

**DESIGN AND DEVELOPMENT OF THE MOBILITY ENHANCEMENT ROBOTIC
WHEELCHAIR**

by

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The electric powered wheelchair (EPW) currently provides mobility for an estimated 330,000 people with disabilities in the USA and is expected to rise due to the aging of the baby boomers and injured troops returning from war. Even though the EPW was developed to provide an increase in mobility, current designs are primarily for usage in indoor environments. As a result, when users leave the confines of their home they may encounter hazardous environments such as uneven terrain and architectural barriers. These types of environments increase the users' risk of tipping or falling out of the wheelchair which may lead to serious injury or death.

The Mobility Enhancement Robotic Wheelchair (MEBot) was developed to increase user safety and to provide the ability to overcome uneven terrain and architectural barriers. MEBot provides advanced features to increase the users' safety including self-leveling, curb climbing, and driving wheel position selection. The self-leveling feature maintains the position of the seating system when driving up, down, or across slopes which decreases the possibility of the user tipping or falling out of the wheelchair. The curb climbing feature allows the user to overcome up to an 8 inch curb. Finally, selecting the driving wheel position allows the user to configure MEBot as either a front wheel drive, mid wheel drive, or rear wheel drive power chair. With the addition of the advanced features, MEBot increases the safety and ability of the user to drive in outdoor environments while maintaining maneuverability when used in an indoor environment.

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PREFACE

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1.0 INTRODUCTION

In 2010, 3.6 million people in the USA aged fifteen years and older used a wheelchair (Brault, 2012). This number is expected to rise due to the aging population of the baby boomers and the return of troops from the war in Afghanistan and Iraq. Of the 3.6 million people using a wheelchair, an estimated 330,000 use an electric powered wheelchair (EPW). This estimation is based on the percentage of EPW users in 2000 of 9.1% (Kaye, Kang, & LaPlante, 2000). Unfortunately, estimating the rise of the use of wheelchairs is uncertain due to the limitations of current national survey methods (La Plante, 2004).

The EPW is a mobility device for people with disabilities that provides mobility, independence (Edwards & McCluskey, 2010), community integration, and an improved quality of life (Evans, Neophytou, De Souza, & Frank, 2007). Current EPW designs were developed based on the notion they would be primarily used in indoor environments. However, users often use their EPWs in outdoor environments when traveling to work, going to doctor's appointments, socializing with friends and family, or going to community events. Traveling outdoors often leads to the user encountering uneven terrain, steep slopes, cross slopes, slippery surfaces, and architectural barriers such as curbs and stairs. These types of environments and barriers put the user at risk of tipping or falling out the EPW due to the lack of stability and barrier negotiation capabilities of current EPWs (Ding & Cooper, 2005).

One study revealed that the most common accidents were caused by the loss of traction, being immobilized, or the loss of stability (Salatin, 2011). Statistics from 2003 showed that in the United States, more than 100,000 wheelchair related injuries were treated in emergency departments, with tips and falls accounting for 65-80% of the injuries (Xiang, Chany, & Smith, 2006). Another study reported that of 109 participants, 42% had experienced a tip or fall within the last 5 years. Furthermore, 27% caused injuries needing medical attention, including 13 hospitalizations (Gaal, Rebholtz, Hotchkiss, & Pfaelzer, 1997). As such, as the number of wheelchair users continues to rise, the likelihood of EPW related accidents will also increase.

In an effort to decrease the probability of an accident occurring in outdoor environments, the Mobility Enhancement Robotic Wheelchair (MEBot) has been designed with advanced features to overcome uneven terrain, slopes, slippery surfaces, and architectural barriers while maintaining indoor maneuverability equivalent to current EPWs. MEBot features a 6 wheeled design that allows each wheel to move up and down. This up-and-down movement allows MEBot to maintain the angle of the seating system when traversing up, down, or across slopes. This feature, called self-leveling, detects the angle change of the slope and compensates by moving the wheels up or down. The result decreases the likelihood of the user tipping or falling out of the EPW by changing the wheelchair's center of gravity and thus improving its stability. MEBot also features a curb climbing application that allows the user to safely overcome an 8 inch curb while maintaining its center of gravity within a safe limit. In order to decrease the occurrence of a user losing traction or becoming immobilized, traction control allows MEBot to travel through mud, sand, or snow. Traction control detects slippage of the driving wheels and corrects for the change of speed of the slipping wheel to prevent the wheelchair from veering off course. The goal is for MEBot to provide mobility to people with disabilities in indoor and

outdoor environments through features developed to decrease the possibility of injury when encountering uneven terrain and architectural barriers.

1.1 LITERATURE REVIEW

1.1.1 The Electric Powered Wheelchair

1.1.1.1 Standard Electric Powered Wheelchairs

The first electric powered wheelchair (EPW) was invented by Canadian inventor George Klein in the early 1950s. In 1956, Everest & Jennings was the 1st company to mass manufacture the electric wheelchair (Bellis, 2014). Since Klein's invention almost a half a century ago, current EPWs continue to use similar components including electric motors, batteries, and a joystick. However, the design of current EPWs has improved with the addition of three different drive wheel configurations that include Rear Wheel Drive (RWD), Mid Wheel Drive (MWD), and Front Wheel Drive (FWD) (Figure 1).

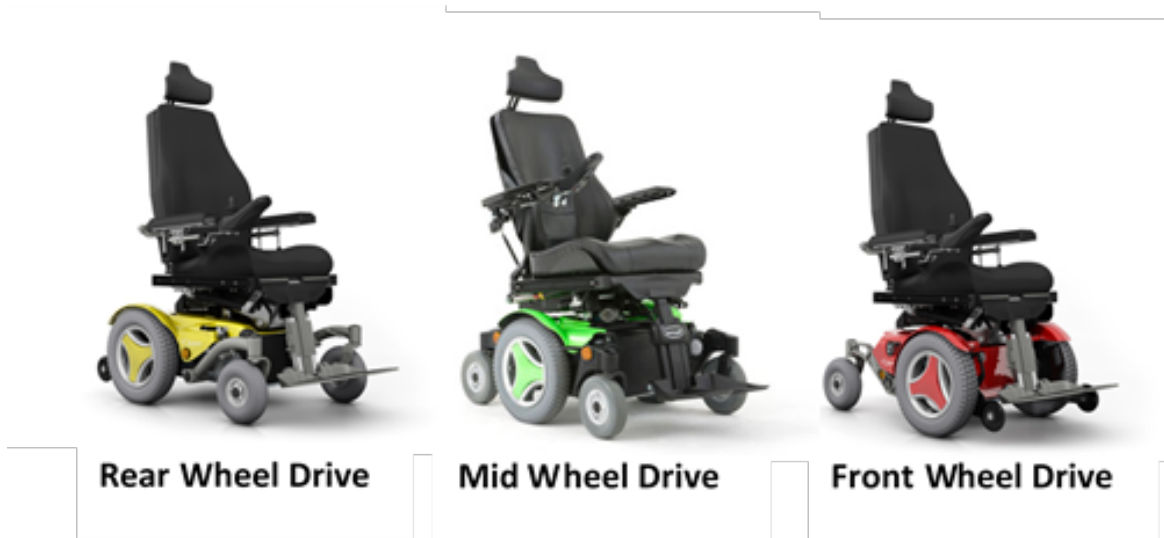


Figure 1: Wheelchair Drive Wheel Configurations

The different locations of the drive wheels effect the EPWs maneuverability and driving dynamics. The location of the drive wheels with respect to the EPW's center of gravity (CoG) determines its stability and ease of operation. MWD EPWs provide the highest amount of maneuverability due to the drive wheels being placed near the CoG which allows the chair to turn 360 degrees within its own wheelbase. They feature a six wheel design consisting of two front casters, two rear casters, and two driving wheels. Consequently, if either of the front or rear casters experience a sideways force, the chair could veer off course. FWD EPWs are the second most maneuverable using only four wheels where the driving wheels are in front of the CoG. FWD typically performs better when climbing obstacles or going over rough terrain since the driving wheels are the first to contact the obstacle. However, since its CoG is more towards the rear of the chair, it may tend to fishtail when driving over rough terrain or at higher speeds. For RWD EPWs, the driving wheels are placed behind the CoG with two casters in the front. RWD tends to be the most stable at higher speeds but lacks the maneuverability of MWD or FWD. They are also the simplest to control since they drive similar to a vehicle.

These types of EPWs have primarily been designed for indoor usage on flat surfaces with low thresholds. However, users typically also use these types of EPWs in outdoor environments where they encounter uneven terrain, slopes, and curbs. The standard EPW is limited when it comes to traveling on slopes and climbing curbs due to stability and safety concerns. Table 1 shows the maximum capability values of several wheelchairs for traveling on slopes and climbing curbs (Permobil, 2014) (Quantum, 2014) (Invacare, 2014).

Table 1. Slope and curb limitations for several EPWs

EPW Name	EPW Type	Up & Down Slope	Sideways Slope	Curb
Permobil M300	MWD	9°	9°	3 in.
Permobil C300	FWD	10°	6°	2.75 in.
Permobil C350	RWD	10°	6°	3 in.
Permobil C500	FWD	12°	10°	3 in.
Quantum Q6 Edge	MWD	6°	N/A	2 in.
Invacare TDX SP	MWD	9°	N/A	3 in.

1.1.1.2 Advanced Electric Powered Wheelchairs

Advanced electric powered wheelchairs can be defined as an EPW that has additional features such as curb climbing, stair climbing, and/or enhanced outdoor capabilities. The TopChair (Figure 2) is a RWD EPW that has been developed with the addition of a track under the base that is only activated when climbing stairs or curbs (TopChair, 2014). When the user attempts to climb a set of stairs, the front casters and rear driving wheels raise up to allow only the track to make contact with the ground. TopChair then acts as a “tank” to ascend the stairs. Once the user reaches the top of the stairs, the front casters and rear driving wheels lower to allow for normal operation. One study compared the TopChair and Storm3 power wheelchair using indoor and outdoor trials. The results of the trials showed the participants slightly preferred the Storm3 power wheelchair based on its weight, dimensions, and effectiveness. However, the participants also tested the curb and stair climbing capabilities of TopChair. Most of the participants felt that the curb and stair climbing capabilities were easy to use (22/25 for curb, 21/25 for stairs) and helpful (24/25 and 23/25). While a few participants felt insecure (4/25 and 6/25, respectively) (Laffont, et al., 2008).



Figure 2. TopChair stair-climbing wheelchair

Another advanced EPW, the Observer Maximus (Figure 3) is a 4x4 wheelchair that is equipped with a gyroscope to synchronize the angle of the seat in relation to the ground when climbing obstacles. The Observer Maximus uses an all-wheel drive design with 15.7 inch wheels to ascend and descend stairs. When going up and down stairs or a hill, the chair changes its center of gravity by keeping the seating system in the same position as you were driving on a flat surface which makes driving more secure, comfortable, and safer (Unlimited Wheelchair Observer, 2014). However, due to its four-wheel-drive and larger design, it lacks indoor mobility and may cause damage to carpeting.



Figure 3. Observer Maximus 4x4 wheelchair

Other examples of advanced EPWs include the Galileo wheelchair, Ibot 3000, and a prototype robotic wheelchair from the Chiba Institute of Technology. Unfortunately, all of these examples are not commercially available. The Galileo wheelchair is based on technology that is already used by the United States Army on remote-controlled robots in Afghanistan and Iraq (Alaveras, 2011). The technology combines a wheel and a track into a single component. A simple mechanism enables the switching back and forth between being a wheel or a track in seconds. The technology provides the benefits of the wheel being energy efficient, providing a smooth ride, and being suitable for high speeds while the tracks provide traction for overcoming obstacles such as rough terrain and climbing up and down stairs (Elizey, 2008). The current status of the development of the Galileo wheelchair is unknown.

The Ibot 3000, which is no longer on the market, was a technologically advanced EPW designed to address the limitations of standard EPWs. The Ibot 3000 had the ability to dynamically balance on 2 wheels to elevate the user to the height of a standing person, to be configured as a four-wheel-drive EPW for enhanced outdoor mobility including curb climbing, and to perform stair climbing (Uustal & Minkel, 2004). The Chiba Institute's prototype robotic wheelchair turns its wheels into legs. The wheelchair is equipped with 4 independently powered wheels that are mounted on 5 axes. The wheels have sensors that continually scan for an obstacle and determine whether the wheelchair can roll over the obstacle or not. If simply rolling over it is not an option, the axes shift and turn into legs. The chair then assesses the obstacle to determine whether or not it can negotiate the step. Meanwhile, the 3 other legs realign themselves to keep the chair stable. The chair performs the climbing process automatically and keeps the user comfortably level when negotiating obstacles or going on ramps (Szondy, 2012).

1.1.2 Advanced Outdoor Mobility Robots

Future advances in wheelchair design may be developed based on robots that are currently being used in the research, defense, and tree harvesting fields. They've been developed to traverse through environments with extremely uneven terrain and large obstacles. In order to do so, their designs had to stray away from the common wheeled vehicle. However, robots with traditional wheels can have the capability to travel over uneven terrain with a design that consists of 6 wheels attached to a suspension system.

One popular robot that uses this design is the *Curiosity* rover (Figure 4) developed by NASA to explore the Gale Crater on Mars (NASA, 2014). It uses six 20 inch diameter wheels that are configured in a rocker-bogie suspension where each wheel is independently actuated and geared. This suspension configuration allows *Curiosity* to climb in soft sand and over rocks up to 26 inches in height (NASA, 2013). The front and rear wheels can be independently steered which allows the robot to turn in place (Makovsky, Hott, & Taylor, 2009). Another robot that uses a similar design to *Curiosity* is the Shrimp robot designed by BlueBotics (Figure 5). It features a passive structure that doesn't need to actively sense obstacles in order to climb them. The mechanical structure adapts to the terrain profile and allows the robot to easily overcome vertical obstacles twice its wheel diameter and climb stairs with the use of its 6 motorized wheels (BlueBotics, 2014).

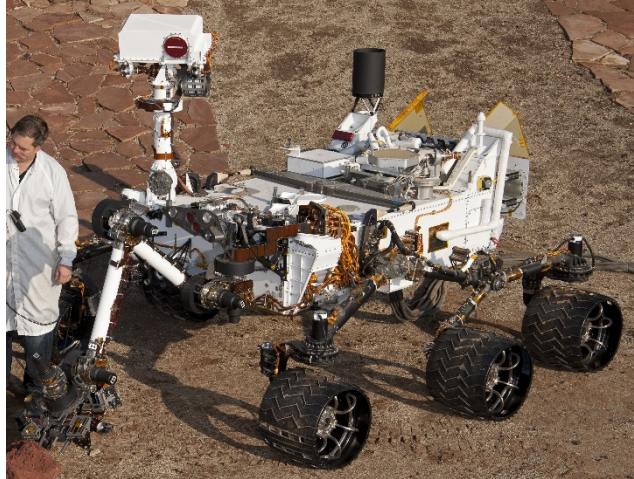


Figure 4. NASA's Curiosity rover



Figure 5. BlueBotics' Shrimp robot

Another promising design that may eventually impact the wheelchair market uses legs to walk over difficult terrain. DARPA's Legged Squad Support System (LS3) (Figure 6) is a semi-autonomous legged robot that has been developed to reduce the physical weight troops carry on the battlefield. Its 4 legged design operates similar to how a dog walks where sensors constantly monitor the terrain and provide feedback to maintain stability when traveling over rough terrain. It can carry 400 pounds of gear while autonomously following its leader or traveling to designated GPS coordinates (DARPA, 2014). With a design similar to the LS3, John Deere's

Walking Forest Machine (Figure 7) features a 6 legged design that automatically adapts to the forest floor when moving forward, backward, sideways, and diagonally. Sensors in each of its legs react automatically when it encounters soft, sloped, or uneven terrain. The feedback from the sensors allows the machine to distribute its weight equally to each of its legs. It also has the ability to step over obstacles that cross its path and adjust its ground clearance and height with every step (John Deere, 2014).

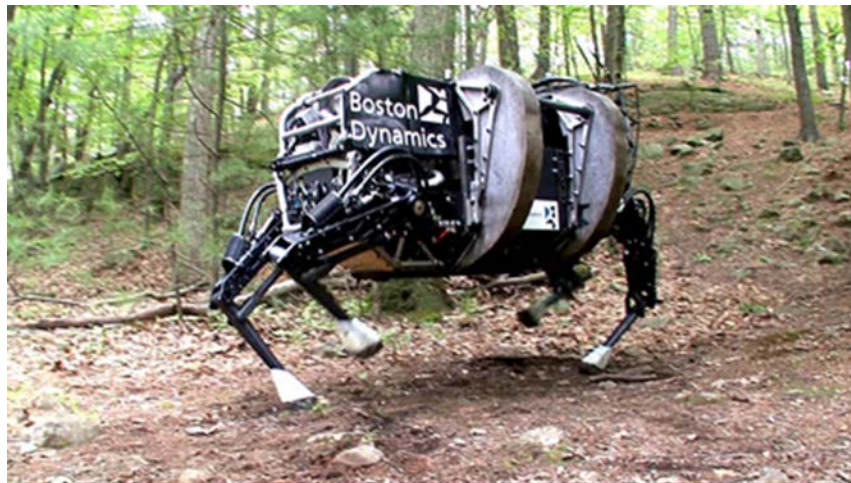


Figure 6. DARPA'S Legged Squad Support System



Figure 7. John Deere's Walking Forest Machine

Future advances in power wheelchair design may look at the robotics industry for guidance to develop mobility devices that can overcome extreme terrains and architectural barriers such as curbs and stairs. Although there are power wheelchairs that are currently available that have the capability to overcome all types of terrain, they are larger, less maneuverable, and not intended for indoor use. The previously described advanced robots are only a couple examples of the vast number of designs that could impact wheelchair development. Although if designs similar to LS3 are used to develop new mobility devices, the term “wheelchair” may become extinct.

2.0 PRELIMINARY DESIGN

2.1 PROBLEM STATEMENT

For Electric Power Wheelchair (EPW) users, going outside the home to go to a friend's house or work are opportunities for a feeling of freedom and increased quality of life. However, research has shown that when traveling in outdoor environments or into buildings and houses, the EPW user may encounter obstacles that the EPW wasn't designed to travel over which puts the user at a risk of tipping or falling out of the wheelchair which may lead to serious injury or death.

For EPWs to be used efficiently the environments they're used in must be accessible or an EPW that has the ability to safely travel in outdoor environments must be developed. Unfortunately, many buildings and houses, specifically older buildings, do not meet the standards of the American with Disabilities Act which restrict EPW users' access to these buildings due to obstacles such as steps or steep ramps. This restriction often causes users to attempt to overcome the obstacle which may lead to the user tipping or falling out of the EPW. Tips and falls are also common when users are driving in outdoor environments where they may encounter uneven terrain such as grass, dirt, and gravel or architectural barriers such as steep slopes and curbs.

Since changing the environment is an unlikely possibility in many situations, an EPW capable of overcoming such obstacles must be designed. As a result, MEBot was designed for

the user to safely traverse through outdoor environments or into otherwise inaccessible buildings and houses. The ability to be unrestricted from getting to places that are typically impossible can greatly impact the users' independence, freedom, and quality of life.

2.2 PREVIOUS DESIGN

The Personal Mobility and Manipulation Appliance II (PerMMA II) was developed based on feedback from end-users that identified curbs and sets of 3 or 4 steps to be barriers when driving in the community or visiting friends and family (Cooper, et al., 2012). As a result, the development of an EPW to overcome such barriers was envisioned. PerMMA II (Figure 8) features a 6 wheel design where the front and rear wheels are able to independently move up and down via pneumatic actuators. The drive wheels utilize hub motors that are mounted to the frame via a carriage system that moves up and down with a pneumatic sleeve spring. The drive wheels can also move forward and backward with an electric linear actuator. The ability of the wheels to move independently of each other allows PerMMA II to climb up to 6 inch curbs and perform self-leveling which maintains the position of the seating system in relation to the driving surface. Additionally, the forward and backward movement of the driving wheels improves obstacle negotiation, driving maneuverability, and navigating challenging terrain such as gravel, sand, grass, or cross slopes.



Figure 8. Personal Mobility and Manipulation Appliance II Prototype

The finished prototype of PerMMA II was able to successfully climb a 6 inch curb, perform self-leveling, and change the position of its driving wheels. Unfortunately, each of the tasks needs additional work in order to be useful during everyday operation. The issues are due to a combination of mechanical capabilities and software programming. For example, the amount of time it took to complete the curb climbing sequence was 2 minutes 30 seconds. Such a long length of time could put the user at risk of being caught in traffic when crossing an intersection which may lead to serious injury. The cause of the long length of time was due to multiple factors: 1) The linear actuator that manages the horizontal location of the driving wheels takes 30 seconds to move the driving wheels from the forward to rearward position and vice versa. This operation is performed twice during the curb climbing sequence. 2) The number of steps it takes to climb a curb. 3) The sequence of steps in the curb climbing process are not performed immediately one after the other. 4) The user's weight is unable to be measured which affects the position of the center of mass of the wheelchair.

Another issue that impacts the effectiveness of PerMMA II is its ability to perform self-leveling. One of the requirements for self-leveling to be successful is knowing the position of

each of the 6 wheels. This position was measured by adding position sensors to the pneumatic actuators. Unfortunately, the operation of the position sensors provided inaccurate measurements and at times didn't work at all (Figure 9). Furthermore, the horizontal position of the driving wheels with respect to the center of mass impacts the self-leveling capability. Also impacting self-leveling was the limitation of the vertical and horizontal movement of the driving wheels. With a total range of 7 inches horizontally and 3.3 inches vertically, the movement of the driving wheels restricted the steepness of slope or cross slope that PerMMA II could successfully climb and perform self-leveling. For example, when PerMMA II would travel down a steep slope, the wheelchair would tend to tip forward because the center of mass moved toward the front of the wheelchair to a point past the driving wheels.

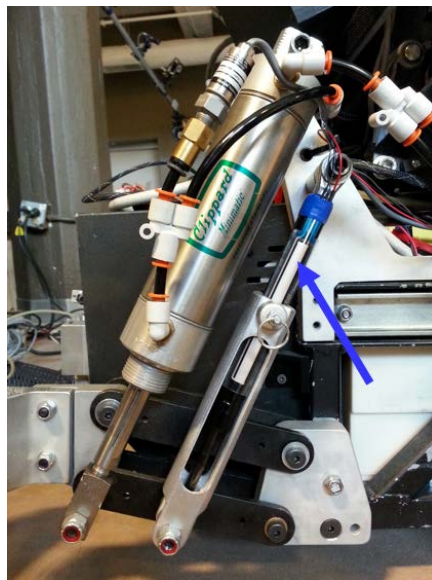


Figure 9. Position sensors added on gas spring

Other issues that were encountered involved the mounting location of the linear actuator for the horizontal drive wheel movement. The actuator was mounted on the bottom of the wheelchair which impacted its ground clearance when driving and climbing curbs. Figure 10 shows the minimum ground clearance when PerMMA II is in its lowest position. The driving

wheels had an unintentional camber which was determined to be due to the strength of the material the driving wheels were mounted to and the miss sizing of the hole that the axle fits through.



Figure 10. Driving wheel electric actuator clearance in lowest position

Finally, the overall operation of the pneumatics required a large amount of air to operate. The system uses compressed CO₂ as its air supply (Figure 11). Unfortunately, the lack of consistency of the pressure from the CO₂ impacts the performance of the system. It is speculated that the expansion chamber is not large enough to allow the compressed CO₂ (liquid CO₂) to fully convert into its gaseous state. As a result, some liquid CO₂ may get into the system and affect the pressure being supplied. Furthermore, the temperature of the system decreases as the CO₂ is used which also impacts the consistency of the pressure output. The pneumatic sleeve spring on the driving wheels are different from the pneumatic actuators used on the front and rear casters. The driving wheels use a sleeve style air pressured spring (Figure 12) while the front and rear casters use standard pneumatic actuators (Figure 13). Sleeve style air

pressured springs require more air to extend because the entire bladder has to inflate unlike standard pneumatic actuators that only require their cylinder to be inflated.



Figure 11. CO2 tank (1) and expansion chamber (2)

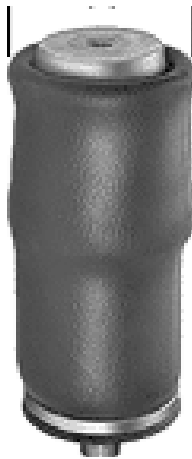


Figure 12. Sleeve style air pressured spring



Figure 13. Standard pneumatic actuator

2.3 DESIGN CRITERIA

The priority design criterion for MEBot was based on improving the capabilities of PerMMA II. The 1st criteria for MEBot is to be able to climb an 8 inch curb in less than 30 seconds. This criterion is based on the approximate time allowed for pedestrians to cross the street during a red light. The 2nd criterion addresses the limited driving wheel movement of PerMMA II. Increasing the horizontal movement to 14 inches will allow MEBot to be configured as a front wheel drive, mid-wheel drive, or rear wheel drive power chair. Another advantage of the increased movement will decrease the likelihood of MEBot becoming stuck in difficult terrains because it would have the ability to “crawl” over soft terrain such as mud, sand, or snow. For example, when a person is rowing in a canoe they move the oars forward, push them down into the water, and move them back in order to continue to move the canoe forward. The same concept would be applied when MEBot is crawling over the soft terrain. Furthermore, increasing the vertical movement of the driving wheels to 8 inches will allow MEBot to perform self-leveling when traversing over rough terrain, slopes (up to 17°), and cross slopes (up to 20°).

The secondary priority design criterion was for MEBot to have a passive suspension system, traction control, and a self-balancing mode. Passive suspensions are those that are found on common vehicles. They incorporate a shock absorber to damp out the vertical motion of the wheel when the vehicle travels over uneven terrain. The passive suspension system will also prevent unnecessary load on the pneumatic actuators in the event of complete air loss. MEBot utilizes high pressure gas springs to act as shock absorbers. Traction control and a self-balancing are primarily programming challenges of which don't affect the mechanical design of MEBot.

The remaining criteria are based on fixing the issues of PerMMA II which include addressing the driving wheel camber, decreasing the air consumption of the pneumatic actuators, and improving wiring management. Table 2 below compares the abilities of PerMMA II and the design criteria for MEBot. Finally, the overall dimensions of MEBot must be similar to current EPWs in order to remain maneuverable in indoor environments.

Table 2. PerMMA II and MEBot comparison

Comparison Item	MEBot	PerMMA II
Time to perform curb climbing	30 seconds	2 minutes and 30 seconds
Maximum curb height	8 inches	6 inches
Horizontal drive wheel movement	14 inches	7 inches
Vertical drive wheel movement	8 inches	3.3 inches
Number of actuators	4 pneumatic actuators, 2 electronic actuators	4 pneumatic actuators, 2 pneumatic sleeve springs
Air supply	Compressed air	Compressed CO2
Ground clearance	1-9 inches	0.5-3.8 inches
Driving wheel camber	Steel mounted, tight fit axle housing	Aluminum mounted, loose fit axle housing

2.4 PROJECT MANAGEMENT

From the beginning of the design process, project management consisted of weekly meetings to discuss the progress made during the previous week. Simple updates were given during meetings held on the 2nd and 4th Mondays of the month. The updates were presented in front of other students working on other projects and several faculty members. They included a summary of the progress of the project and goals or tasks to be completed for the following week. The meetings held on the 1st and 3rd Mondays involved only the project team which allowed for more in-depth discussions. Feedback about designs was discussed along with resolving any issues that were encountered during the design process.

Once the designs were completed and finalized, manufacturing of the custom components and ordering of the purchased components could begin. The custom components were manufactured in the machine shop at HERL. Drawings of the components were provided for the shop staff based on the length of time it would take to manufacture each component. Components that would take longer to manufacture were started 1st. An online excel sheet (Table 3) was created that allowed members of the shop staff to know whether each of the components needed additional work or was completed.

Table 3. Component manufacturing status

Part name	Quantity	Difficulty	Process	Status
Front caster actuator mount	2	Medium	EDM, Manual mill, welding	Welding
Front caster attachment bracket	2	Easy	EDM, Manual mill, grinder	Need to be CNC
Front caster linkage	2	Easy	Grinder	Completed
Front top actuator mount	2	Easy	Grinder	Completed
Front caster brace	1	Easy	Waterjet	Completed
Rear caster attachment bracket	2			Completed
Rear caster linkage	2	Easy	Grinder	Completed
Rear caster linkage fins	4	Easy	EDM or waterjet	Completed
Rear pneumatic mount rod	1	Medium	Manual lathe, manual mill	Completed
Rear gas spring mount rod	1	Medium	Manual lathe, manual mill	Completed
Rear electronics boxes	1	Easy	SLS or fortus	Not started
Main frame	1	Hard	Waterjet, welding	Completed
Inner frame	1	Medium	Bandsaw, manual mill, welding	Spacers need welded in
Inner frame threaded spacer	12	Easy	Manual mill	Completed
Driving wheel mount plate	2	Easy	Waterjet	Completed
Drive wheel linkage	2	Medium	Waterjet, welding	Completed
Drive wheel linkage bolt	2	Hard	CNC mill, CNC lathe	Not started
Gas spring attachment	2	Medium	Manual lathe, manual mill	Not started
Pneumatic actuator attachment	2	Medium	Manual lathe, manual mill	Not started
Pneumatic actuator connector	4	Easy	Manual mill	Needs holes drilled and tapped
Lead screw connection	1	Medium	EDM, manual mill	V-shape piece left

3.0 DETAILED DESIGN

3.1 MANUFACTURING PROCESS PLAN

MEBot was designed to be assembled with 7 smaller assemblies. The assemblies include the frame along with left and right configurations of the front casters, driving wheels, and rear casters. The frame is made out of 0.25 inch thick 6061-T6 aluminum of which is cut out on a waterjet and welded together. The frame was chosen to be made out of aluminum in order to significantly save weight when compared to steel. An inner support frame of 1 inch square low carbon steel tubing with a thickness of 0.083 inches provides a location for mounting the seating system, lead screw assembly, and linear rail system for the driving wheels. The front and rear caster assemblies comprise of components made out of various thicknesses of low carbon steel that are manufactured with the use of an electrical discharge machine (EDM) (Figure 14), waterjet (Figure 15), manual lathe (Figure 16), and manual mill (Figure 17). The driving wheel assemblies are also made out of low carbon steel and are manufactured with the use of a waterjet and manual lathe. All of the components are then bolted together to form the base of MEBot.



Figure 14. Electrical discharge machine (EDM)



Figure 15. Waterjet machine



Figure 16. Manual lathe



Figure 17. Manual mill

3.2 PURCHASED COMPONENT SELECTION

3.2.1 Lead Screw Assembly

The lead screw assembly provides the horizontal movement of the driving wheels via an electric motor, encoder, and Acme lead screw. The Acme lead screw was selected based on the necessary force to move the driving wheels when curb climbing and changing the driving wheel position. The force was estimated based on the approximate weight of MEBot (≈ 400 pounds) and a 250 pound user. Under the worst-case scenario, it is theorized that a maximum force of approximately 35% of the combined weight of the chair and user would be experienced when changing the driving wheel position in order to get unstuck from mud or sand. As such, the lead screw would experience a force of approximately 230 pounds.

The Nook PowerAC 5/8" Acme lead screw assembly (model # 068-RA/CN/U2/18.00/20068/FS) was chosen based on its dynamic load capacity of 1953 pounds and low amount of torque required to raise 1 pound of 0.058 in-lb. A customized configuration of the lead screw was necessary due to the fact that none of the standard lengths available provided exactly 14 inches of travel. The customized configurations provided multiple options for the end

configurations of the lead screw. For ease of mounting into MEBot, the Ezze-Mount bearing support was chosen for both ends of the lead screw. One end would be configured as a universal single bearing support and the other end would be a universal double bearing support with the Nema-23 motor mount option.

