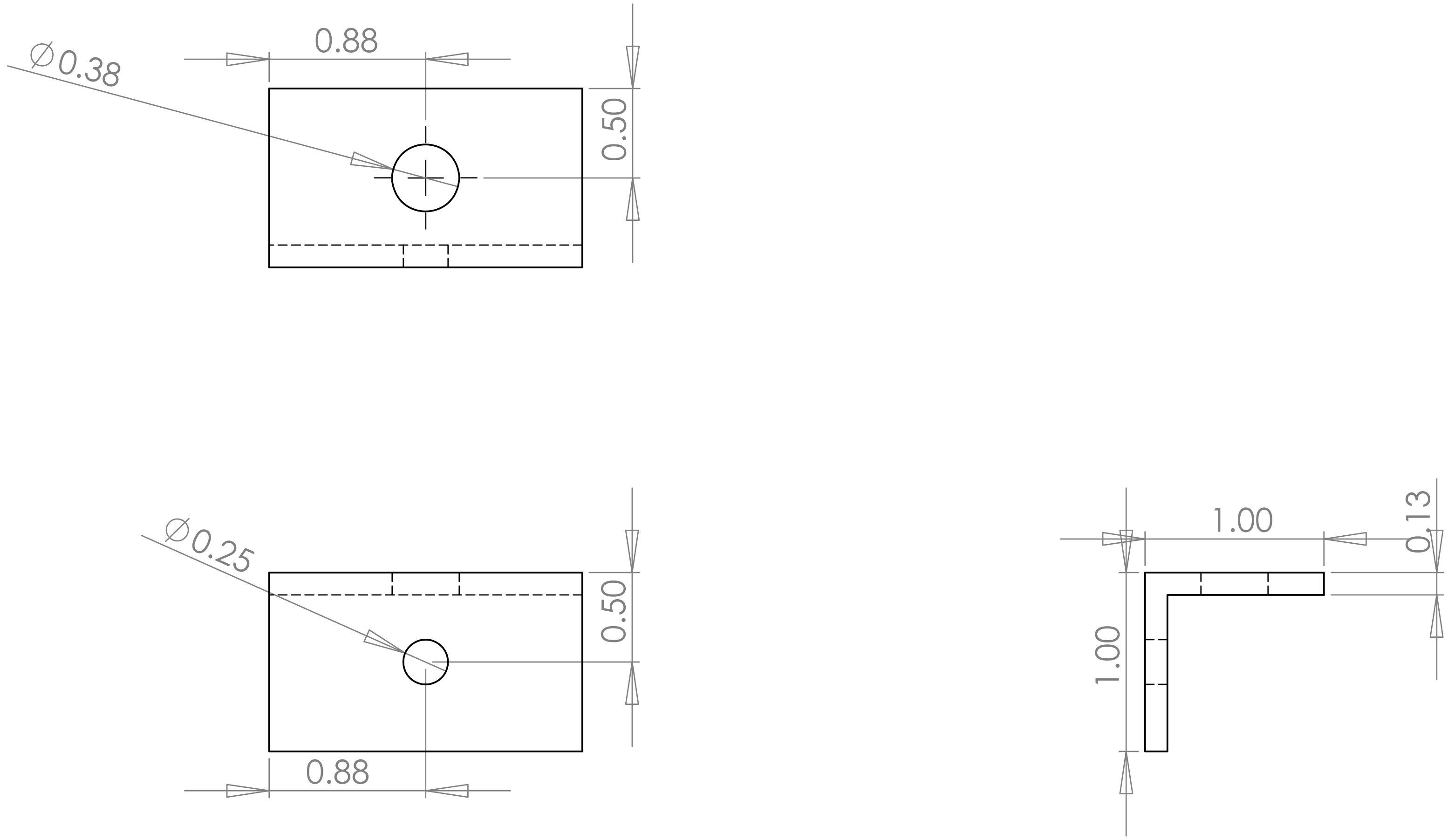
TITLE:
Bike Handlebars

SIZE C DWG. NO. Pusher Device REV 2

SCALE: 1:5 WEIGHT: SHEET 25 OF 30



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Worcester Polytechnic Institute
DIMENSIONS ARE IN INCHES	DRAWN	LM	2/25/10	TITLE:
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	Stem Bar Arm
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE C DWG. NO. Pusher Device REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:5 WEIGHT: SHEET 26 OF 30



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES

TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	4/12/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

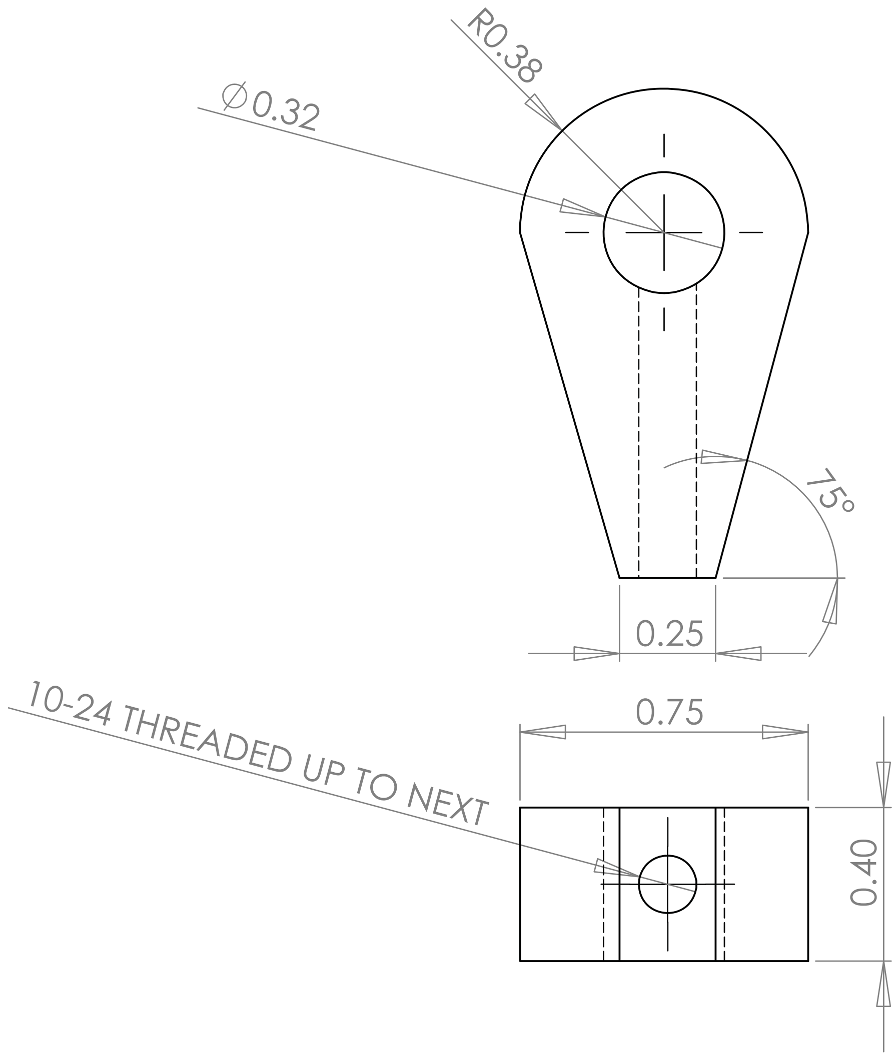
TITLE:

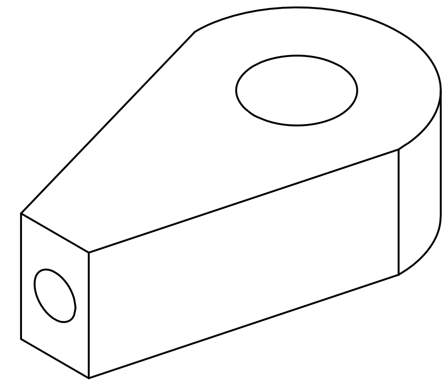
Steered Wheel Arm

SIZE	DWG. NO.	REV
A	Pusher Device	1

SCALE: 2:1 WEIGHT: SHEET 27 OF 30

5 4 3 2 1





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DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ± .05
THREE PLACE DECIMAL ± .005

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LM	4/12/10
CHECKED	GVR	4/16/10
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