Once the lead screw had been selected, a motor was selected that provided enough torque and speed to move the driving wheels under the worst-case scenario and be able to complete the curb climbing sequence under 30 seconds. The calculation of the motor torque required resulted in a torque of 13.3 in-lb based on the calculation of Equation 1. The necessary RPM of the motor was calculated based on the length of the lead screw (14 inches), turns per inch (8), and time to move the driving wheels the full length of the lead screw (10 seconds). As a result of Equation 2, the speed of the motor must be at least 672 RPM.

$$\frac{1 \text{ pound}}{0.058 \text{ in-lb}} = \frac{230 \text{ pounds}}{X} \rightarrow X = \frac{(0.058 \text{ in-lb})(230 \text{ pounds})}{1 \text{ pounds}} = 13.3 \text{ in-lb}$$

Equation 1. Lead screw motor torque calculation

$$14 \text{ inches} \times \frac{8 \text{ turns}}{1 \text{ inch}} \times \frac{1 \text{ revolution}}{1 \text{ turn}} \times \frac{1}{10 \text{ seconds}} \times \frac{60 \text{ seconds}}{1 \text{ minute}} = 672 \text{ RPM}$$

Equation 2. Lead screw motor speed calculation

The selection of the motor was based on the following specifications: 1) input voltage of 24 VDC 2) Nema-23 motor size 3) output torque of 13.3 in-lb (213 oz-in) 4) minimum speed of 672 RPM. As a result of the necessary specifications, a National Instruments Nema-23 stepper motor (model # 780084-01) was chosen. It provides a maximum output torque of 380 oz-in and a maximum speed of 3000 RPM. This model was chosen due to its dual shaft configuration that

allows for the addition of an encoder (model # 780251-01) in order to provide the location of the driving wheels. The specification sheets for the Acme lead screw, stepper motor, and encoder can be viewed in Appendix A.

3.2.2 Gas Springs

Gas springs are incorporated into the design of MEBot to act as a failsafe in the event that the pneumatic system loses all its air and to decrease the force required by the pneumatic actuators to move the driving wheels and rear casters up and down. The gas springs were chosen such that when the weight of the chair and user are applying force to the system, MEBot would be at or near its lowest ground clearance. This causes all or a majority of the weight to be placed on the gas springs thus decreasing the force placed on the pneumatic actuators.

3.2.2.1 Driving Wheel Assembly

The gas spring incorporated in the driving wheel assembly experiences a force based on one quarter of the combined weight of the wheelchair and the user considering there are a minimum of 4 wheels on the ground at any given time. Figure 18 shows the dimensions of the driving wheel linkage and the location of the forces that are relevant to calculating the force being placed on the gas spring. The weight of the wheelchair (W) and the force of the gas spring (F_{G1}) are used in Equation 3 through Equation 5 to calculate the force experienced by the gas spring. The calculated force of 2351.5 N (529 lbf) was then used to choose a gas spring of equal force or greater to counteract force W . As a result, gas springs manufactured by Industrial Gas Springs, Inc. were chosen (model # 91G100282MM). Gas springs with 2 different compressed forces (864 and 442 pounds) were chosen in the event that force W was greater or less than estimated

due to a lighter weight user or a center of mass that did not result in each of the 4 wheels witnessing a quarter of the weight. Additionally, the stroke length of the gas spring was limited to approximately 2 inches due to space restrictions.

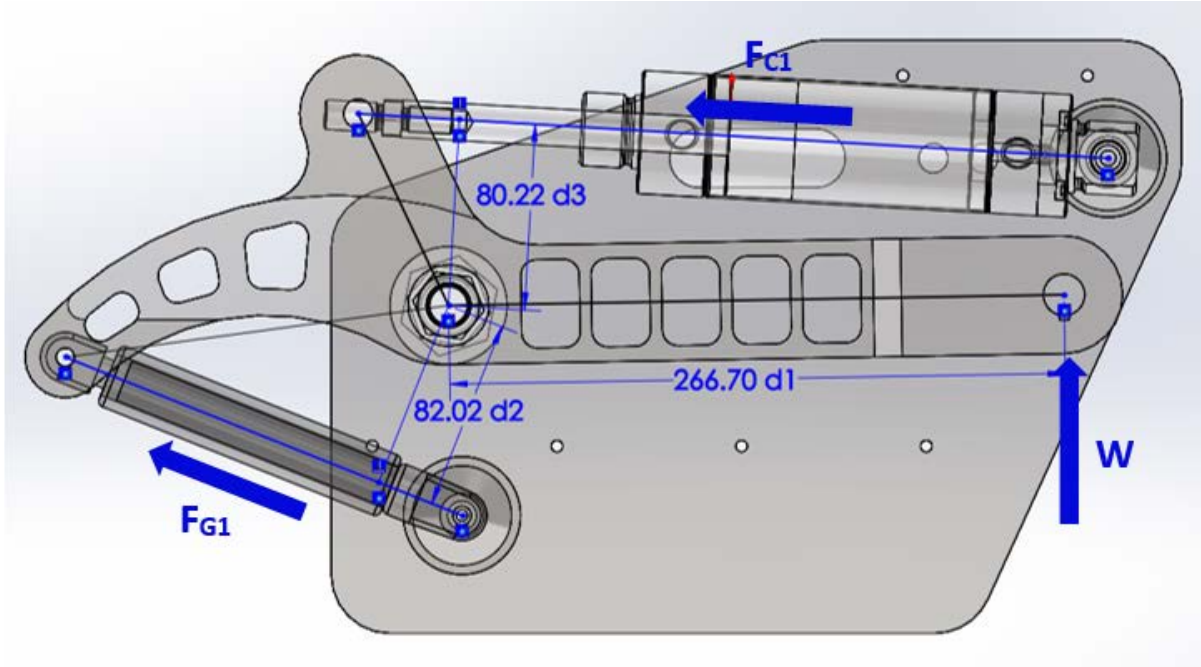


Figure 18. Driving wheel gas spring free body diagram

$$W = \left(\frac{1}{4}\right) (650 \text{ pounds}) \left(\frac{1 \text{ kg}}{2.2 \text{ pounds}}\right) \left(9.81 \frac{\text{m}}{\text{s}^2}\right) \left(\frac{1 \text{ N}}{1 \text{ kg} \frac{\text{m}}{\text{s}^2}}\right) = 724.6 \text{ N}$$

Equation 3. Weight of wheelchair W calculation

$$Wd1 - F_{G1}d2 = 0$$

Equation 4. Driving wheel gas spring force calculation equation 1

$$F_{G1} = \frac{d1}{d2} W = \frac{266.7 \text{ mm}}{82.0 \text{ mm}} (723 \text{ N}) = 2351.5 \text{ N}$$

Equation 5. Driving wheel gas spring force calculation equation 2

3.2.2.2 Rear Caster Assembly

The rear caster assembly also incorporated gas springs into its design for the same reason as described for the driving wheel assembly. However, the force experienced by the rear caster gas springs is different because of having a different geometry. Figure 19 shows the free body diagram of the rear caster linkage and the relevant dimensions and forces needed to calculate the force experienced on the gas spring. The same estimated weight of the wheelchair (W), Equation 3, was used to calculate the force F_{G2} . The result of the calculations from Equation 6 and Equation 7 yielded a force of 1012.9 N (228 lbf). The stroke of the selected gas spring needed to be at least 7.5 inches. A gas spring was chosen from McMaster-Carr with a compressed force of 175 pounds and a stroke length of 7.87 inches (model # 9416K28). Specification sheets for each of the gas springs can be viewed in Appendix A.

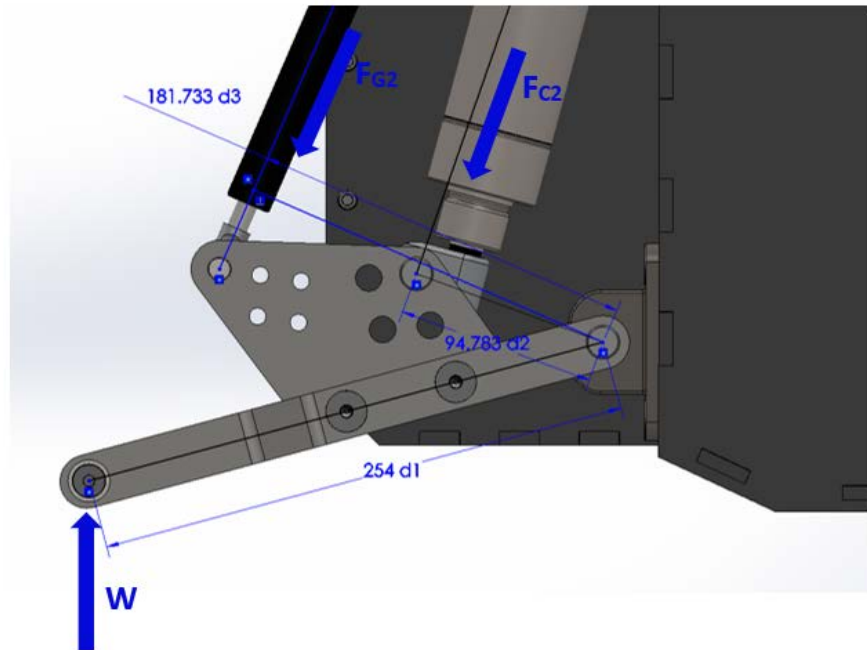


Figure 19. Rear caster gas spring free body diagram

$$Wd1 - F_{G2}d3 = 0$$

Equation 6. Rear caster gas spring force calculation 1

$$F_{G2} = \frac{d1}{d3} W = \left(\frac{254 \text{ mm}}{181.7 \text{ mm}} \right) (724.6 \text{ N}) = 1012.9 \text{ N}$$

Equation 7. Rear caster gas spring force calculation 2

3.2.3 Pneumatic Actuators

Pneumatic actuators were chosen to provide the up-and-down movement of the driving wheels and rear casters due to the high amount of force they can exert both pushing and pulling and also the quickness of which they can extend and retract. These were advantages when compared to electric actuators that provide equivalent output forces. Hydraulic actuators were also considered but were ruled out due to the additional reservoirs and pumps that would be needed for them to operate. As a result, pneumatic actuators with position feedback from Bimba Manufacturing were chosen due to the ability to customize the actuator based on the required force and stroke length. The ability to have built in position sensors will provide accurate feedback of the extension of the actuator which determines the ground clearance of the wheelchair. The system will operate with a maximum air pressure of 150 psi that is supplied from 2 on board high-pressure air tanks.

3.2.3.1 Driving Wheel Assembly

The pneumatic actuators of the driving wheel assembly were chosen based on the theory they would only need to overcome the force of the gas springs to move the driving wheels up or down. Therefore, the maximum amount of force the pneumatic actuators would need to apply would occur when the wheelchair would be in its elevated position (i.e the actuator would be retracted). In this position, the necessary force would be approximately the extended force of the

gas spring minus the weight of the wheelchair which is calculated to be between 477.5 and 169.5 pounds depending on the gas spring being used.

The larger force (F) of 477 pounds and pressure (p) of 150 psi (air pressure of the system) were used to determine the bore diameter calculated from Equation 8 and Equation 9. Based on the force requirement, a pneumatic actuator with a 2 inch bore would provide the necessary force. Additionally, in order for the driving wheels to move vertically 8 inches, the required stroke length is 3 inches. As such, a Bimba position control pneumatic actuator (Figure 20) with a 2 inch bore and 3 inch stroke length was custom configured (model # PFC-313-XP).

$$F = pA = p(\pi r^2)$$

Equation 8. Force versus pressure equation

$$r = \sqrt{\frac{F}{\pi p}} = \sqrt{\frac{477 \text{ pounds}}{\pi * 150 \text{ psi}}} = 1 \text{ inch} \rightarrow d = 2 \text{ inches}$$

Equation 9. Driving wheels pneumatic actuator diameter calculation



Figure 20. Bimba position control pneumatic actuator

3.2.3.2 Rear Caster Assembly

The rear caster assembly uses pneumatic actuators for the same reason as the pneumatic actuators for the driving wheels. They will also have the built in position sensors in order to

know the height of the rear casters. Unfortunately, the gas springs purchased from McMaster-Carr don't provide an extended force. Therefore an estimated extended force of 111 N (25 lbf) was used to calculate the required force, F_C , of the pneumatic actuator. Using the free body diagram in Figure 19, Equation 10 is the summation of the torques of which F_C can be solved for. Equation 11 and Equation 12 show the sequence of steps to calculate the required force of the gas spring of 1728.7 N (388.6 lbf). As such, the required bore diameter can be calculated using Equation 8. Solving for r yielded a result of 0.91 inches or a diameter of approximately 2 inches as calculated from Equation 13.

The rear casters have a vertical range of 8 inches of which the pneumatic actuator must have a stroke length of 4 inches. As such, a Bimba pneumatic actuator with position sensors, a 2 inch bore, and a stroke length of 4 inches was custom configured (model # PFC-314-XP).

$$Wd_1 - F_G d_3 - F_C d_2 = 0$$

Equation 10. Rear caster pneumatic actuator required force equation 1

$$Wd_1 - F_G d_3 = F_C d_2$$

Equation 11. Rear caster pneumatic actuator required force equation 2

$$F_C = \frac{Wd_1 - F_G d_3}{d_2} = \frac{(724.6 \text{ N})(254 \text{ mm}) - (111 \text{ N})(181.7 \text{ mm})}{94.8 \text{ mm}} = 1728.7 \text{ N}$$

Equation 12. Rear caster pneumatic actuator required force equation 3

$$r = \sqrt{\frac{F}{\pi p}} = \sqrt{\frac{388.6 \text{ pounds}}{\pi * 150 \text{ psi}}} = 0.91 \text{ inches} \rightarrow d \approx 2 \text{ inches}$$

Equation 13. Rear caster pneumatic actuator diameter calculation

3.2.3.3 Air Consumption Calculation

The air consumption rate of the pneumatic actuators is important due to the dependence of the amount of air volume available from the air tanks. If only enough air is available for MEBot to elevate and/or perform curb climbing a couple times, the design won't be practical because the user will constantly have to refill the air tanks. The air consumption rate is based on the actuator bore diameter, stroke, air pressure, and complete cycles (extension and retraction of the cylinder) per minute. Equation 14 through Equation 20 shows the process to determine the air consumption for the pneumatic actuators moving the rear casters with 2 inch bores and 4 inches of stroke operating at 2 cycles per minute and 150 psi of air pressure. 2 cycles per minute were chosen based on the time period and number of times the actuators would extend and retract during curb climbing.

$$\pi \left(\frac{d}{2}\right)^2 = \pi \left(\frac{2 \text{ in. bore}}{2}\right)^2 = 3.14 \text{ sq. in.}$$

Equation 14. Air consumption (4 inch stroke) - area of piston

$$3.14 \text{ sq. in.} \times 4 \text{ in. stroke} = 12.56 \text{ cu. in.}$$

Equation 15. Air consumption (4 inch stroke) - consumption per stroke

$$12.56 \text{ cu. in.} \times 2 = 25.12 \text{ cu.in. per cycle}$$

Equation 16. Air consumption (4 inch stroke) - consumption per cycle

$$25.12 \text{ cu.in.} \times 2 \frac{\text{cycles}}{\text{minute}} = 50.24 \frac{\text{cu. in.}}{\text{min.}} \text{ of 150 psi air}$$

Equation 17. Air consumption (4 inch stroke) - volume of 150 psi air consumed per minute

$$\frac{50.24 \frac{\text{cu. in.}}{\text{min.}}}{1728 \frac{\text{cu. in.}}{\text{cu. ft.}}} = 0.0291 \frac{\text{cu.ft.}}{\text{min}}$$

Equation 18. Air consumption (4 inch stroke) - convert cu. in. to cu. ft.

$$\frac{150 \text{ psi} + 14.7 \text{ psi}}{14.7 \text{ psi}} = 11.20$$

Equation 19. Air consumption (4 inch stroke) - compression ratio

$$0.0291 \frac{\text{cu.ft.}}{\text{min}} \times 11.20 \text{ compression ratio} = 0.326 \text{ cu.ft. used per minute}$$

Equation 20. Air consumption (4 inch stroke) - cubic feet used per minute

The total consumption of the system is based on the 2 pneumatic actuators moving the driving wheels and the 2 pneumatic actuators moving the rear casters. With 0.652 cu. ft used per minute by the rear caster pneumatic actuators and 0.244 cu. ft used per minute used by the driving wheel pneumatic actuators, the total air consumption was calculated to be 0.896 cu. ft used per minute. However, this is the amount of air that is needed at atmospheric pressure. The pneumatic system for MEBot operates at 150 psi. At this pressure, MEBot would need a total of 0.0509 cu. ft of compressed air (Equation 18 + Equation 25).

$$\pi \left(\frac{d}{2}\right)^2 = \pi \left(\frac{2 \text{ in. bore}}{2}\right)^2 = 3.14 \text{ sq. in.}$$

Equation 21. Air consumption (3 inch stroke) - area of piston

$$3.14 \text{ sq. in.} \times 3 \text{ in. stroke} = 9.43 \text{ cu. in.}$$

Equation 22. Air consumption (3 inch stroke) - consumption per stroke

$$9.43 \text{ cu. in.} \times 2 = 18.86 \text{ cu. in. per cycle}$$

Equation 23. Air consumption (3 inch stroke) - consumption per cycle

$$18.86 \text{ cu. in.} \times 2 \frac{\text{cycles}}{\text{minute}} = 37.72 \frac{\text{cu. in.}}{\text{min.}} \text{ of 150 psi air}$$

Equation 24. Air consumption (3 inch stroke) - volume of 150 psi air consumed per minute

$$\frac{37.72 \frac{\text{cu.in.}}{\text{min.}}}{1728 \frac{\text{cu.in.}}{\text{cu.ft.}}} = 0.0218 \frac{\text{cu. ft.}}{\text{min}}$$

Equation 25. Air consumption (3 inch stroke) - convert cu. in. to cu. ft.

It is important to know how many cycles the pneumatic actuators can be used before the air tanks need to be refilled. Currently, two 62 cu. in. air tanks at 3000 psi will be used to supply the compressed air to the pneumatic actuators. These two tanks will be able to supply 1.435 cu. ft. of air compressed at 150 psi (Equation 27). Therefore, the pneumatic actuators will be able to go through 28 cycles (Equation 28).

$$\frac{(2*62 \text{ cu. in.})*(3000 \text{ psi})}{150 \text{ psi}} = 2480 \text{ cu. in.}$$

Equation 26. Total volume of air at 150 psi provided by both canisters

$$\frac{2480 \text{ cu. in.}}{1728 \frac{\text{cu. in.}}{\text{cu. ft.}}} = 1.435 \text{ cu.ft.}$$

Equation 27. Convert cu. in. to cu. ft.

$$\frac{1.435 \text{ cu.ft.}}{0.0509 \text{ cu.ft.}} = 28.19 \text{ cycles}$$

Equation 28. Number of cycles before needing refilled

3.2.4 Electric Actuators

Electric actuators are used to move the front casters up and down. They were chosen instead of pneumatic actuators because of the limited space available on the front of MEBot and also in order to decrease air consumption. The limited space is due to the location of the actuators for the power seating functions of the seating system. The difference in length of 38 mm (1.5 inches)

between the pneumatic actuators and the electric actuators would cause the mounting locations for the pneumatic actuators to interfere with the actuators for the seating system. The front actuators are primarily used when MEBot is configured as a mid-wheel drive or rear wheel drive powered wheelchair and during the start of the curb climbing sequence. The requirements for the electric actuator was to have enough force to lift MEBot, be fast enough to perform self-leveling and to operate with 24 VDC. Therefore, electric actuators from Midwest Motion Products were chosen as the best option (model # MMP LA3-24V-40-A-50-P). They are able to withstand a static load of 2300 N (517 lbs) and a load capacity of 1200 N (270 lbs) which is well within the required load capacity of 725 N (162.5 lbs). Unfortunately, the trade-off between their force output and speed may impact MEBot's ability to perform self-leveling when traveling at high rates of speed. Similar to how the pneumatic actuators have position sensors built in, the electric actuators include a potentiometer which provides feedback in order to know the height of the front casters. The specification sheet for the electric actuators can be viewed in Appendix A.

3.2.5 Omni-directional Wheels

The front and rear casters are equipped with omni-directional wheels that are capable of moving in virtually any direction. They were chosen to replace the swivel casters typically found on EPWs. The advantage of using omni-directional wheels allow MEBot to use a simple lever and actuator for the front and rear casters which replaced the 4 bar linkage system that was used on PerMMA II. The 4 bar linkage system allowed the swivel caster to remain in parallel with the ground when moving up and down. Omni-directional wheels also eliminate the unwanted turning of typical EPWs when transitioning from driving forward to backwards and vice versa because of the removal of the casters needing to swivel. The Rotacaster omni-directional wheel

manufactured by the Kornylak Corporation was chosen due to its high load capabilities (model # RW630). The triple configuration (Figure 21) can support a load capacity of 125 kg (275 lbs).



Figure 21. Rotacaster triple body omni-directional wheel

3.2.6 Linear Bearing Rails

In order for the driving wheel assembly to move horizontally, linear bearing rails were used to guide and support the load experienced by the driving wheels. 2 different types of rails were used from the Rollon Corp., the Easy Rail (model # SN35-130-350-530) and a telescopic rail (model # DSS28-370). The dimensions of both of the rails needed to be able to fit on the side of the frame (i.e. not be too long in length) and have enough stroke length to allow the driving wheels to move 14 inches. Therefore, the maximum length that the rails could be is 545 mm (21.52 inches). The Easy Rail (Figure 22) and the telescopic rail (Figure 23) are 530 mm (20.9 inches) and 370 mm (14.6 inches) in length and provide 350 mm (13.8 inches) and 380 mm (15 inches) of stroke, respectively.

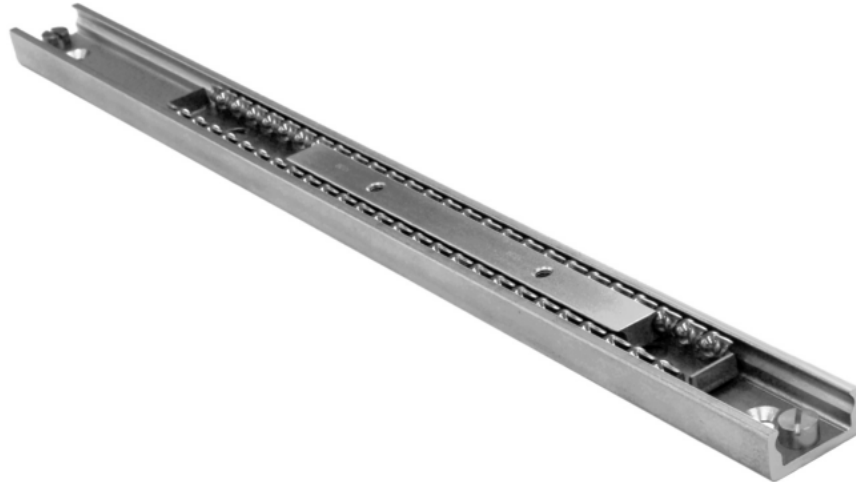


Figure 22. Rollon Easy Rail



Figure 23. Rollon telescopic rail

3.3 CUSTOM COMPONENT DESIGN

3.3.1 Front Caster Assembly

The front caster assembly (Figure 24) consists of 4 custom components: top actuator mount (1a), caster attachment bracket (3a), caster linkage (4a), and caster actuator mount (5a). All of the components are manufactured out of 1018 low carbon steel. The top actuator mount and caster attachment bracket are bolted to the frame while the caster linkage is attached to the caster

attachment bracket with a pin. The caster actuator mount and top actuator mount hold the electric actuator (2a) in place with pins. Finally, the omni-directional wheel (6a) is attached to the caster linkage.

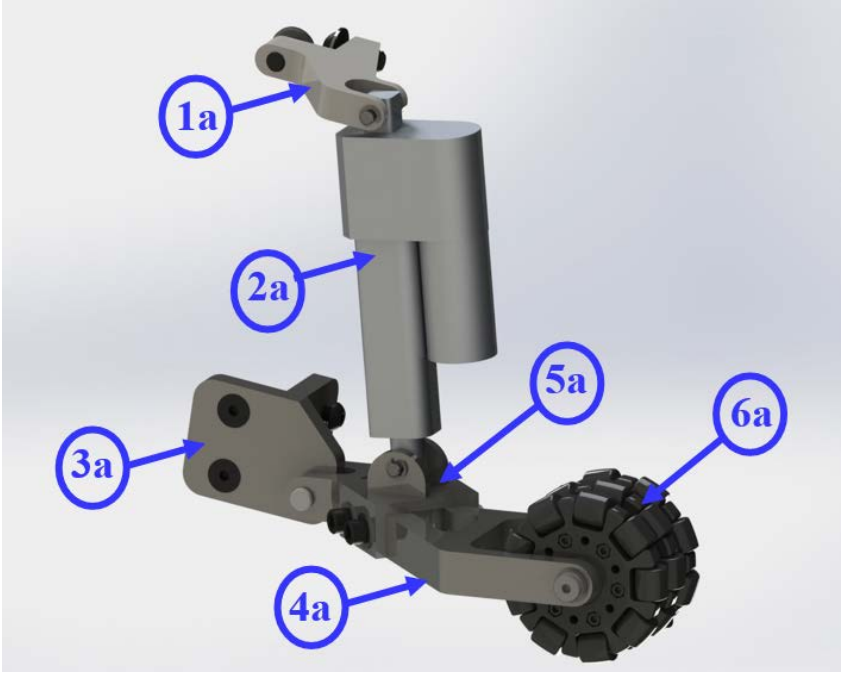


Figure 24. Front caster assembly

3.3.2 Rear Caster Assembly

For the rear caster assembly (Figure 25), two custom components are needed which include the rear caster attachment bracket (4b) and rear caster linkage (5b). The rear caster attachment bracket is bolted to the frame and pinned to the rear caster linkage. The gas spring (1b) and pneumatic actuator (3b) are also connected to the rear caster linkage with pins. Once again, an omni-directional (2b) wheel is attached to the rear caster linkage.

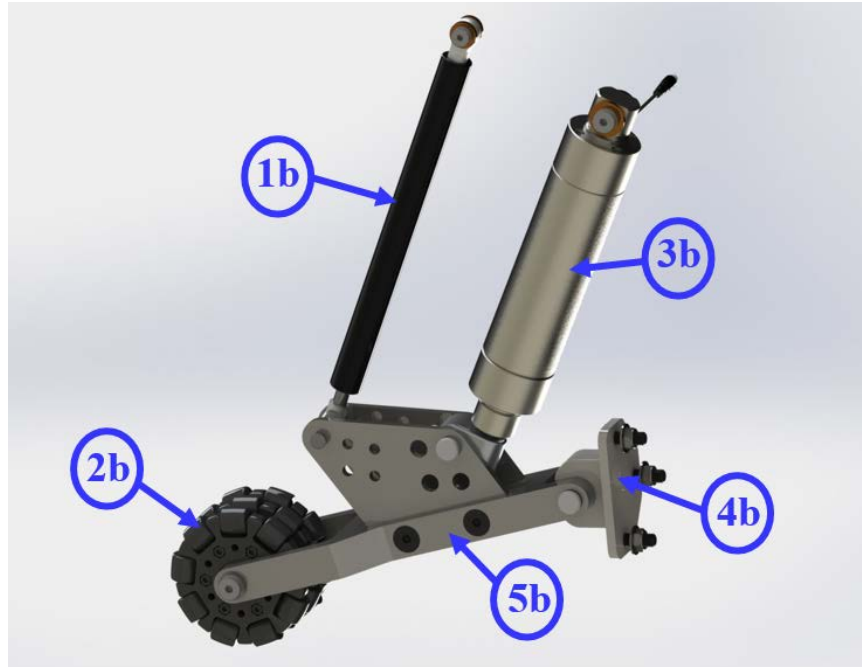


Figure 25. Rear caster assembly

3.3.3 Frame Assembly

The frame assembly (Figure 26) includes the mainframe assembly (1c), inner frame assembly (2c), rear gas spring mount rod (3c), and rear pneumatic mount rod (4c). The inner frame assembly is bolted in place with the use of the same bolts that are used to mount the linear bearing rails to the main frame. Since the rear gas spring and rear pneumatic mount rods are made from steel and the frame is aluminum, they are unable to be welded together. As such, the mount rods are tightly sandwiched between the 2 sides of the main frame to hold them in place.

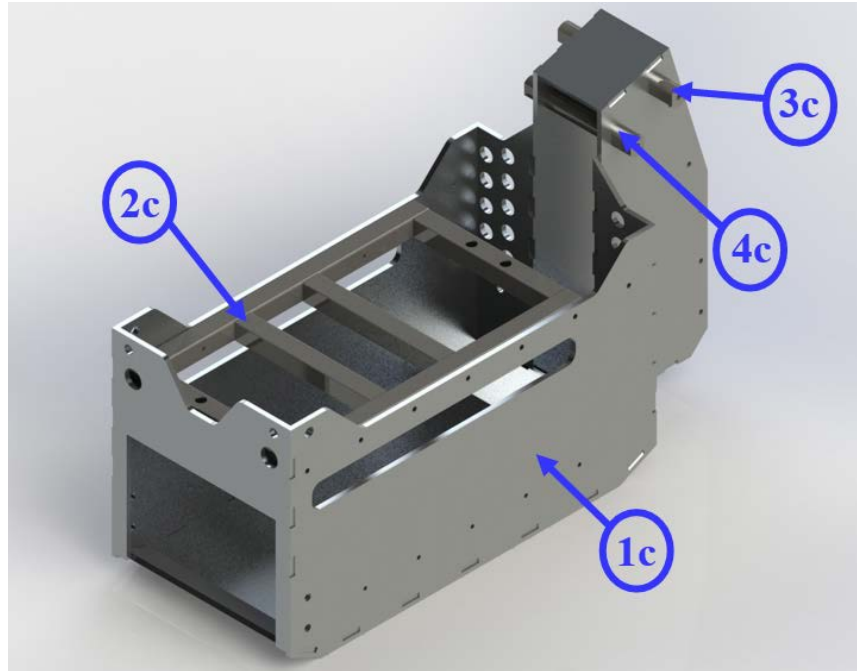


Figure 26. Frame assembly

3.3.3.1 Main Frame Assembly

The main frame serves as the base to attach the front and rear caster assemblies, the driving wheel assemblies, and the seating system. Additionally, the batteries, pneumatic manifold, air tanks, and electronics are housed inside of the frame. For the main frame assembly (Figure 27) the components were cut out of 0.25 inch thick 6061-T6 aluminum on the waterjet, assembled together, and then welded. In order to make the assembly process and welding easier, the frame was designed to fit together using tabs and slots. However, the perfect dimensions to do so were unknown which resulted in creating a test piece (Figure 28). The test piece had several slots cut in it that increased in size by 0.005 inches. It was determined that for the best fit, the slot would be 0.005 inches larger than the dimensions of the tab.

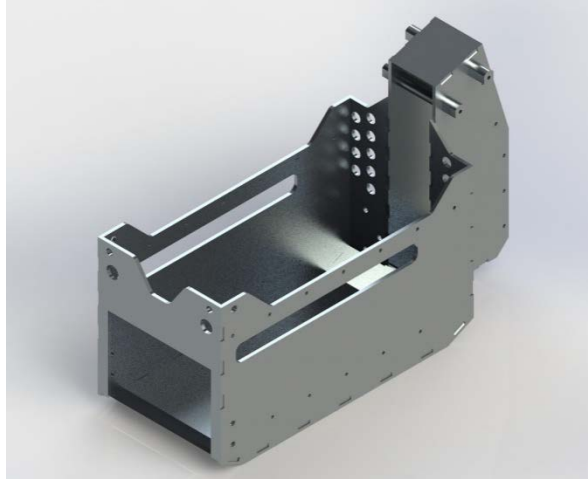


Figure 27. Main frame assembly

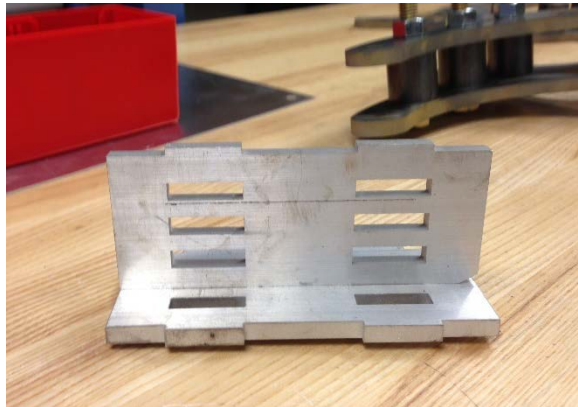


Figure 28. Main frame test piece

3.3.3.2 Inner Frame Assembly

For the inner frame assembly (Figure 29), 1 inch square tubing with a thickness of 0.083 inches was used to create a rectangular support that serves as the mounting structure for the seating system, support for the main frame, attachment location for the linear bearing rails of the driving wheel assemblies, and attachment location for the lead screw assembly. The entire assembly is welded together including the threaded spacers for the mounting of the linear bearing rails.