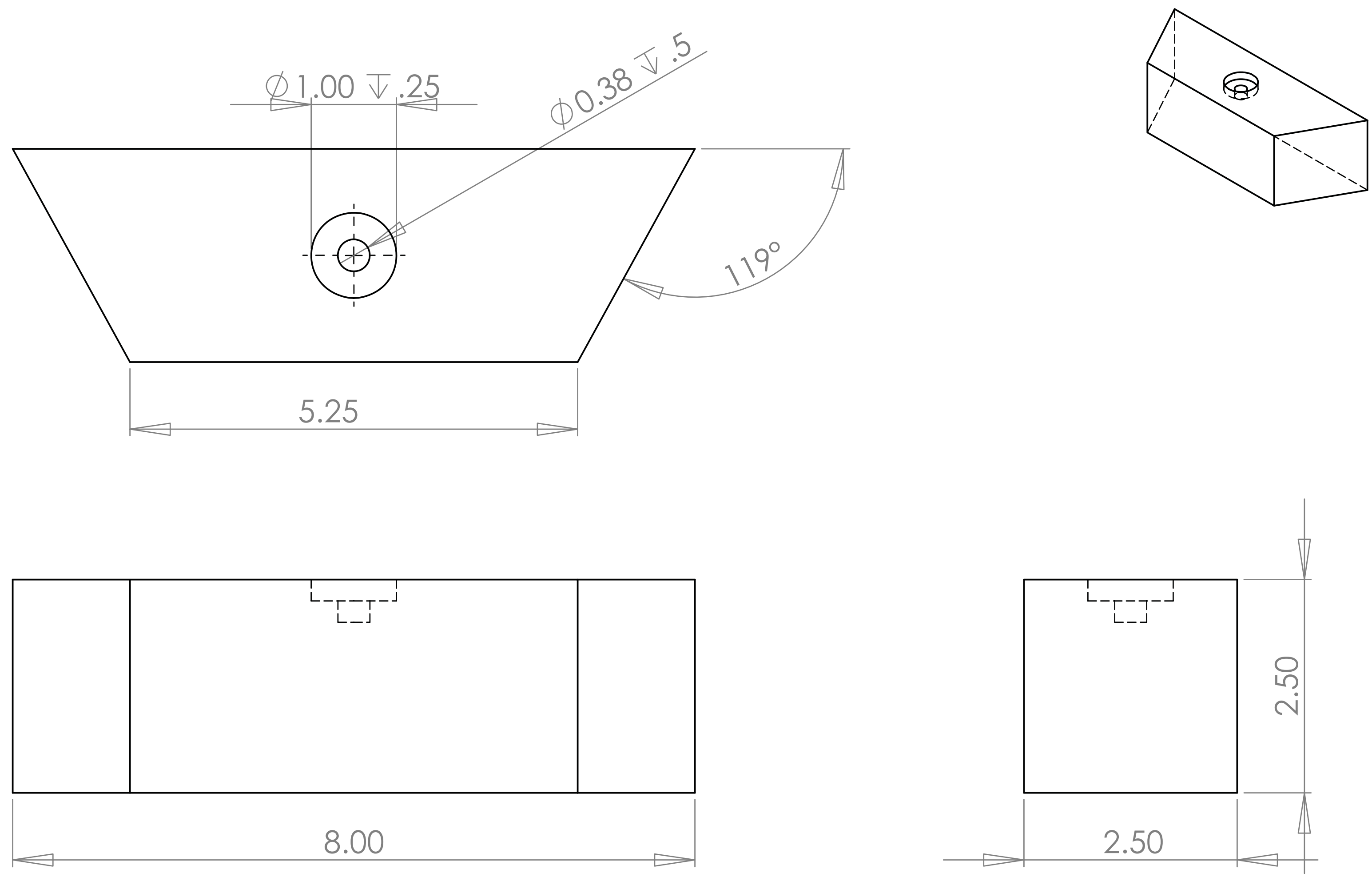
TITLE:

Tie Rod

SIZE	DWG. NO.	REV
A	Pusher Device	1

SCALE: 2:1 WEIGHT: SHEET 28 OF 30

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES	DRAWN	LM	4/12/10	
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10	TITLE: Weight
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE A · DWG. NO. Pusher Device · REV 1
FINISH				
DO NOT SCALE DRAWING				SCALE: 2:1 · WEIGHT: · SHEET 29 OF 30