Figure 29. Inner frame assembly

3.3.4 Drive Wheel Assembly

The assemblies of the driving wheels include the components that allow for the vertical and horizontal movement of the driving wheels. The Easy Rail (3d) and the telescopic rail (5d) provide the support and track for the assembly to move horizontally while the pneumatic actuator (2d), gas spring (6d), and drive wheel linkage (4d) work together to provide the vertical movement of the drive wheel (1d).

The orientation of the pneumatic actuator on the driving wheels varies significantly from that of PerMMA II which are mounted vertically. In order for MEBot to obtain 8 inches of vertical movement, the pneumatic actuator orientation must be horizontal due to limited space availability. If mounted vertically, it would interfere with the electric actuators of the seating system. As a result, a linkage assembly was designed to account for the limited availability of space. The drive wheel linkage supports the weight of MEBot while the pneumatic actuator provides the vertical movement by retracting to elevate and extending to lower MEBot.

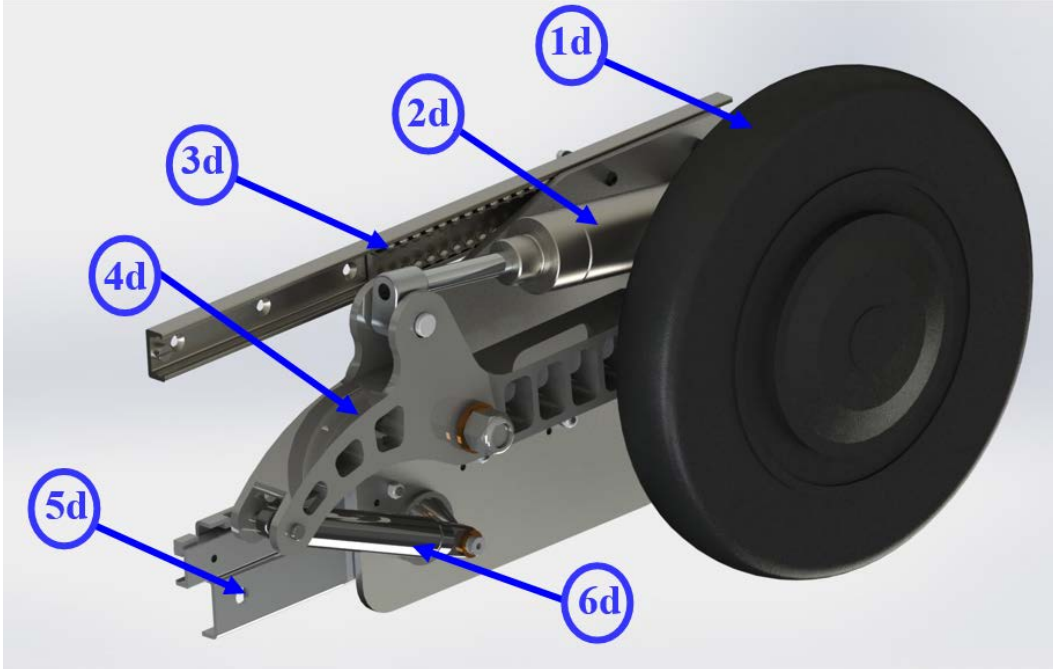


Figure 30. Driving wheel assembly

As mentioned in section 2.2, one of the issues of PerMMA II were that the driving wheels had an unintentional camber. In order to prevent the same issue from occurring with MEBot, an axle test was used to determine the tightest fit possible to prevent any unwanted movement or camber by cutting 2 different size holes for the axle and keyway to fit into (Figure 31). It was determined that a diameter of 0.708 inches would provide the tightest fit for the drive wheel to be mounted to the drive wheel linkage.



Figure 31. Hub motor axle test component

3.4 FINITE ELEMENT ANALYSIS

After the overall designs were completed for each of the custom components, Finite Element Analysis (FEA) was performed using the simulation package included in the SolidWorks 3-D modeling program. FEA is a numerical technique that cuts the model into small shapes called elements that are connected to each other by nodes. The software then uses a finite element method that considers the forces placed on each element and provides a visual representation of the amount of stress or strain being placed on the component. The result is based on the material, specified boundary conditions that include fixtures and loads, and type and size of the mesh.

An important step when performing FEA is meshing the model which divides the model into elements. SolidWorks simulation provides the option to automatically generate the mesh based on a global element size, tolerance, and local mesh control. Mesh control is used to specify a different element size from the global size on the faces, edges, or vertices of the component. SolidWorks also has the option to specify a global element size or for it to

automatically be estimated based on the component's volume, surface area, and geometry. The size of the mesh determines the number of elements and nodes which are based on the model's element size, mesh tolerance, mesh control, and geometry. The accuracy of the result can be improved by decreasing the size of the mesh. However, smaller mesh sizes increase the amount of CPU time due to the increased number of elements (Dassault Systems, 2012).

SolidWorks simulation provides the option to generate the mesh using 2 different kinds of elements, linear tetrahedral or parabolic tetrahedral. Linear tetrahedral elements are used in a draft quality mesh while parabolic tetrahedral elements are used in a high quality mesh (Figure 32). Linear tetrahedral elements, also known as 1st order elements, are made up of 4 corner nodes connected by 6 straight edges. Parabolic tetrahedral elements consist of 4 corner nodes, 6 mid side nodes, and 6 edges. They are also referred to as 2nd order elements. The higher quality mesh was used for this project because parabolic elements have the ability to better represent curved boundaries more accurately and provide better mathematical approximations (Dassault Systems, 2012). The downfall of using a higher quality mesh is that it requires more computational resources than linear elements which is similar to decreasing the mesh size.

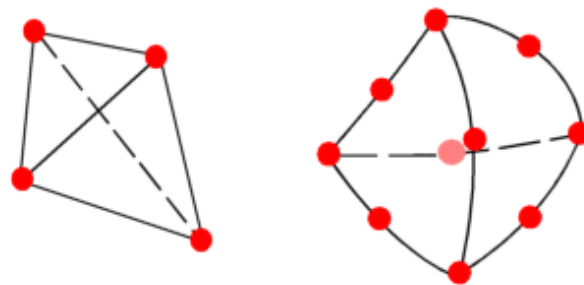


Figure 32. Element types: Linear tetrahedral (left) and Parabolic tetrahedral (right)

The visual results of the simulations may be misleading due to the fact that the default for SolidWorks is to show the result in its deformed shape. As a result, the deformed shape is typically scaled up to better visualize where the stresses and displacements occur.

3.4.1 Front Caster Assembly

The forces applied to the front caster assembly include the weight of the wheelchair and user plus a dynamic force when driving in a straight line or turning. Therefore, the force applied to the assembly when driving in a straight line was estimated to be 200 lbs, which is $\frac{1}{4}$ the weight of MEBot and the user plus a force of 25% of the combined weight of MEBot in the user. When the user would be turning, a sideways force experienced by the assembly during the worst-case scenario was estimated to be 250 lbs. These 2 scenarios were applied to each of the custom components in the assembly during the FEA.

The fixture and force locations for the front top actuator mount (Figure 33) are shown with green symbols and pink arrows, respectively. The fixtures were chosen to be the faces that are in contact with the main frame and holes where the bolts hold the actuator mount to the main frame. Vertical forces were applied to the locations where the electric actuator is connected to the actuator mount via a pin. The FEA resulted in a maximum von Mises stress of 105.3 MPa (Figure 34) which translates to a factor of safety of 3.34. Table 4 shows the von Mises stress results and factors of safety of each of the components of the front caster assembly. Explanations for the chosen locations of the fixtures and forces and the results of the FEA for the remaining components can be viewed in 0.

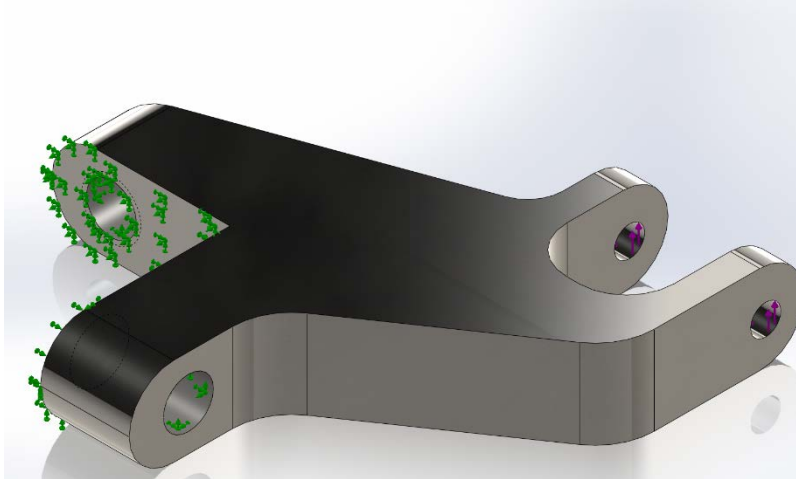


Figure 33. Front top actuator mount fixture and force locations

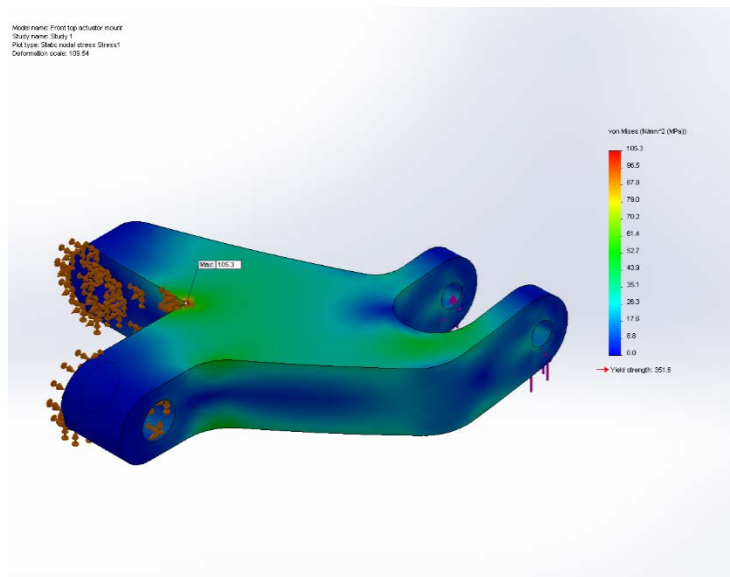


Figure 34. Front top actuator mount FEA result

Table 4. Front caster assembly FEA results

Component	Material	von Mises stress (MPa)		Factor of Safety	
		Vertical	Horizontal	Vertical	Horizontal
Front top actuator mount	AISI 1020 Steel	105.3	69.2	3.34	5.08
Front caster attachment bracket	AISI 1020 Steel	6.8	15.2	51.44	23.1
Front caster linkage	AISI 1020 Steel	124.5	75.8	2.82	4.64

3.4.2 Rear Caster Assembly

The same forces that were applied to the front caster assembly were applied to the components of the rear caster assembly because of their similarity in design and function. The fixture locations for the rear caster linkage were chosen to be the locations where the pins for mounting the pneumatic actuator and gas spring are placed. A fixed hinge was also utilized where the linkage attaches to the attachment bracket. Bolt connections were added to simulate the bolts that hold the rear caster linkage together. Finally, the forces were applied to the locations where the axle for the omni-directional wheel is mounted via a bolt. Figure 35 shows the fixtures and force locations applied to the rear caster linkage during a vertical load and Figure 36 shows the result of the FEA. Table 5 lists the results of the stresses and factors of safety for the 2 components of the rear caster assembly. Images of the locations of the fixtures and forces and results of the remaining scenarios and components can be viewed in 0.

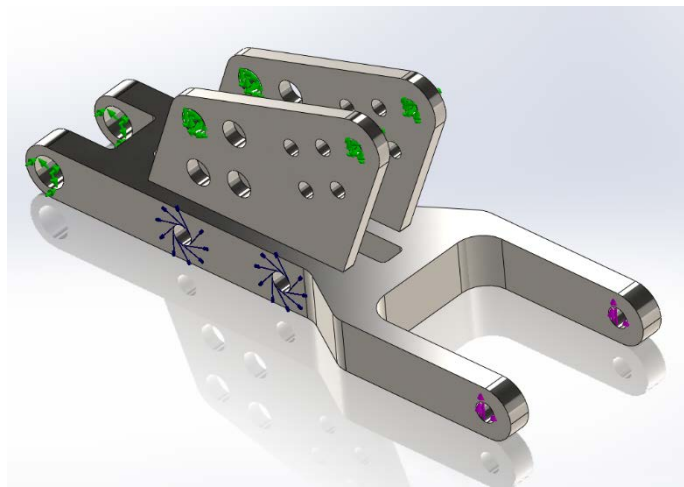


Figure 35. Rear caster linkage fixture and force locations

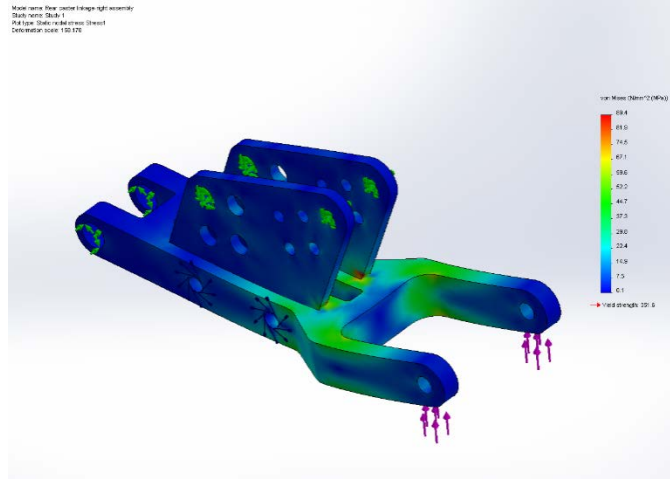


Figure 36. Rear caster linkage FEA result

Table 5. Rear caster assembly FEA results

Component	Material	von Mises stress (MPa)		Factor of Safety	
		Vertical	Horizontal	Vertical	Horizontal
Rear caster linkage	AISI 1020 Steel	89.4	123.3	3.30	2.85
Rear caster attachment bracket	AISI 1020 Steel	6.7	109.8	52.3	3.20

3.4.3 Frame Assembly

The FEA of the frame assembly consisted of simulating the load of the seating system on the inner frame assembly and of the forces placed on the rear pneumatic and gas spring mounts. Multiple simulations were performed on the inner frame assembly that included the inner frame as a single part, an assembly of beams, and an assembly of the inner frame and main frame.

Simulating the frame as a single part involves saving the assembly of square tubing as a part file in SolidWorks. This causes the original assembly to become one entity and set of multiple components. Figure 37 shows the location of the forces and fixtures. The force was applied to where the load of the seating system occurs and the fixtures were applied to where the inner frame is bolted to the main frame. The inner frame could also be simulated as an assembly

of beams since it was originally created as an assembly of weldments in SolidWorks. The location of the forces were applied to the same locations as the single part simulation. However, the fixtures for the beam assembly are unable to be applied to the locations where the inner frame is bolted. This is due to the characteristic of the assembly when it is simulated as a beam. As a result, the spacer inserts and holes in the inner frame were suppressed during the simulation. The fixtures are then applied to connections between each of the square tubes (Figure 39). The results of the single part (Figure 38) and the assembly of beams (Figure 40) yielded very similar results with a difference between the maximum von Mises stress of 2.8 MPa.

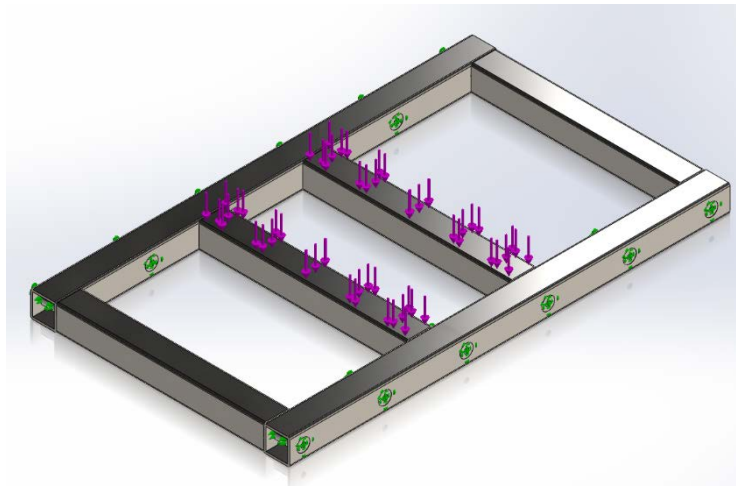


Figure 37. Inner frame assembly fixture and force locations - single part

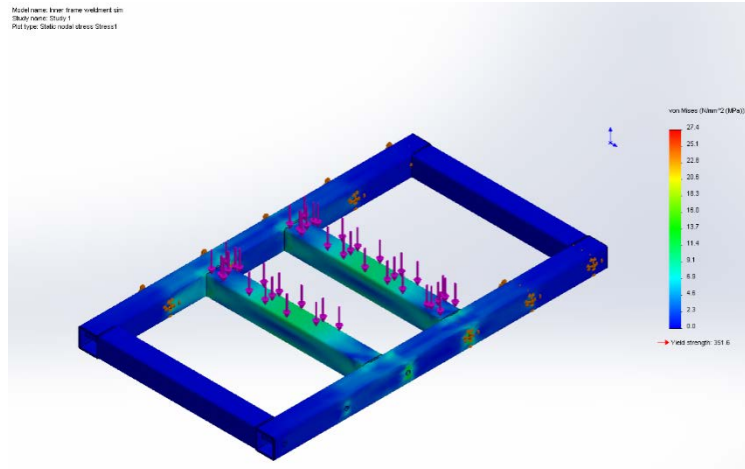


Figure 38. Inner frame assembly FEA result - single part

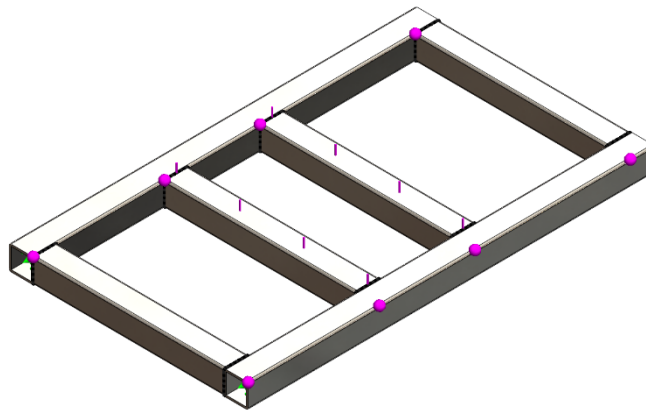


Figure 39. Inner frame assembly fixture and force locations - beam assembly

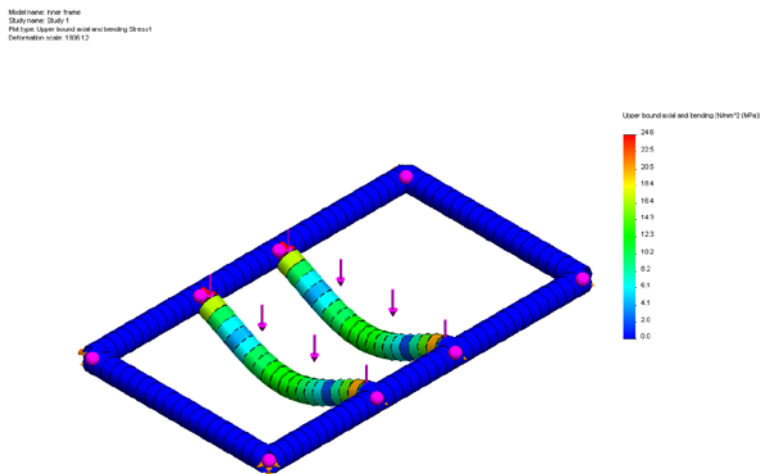


Figure 40. Inner frame assembly FEA result - beam assembly

The FEA of the assembly of the inner frame and main frame consisted of creating an assembly with the inner and main frame as parts connected with bolts. This assembly provided the most similar configuration when compared to the real world assembly. SolidWorks allows for bolt connections to be considered during the analysis. The bolt connections can be viewed in Figure 41 where large navy blue asterisks indicate each of the bolt connections. With 12 bolts holding the inner frame in place, the maximum force experienced by each bolt is approximately 137.9 N (31 lbf) which is calculated by adding the weight of the seating system (approximately 125 lbs) and the maximum weight of a user (250 lbs) and dividing by the number of bolts (12 bolts). The force was applied to the same location as previously discussed for the inner frame single part simulation. The entire bottom of the main frame was fixed for the analysis. Figure 42 shows the result of the simulation of the assembly of the inner and main frame. The maximum von Mises stress was very similar to that of the 2 previous simulations performed on the inner frame assembly. Table 6 provides a comparison between the results of the 3 simulations.

Table 6. Comparison of frame assembly simulations

Simulations	Von Mises Stress (MPa)
Inner frame - single part	27.4
Inner frame - beam assembly	24.6
Inner frame and main frame assembly	29.1

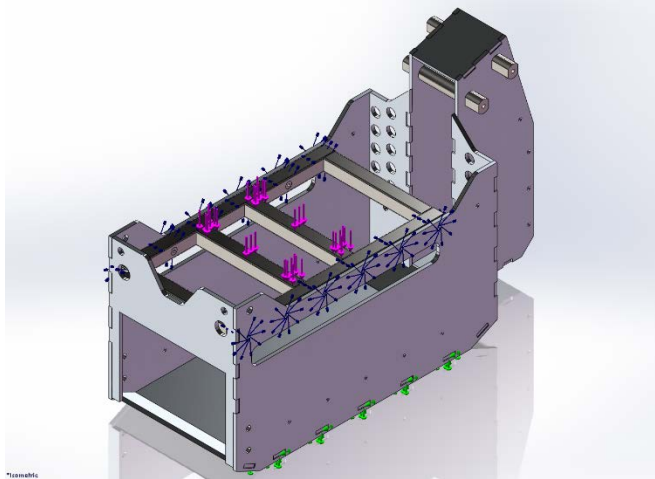


Figure 41. Frame assembly fixture and force locations - seating system

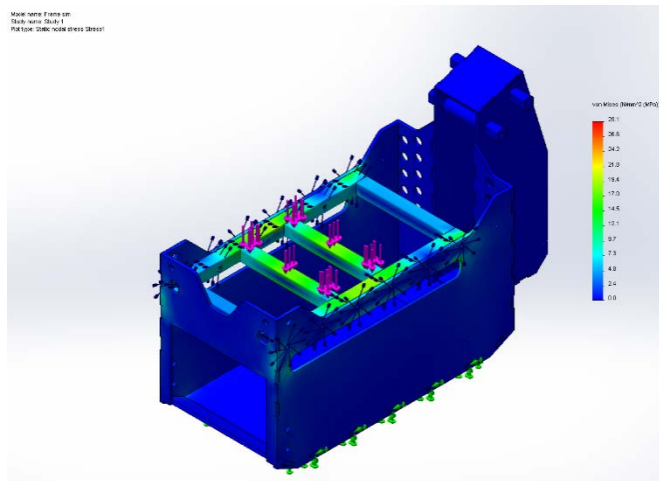


Figure 42. Frame assembly FEA result - seating system

The analysis of the forces placed on the rear gas springs and pneumatics determined whether the rear of the main frame could withstand such forces. A force of 200 lbs was applied to where the gas spring mounts to the main frame while a force of 50 lbs was applied to the pneumatic actuator mount. These forces simulate the weight of the chair through the gas spring and pneumatic actuator. The bottom of the frame was fixed. The fixture and force locations along with the FEA result can be viewed in 0.

3.4.4 Drive Wheel Assembly

The drive wheel assembly is a rather complex assembly to perform FEA on as a whole. Therefore, the assembly was simplified by replacing the pneumatic actuator and gas spring with solid titanium rods. The titanium rods take place of the connections between the driving wheel linkage and driving wheel plate that were originally connected with the pneumatic actuator and gas spring. This simplification also simplifies the meshing process and decreases the amount of CPU time. The driving wheel linkage bolt was also simplified by removing the threads and nut (Russ, 2011).

The force, fixtures, and connections were applied to the assembly based on the scenario when the MEBot would experience its maximum load of 650 lbs (total weight of user and MEBot). The force was applied as a remote load to the location where the axle of the drive wheel motor attaches to the drive wheel linkage. The remote load more accurately simulates the force and torque placed on the assembly when compared to a vertical force applied to the same location. Fixtures were applied to the locations where the driving wheel mount plate is attached to the linear bearing rails which consist of 6 bolts. Pin and bolt connections were used to connect the titanium rods to the drive wheel linkage and mounts for the gas spring and pneumatic actuator. Pins were used at the location where the titanium rods connect to the drive wheel linkage and bolt connections were the rods attach to the mount plate. Figure 43 shows the location of the fixtures (green symbols), remote load (orange symbol), and bolt connections (navy blue symbols). The result of the FEA (Figure 44) showed that the maximum von Mises stress was 225.1 MPa and occurred where the drive wheel mount plate attaches to the linear bearing rails. However, the stress was below the tensile strength of the drive wheel plate with a factor of safety of 1.56.

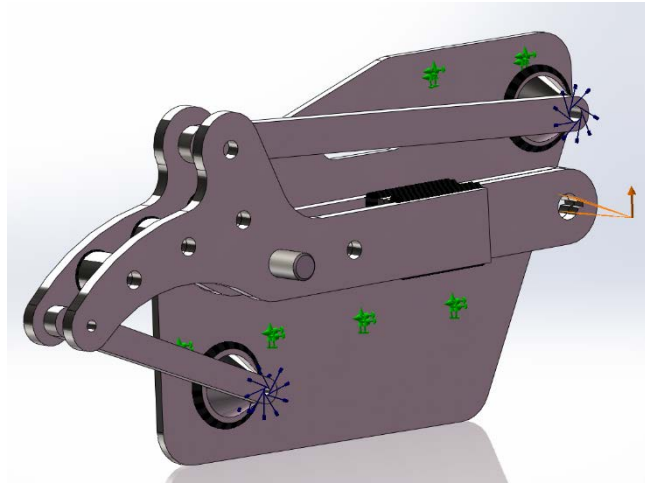


Figure 43. Drive wheel assembly fixture and force locations

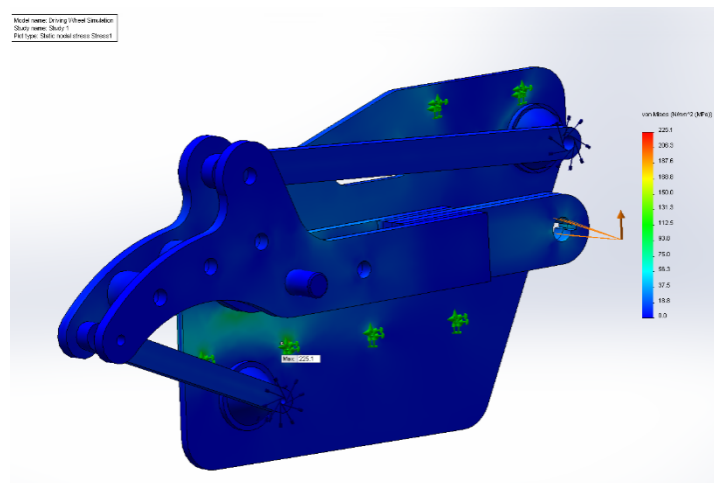


Figure 44. Drive wheel assembly FEA result

FEA was also performed on the drive wheel linkage independently because of the necessity that it be able to withstand the large forces and not flex when under load which may cause camber of the driving wheels. Once again, a remote load was applied to the location where the drive wheel motor axle fits through the linkage and fixtures were applied where the gas spring and pneumatic actuator attaches to the linkage with pins. Additionally, bolt connections were added where the spacers were used between the plates of the linkage. The welds were also added to the simulation around the edges of the spacers and the plates that are

sandwiched together (Figure 45). The result of the simulation yielded a maximum von Mises stress (Figure 46) of 56.3 MPa with a factor of safety of 6.22 and maximum displacement of 0.0063 inches (Figure 47).

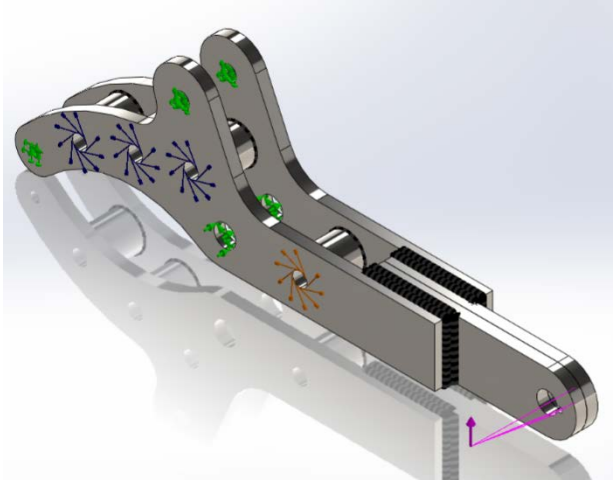


Figure 45. Drive wheel linkage fixture and force locations

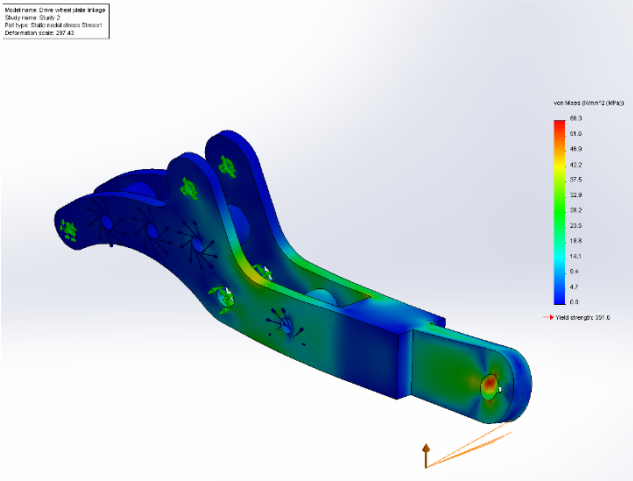


Figure 46. Drive wheel linkage FEA result

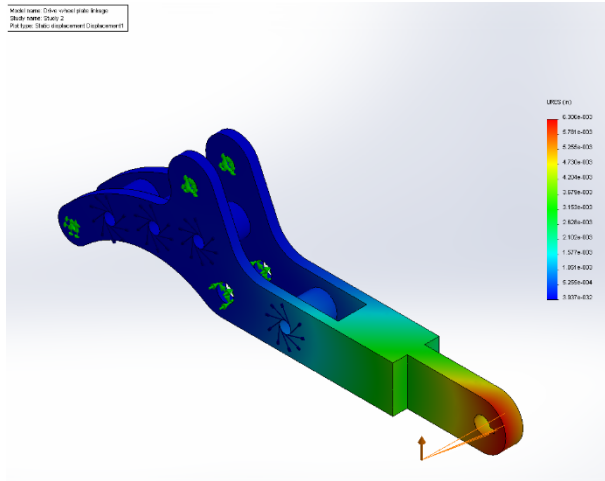


Figure 47. Drive wheel linkage displacement result

3.5 COST TO MANUFACTURE

MEBot was designed with a combination of custom and purchased components. The cost of the purchased components and material can easily be added by obtaining quotes from the manufacturers. Table 7 shows the cost of each of the purchased components and quantity of each that are needed for one wheelchair. The cost of the hardware is approximated because the hardware was purchased in bulk at a lower cost. However, purchasing in bulk resulted in having more than the necessary number of pieces of some of the hardware. The total cost of all of the purchased components is approximately \$8418.99. Unfortunately, determining the cost of the custom components is not as trivial. Many of the custom components require multiple processes from different machines. For example, the front top actuator mount requires the use of three machines to produce the final part. Since the custom components were manufactured at HERL, determining their cost to manufacture is difficult due to the fact that the components for MEBot are not the only ones being manufactured since the shop is also utilized for other projects.

Furthermore, multiple variables contribute to estimating the cost for operating the machines including machine depreciation, maintenance, utilities, and labor costs.

Table 7. Purchased component costs

Component	Cost	Quantity	Total
Lead screw assembly	\$1408.92	1	\$1408.92
Lead screw-stepper motor	\$316.00	1	\$316.00
Lead screw-encoder	\$223.00	1	\$223.00
Lead screw-stepper drive	\$325.00	1	\$325.00
Gas springs-driving wheel assembly	\$82.35	2	\$164.70
Gas springs-rear caster assembly	\$18.00	2	\$36.00
Pneumatic actuators-driving wheel assembly	\$478.80	2	\$957.60
Pneumatic actuators-rear caster assembly	\$486.15	2	\$972.30
Electric actuators	\$187.00	2	\$374.00
Omni-directional wheels	\$44.00	4	\$176.00
Linear bearing rail-easy rail	\$160.81	2	\$321.62
Linear bearing rail-telescopic rail	\$441.15	2	\$882.30
Hub motors	\$296.95	2	\$593.90
Aluminum	\$477.90	N/A	\$477.90
Steel	\$939.75	N/A	\$939.75
Hardware	≈ \$250.00	N/A	≈ \$250.00

4.0 FOCUS GROUP PROTOTYPE EVALUATION

4.1 METHODOLOGY

A focus group was performed to gather feedback about the design of MEBot that is currently in the prototype stage and to generate ideas about how to improve MEBot for future prototype iterations. The focus groups were conducted at the Human Engineering Research Laboratories where videos and demonstrations of the advanced applications of MEBot were presented. Since the prototype of MEBot wasn't completed at the time of the focus group, PerMMA II was used for the demonstrations. Participants completed a questionnaire about their background, disability, and current wheelchair. They also participated in a recorded focus group discussion about the demonstrations of the advanced applications of MEBot.

4.1.1 Participants

A total of 12 EPW users (N =12) participated in the focus group study. The participants were recruited through Institutional Review Board (IRB) approved registries developed by the Human Engineering Research Laboratories or the Department of Physical Medicine and Rehabilitation. An IRB approved flyer for the study was developed for distribution to local rehabilitation facilities, outpatient facilities, and disability organizations. The flyers provide the name of the

study, eligibility criteria, study descriptions and instruct potential participants to contact a clinical coordinator for additional information.

The inclusion criteria were wide-ranging in order to have an assorted participant population. The inclusion criteria consisted of (1) male or female 18 years of age or older, (2) independently uses a power wheelchair as primary means of mobility (defined as using the wheelchair >8 hours/day), and (3) actively using their power wheelchair outside of the home (defined as leaving the home at least three times a week). The study was not limited to a specific disease, disability, or condition and no exclusion criteria were based on race, ethnicity, gender, or HIV status.

4.1.2 Data collection

A questionnaire (Appendix E) was developed that was broken up into parts to gather information about each participants' personal demographics, current power wheelchair, training and accidents, and outdoor driving characteristics. The questionnaire also included parts relevant to the participants' likelihood of using the different MEBot applications and about their preference on the control interface including what types of switches would be used and the layout of the menu system for the control interface. The questionnaire consisted of the following parts:

1. Part A - Personal Demographics
2. Part B - Current Wheelchair Information
3. Part C - Power Wheelchair Training in Accidents
4. Part D - Outdoor Driving Characteristics
5. Part E - MEBot applications
6. Part F - MEBot Control Interface

Confidentiality of the data was maintained by keeping all research records in filing cabinets within a locked file room within the Department of Rehabilitation Science and Technology (RST). Records that contained direct subject identifiers were stored separately with a different identification code within a locked file room within RST. Electronic data was stored on a server associated with RST where access to both the electronic and paper-based files are restricted to the Principal Investigator and the associated research staff working on the project.

4.2 RESULTS

The data collected from the questionnaires were entered into a Microsoft Excel spreadsheet. The data showed that the 50% were male and 50% were female. The most common disability for using their EPW was spinal cord injury with 50 % (Table 8).

Table 8. EPW Personal Demographics

EPW Personal Demographics (N=2)			
58.3% Male		41.7% Female	
50% Married	41.7% Single	8.3% Living As If Married	
46.9 Age (avg)		16.04 Std Dev	
Ethnicity		Education	
100% Caucasian		42.7% Masters degree	
0% African-American		33.3% High School Diploma or GED	
0% Asian		16.7% Bachelors Degree	
0% American Indian		8.3% Associate Degree	
0% Native Hawaiian		0% Vocational/Technical School	
0% Two or More Races		0% Doctorate, Law, Etc.	
Disability		Employment	
50% Spinal Cord Injury		38.5% Full-Time, Outside Home	
25% Other		23.1% Part-Time, Outside Home	
16.7% Cerebral Palsy		15.4% Disabled, Unable to Work	
8.3% Muscular Dystrophy		15.4% Other	
		7.6% Part-Time, Inside Home	
		0% Full-Time, Inside Home	
		0% Retired, not because of disability	
		0% Unemployed	

The participants had an average of 16.3 years of experience using an EPW, use their current EPW for an average of 3.32 years, spend an average of 14.6 hours per day in their EPW, and drove their EPW outside of their home an average of 6.58 days per week. Most of the participants used either a mid-wheel drive EPW (50%) or front wheel drive EPW (41.7 %) compared to a rear wheel drive EPW (8.3%) (Table 9).

Table 9. Current Wheelchair Type and Use

Current Wheelchair Type and Use	
Wheelchair Usage	
16.3 Years using an EPW (avg)	
3.32 Years using current EPW (avg)	
14.6 Hours per day using EPW (avg)	
6.58 Days/week driving EPW outside of their home (avg)	
Wheelchair Type	
50% Mid-Wheel Drive	
41.7% Front Wheel Drive	
8.3% Rear Wheel Drive	

Most of the participants had less than 30 minutes (36.4%) or no training (27.3%) when they received their current power wheelchair while only 27.3% took a driving test to see if they could safely drive their EPW (Figure 48) (Figure 49). When asked about previous accidents, 34.8% of the participants had gotten stuck and 34.8% tipped their wheelchair over while 30.4% had ran into something before with their wheelchair (Figure 50).

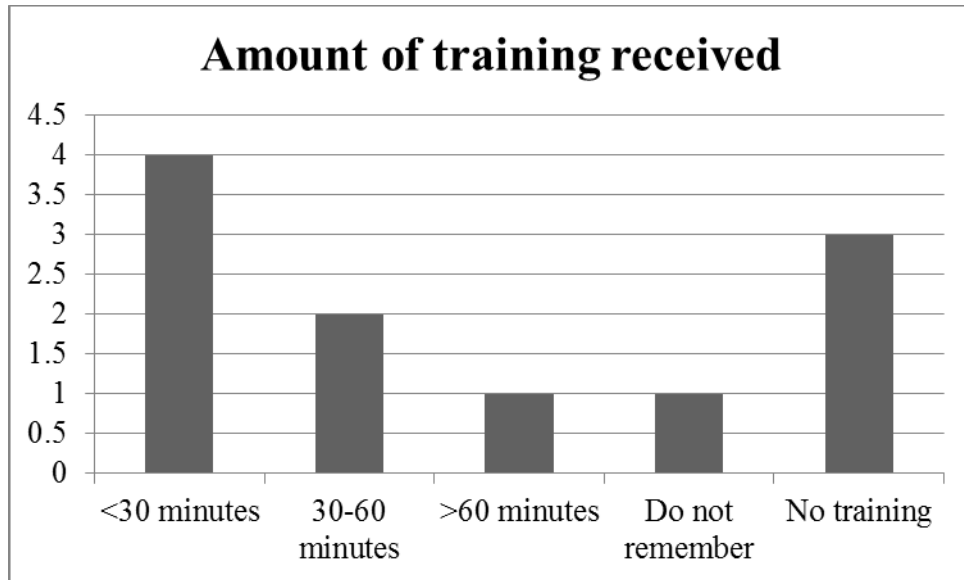


Figure 48. Amount of training received

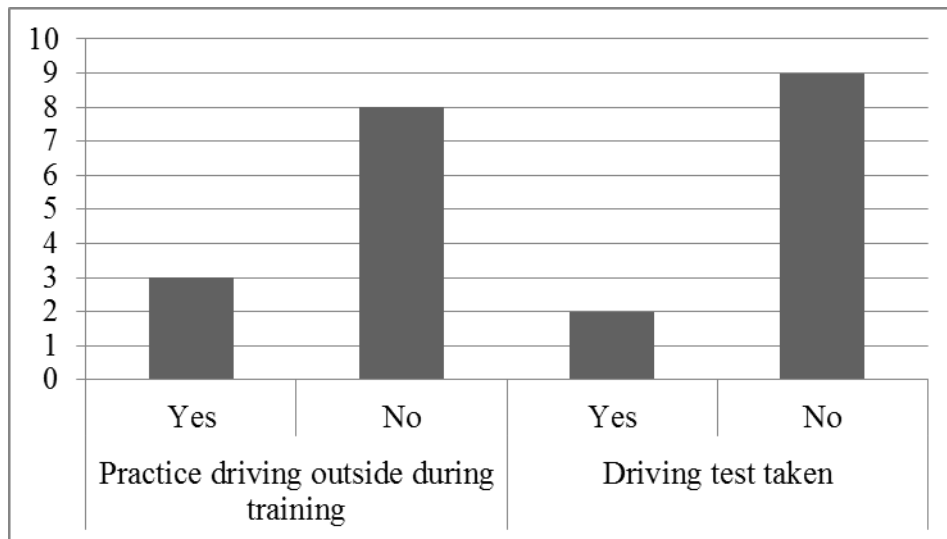


Figure 49. Practice driving outside and driving test taken

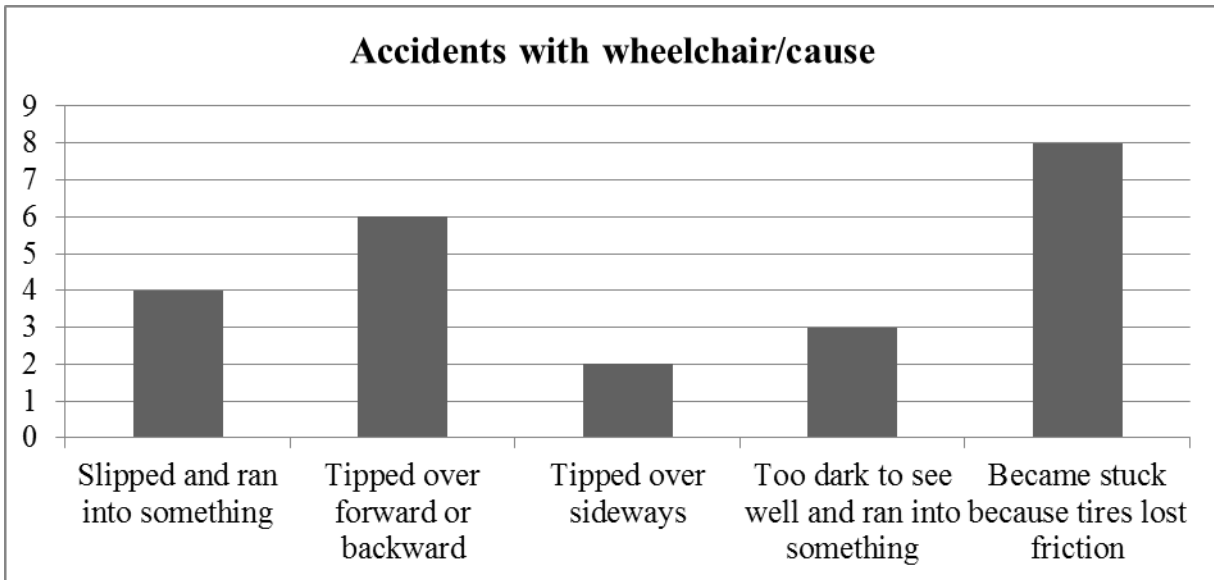


Figure 50. Accidents with wheelchair/cause

The following five graphs show how the participants used their EPW during the past week which included the places they visited (Figure 51), obstacles and terrain they encountered (Figure 52 & Figure 53), and whether they went over the obstacle or terrain independently, with assistance, or avoided it (Figure 54 & Figure 55). The most common places the participants visited were the grocery store, restaurants, work, and the Dr.'s office. Furthermore, the most encountered obstacle or terrain was traversing up and down ramps, concrete, curb cuts, and door thresholds. When the participants encountered their most encountered obstacles or terrain, a majority of them went over the obstacle or terrain by themselves. As for the least encountered obstacle or terrain of sand, dirt/mud, or gravel, the participants were split between avoiding it and going over it with help.

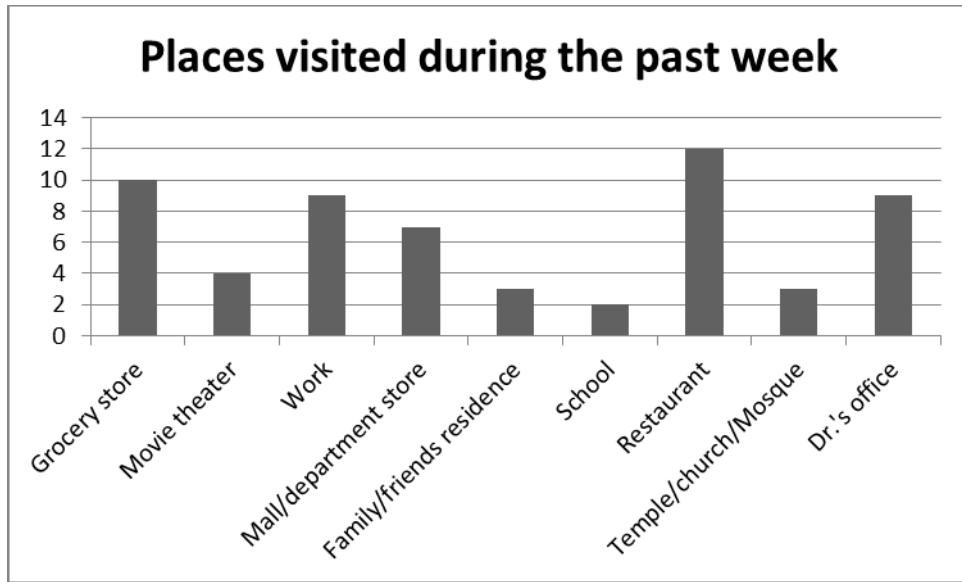


Figure 51. Places visited during the past week

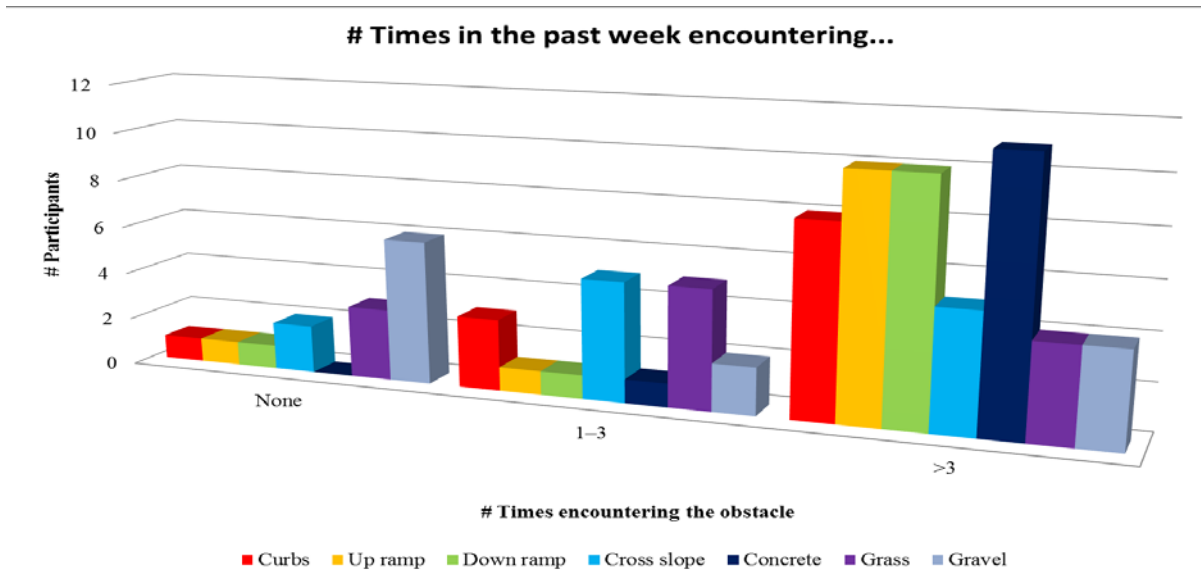


Figure 52. # Times encountering an obstacle or terrain

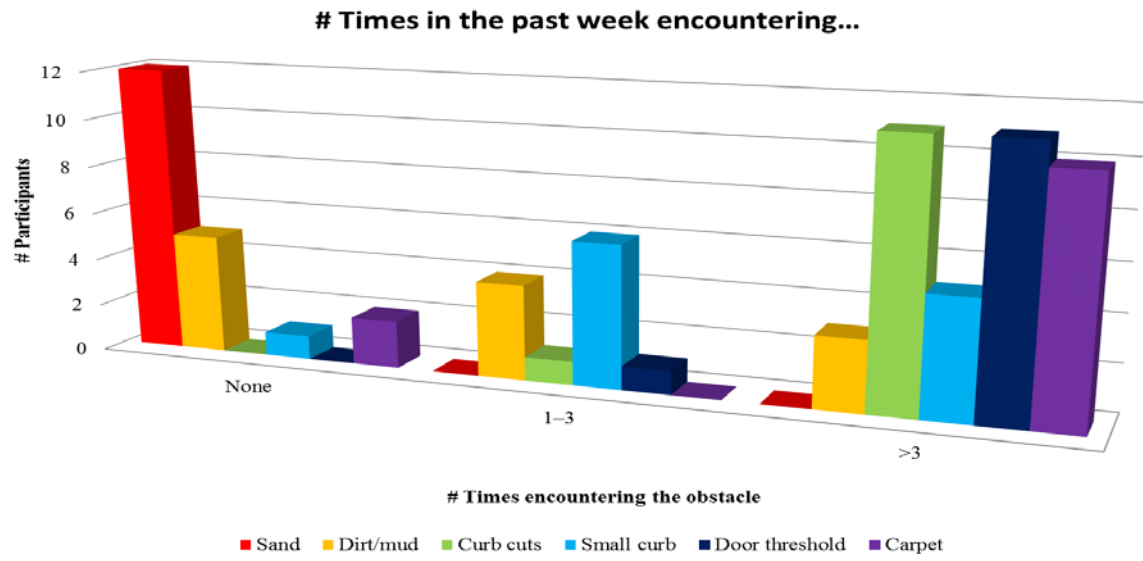


Figure 53. # Times encountering an obstacle or terrain (continued)

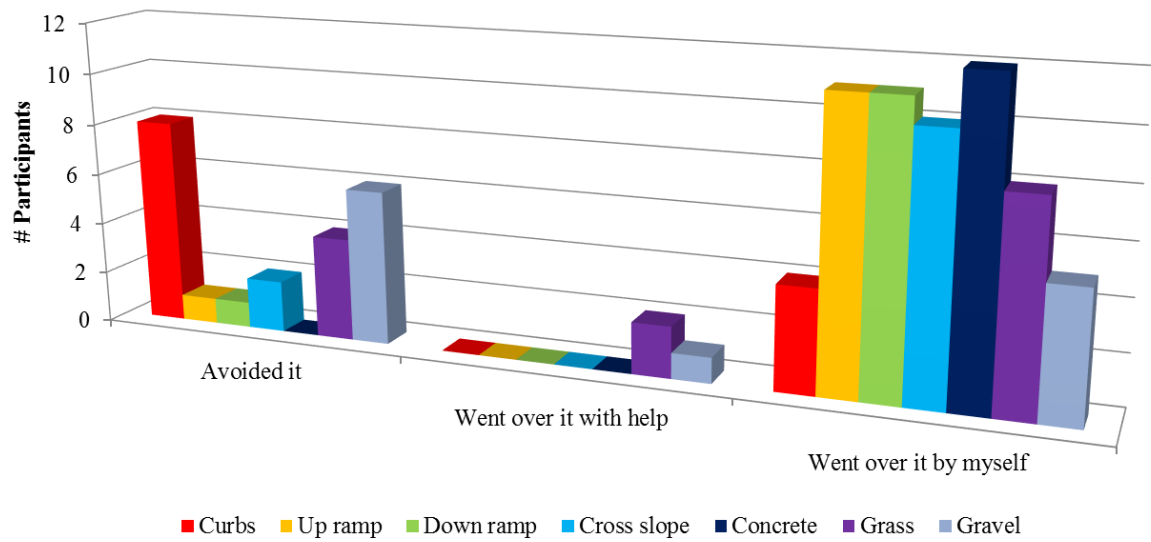


Figure 54. Action taken when obstacle or terrain was encountered

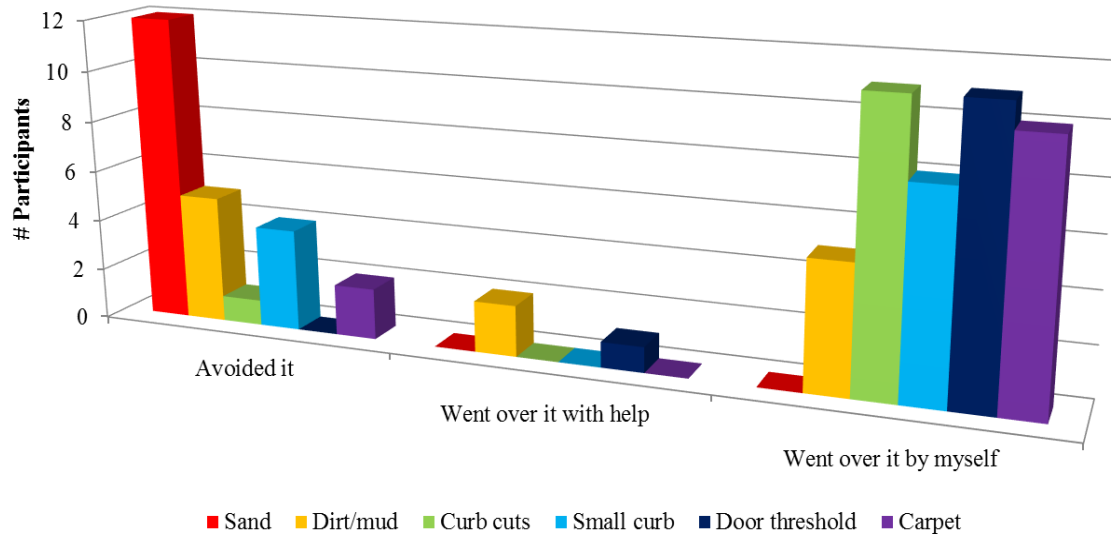


Figure 55. Action taken when obstacle or terrain was encountered (continued)

After the video and prototype demonstrations of the advanced features of MEBot, the participants rated the likeliness they would use each feature. The results showed that self-leveling, curb climbing, and traction control were the most likely to be used while the selectable driving wheel position and two wheel balance features were less likely to be used (Figure 56).

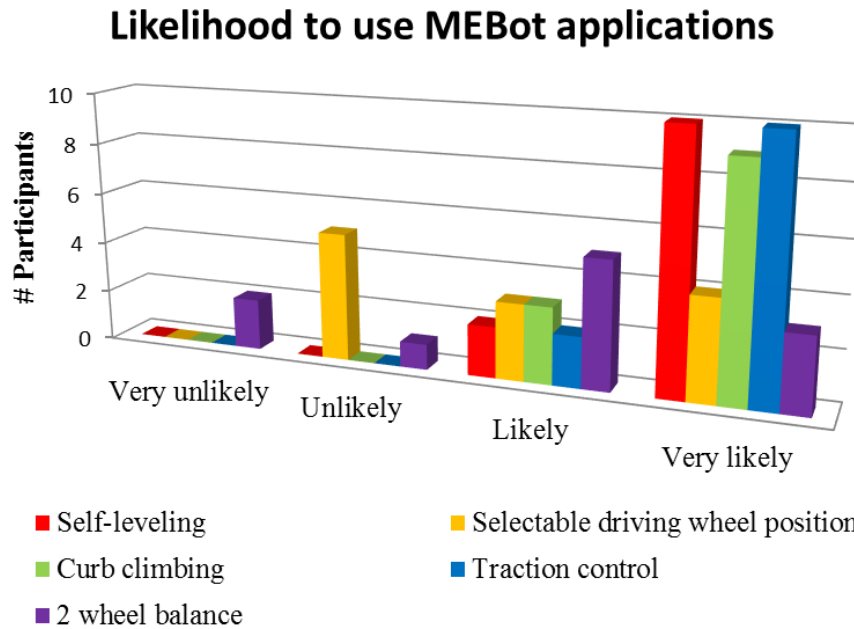


Figure 56. Likelihood to use MEBot applications

During the discussion portion of the focus group, participants were asked questions about which feature they would use the most and least. The majority of the participants stated that curb climbing would clearly be the most important feature. However, the same wasn't true for the feature that the participants would least likely use as they were split between the two wheel balance (Segway function) function and changing the driving wheel position. Moreover, it was interesting to note that self-leveling, traction control, and curb climbing were the features the participants were very likely to use when answering the questionnaire. The responses during the discussion can be viewed in Table 10.

Table 10. Responses during focus group discussion

Question Asked/Replies	Responses
<p>What would be the feature that you would most likely use the most?</p> <p>P3: "The curb climbing opens it up a lot." P4: "...so curb climbing is absolutely by far the highest and that's because it's a functionality I just can't get today in anything that is available to me." P5: "...curb climbing, if I don't get too scared." P6: "I would definitely use the curb climbing." P8: "...Curb climbing because I do that often." P10: "I would have to decide between the curb climbing and self-leveling for cross slopes." P11: "If I had the choice to choose one of the features to add to my current chair, it would be curb climbing."</p>	<p>7</p>
<p>Which feature would you least likely use?</p> <p>P1: "[Probably the] Segway function, I'm pretty tall to begin with so I don't do that much looking of the people." P5: "I would probably never change the wheel position, once it's there it's there, you get used to driving whether it's a mid-wheel or front wheel." P10: "I would say the two wheel balancing and then the changing the driving wheel position." P11: "The one that I would probably have to let go would be the changing of the driving wheel positions." P12: "...Probably the two wheel balance because your casters are not entirely out of the way and I would rather have them there as a piece of mind kind of thing."</p>	<p>5</p>

4.3 DISCUSSION

The results of the focus groups provided insight into how current EPW users use their wheelchairs and the common obstacles and terrain they encounter during a typical week and whether they are able to independently go over the obstacle or terrain. Their independence for being able to go over the obstacles they encounter the most may be due to the amount of experience they have had using their EPW. Another reason may be that the obstacle wasn't too steep in which it didn't put their current wheelchair in a position that may have caused it to tip over. All of the participants also stated that they have fallen out of their wheelchair several times. The causes included not paying attention when using a curb cut, the front casters digging into gravel, and driving down a steep hill.

The applications that the participants would most likely use were self-leveling, curb climbing and traction control. Self-leveling could benefit users without power seating functions by allowing them to shift their center of gravity forwards or backwards when going up or down ramps, respectively. Users with power seating functions are able to tilt to shift their center of gravity. Additionally, the ability for MEBot to perform lateral tilting would benefit users with and without power seating functions by allowing them to perform lateral pressure relief and traverse across slopes. For curb climbing, the participants discussed that it would open the possibility of visiting businesses with a single step at the entrance. Other applications that curb climbing could possibly be used for is going over outdoor obstacles such as logs. However, curb climbing wasn't developed for overcoming such obstacles. As for traction control, the participants would primarily use it during the winter when going outside in the snow. The participants were also asked which applications they would least likely use. Segway mode (two wheel balance) wasn't popular because of lack of necessity. "It would just be used for fun and to show off.," one participant said.

The participants brought up multiple concerns about the pneumatic system including how long the air supply will last, traveling with the high-pressure air (HPA) tanks on airplanes, and the amount of noise that is produced when the position of the wheels are moving. For MEBot, the calculated number of cycles that the pneumatic actuators can perform is approximately 45. This calculation combined all four pneumatic actuators in which each actuator would fully extend and fully retract at the same time. Therefore, the length of time that the air supply will last is dependent upon the number of changes in the uneven terrain or transitions from a flat surface to a slope surface. One suggestion was to have a gauge that the user can see that shows the amount of air left in the tanks or that the user is alerted with a notification on the joystick

display. The participants also suggested that a small air compressor be included or attached to the wheelchair in case of an emergency. The concern with taking the HPA tanks on airplane was researched and found that the regulators of the tanks would need to be removed in order for the Transportation Safety Administration (TSA) to look inside of the tank. However, many HPA tank manufacturers do not recommend that the end-user remove the regulator. They recommend that a certified airsmith or a factory trained technician remove the regulator. Another option is to mail the HPA tanks to your destination (Mills, 2004). The last concern regarding the pneumatic system was the amount of noise that is produced when MEBot is performing its calibration for self-leveling and also while self-leveling is activated. The increased noise is caused by the pneumatic sleeve style compressed springs that are currently used for the driving wheels on PerMMA II. The sleeve style springs only operate in one direction, unlike the pneumatic actuators on the front and rear casters that are two-way. The noise that the participants were hearing during the demonstration is the release of air to the atmosphere by the pneumatic sleeve style springs. These style of pneumatic actuators were replaced by the two-way pneumatic actuators in MEBot and will therefore decrease the amount of noise produced by the system. However, it was discussed that self-leveling will most likely be only used in outdoor environments where the ambient noise would be less noticeable.

The design of the control interface and its ease of navigation through the menus were also discussed and several suggestions for changes were provided. The suggestions included ways to customize applications to be “favorites” that can be easily accessed, showing all of the applications and their options on a single screen rather than having to navigate through a menu system to select an application and then another menu to select an option, and to have the ability to activate an application with one switch. Other suggestions included the ability to be able to

modify how the applications are used for expert users. For example, when selecting front wheel drive, mid-wheel drive, and rear wheel drive, the driving wheels will go to a preset location for each of the configurations. Expert users would be allowed to position the driving wheels at any location along the length of the track system.

5.0 POST DESIGN

5.1 COMPETITIVE COMPARISON

The availability of a wheelchair that is able to maneuver indoors, travel over uneven terrain outdoors, provide comfort and pressure relief with power seating functions, and enhance safety and independence is extremely limited. Many EPWs can only offer one or two of the previously stated capabilities. Therefore, some users may have one wheelchair for indoor use and one for outdoor use in order to have the best of both worlds. As such, MEBot was designed in an attempt to provide the user with all of the capabilities in a single EPW.

For MEBot to be considered both an indoor and outdoor wheelchair, its dimensions must be competitive with current standard EPWs that provide indoor maneuverability and its obstacle capabilities must be equivalent to advanced EPWs. Table 11 and Table 12 compare the dimensions and obstacle capabilities of several standard and advanced EPWs. Table 14 categorizes each of the wheelchair models as standard or advanced based on their obstacle capabilities and features. For example, the Permobil C300 is a standard EPW because it is limited to climbing small curbs (<3 inches) and doesn't offer additional features such as self-leveling or stair climbing. However, the TopChair is considered an advanced EPW because it can climb stairs and steep slopes.