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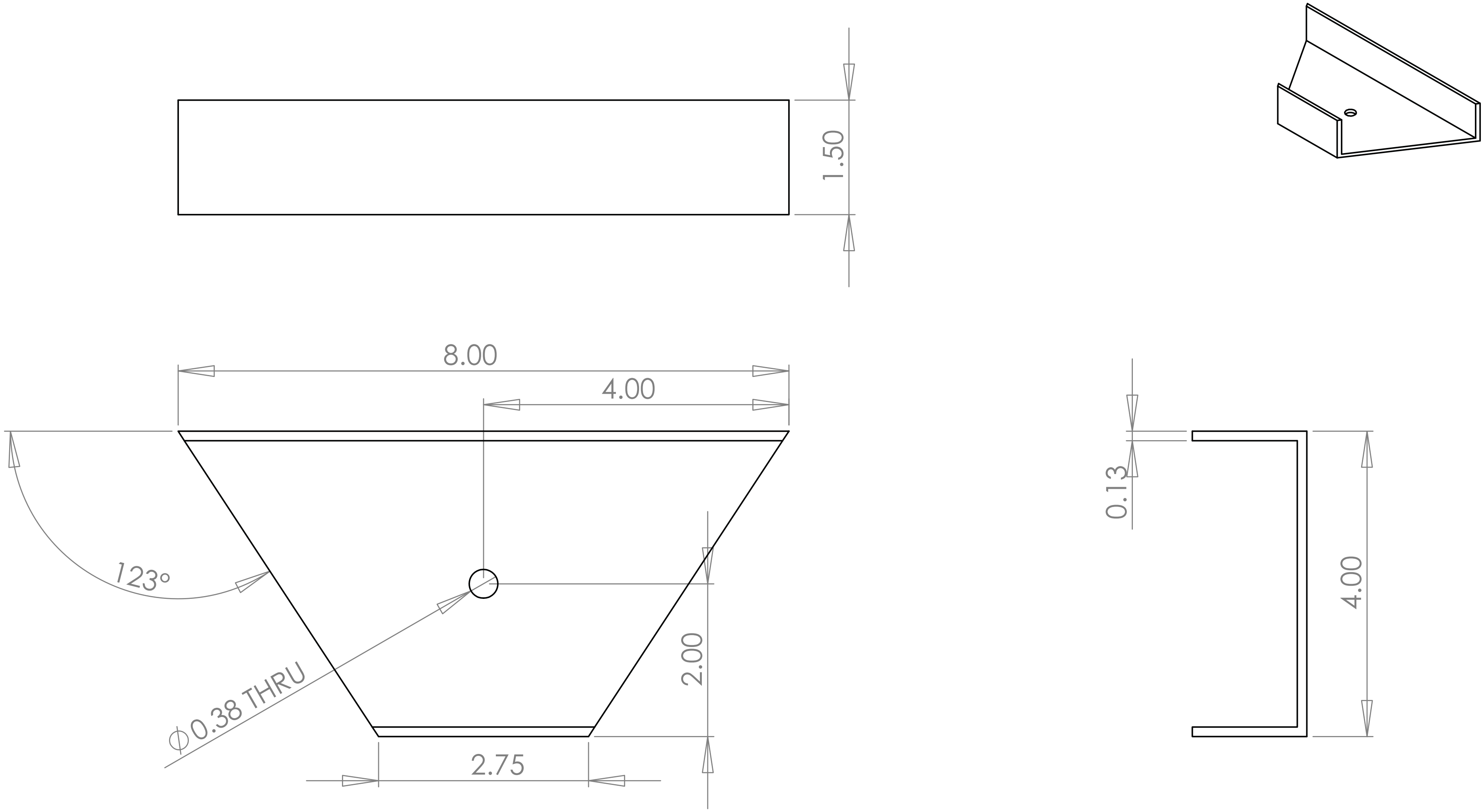
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES	DRAWN	LM	4/12/10
TOLERANCES: ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ± .05 THREE PLACE DECIMAL ± .005	CHECKED	GVR	4/16/10
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

TITLE:

Weight Tray

SIZE	DWG. NO.	REV
A	Pusher Device	1

SCALE: 1:2 WEIGHT:

5 4 3 2 1