When compared with the average dimensions of standard EPWs, MEBot's dimensions are 1.39 inches wider and 0.53 inches shorter. Taking into account that the ADA minimum width for a door is 32 inches, MEBot would have room to spare to fit through the door opening (Department of Justice, 2010). However, some buildings or apartment complexes may have doors ranging from 28 inches to 36 inches. MEBot's obstacle capabilities are also much greater than those of standard EPWs specifically when considering curb climbing where the maximum curb height for a standard EPW is 3 inches compared to 8 inches for MEBot (Table 12).

Table 11. Comparison of EPW dimensions

Wheelchair Model	Length	Width	Turning radius	Max user weight
Permobil C300	42.5"	24.25"	25"	300 lbs
Permobil C350	42"	25"	37"	300 lbs
Permobil M300	41"	24"	26"	300 lbs
Permobil C500	49.5"	25.5"	28"	300 lbs
Invacare TDX SP	42.9"	25.5"	22"	300 lbs
Quantum Q6 Edge	35.5"	24"	20"	300 lbs
TopChair	45.2"	27.2"	33.5"	243 lbs
Observer Maximus	38.6"	28.7"	19.3"	331 lbs
Extreme X8	45.25"	28"	52"	400 lbs
MEBot	41.7"	26.1"	20.85"	250 lbs

Table 12. EPW maximum obstacle capabilities

Wheelchair Model	Upslope	Downslope	Side Slope	Curb Height
Permobil C300	10°	10°	6°	2.4"
Permobil C350	10°	18°	12°	3"
Permobil M300	10.5°	16°	14.5°	3"
Permobil C500	12°	12°	10°	3"
Invacare TDX SP	9°	9°	N/A	3"
Quantum Q6 Edge	6°	6°	N/A	2"
TopChair	33°	33°	N/A	1.8"
Observer Maximus	45°	45°	30°	5.9"
Extreme X8	15°	15°	N/A	6"
MEBot*	17°	17°	20°	8"

*Maximum slope when using the self-leveling feature.

One of the major limitations for advanced EPWs is their decreased indoor maneuverability which is usually caused by their increased turning radius (Table 11) and larger diameter wheels. For example, the average turning radius of the three advanced EPWs is 34.9 inches or 40% greater than the turning radius of MEBot. Furthermore, the Observer Maximus and Extreme X8 are both driven with a four-wheel drive system where a motor or motors are driving each of the four wheels. These type of designs typically experience a high amount of friction when turning which may damage indoor surfaces such as carpeting.

In order for MEBot to be competitive with both standard and advanced EPWs, it must provide the all of the features available for both types. In Table 13, a breakdown of each of the features provided by both types is shown. None of the standard EPWs provide any additional features such as self-leveling, curb climbing, or stair climbing. The advanced EPWs that do offer additional features, lack either one or both of the power seat functions or seat elevator with the exception of the Extreme X8 wheelchair. Finally, MEBot is the only EPW that has traction control and the capability to perform self-leveling laterally. Lateral self-leveling not only enhances safety when traversing cross slopes, it also allows the user to benefit from being able to perform pressure relief laterally. These additional features further separate MEBot from the standard or advanced EPW.

Table 13. Comparison of EPW features

Wheelchair Model	Self-Leveling (Front/Back)	Self-Leveling (Laterally)	Power Seat Functions	Seat Elevator	Traction Control	Stair climbing
Group 1 EPW						
Group 2 EPW			X	X		
Group 3 EPW			X	X		
Group 4 EPW			X	X		
Permobil C300			X	X		
Permobil C350			X	X		
Permobil M300			X	X		
Permobil C500			X	X		
Invacare TDX SP			X	X		
Quantum Q6 Edge			X	X		
TopChair	X		X			X
Observer Maximus	X					X
Extreme X8			X	X		X
MEBot	X	X	X	X	X	

Table 14. EPW descriptions

Wheelchair Model	# Wheels	Drive Wheel Configuration	Description
Permobil C300	4	Front	Standard EPW
Permobil C350	4	Rear	Standard EPW
Permobil M300	6	Mid	Standard EPW
Permobil C500	4	Front	Standard EPW
Invacare TDX SP	6	Mid	Standard EPW
Quantum Q6 Edge	6	Mid	Standard EPW
TopChair	4	Rear	Advanced EPW with stair climbing
Observer Maximus	4	Mid	Advanced 4x4 EPW with curb and stair climbing
Extreme X8	4	Rear	Advanced 4x4 EPW for outdoors
MEBot	6	Front/Mid/Rear	Advanced EPW for outdoors and curb climbing

5.2 MANUFACTURING STATUS

Currently, a majority of the manufacturing of the custom components has been completed. The remaining custom components that need manufactured include the drive wheel linkage bolts, mount for the seating system, mounts for the high-pressure air tanks and manifold, battery box for the LiFePO₄ batteries, cover for the front of the frame, and an adapter to connect the DC motor to the lead screw mount. Figure 57 shows the components of the front caster assemblies, Figure 58 shows the components of the rear caster assemblies, and Figure 59 shows all of the components that have been manufactured or purchased. Figure 60 shows an assembly of the manufactured and purchased components of the frame, front caster assemblies, and rear caster assemblies.

In addition to the remaining custom components, multiple modifications and tasks need to be completed to finalize the manufacturing of MEBot. The remaining modifications and/or tasks include the following: (1) Drilling and tapping the top rear pneumatic and gas spring mounts to allow for the shoulder bolt to be screwed into the mount. (2) Cutting and re-welding the inner frame to line up with the mounting holes on the lead screw. (3) Welding the inner frame spacers into the inner frame. (4) Modifying the holes in the aluminum frame to line up with the inner frame. (5) Weld the pneumatic and gas spring connections to the drive will plate. (6) Weld the electronics box. (7) Decrease the gap between the rear electronics boxes and the frame. (8) Design a connection method to connect the lead screw and lead screw connection. (9) Replace soft pins with hard pins or shoulder bolts. (10) Secure and neatly route all electrical wires and air hoses.



Figure 57. Front caster components



Figure 58. Rear caster components

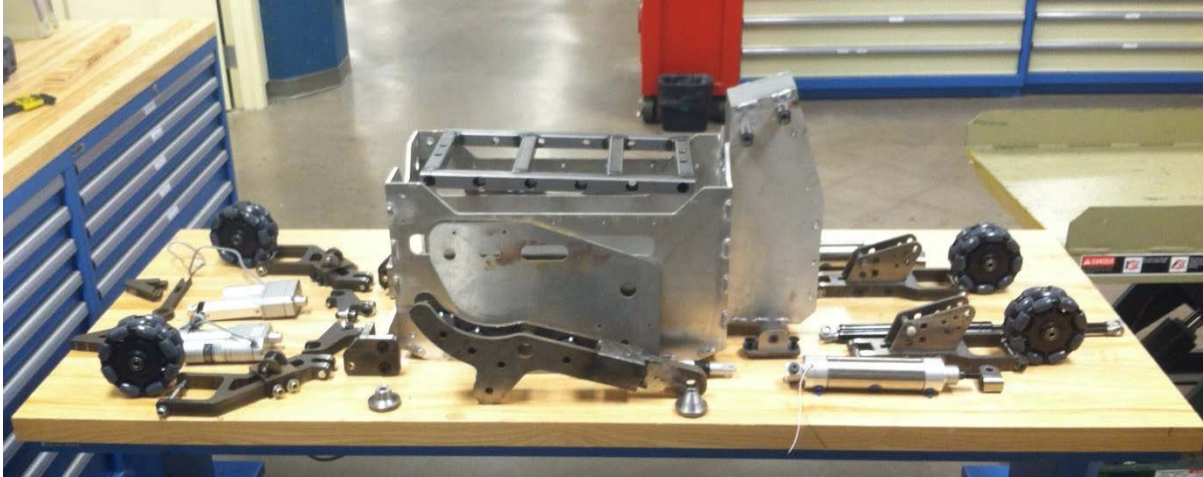


Figure 59. Compilation of manufactured and purchased components

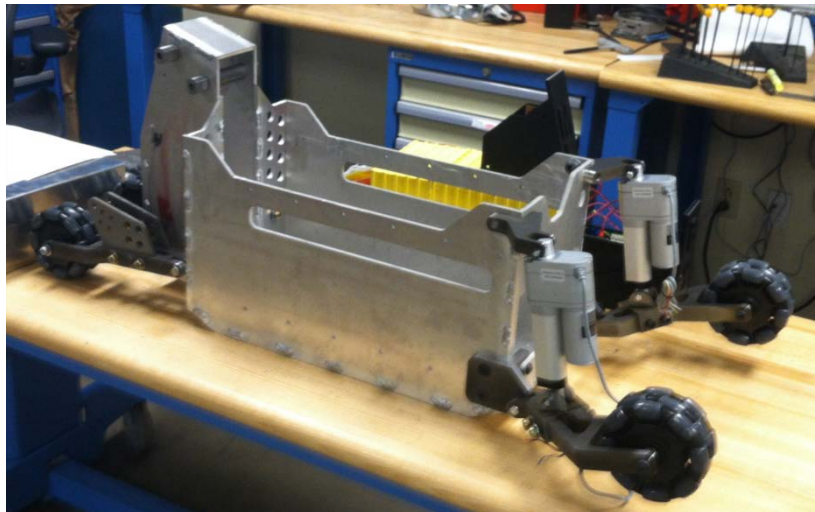


Figure 60. Assembly of the frame, front caster assemblies, and rear caster assemblies

6.0 CONCLUSION

The design and development of MEBot focused on addressing the issues of PerMMA II and improving its outdoor capabilities with advanced features to increase users' safety and independence. PerMMA II was originally developed to climb curbs and sets of three to four steps (Cooper, et al., 2012). PerMMA II was successful in climbing a six-inch curb. However, its development never progressed to be able to climb three to four steps due to the limitations of its range of motion. As such, the original design criteria for MEBot were to be able to climb curbs up to 8 inches high and be able to climb three to four steps. Since PerMMA II was successful at climbing a curb, it was theorized that slight changes to its design would allow MEBot to successfully climb small sets of steps. Unfortunately, after numerous attempts to modify the design and performing simulations for climbing steps, it was determined that slightly modifying PerMMA II's design wouldn't be feasible for climbing steps. As a result, numerous other designs (not based on PerMMA II) were developed and simulated, each not successful for climbing steps. After running out of new design ideas and taking into account the simulations, the final conclusion was that climbing steps in an EPW is too dangerous because any failure of the EPW could result in the user being seriously or fatally injured. Unfortunately, the attempts to develop a step climbing EPW were time-consuming and resulted in delaying the development of MEBot. However, the final design of MEBot (Figure 61) meets all of the design criteria outlined in section 2.3.



Figure 61. CAD rendering of MEBot

Once all of the purchased components were specified and custom designs were finalized, the manufacturing of the custom components could begin. Very early it was realized that there were problems with the details of the design (i.e. tolerances were not tight enough to prevent unwanted movement or that shoulder bolts require a counterbore in the component they are screwed into). Additionally, when two components needed to fit together, they cannot be manufactured to be the same size because one needs to be slightly larger or smaller than the other (i.e. the rear caster linkage requires 0.25 inch thick fins to fit into channels in order for them to be bolted together). Also, there were issues with the CAD models that were downloaded from the manufacturer's website. Many of the custom components were based off of the design and dimensions of the purchased components. As a result, when some of the purchased components were received, their dimensions were different from the CAD model, resulting in changes being needed in the CAD model or modifications performed on the custom components if they were already manufactured. Finally, the purchasing of the components that needed to be purchased were continually delayed which further impacted the progress of the project.

In conclusion, the improvements made to MEBot provide a positive indication that its performance will be superior when compared to PerMMA II. All of the issues that were encountered from the design of PerMMA II were addressed in the design of MEBot. The unique design of the driving wheel linkage, increased horizontal motion of the driving wheels, and faster lead screw actuator will allow MEBot to successfully climb up to an 8 inch curb in under 30 seconds. Furthermore, the increased horizontal motion of the driving wheels will allow MEBot to “crawl” out of situations when it becomes stuck in soft terrain. Finally, the improvements made to increase the vertical movement of the driving wheels and rear casters along with the inclusion of position sensors incorporated in the pneumatic actuators will allow MEBot to successfully perform self-leveling when traversing over uneven terrain and up, down, or across slopes. Fixing all of the issues from PerMMA II along with improving some of its capabilities will allow MEBot to keep its users safer while allowing them to be more independent and experience a higher quality of life.

6.1 FUTURE WORK

Future work on MEBot will consist of finishing the manufacturing of the custom components and assembling the entire wheelchair to test for clearance and interference issues. MEBot can then be disassembled and painted for protective and aesthetic purposes. After reassembly, testing of the operation of the electronics and software programs for driving, curb climbing, self-leveling, traction control, and self-balancing can be performed using a manufactured driving course with both indoor and outdoor environmental obstacles. For example, the obstacles may include curbs (2, 4, 6, and 7 inches in height), ramps (6, 10, and 15 degree slopes), and uneven terrain (gravel, speed bump, dirt, and grass).

Once MEBot operates as intended, user feedback can be collected through focus group studies, case studies, and clinical trials. For the focus group studies, the advanced features of MEBot would be demonstrated and users would provide feedback about whether or not they would use the features. Case studies would allow EPW users to test MEBot in their home and community environment. As for the clinical trials, users would compare the abilities of MEBot with other EPWs (front, mid, and rear wheel drive). Testing of MEBot would also include confirming that its design can perform up to the standards developed by the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA). The RESNA standards include numerous tests such as evaluating turning radius, static and dynamic stabilities, and impact and fatigue strengths (ANSI/RESNA, 2009) (ANSI/RESNA, 2009).

Currently, the electronics used in MEBot are very similar to those used in PerMMA II in which an EBX-Cobra Computer will be used for the controller. However, new to MEBot will be the Beaglebone Black which will be used to develop the Graphical User Interface (GUI). These two components will be connected through a Universal Asynchronous Receiver/Transmitter (UART). Future work for the electronics consists of replacing the Cobra Computer with a PIC microcontroller. The downfall of using the Cobra Computer is the amount of space it takes up and the limited output capabilities specifically the lack of USB, I2C, or SPI when compared to microcontrollers. The Beaglebone Black provides all of the previous options but is limited in the number of inputs and outputs. Therefore, more input and output lines can be added by incorporating a PIC microcontroller.

The additional advanced features that are incorporated into MEBot will require the development of a custom, user-friendly GUI. A screen will be incorporated into the joystick to provide feedback to the user. The design of the GUI would feature a home screen with secondary

menus that allow the user to use the joystick to navigate through the menus in order to select between the advanced features. The home screen would provide information including the driving mode, battery level, and icons to indicate if any of the advanced features are turned on. Furthermore, users will need to be trained on how to use the different advanced features. For example, users may not know the advantages and disadvantages between the different driving wheel configurations. They will also need to understand when to activate the curb climbing application or how using traction control changes the driving characteristics of MEBot.

The current MEBot prototype will use the Permobil Corpus 3G seating system with power seat functions including tilt, recline, and elevating leg rests (Permobil, 2011). A seat elevator isn't needed since MEBot can be elevated using the pneumatic actuators. In the event that MEBot becomes commercialized, either a collaboration with Permobil will need to occur or a new seating system will need to be designed and manufactured. Lastly, testing of different pressures of the gas springs for the driving wheels and rear casters will need to be experimented to find the perfect balance between being too stiff or too soft. For example, a user who weighs 120 pounds may require a different pressure set of gas springs compared to a user who weighs 250 pounds. Therefore, MEBot will need to be custom configured to each user based on their weight.

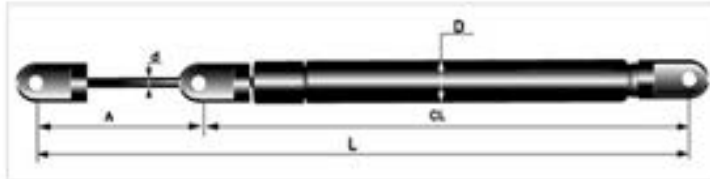
APPENDIX A

PURCHASED COMPONENTS SPECIFICATION SHEETS

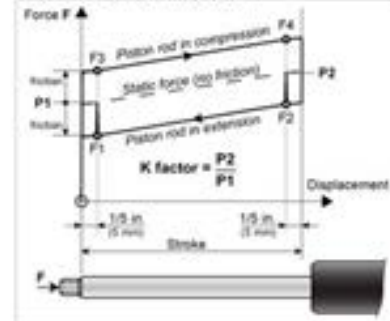
REQUEST A QUOTE

VOLUME LINE METAL EYELET

Specifications for 91G100282MM****



How Force is Calculated



Gas Springs P / N	91G100282MM****
cad_drawing	yes
Rod Dia. (d)	18mm
Cyl Dia. (D)	28mm
Stroke (A)	2.28 in.
Ext. Length (L)	9.56 in.
Compression Length (CL)	7.28 in.
Eye Dia.	8mm
Force Range (lbs.)	100 to 875 lbs.

Body Material	Carbon Steel w/Black Epoxy Paint
Rod Material	Black Nitrided Carbon Steel
P1	Static Force Extended
P2	Static Force Compressed
K Factor	$P2/P1 = 1.35$ (approx)
Damping	40mm (approx)
Survival Temperature Range	-31°F to 158°F
Operating Temperature Range	-15°F to 158°F
Net Weight	n/a

REQUEST A QUOTE

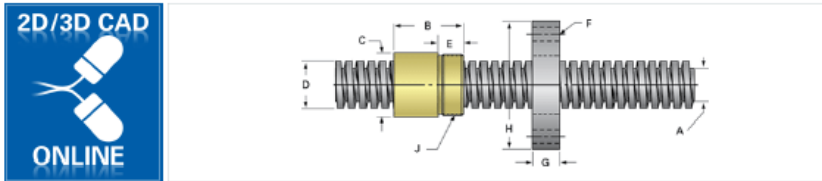
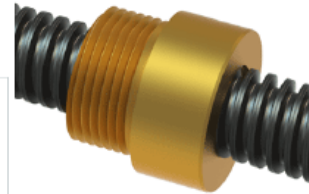
[Click here to find Mounting Hardware Dimensions →](#)

BR-B200, BR-C00, BR-D00

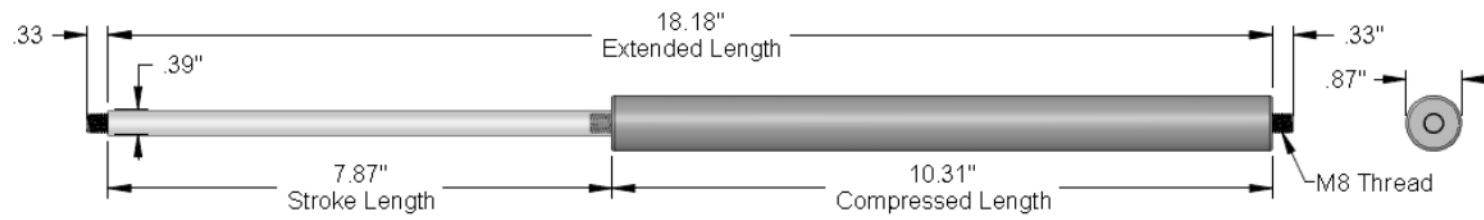


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Rolled Inch Acme Screw	
Product Info	
Screw Code	068-RA
Thread Direction	RH
Screw Material	4140 Series
Details	
Lead [in]	0.125
Starts	1
Pitch [in]	0.125
Turns Per Inch	8
Threads per Inch	8
Thread Code	068
Fom	2C
End Code for Types 1,2,3,5 [* Journals may show tracings of the thread]	10
End Code for Type 4 [* Journals may show tracings of the thread]	6
Dimensions	
A - Root Diameter Minimum [in]	0.457
D - Nominal Rod Diameter [in]	0.625
Part Numbers	
3 ft. Part Number	11068
6 ft. Part Number	12068
12 ft. Part Number	13068
20 ft. Part Number	
Performance Specifications	
Lead Accuracy +/- [in/in]	0.0003
Weight	
Screw Weight [lb./ft.]	0.84
Inch Acme Nut with Optional Flange	
Product Info	
Part Number	20068
Thread Direction	RH
Type	Bronze
Details	
Lead [in]	0.125
Starts	1
Pitch [in]	0.125
Turns Per Inch	8
Lash (Maximum Axial) [in]	0.008
Nominal Rod Diameter [in]	0.625
Threads per Inch	8
Thread Code	068
Fom	2C
Dimensions	
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C [in]	1.12
E [in]	0.50
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F BCD [in]	2.090
G [in]	0.53
H [in]	2.60
J [in]	.937-16
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Torque to Raise 1 lb. [in.-lb]	0.058
Flange Part Numbers	
Flange No-Lash Part Number	
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Nut Weight [lb]	0.22
Performance Specifications	

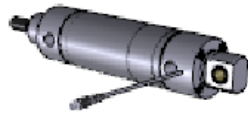


McMASTER-CARR CAD http://www.mcmaster.com © 2005 McMaster-Carr Supply Company	PART NUMBER	9416K156
	Steel Gas Spring	
<small>Unless otherwise specified, dimensions are in inches. Information in this drawing is provided for reference only.</small>		



Position Feedback Cylinder (PFC)

Your configured part number: PFC-313-XP
Additional accessories: (NO ACCESSORIES)



Features and Benefits

- **Continuous Rod Position Feedback:**
 - 0 to 10 VDC analog signal, infinite resolution
 - Consistent linearity to $\pm 1\%$ of full stroke
 - Accuracy: 1% of stroke length
- **Multiple Bore Sizes and Options:**
 - Select the size and options that fit the application
- **Closed Loop Pneumatic Control:**
 - Combining the PFC with Bimba's PCS or SPCS system creates a closed loop motion control system with accuracies within .004" per inch of stroke

Engineering Specifications

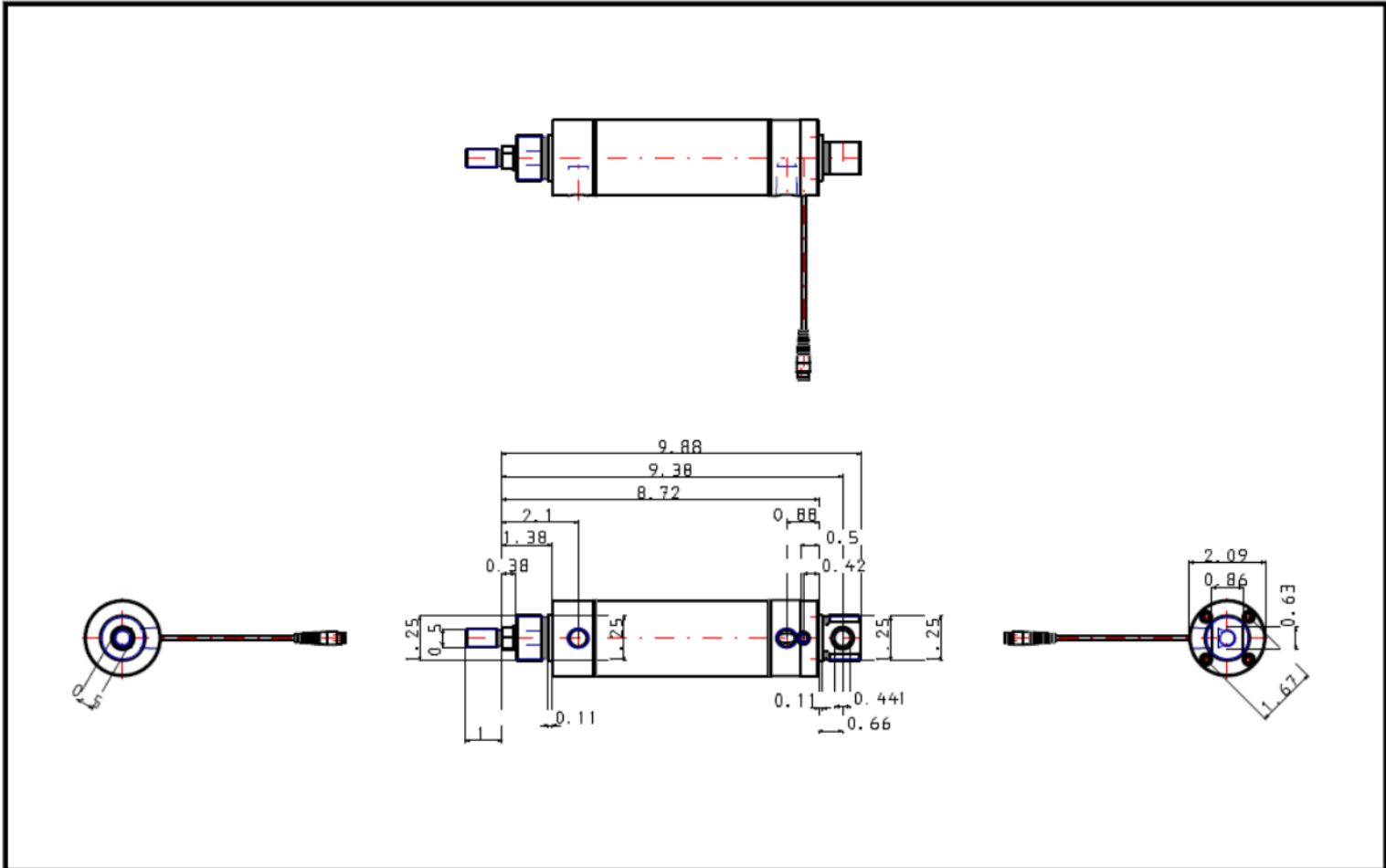
Pressure Rating: 150 PSI
Temperature Range: 0° F (-17° C) to 200° F (95° C)
Buna N Seals: -20° F (-29° C) to 200° F (95° C)
Maximum Speed: 25 in./sec.
Signal Input: 10 VDC
Rated Life of Probe: 10 million cycles
Materials:
Rod: Hard chrome plated carbon steel with blackened threads, wrench flats
Body: 304 stainless steel
End Cap: Anodized aluminum Alloy
Rod Bushings: Sintered bronze

Service and Design Capabilities

- **Custom design capabilities for your needs**
- **Common modifications include:**
 - Custom rod threads/lengths
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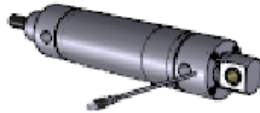
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Position Feedback Cylinder (PFC)

Your configured part number: PFC-314-XP
Additional accessories: (NO ACCESSORIES)



Features and Benefits

- **Continuous Rod Position Feedback:**
 - 0 to 10 VDC analog signal, infinite resolution
 - Consistent linearity to $\pm 1\%$ of full stroke
 - Accuracy: 1% of stroke length
- **Multiple Bore Sizes and Options:**
 - Select the size and options that fit the application
- **Closed Loop Pneumatic Control:**
 - Combining the PFC with Bimba's PCS or SPCS system creates a closed loop motion control system with accuracies within .004" per inch of stroke

Engineering Specifications

Pressure Rating: 150 PSI
Temperature Range: 0° F (-17° C) to 200° F (95° C)
Buna N Seals: -20° F (-29° C) to 200° F (95° C)
Maximum Speed: 25 in./sec.
Signal Input: 10 VDC
Rated Life of Probe: 10 million cycles

Materials:

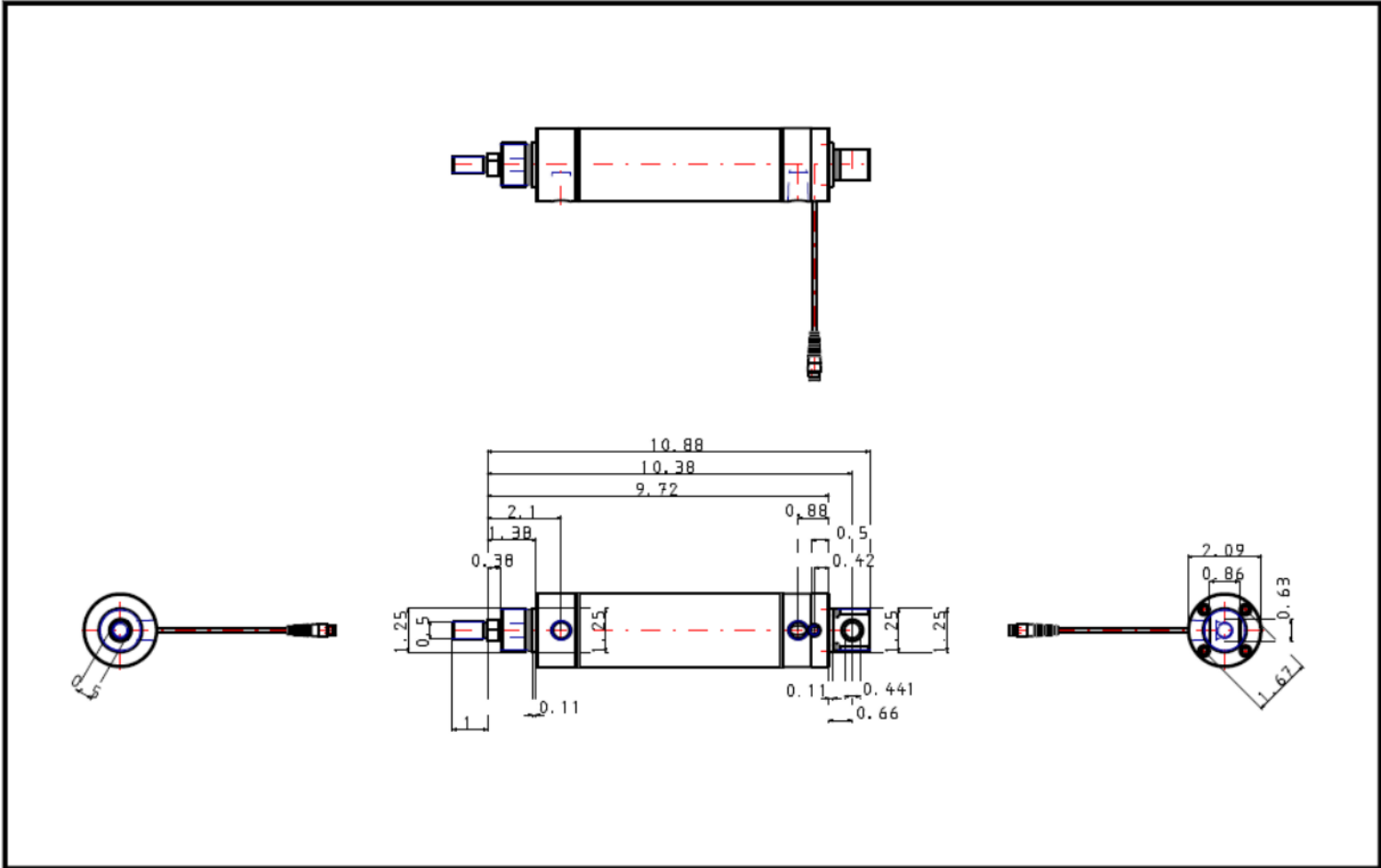
Rod: Hard chrome plated carbon steel with blackened threads, wrench flats
Body: 304 stainless steel
End Caps: Anodized aluminum Alloy
Rod Bushings: Sintered bronze

Service and Design Capabilities

- **Custom design capabilities for your needs**
- **Common modifications include:**
 - Custom rod threads/lengths
 - Customer logo/part# on cylinder body
 - Longer stroke lengths

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Monee, IL 60449-0068
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Toll Free: 800-44-BIMBA
E-mail: cs@bimba.com
www.bimba.com

Leaders in Actuation.



PFC-314-XP
(NO ACCESSORIES)

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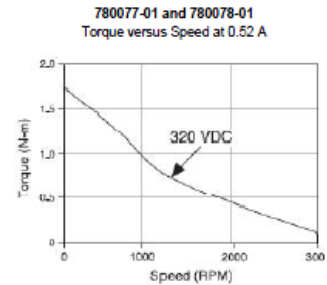
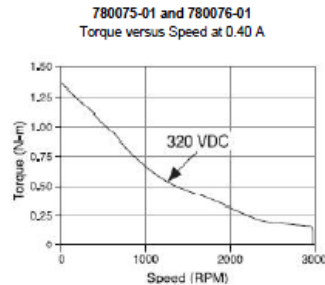
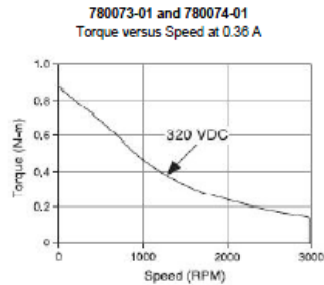
PROPRIETARY DRAWING - Reference Only

NEMA 23 Motor

Electrical	
Step angle	1.8 deg
Steps per revolution	200
Angular accuracy	±3%
Phases	2
Industry Standards	
Industrial standards	CE, cUR, UR
RoHS Compliance	Yes
Physical	
Operating temperature	-20 to 40 °C
Rated ambient temperature	40 °C
Shaft load (20,000 hours at 1,500 rpm)	
Radial	20 lb (9.1 kg) at shaft center
Axial push	6 lb (2.7 kg)
Axial pull	50 lb (22.7 kg)
Recommended heat sink size	10 x 10 x 1/4 in. aluminum plate
Recommended encoder	780251-01

NI Part Number	Manufacturer Part Number	Dual Shaft	Drive	Amps/Phase	Holding Torque oz-in. (N . m)	Rotor Inertia oz-in.-s ² (kg-m ² x10 ⁻³)	Phase Inductance mH	Phase Resistance Ω ±10%	Detent Torque oz-in. (N . m)	Thermal Resistance °C/watt	Max Speed rpm		
780073-01	T21NRLC-LNN-NS-00	no	P70360	0.40	180 (1.27)	0.0034 (0.0248)	209	42.9	2.97 (0.021)	4.64	3000		
780074-01	T21NRLC-LDN-NS-00	yes			0.46	280 (1.98)	0.0056 (0.0408)	209	41.4	5.95 (0.042)		3.69	
780075-01	T22NRLC-LNN-NS-00	no				0.67	380 (2.68)	0.0084 (0.0612)	136	23.5		6.94 (0.049)	3.04
780076-01	T22NRLC-LDN-NS-00	yes		2.7			180 (1.27)	0.0034 (0.0248)	4.6	0.85		2.97 (0.021)	4.64
780077-01	T23NRLC-LNN-NS-00	no			2.5		280 (1.98)	0.0056 (0.0408)	7.1	1.23		5.95 (0.042)	3.69
780078-01	T23NRLC-LDN-NS-00	yes				3.0	380 (2.68)	0.0084 (0.0612)	6.2	1.00		6.94 (0.049)	3.04
780079-01	T21NRLH-LNN-NS-00	no	P70530	2.7			180 (1.27)	0.0034 (0.0248)	4.6	0.85		2.97 (0.021)	3000
780080-01	T21NRLH-LDN-NS-00	yes			2.5		280 (1.98)	0.0056 (0.0408)	7.1	1.23		5.95 (0.042)	
780081-01	T22NRLG-LNN-NS-00	no				3.0	380 (2.68)	0.0084 (0.0612)	6.2	1.00		6.94 (0.049)	
780082-01	T22NRLG-LDN-NS-00	yes		2.7			180 (1.27)	0.0034 (0.0248)	4.6	0.85		2.97 (0.021)	
780083-01	T23NRLH-LNN-NS-00	no			2.5		280 (1.98)	0.0056 (0.0408)	7.1	1.23		5.95 (0.042)	
780084-01	T23NRLH-LDN-NS-00	yes				3.0	380 (2.68)	0.0084 (0.0612)	6.2	1.00		6.94 (0.049)	

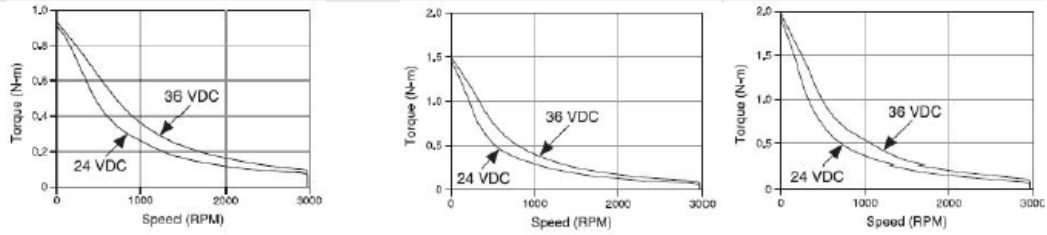
Torque versus Speed



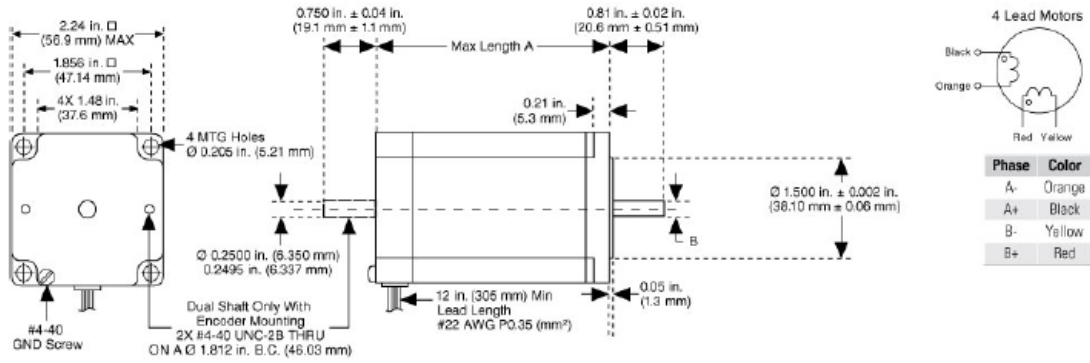
780079-01 and 780080-01
Torque versus Speed at 2.7 A

780081-01 and 780082-01
Torque versus Speed at 2.5 A

780083-01 and 780084-01
Torque versus Speed at 3.0 A



Dimensions and Wiring



NI Part Number	Manufacturer Part Number	Dual Shaft	Max Length A in. (mm)	B Diameter in. (mm)	Net Weight lb (kg)
780073-01	T21NRLC-LNN-NS-00	no	2.21 (56.1)	0.2500 (6.350)	1.6 (0.7)
780074-01	T21NRLC-LDN-NS-00	yes	3.06 (77.7)	0.2495 (6.337)	2.3 (1.0)
780075-01	T22NRLC-LNN-NS-00	no	4.06 (103.1)	0.2500 (6.350)	3.2 (1.5)
780076-01	T22NRLC-LDN-NS-00	yes	2.21 (56.1)	0.2495 (6.337)	1.6 (0.7)
780077-01	T23NRLC-LNN-NS-00	no	3.06 (77.7)	0.313 (7.940)	2.3 (1.0)
780078-01	T23NRLC-LDN-NS-00	yes	4.06 (103.1)	0.2500 (6.350)	3.2 (1.5)
780079-01	T21NRLH-LNN-NS-00	no	2.21 (56.1)	0.2500 (6.350)	1.6 (0.7)
780080-01	T21NRLH-LDN-NS-00	yes	3.06 (77.7)	0.2495 (6.337)	2.3 (1.0)
780081-01	T22NRLG-LNN-NS-00	no	4.06 (103.1)	0.2500 (6.350)	3.2 (1.5)
780082-01	T22NRLG-LDN-NS-00	yes	2.21 (56.1)	0.2495 (6.337)	1.6 (0.7)
780083-01	T23NRLH-LNN-NS-00	no	3.06 (77.7)	0.313 (7.940)	2.3 (1.0)
780084-01	T23NRLH-LDN-NS-00	yes	4.06 (103.1)	0.2500 (6.350)	3.2 (1.5)



P/N: MMP LA3-24V-40-A-50-P

TECHNICAL FEATURES:

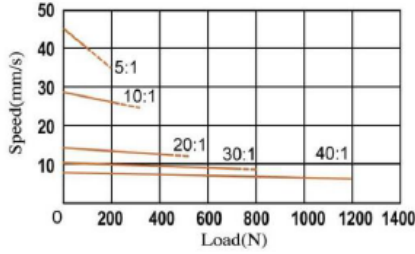
- † LOW NOISE DESIGN
- † ENHANCED CORROSION RESISTANCE
- † ALUMINUM OUTER TUBE
- † ZINC ALLOY HOUSING
- † NON-ROTATING ALUMINUM INNER TUBE
- † POWDER METAL GEARS
- † LUBRICATED FOR LIFE



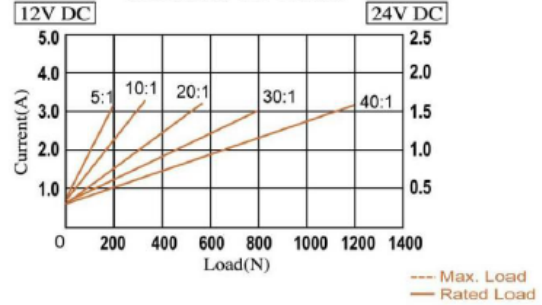
Gear Ratio	40 : 1
Input Voltage	24 VDC
Load Capacity (Force)	270 Lbs. (1200N)
Static Load	517 Lbs. (2300N)
Stroke Length	2.0" (50mm)
Speed @Full Load	0.24"/sec
Clevis Ends	Ø6.4mm dia. Mounting Holes on each end
Screw Type	ACME Screw
Duty Cycle	Max Recommended Duty = 50%
Operating Temp Range	-26°C ~ 65°C (-15°F ~ 150°F)
Limit Switches	Built-in, for both ends of travel (factory preset)
Potentiometer	10K 10 Turns
IP Grade	IP65



Speed vs Load



Current vs Load



Stroke	50	100	150	200	250	300
A	158	209	260	311	362	413
B	208	309	410	511	612	713

Standard (mm)

A: Retracted Length
B: Extended Length
Stroke = B - A

Wiring Details: [with or without potentiometer]

- + voltage to black wire = Extend
- + voltage to red wire = Retract

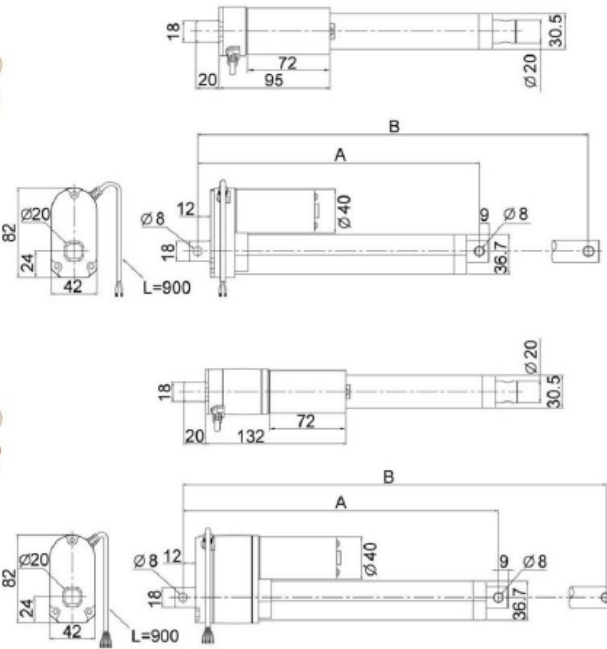
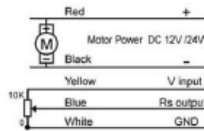
Stroke	50	100	150	200	250	300
A	195	246	297	348	399	450
B	245	346	447	548	649	750

Potentiometer (mm)

A: Retracted Length
B: Extended Length
Stroke = B - A

Stroke (mm)	Resistance (Ω)
50	0.3-9.3K
100	0.3-9.7K
150	0.3-8.6K
200	0.3-9.6K
250	0.3-9.3K
300	0.3-9.3K

Value of POT
Remark tolerance: ±0.3K



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RW630 - Triple Body



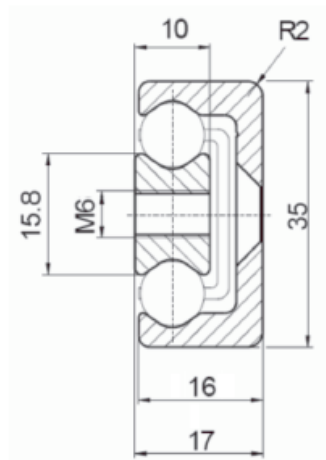
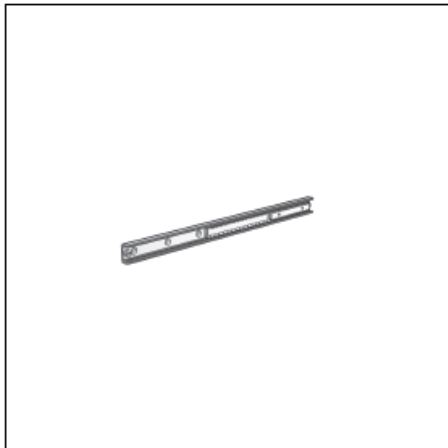
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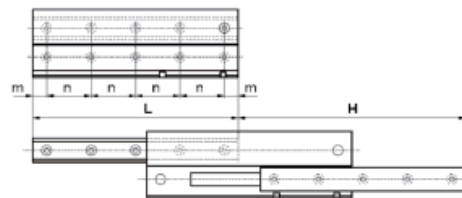
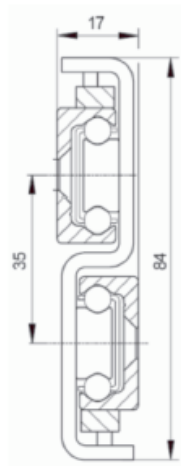
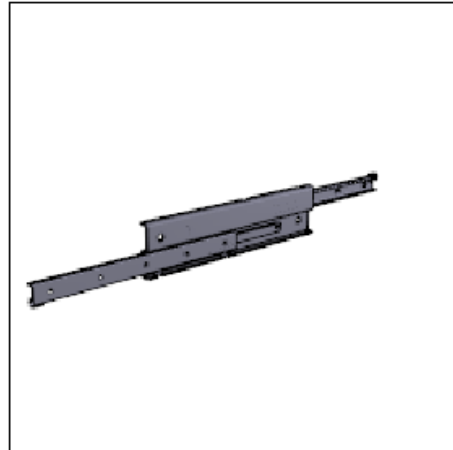
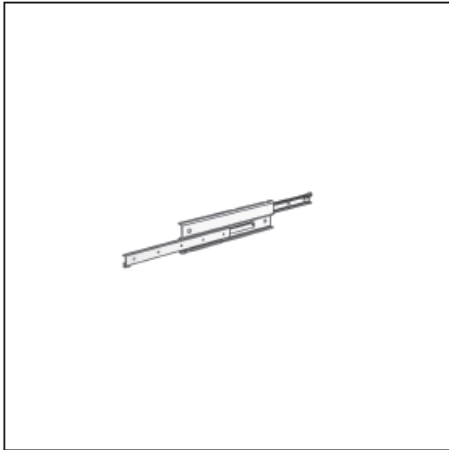
Product Code: RW630

Description

Diameter: 125mm/4.92"
Width: 64mm/2.50"
Bore: 10.0mm/.394" with bearing
Load Capacity: 124.74kg/275 lbs.
Weight = .454kg/16oz



GUI (Family)	SN
DIM (Section)	35
INFO (Catalogue)	Catalogue
TIPCUR (Slider Type)	SINGLE
S (Slider Length / mm)	130
S1 (Slider Length 1 / mm)	0
S2 (Slider Length 2 / mm)	0
H (Stroke / mm)	350
L (Rail length / mm)	530
M (/ mm)	25
N (/ mm)	80
K (/ mm)	50



GUI (Rail)	DSS
DIM (Dimension)	28
INFO (Catalogue)	Catalogue
H (Stroke / mm)	380
L (Length / mm)	370
M (/ mm)	25
N (/ mm)	80
NN (No. holes)	5

APPENDIX B

FINITE ELEMENT ANALYSIS RESULTS

The following images provide the fixture locations, force locations, and results of the FEA of the remaining components not described in section 3.4. Short descriptions of the location of the forces and fixtures are provided.

B.1 FRONT CASTER ASSEMBLY

Front Top Actuator Mount: The fixtures were chosen to be placed where the actuator mount is in contact with the mainframe and the locations where the bolts hold the actuator mount to the mainframe. The horizontal force was applied to locations where the pins go through the actuator mount that hold the electric actuator (Figure 62).

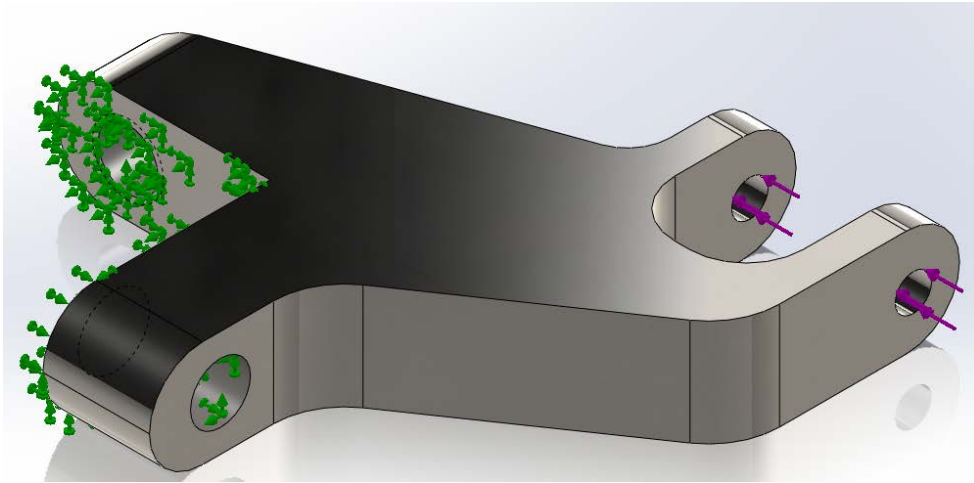


Figure 62. Front top actuator mount fixture and force locations - horizontal force

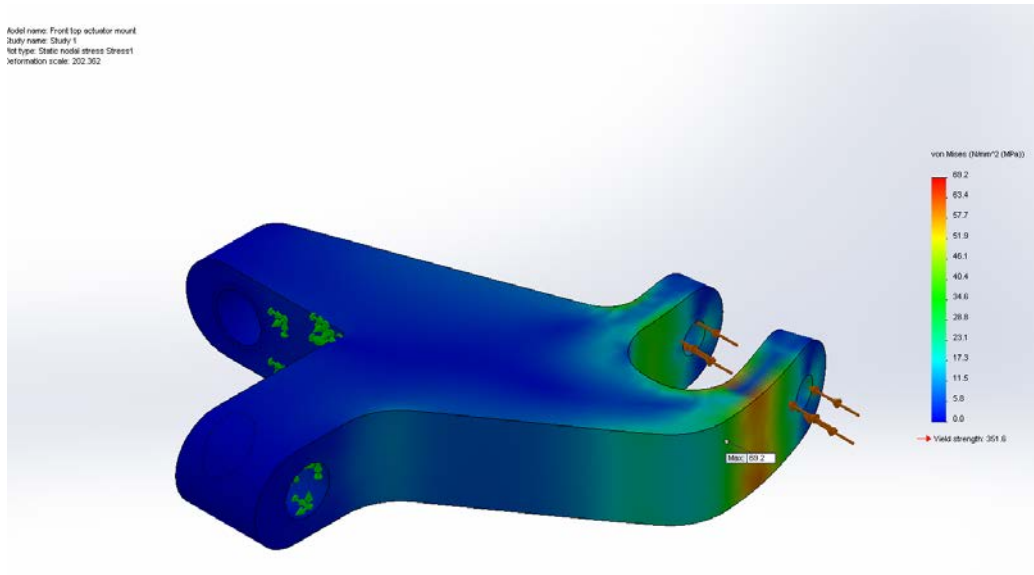


Figure 63. Front top actuator mount FEA result - horizontal force

Front Caster Linkage: The fixtures were placed where the linkage attaches to the front caster attachment bracket via a pin. The vertical force (Figure 64) and horizontal force (Figure 66) were applied to the location where the axle slides through the linkage to mount the omnidirectional wheel.

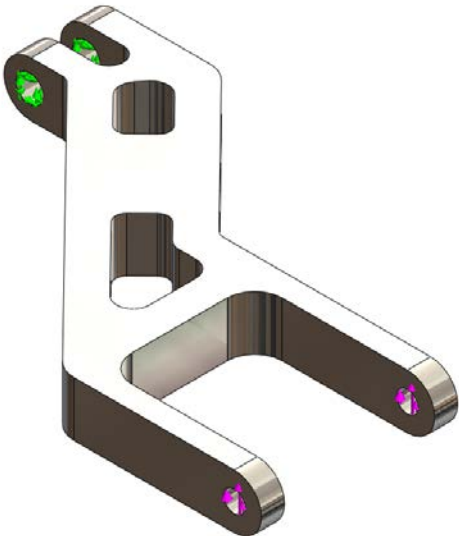


Figure 64. Front caster linkage fixture and force locations - vertical force

Model name: Front caster linkage
Study name: Study 1
Plot from: Static model stress (stress1)
Deformation scale: 40.2715

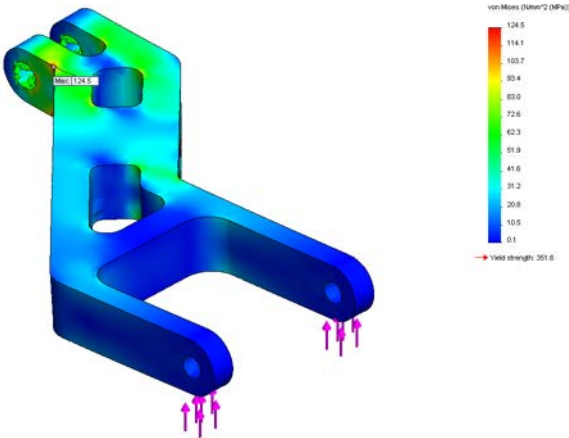


Figure 65. Front caster linkage FEA result - vertical force

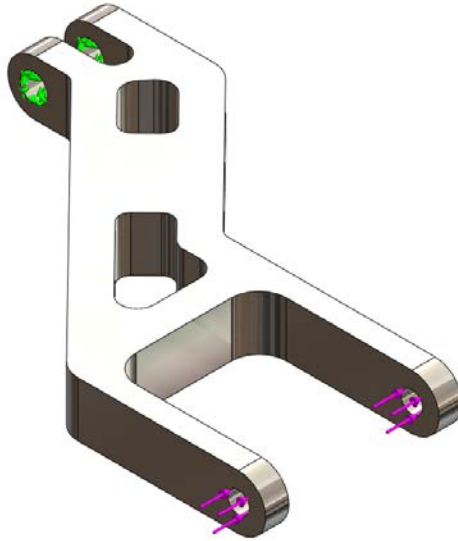


Figure 66. Front caster linkage fixture and force locations - horizontal force

Model name: Front caster linkage
 Study name: Study 1
 Plot type: Static model stress (Stress1)
 Deformation scale: 73.0004

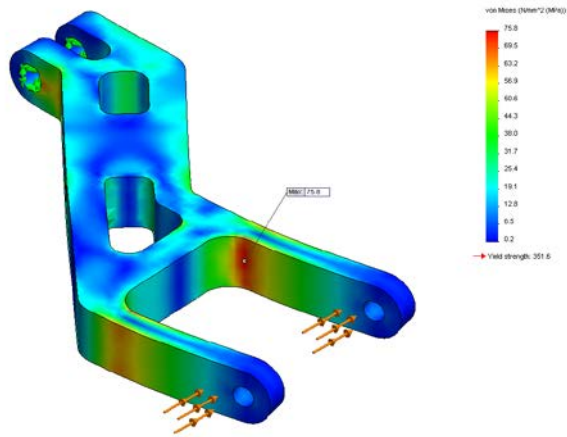


Figure 67. Front caster linkage FEA result - horizontal force

Front Caster Attachment Bracket: The fixtures were selected to be the areas where the bracket comes into contact with the main frame and where the bolts are used to hold the bracket in place. The vertical force (Figure 68) and horizontal force (Figure 70) was applied to where the pin slides through the bracket to hold the front caster linkage in place.

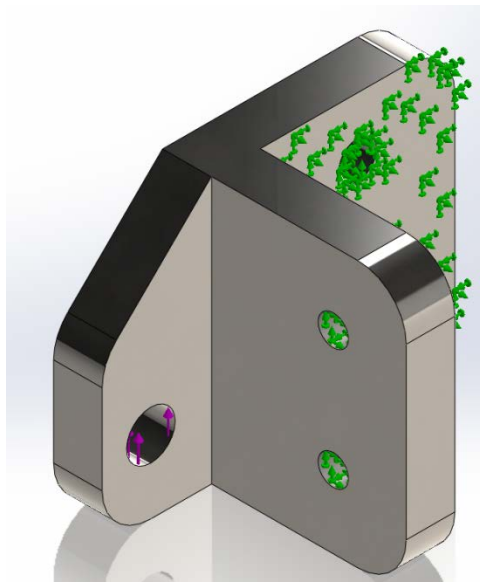


Figure 68. Front caster attachment bracket fixture and load locations - vertical force

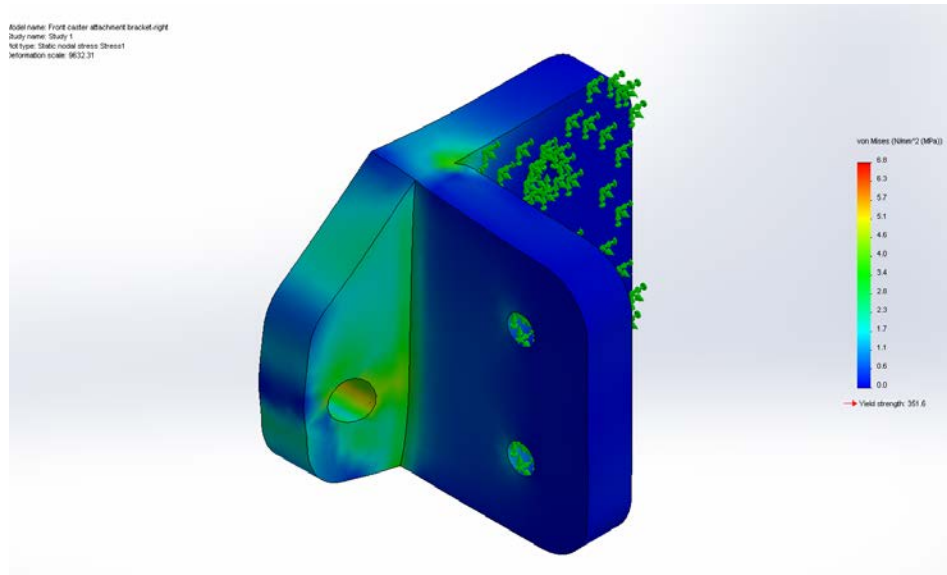


Figure 69. Front caster attachment bracket FEA results - vertical force

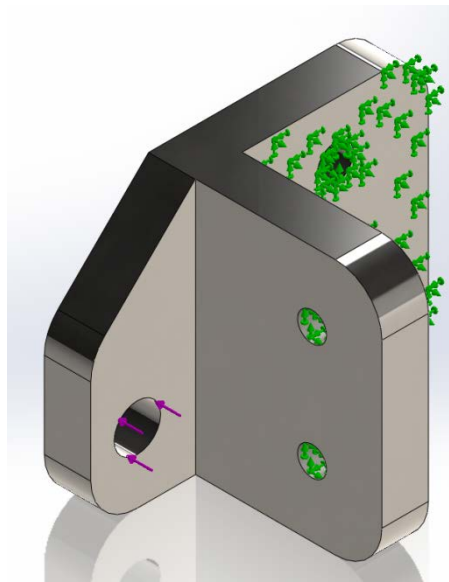


Figure 70. Front caster attachment bracket fixture and load locations - horizontal force

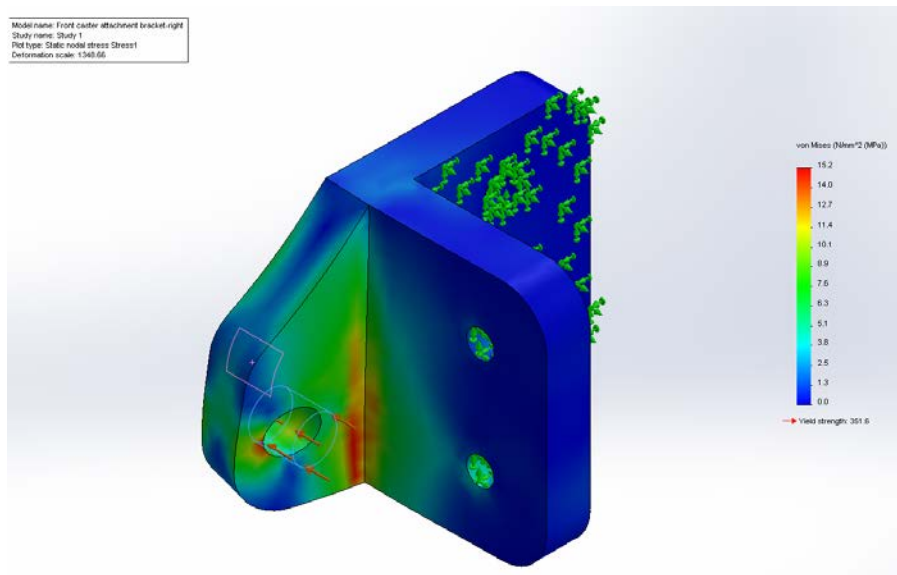


Figure 71. Front caster attachment bracket FEA results - horizontal force

B.2 REAR CASTER ASSEMBLY

Rear Caster Linkage: Two types of fixtures were used to simulate the rear caster linkage. A fixed geometry was applied to the holes where pins are used to attach the gas spring and pneumatic actuator to the linkage. The fixed geometry prevents movement in all axes. A fixed

hinge was applied to the location where the linkage attaches to the rear caster attachment bracket via a pin. The fixed hinge allows for rotation but not translation along the axis. The horizontal force was applied to the holes where the axle for the omni-directional wheels is placed through.

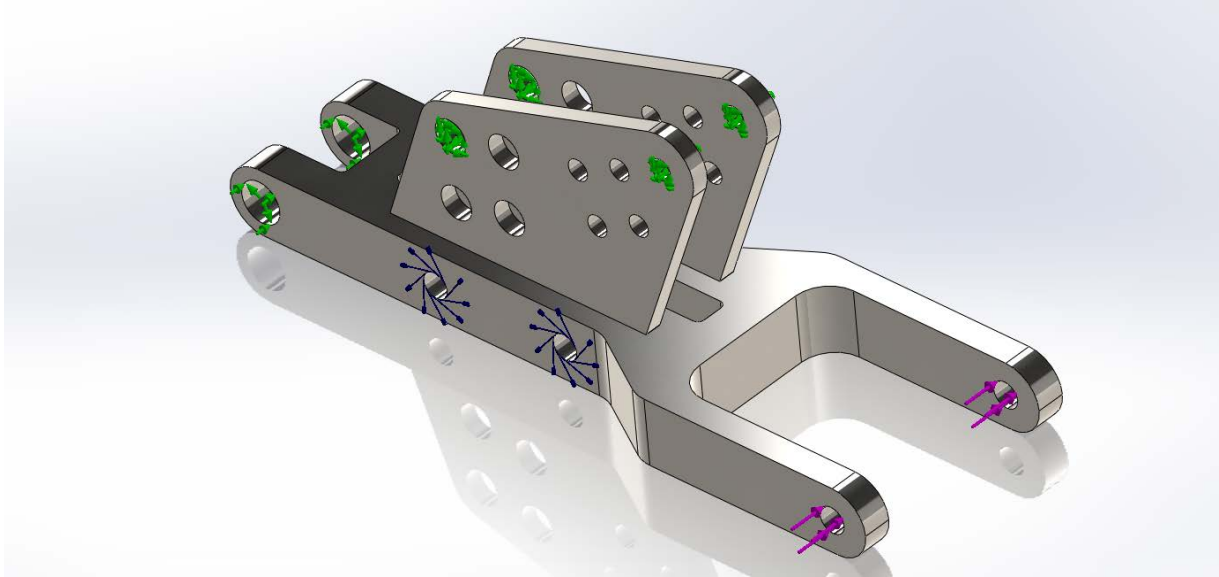


Figure 72. Rear caster linkage fixture and load locations - horizontal force

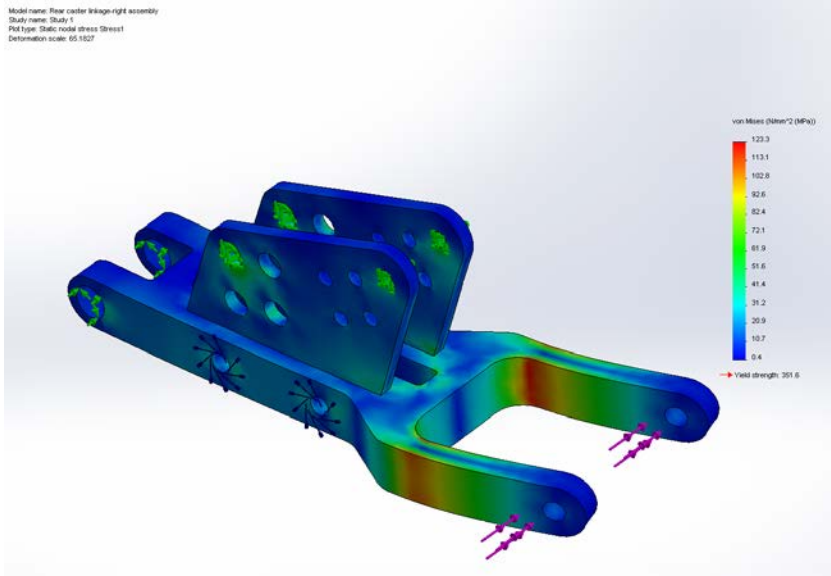


Figure 73. Rear caster linkage FEA results - horizontal force

Rear Caster Attachment Bracket: The fixtures were placed on the countersinks of where the bolts are used to attach the bracket to the main frame. Also, the face that is in contact with the main

frame was also fixed. A vertical force was applied to the hole where the pin fits through to attach the rear caster linkage (Figure 74) while a remote load (Figure 76) was horizontally applied to the same hole. The remote load was intended to simulate the torque being placed on the attachment bracket by the rear caster linkage when the wheelchair would be turning.

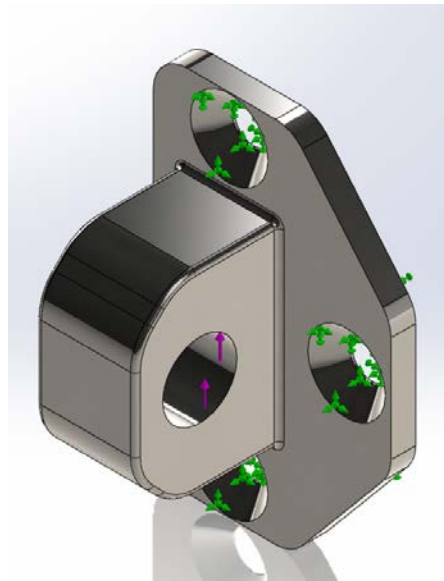


Figure 74. Rear caster attachment bracket fixture and load locations - vertical force

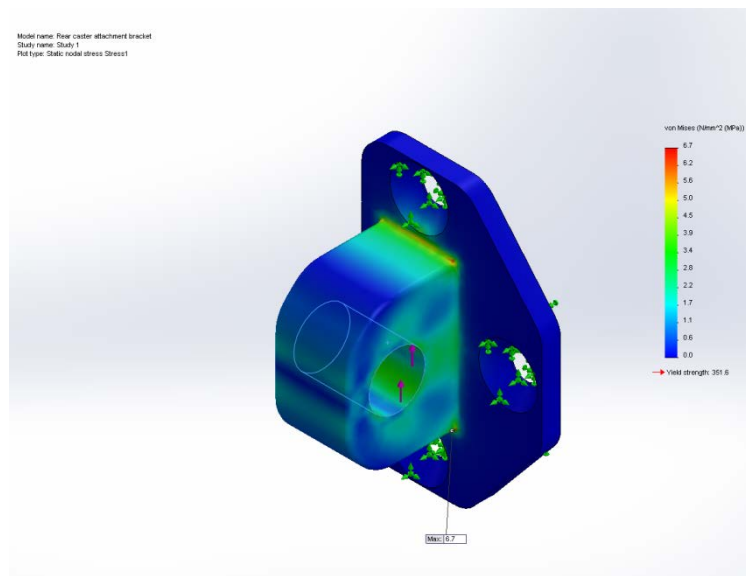


Figure 75. Rear caster attachment bracket FEA results - vertical force

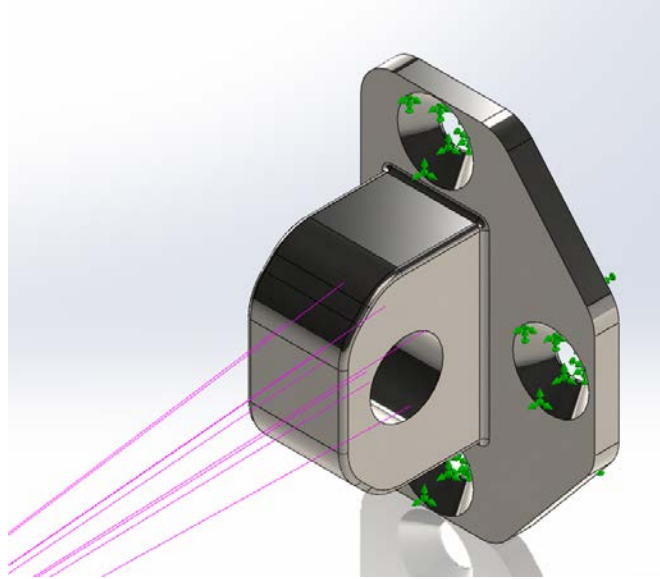


Figure 76. Rear caster attachment bracket fixture and load locations - horizontal force

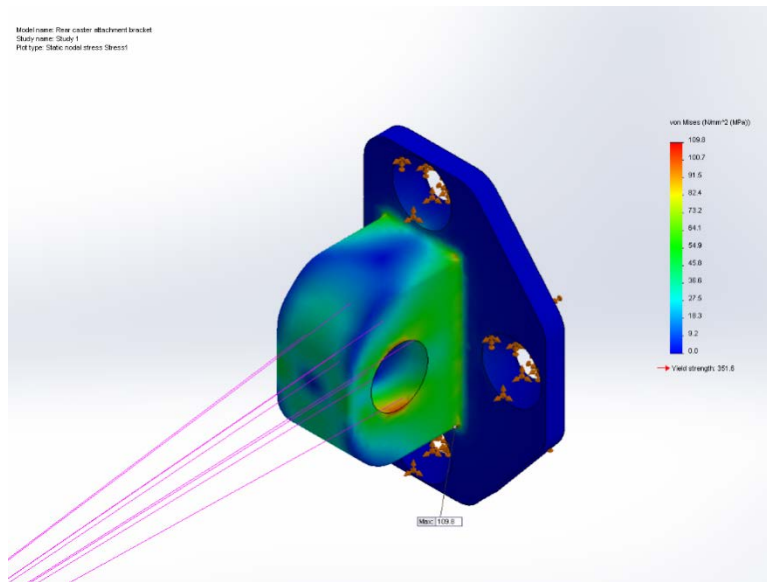


Figure 77. Rear caster attachment bracket FEA results - horizontal force

B.3 FRAME ASSEMBLY

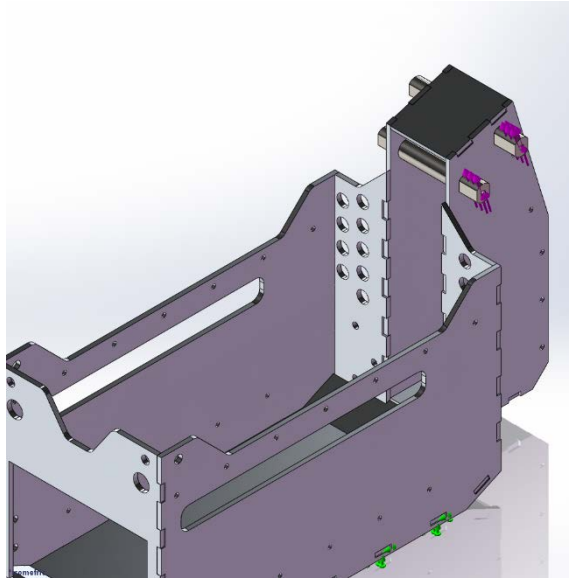


Figure 78. Main frame fixture and load locations - pneumatic actuator and gas spring

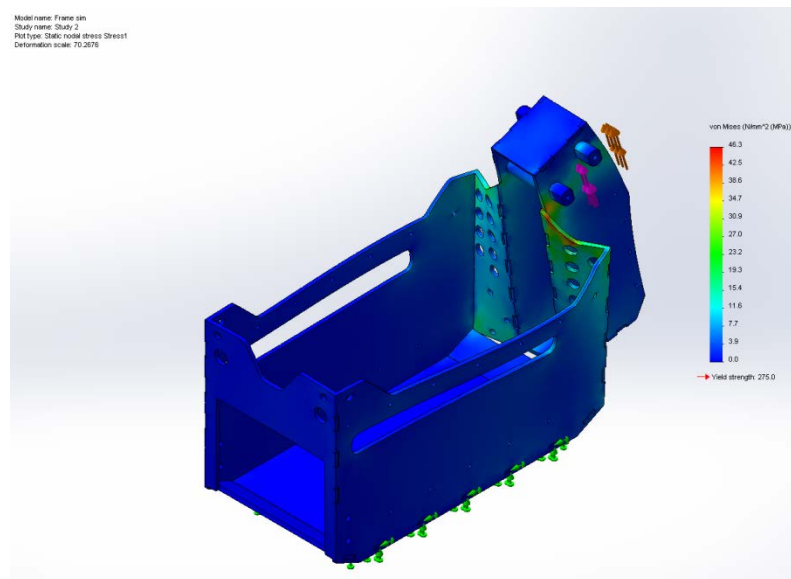
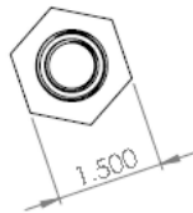
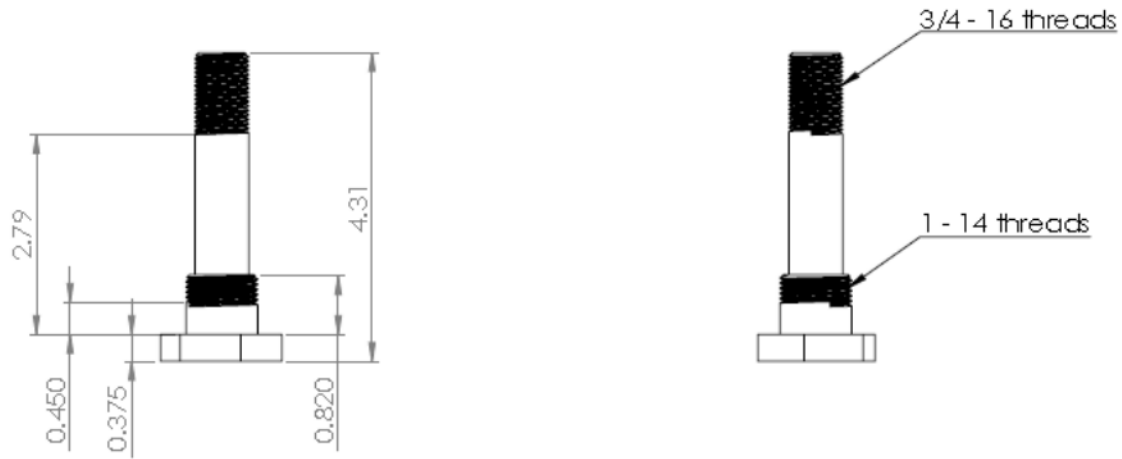


Figure 79. Main frame FEA results - pneumatic actuator and gas spring

APPENDIX C

MECHANICAL DRAWINGS

MEBot V2.0



Part Name/Number:		
Main bolt		
Description:		
Material:	Weight:	Vendor:
Al611020	0.76 lbs	

5

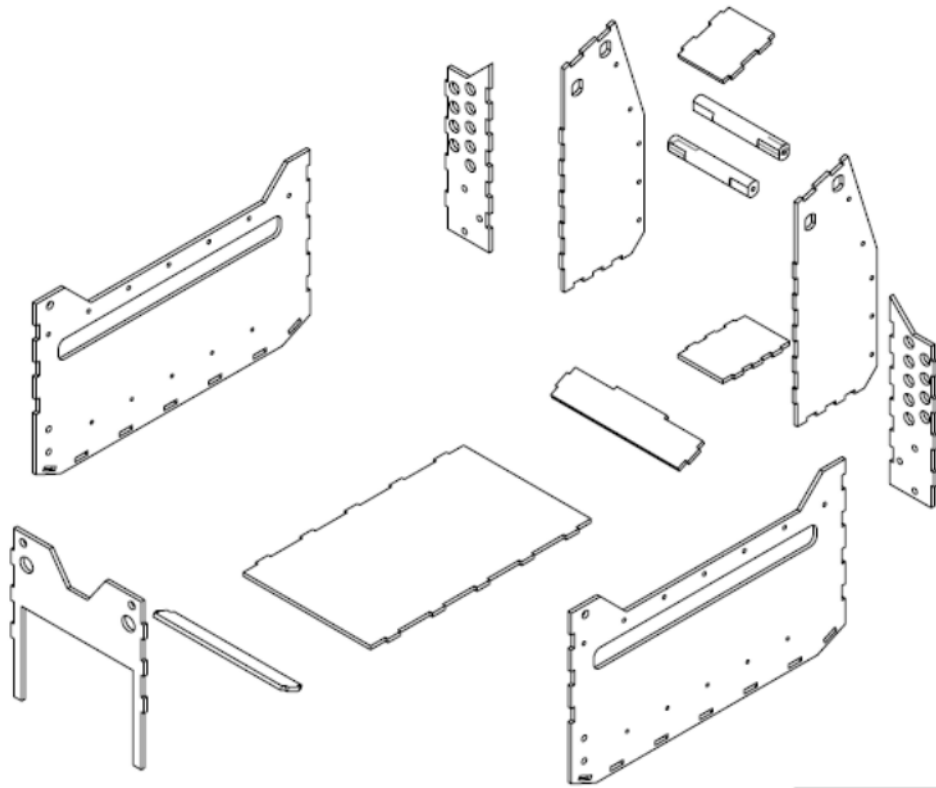
4

3

2

1

MEBot V2.0



Part Name/Number:		
weldframe		
Description:		
Material:	Weight:	Vendor:
	lbs	

5

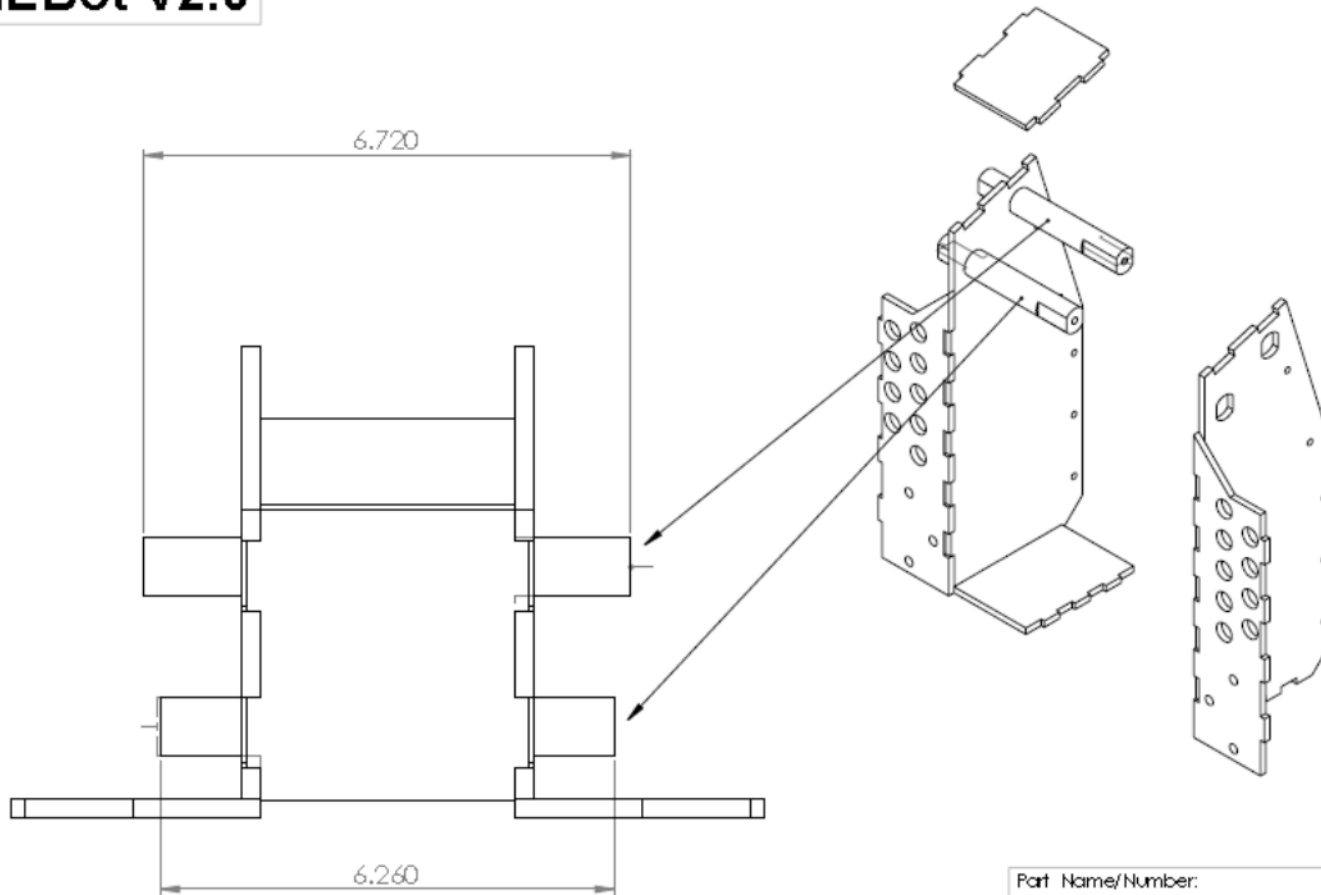
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3

2

1

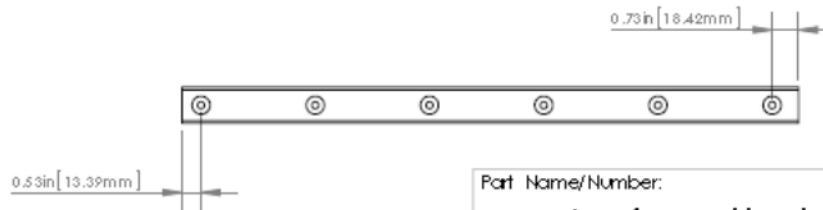
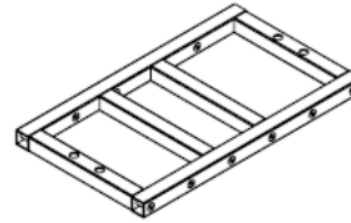
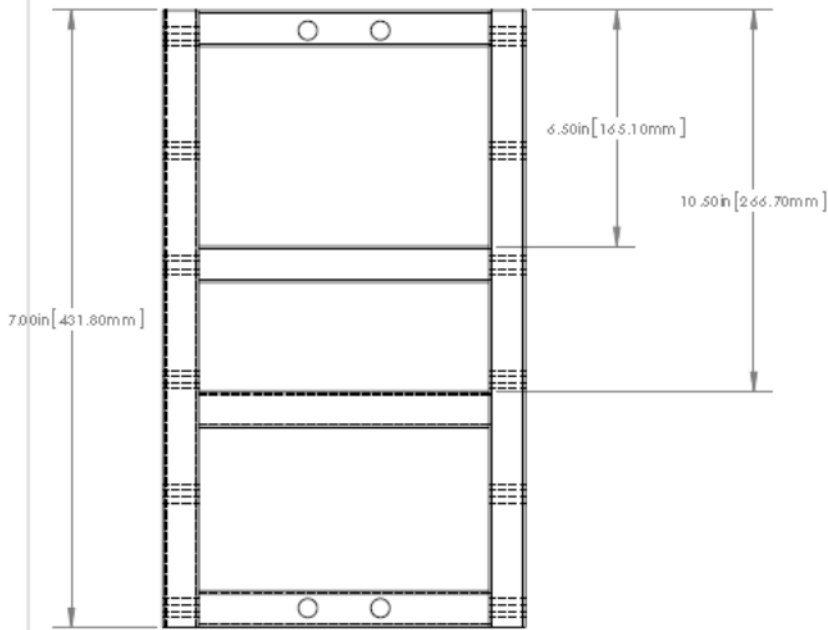
MEBot V2.0



5 4 3 2 1

Part Name/Number:		
weldframe		
Description:		
Material:	Weight:	Vendor:
	lbs	

MEBot V2.0

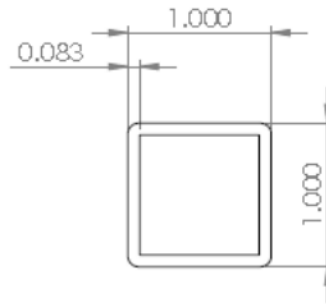


Part Name/Number: Inner frame weldment		
Description: Inner support frame		
Material: Al1020	Weight: 6.06 lbs	Vendor: Custom

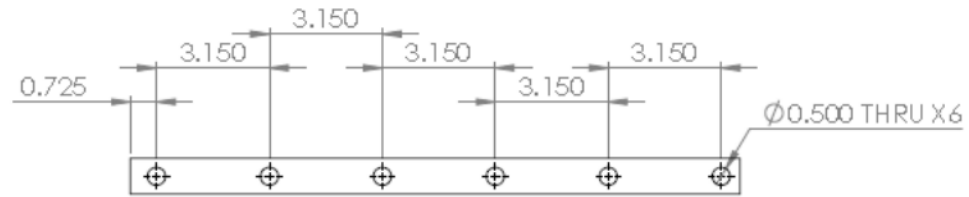
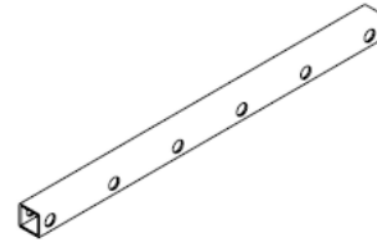
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FINAL\Assemblies\MEBot V2.0 in assemblies\

5 4 3 2 1

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DETAIL A
SCALE 1:1



Part Name/Number:		
Inner frame-side weldment		
Description:		
Material:	Weight: lbs	Vendor:

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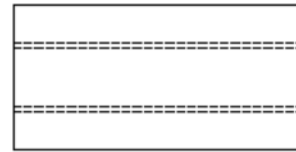
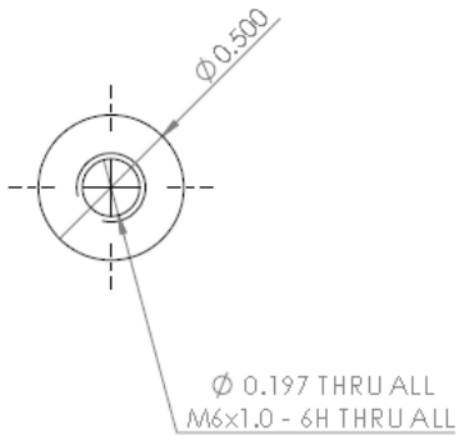
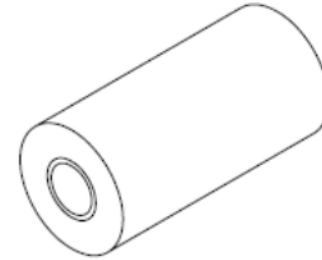
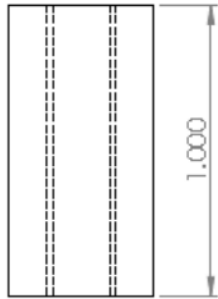
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MEBot V2.0



Part Name/Number:		
Innerframe threaded spacer		
Description:		
0.5" diameter 1" length M6x1 threaded spacer		
Material:	Weight:	Vendor:
AL11020	0.05 lbs	

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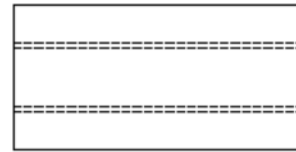
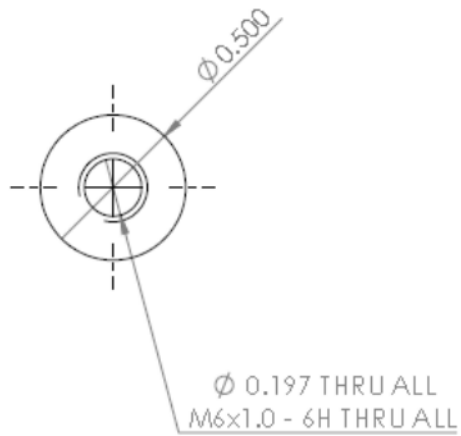
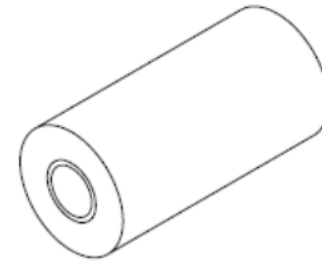
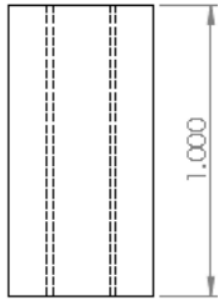
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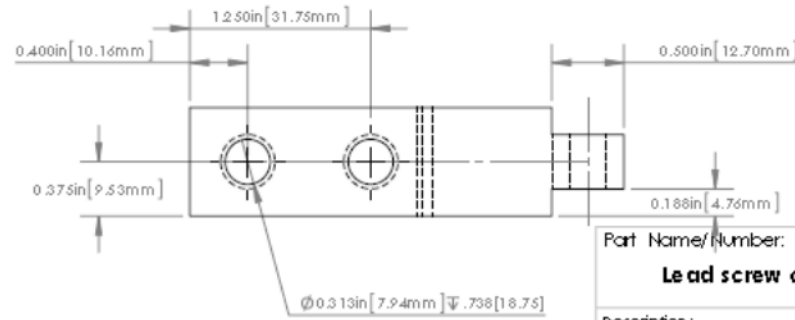
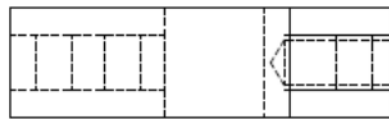
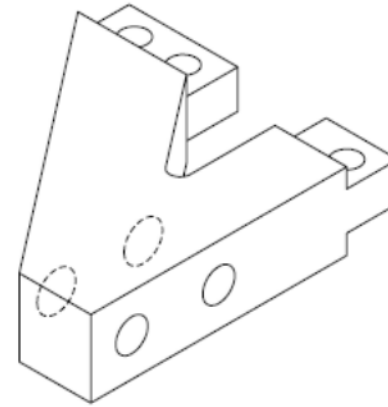
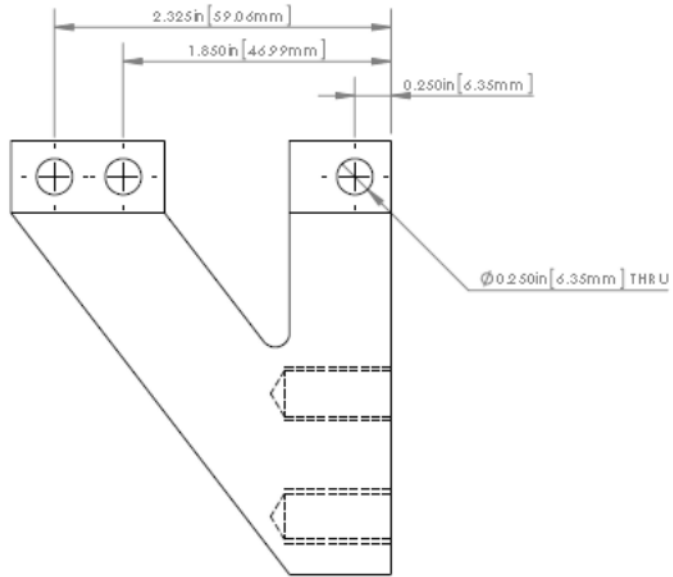
MEBot V2.0



Part Name/Number:		
Innerframe threaded spacer		
Description:		
0.5" diameter 1" length M6x1 threaded spacer		
Material:	Weight:	Vendor:
AL11020	0.05 lbs	

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Part Name/Number:		
Lead screw connection side		
Description:		
Material:	Weight:	Vendor:
	lbs	

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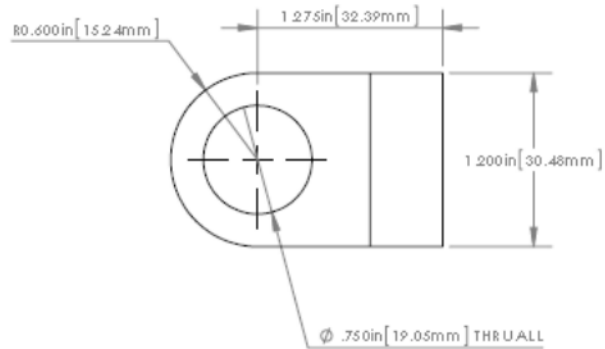
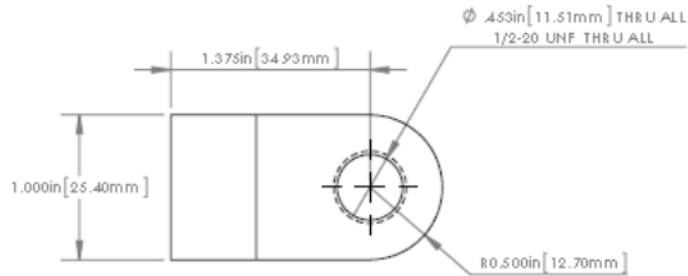
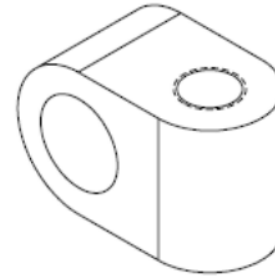
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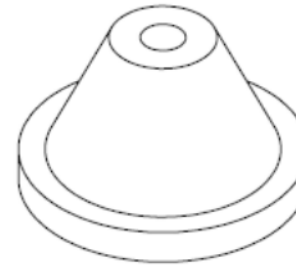
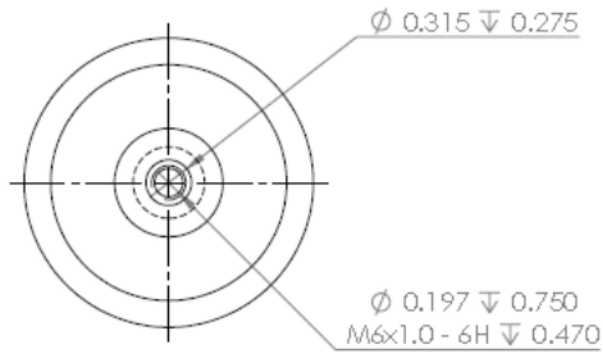
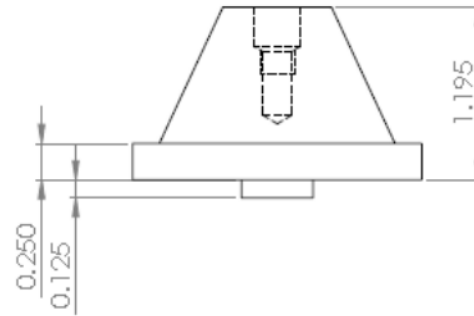
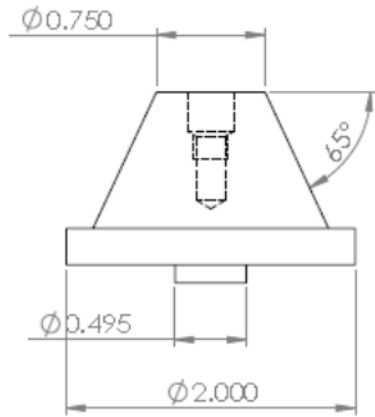
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Part Name/Number:		
Pneumatic actuator connector		
Description:		
connector between pneumatic actuator and linkage		
Material:	Weight:	Vendor:
6061 Alloy	0.13 lbs	custom

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MEBot V2.0



Part Name/Number:		
gas spring attachment V2		
Description:		
Material:	Weight:	Vendor:
	lbs	

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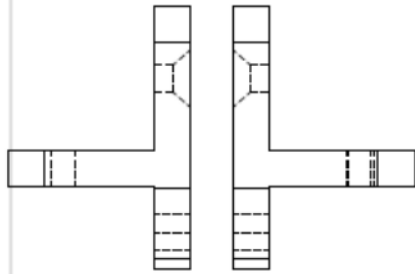
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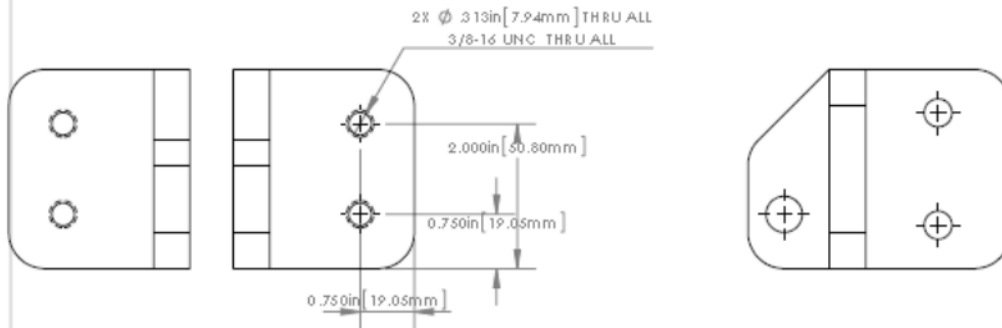
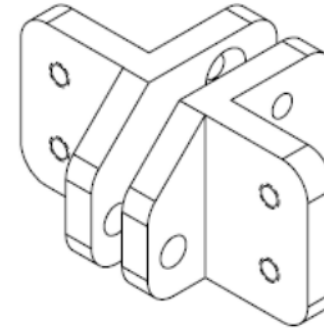
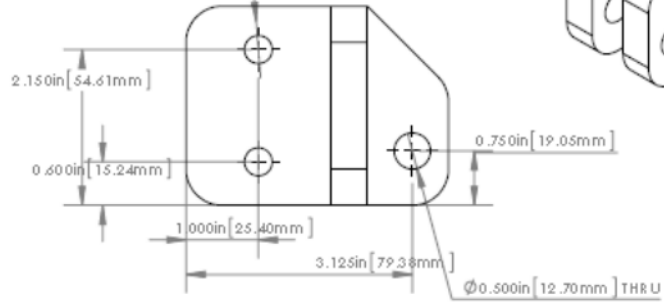
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2x \varnothing .384in [9.80mm] ∇ .500in [12.70mm]
 \sphericalangle \varnothing .781in [19.84mm] \pm 82°



Part Name/Number:		
Front caster attachment bracket		
Description:		
Mount to attach the front caster linkage to the frame		
Material:	Weight:	Vendor:
AB11020	3.95 lbs	Custom

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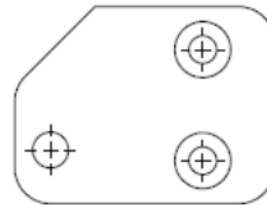
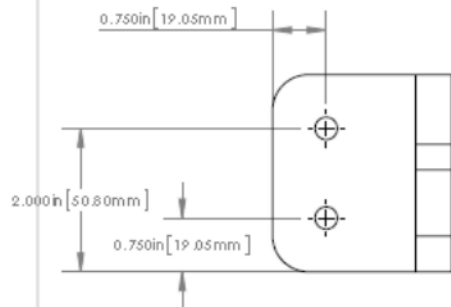
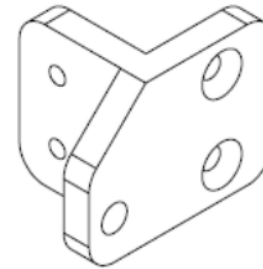
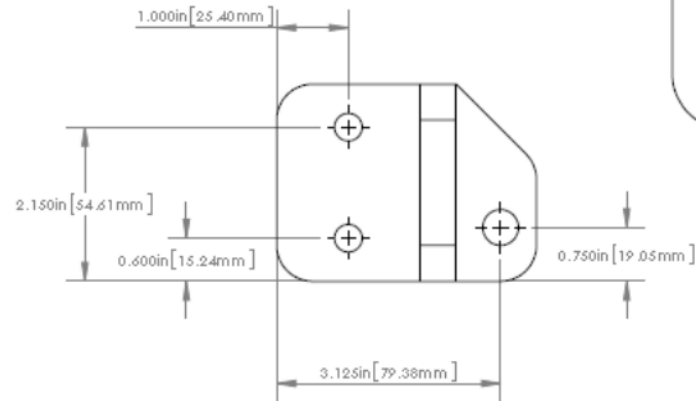
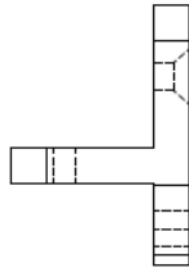
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Part Name/Number:		
Front caster attachment bracket-left		
Description:		
Material:	Weight:	Vendor:
	lbs	

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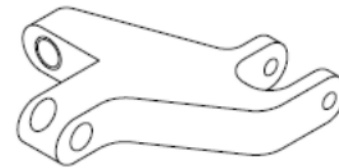
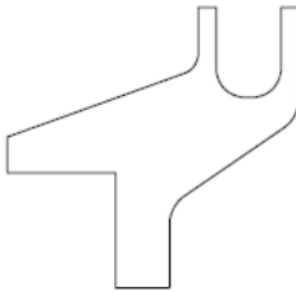
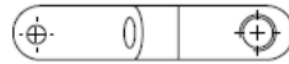
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Part Name/Number: Front top actuator mount		
Description: Mount to attach electric actuator to the frame		
Material: Al61 1020	Weight: 1.12 lbs	Vendor: Custom

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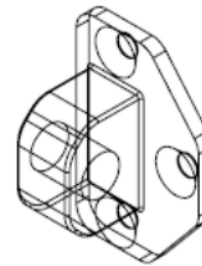
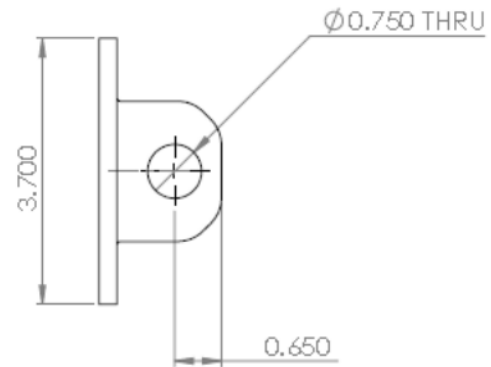
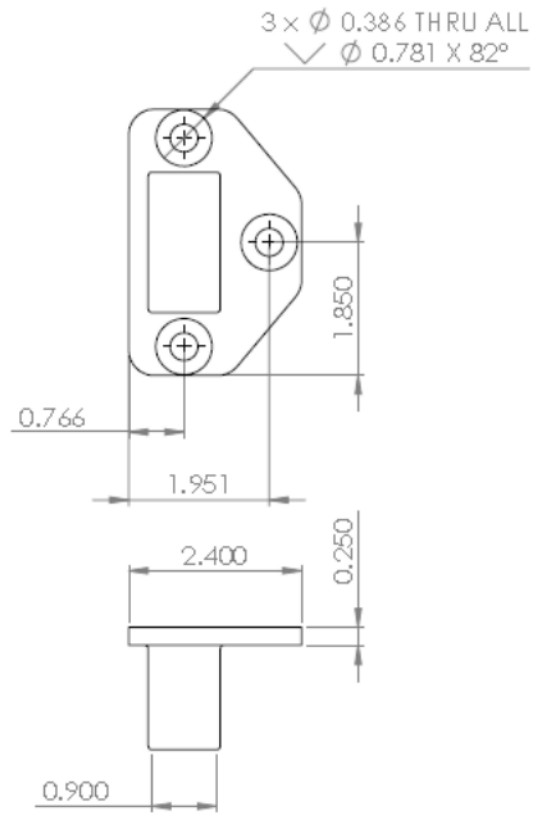
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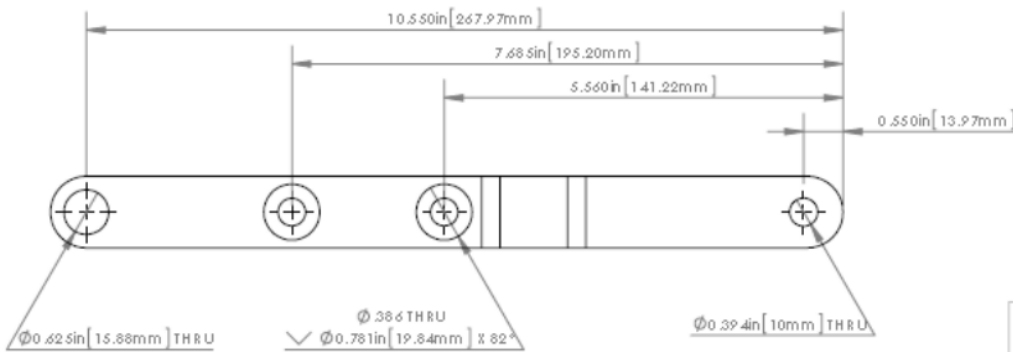
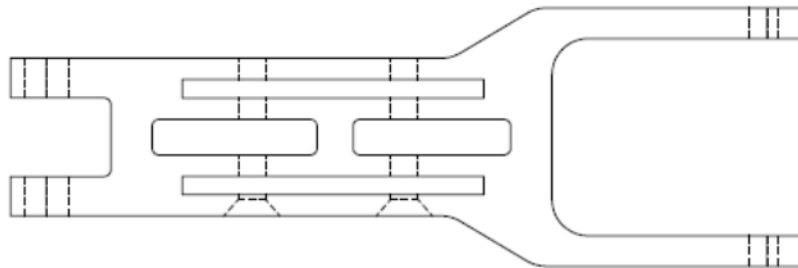
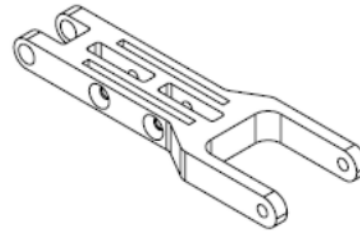
MEBot V2.0



Part Name/Number:		
Rear caster attachment bracket		
Description:		
Mount to attach the rear caster linkage to the frame		
Material:	Weight:	Vendor:
AL1 1020	1.12 lbs	Custom

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MEBot V2.0

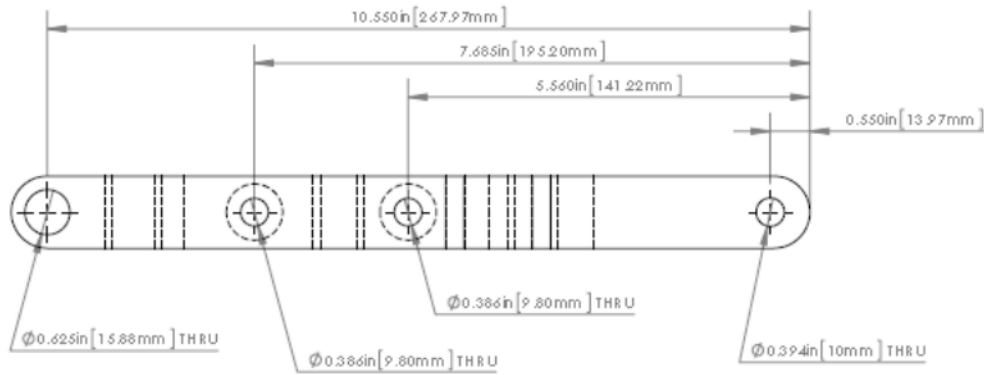
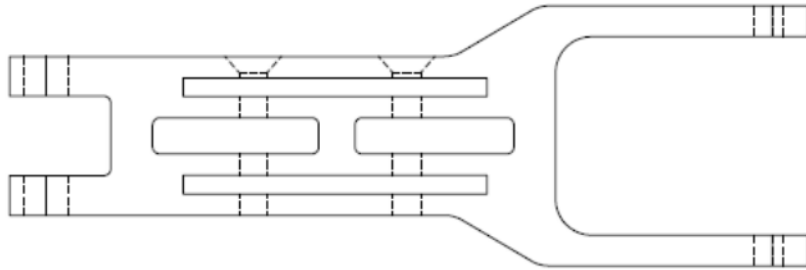
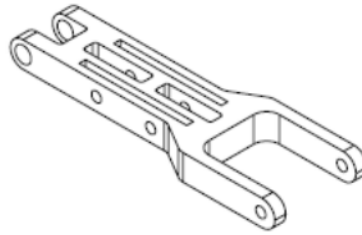


Part Name/Number:		
Rear caster linkage-left		
Description:		
Material:	Weight:	Vendor:
	lbs	

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Part Name/Number:		
Rear caster linkage-right		
Description:		
Material:	Weight:	Vendor:
	lbs	

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APPENDIX D

MEBOT BILL OF MATERIALS

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	VENDOR	QTY.
1	Main frame	Main frame assembly	6061 Alloy	26.94	Custom	1
2	4 inch triple Omni wheel	4" omnidirectional wheel with bearings (not actual component)	N/A	0.751	Kornylak	4
3	Front caster actuator mount-right	Front right actuator mount to attach electric actuator to linkage	AISI 1020	0.8	Custom	1
4	Front caster attachment bracket-right	Front attachment bracket to attach linkage to the frame	AISI 1020	1.97	Custom	1
5	MMP LA3-24V-40-A-50-P	2" stroke, 270 LBF, 24V electric actuator	Material <not specified>	1.55	Midwest Motion	2
6	Front caster linkage	Front linkage that holds the Omni-directional wheel	AISI 1020	4.02	Custom	2
7	Front top actuator mount	Mount to attach electric actuator to the frame	AISI 1020	1.12	Custom	2
8	Front caster actuator mount-left	Front left actuator mount to attach electric actuator to	AISI 1020	0.8	Custom	1

		linkage				
9	Front caster attachment bracket-left	Front left attachment bracket to attach linkage to the frame	AISI 1020	1.97	Custom	1
10	Pneumatic actuator connector	Connector between pneumatic actuator and linkage	6061 Alloy	0.13	Custom	4
11	9416K147	Gas Spring with Threaded Ends, 18.18" Extended Length, 7.87" Stroke, 175 force lbs.	N/A	1.825	McMaster Carr	2
12	PFC-314-XP	2" bore, 4" stroke pneumatic actuator	N/A	2.01462	BIMBA	2
13	Rear caster attachment bracket	Mount to attach the rear caster linkage to the frame	AISI 1020	1.12	Custom	2
14	Rear caster linkage-right assembly	Rear linkage to attach omni-directional wheels to the frame	AISI 1020	6.02	Custom	1
15	Rear caster linkage-left assembly	Rear linkage to attach omni-directional wheels to the frame	AISI 1020	6.02	Custom	1
16	PFC-313-XP	2 inch bore, 3 inch stroke pneumatic actuator	Material <not specified>	N/A	Bimba	2
17	PW-12H	Wheelchair hub motor	N/A	15.9	Golden Motor	2
18	91G100282MM	2.28" stroke, 9.56" Ext. Length, 7.28" Comp. Length gas spring	N/A	1.63	Industrial Gas Springs	2
19	Pneumatic actuator attachment	Mount to attach the pneumatic actuator to the drive plate	AISI 1020	0.54	Custom	2
20	gas spring attachment	Mount to attach the gas spring to the drive plate	AISI 1020	0.52	Custom	2

21	Drive wheel linkage	Linkage connecting the driving wheel to the gas spring and pneumatic actuator	AISI 1020		Custom	1
22	drive wheel linkage bolt	Custom bolt to attach the drive wheel linkage to the drive wheel plate	Material <not specified>	1.16	Custom	2
23	driving wheel mount plate	Mounting plate for all the driving wheel components to mount to	AISI 1020	8.22	Custom	2
24	SN35-130-350-530(0+0)	Rail length 530 mm, slider length 130 mm, stroke 350 mm	Cold drawn steel	2.35	Rollon	2
25	DSS28-370	Length 370 mm, stroke 380 mm DSS - telescopic rail	Cold drawn steel	5.092	Rollon	2
26	Drive wheel linkage	Linkage connecting the driving wheel to the gas spring and pneumatic actuator	AISI 1020		Custom	1
27	068 RA CN U2 18 00 20068 FS	Inch Acme Screw Assembly, 5/8", 4140, 8 Turns Per Inch, RH, 1 Starts, Bronze Nut	N/A	Unknown	Nook Industries	1
28	Lead screw connection assembly	Lead screw assembly to attach the need screw to the driving wheels	AISI 1020	3.134	Custom	1
29	battery 60 Ah	60 amp hour battery	Material <not specified>	3.14		8
30	Rear electronics 1	Electronics assembly in the top rear of the frame	N/A	Unknown	Custom	1
31	Rear electronics 2	Rear electronics box in the bottom of the frame	Material <not specified>	20.67	Custom	1
32	Front caster brace	Cross brace that connects the front caster mounts together	6061 Alloy	0.39	Custom	1

33	Inner frame weldment	Tubular frame assembly to mount the seating system, lead screw assembly, and linear bearing rails	AISI 1020	6.13	Custom	1
34	Manifold	Manifold for the pneumatic actuators	Material <not specified>	1.61	Unknown	1
35	20oz co2 bottle		Material <not specified>	2.68		2
36	90126A033	Zinc-Plated Steel Type A SAE Flat Washer, 1/2" Screw Size, 1-1/16" OD, .07"-.13" Thick	Zinc-Plated Steel	0.01	McMaster Carr	4
37	91255A709	Alloy Steel Button-Head Socket Cap Screw, Black-Oxide, 1/2"-13 Thread, 1-1/8" Long	Alloy steel	0.08	McMaster Carr	4
38	90585A061	Alloy Steel Flat-Head Socket Cap Screw, 3/8"-16 Thread, 1-1/8" Long, Black Oxide	Black-Oxide Alloy Steel	0.041	McMaster Carr	10
39	94945A217	Grade 8 Steel Nylon-Insert Thin Hex Locknut, Zinc-Yellow Plated, 3/8"-16 Thread Size, 9/16" Wide, 17/64" High	Zinc-Plated Steel	0.013	McMaster Carr	18
40	90126A031	Zinc-Plated Steel Type A SAE Flat Washer, 3/8" Screw Size, 13/16" OD, .05"-.08" Thick	Zinc-Plated Steel	0.01	McMaster Carr	22
41	93890A596	Headless Clevis Pin, Grooved, Zinc-Plated Steel, 5/16" Diameter, 1-7/8" Long	Zinc-Plated Steel	0.041	McMaster Carr	4

42	91251A636	Black-Oxide Alloy Steel Socket Head Cap Screw, 3/8"-16 Thread, 3" Length	Black-oxide Alloy Steel	0.11	McMaster Carr	4
43	90965A200	Metric DIN 125 Type 316 Stainless Steel Flat Washer, M10 Screw Size, 20mm OD, 1.8mm-2.2mm Thick	Type 316 Stainless Steel	0.01	McMaster Carr	8
44	90576A117	Metric Zinc-Plated Steel Nylon-Insert Locknut, Class 8, M8 Screw Size, 1.25mm Pitch, 13mm Wide, 8mm High	Zinc-Plated Steel	0.013	McMaster Carr	4
45	92981A312	Alloy Steel Shoulder Screw, 10mm Diameter x 90mm Long Shoulder, M8 Thread	Alloy Steel	0.152	McMaster Carr	4
46	92735A830	Grooved Clevis Pin with Retaining Ring, Zinc-Plated Steel, 3/8" Diameter, 1-3/4" Long, 1-9/16" Usable Length	Zinc-Plated Steel	0.063	McMaster Carr	2
47	6391K173	SAE 841 Bronze Sleeve Bearing for 3/8" Shaft Diameter, 1/2" OD, 1/2" Length	Bronze	0.01	McMaster Carr	6
48	91255A622	Alloy Steel Button-Head Socket Cap Screw, Black-Oxide, 3/8"-16 Thread, 3/4" Long	Black-oxide Steel	0.031	McMaster Carr	4
49	2879T3	SAE 863 Solid Bronze Thrust Bearing for 3/8" Shaft Diameter, 3/4" OD x 1/8" Thick	Bronze	0.01	McMaster Carr	8

50	92981A203	Alloy Steel Shoulder Screw, 8mm Diameter x 20mm Long Shoulder, M6 Thread	Alloy Steel	0.034	McMaster Carr	4
51	2879T5	SAE 863 Solid Bronze Thrust Bearing for 1/2" Shaft Diameter, 1" OD x 1/8" Thick	Bronze	0.02	McMaster Carr	8
52	92981A305	Alloy Steel Shoulder Screw, 10mm Diameter x 30mm Long Shoulder, M8 Thread	Alloy Steel	0.071	McMaster Carr	4
53	91253A634	Alloy Steel Flat- Head Socket Cap Screw, 3/8"-16 Thread, 2-1/2" Length, Black Oxide	Black-Oxide Alloy Steel	0.082	McMaster Carr	4
54	2868T14	SAE 863 Bronze Sleeve Bearing for 1/2" Shaft Diameter, 3/4" OD, 1" Length	Bronze	0.07	McMaster Carr	6
55	92735A515	Grooved Clevis Pin with Retaining Ring, 18-8 Stainless Steel, 1/2" Diameter, 2" Length, 1-13/16" Usable Length	18-8 Stainless Steel	0.124	McMaster Carr	4
56	92735A765	Grooved Clevis Pin with Retaining Ring, Zinc-Plated Steel, 5/16" Diameter, 2" Long, 1-13/16" Usable Length	Zinc-Plated Steel	0.048	McMaster Carr	4
57	6391K212	SAE 841 Bronze Sleeve Bearing for 1/2" Shaft Diameter, 5/8" OD,	Bronze	0.02	McMaster Carr	4

		1/2" Length				
58	92735A520	Grooved Clevis Pin with Retaining Ring, 18-8 Stainless Steel, 1/2" Diameter, 2-1/2" Length, 2-5/16" Usable Length	18-8 Stainless Steel	0.152	McMaster Carr	2
59	90576A115	Metric Zinc-Plated Steel Nylon-Insert Locknut, Class 8, M6 Size, 1mm Pitch, 10mm Width, 6mm Height	Zinc-Plated Steel	0.35	McMaster Carr	18
60	91166A250	DIN 125 Zinc-Plated Class 4 Steel Flat Washer, M6 Screw Size, 12mm OD, 1.4mm-1.8mm Thick	Zinc-Plated Steel	0	McMaster Carr	18
61	2868T18	SAE 863 Bronze Sleeve Bearing for 3/4" Shaft Diameter, 1" OD, 3/4" Length	Bronze	0.16	McMaster Carr	2
62	91294A239	Black Alloy Steel Flat-Head Socket Cap Screw, Class 10.9, M6 Size, 18mm Length, 1.00mm Pitch	Black-Oxide Alloy Steel	0.009	McMaster Carr	18
63	91239A232	Class 10.9 Steel Button-Head Socket Cap Screw, M5 Size, 16 mm Length, .8 mm Pitch	Black-Oxide Alloy Steel	0.007	McMaster Carr	4
64	91166A240	DIN 125 Zinc-Plated Class 4 Steel Flat Washer, M5 Screw Size, 10mm OD, .9mm-1.1mm Thick	Zinc-Plated Steel	0.4	McMaster Carr	4

APPENDIX E

PROTOTYPE FOCUS GROUP QUESTIONNAIRE

Questionnaire Packet Wheelchair Users

Participatory Evaluation of the Mobility Enhancement Robotic Wheelchair (MEBot)

COMPLETION LOG:	DATE:	INITIALS:	TIME:
Subject ID#: _____			
Data Collection	/ /		
Data Entry	/ /		
Verification	/ /		

PART A - Personal Demographics

1. Gender: Male
 Female
2. Age: _____
3. Ethnic Origin: Black or African-American American Indian
 Hispanic or Latino White or Caucasian
 Asian Native Hawaiian
 Two or more races Other: _____
4. What is your impairment/disability? _____

5. Date of onset or injury: ____/____/____
6. What is the highest degree you received?
- High School Diploma or GED
 - Associate Degree
 - Vocational/Technical School
 - Bachelors Degree
 - Masters Degree
 - Doctorate, Law, Etc.

7. Which statement best describes your **CURRENT** work status?

- Working full-time, outside the home
- Working part-time, outside the home
- Working full-time, inside the home
- Working part-time, inside the home
- Retired because of disability
- Retired, but not because of disability
- Housekeeper, homemaker
- Disabled: unable to work because of disability
- Unemployed
- Other: please specify: _____

8. Please indicate which best describes your marital status:

- Single
- Married
- Living with someone as if married

9. How long have you been using a power wheelchair? _____ years

10. How long have you been using your current power wheelchair? _____ years

11. In a typical day, how many hours are you in your wheelchair? _____ hours

12. How many days of the week are you driving your wheelchair outside your house?
_____ days per week

Part B: Current Wheelchair Information

1. Model	
2. Manufacturer	
3. Date received	
4. Other Characteristics	
5. Control Method (i.e. joystick, head array, etc.)	
6. Additional Equipment (i.e. seat elevator, elevating leg rests, tilt-in-space)	
7. Front-wheel, mid-wheel, or rear-wheel drive?	

Part C: Power Wheelchair Training and Accidents

1. How much training did you receive when you obtain your current power wheelchair?

- Less than 30 minutes Between 30 and 60 minutes
 More than one hour Do not remember
 No training

2. Did you practice driving outside at all during your training?

- Yes No N/A

3. Did you have to take any kind of driving test to see if you could safely drive a power wheelchair?

- Yes No N/A

4. Have you had any accidents with your wheelchair before? What caused the accident? Please mark as many items below that apply.

- Your wheelchairs slipped and ran into something
- Your wheelchair tipped over forward or backward
- Your wheelchair tipped over sideways
- It was too dark to see well and you ran into something
- You became stuck because your tires lost friction
- Other experiences, Please explain:

- Other experiences, Please explain:

5. If you would like, please give a short description of any of your accidents and the injuries you sustained, if any.

Part D: Outdoor Driving Characteristics

1. Have you visited any of the following places during the past week?

- | | | |
|--|--|---------------------------------------|
| <input type="checkbox"/> Grocery store | <input type="checkbox"/> Movie Theater | <input type="checkbox"/> Work |
| <input type="checkbox"/> Mall/Department Store | <input type="checkbox"/> Family/Friends' Residence | <input type="checkbox"/> School |
| <input type="checkbox"/> Restaurant | <input type="checkbox"/> Temple/Church/Mosque | <input type="checkbox"/> Dr.'s office |
| <input type="checkbox"/> Other: _____ | <input type="checkbox"/> Other: _____ | |

2. How many times in the past week did you come across...	What did you do <u>most of the time</u> when you came across the obstacle?
Curbs <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Up ramp <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Down ramp <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Cross slope <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Concrete <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Grass <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Gravel <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Sand <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Dirt/mud <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Curb cuts <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Small curb <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Door threshold <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____
Carpet <input type="checkbox"/> None <input type="checkbox"/> 1-3 <input type="checkbox"/> >3	<input type="checkbox"/> Avoided it <input type="checkbox"/> Went over it with help <input type="checkbox"/> Went over it by myself <input type="checkbox"/> Other: _____

Part E: MEBot applications

Please put a check in the box describing the likelihood you would use each of the MEBot applications in the table below. (Descriptions for each application described below)

MEBot applications	Very unlikely	Unlikely	Likely	Very likely	Comments
1. Self-leveling					
2. Selectable driving wheel position					
3. Curb climbing					
4. Traction control					
5. 2 wheel balance					

1. Self-leveling: Maintains the user's position of the seating system when traveling up, down, or across slopes. (I.e. When going up a slope, MEBot will tilt forward to compensate for the upward slope.)
2. Selectable driving wheel position: Provides the user with the ability to configure MEBot as a rear wheel drive, mid-wheel drive, or front wheel drive powered wheelchair.
3. Curb climbing: Allows the user to overcome up to an 8 inch curb.
4. Traction control: Allows MEBot to maintain a straight path when traveling on slippery surfaces. (I.e. snow, ice, wet grass, sand, etc.)
5. 2 wheel balance: Allows MEBot to operate in "Segway mode" (I.e. The caster wheels will be raised leaving only the two drive wheels maintaining contact with the ground)

Part F: MEBot Control Interface

Hardware

1. Would you prefer a toggle, push, or rocker power switch?

Toggle



Push



Rocker



2. Would you prefer that the group of switches and speed knob be located above the LCD screen or below it?

Above

Below

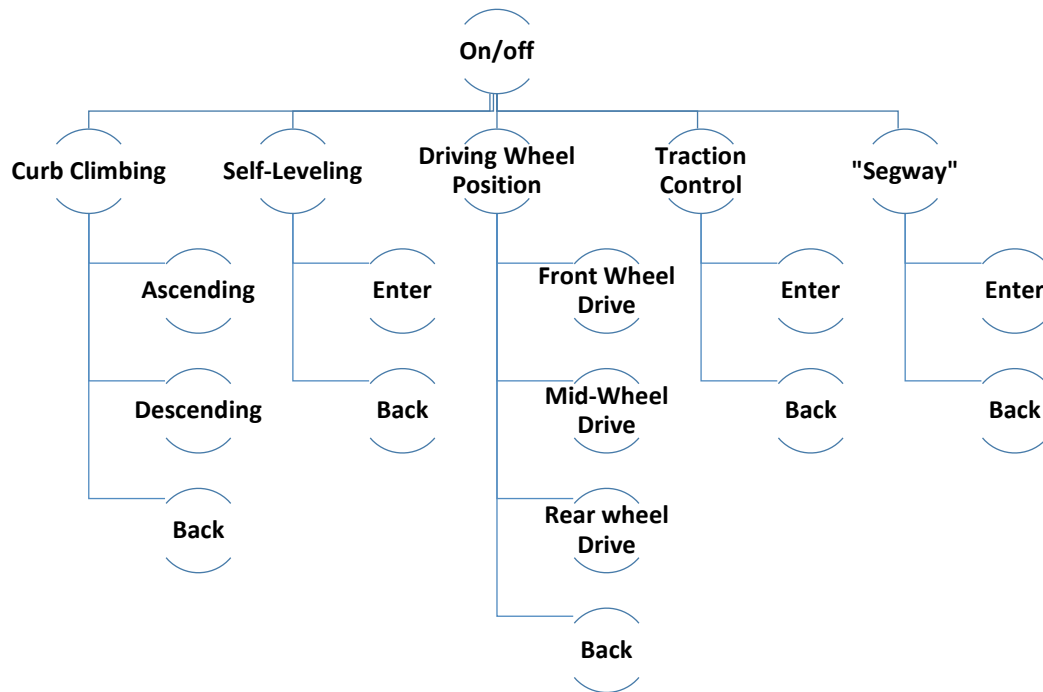
Software

1. Which method would you prefer in order to navigate through the features?
Navigation with each described below.

Joystick Joystick + button 2 buttons

Method	Description
Joystick	Left or right movement: switches between features/options upward movement: selects current feature and advances to submenu
Joystick + button	Left or right joystick movement: switches between features/options Button press: selects current feature and advances to submenu
2 buttons	Button A press: switches between features/options Button B press: selects current feature and advances to submenu

Example feature layout



2. What is your opinion on the navigation through the example feature layout above? (I.e. easy to navigate, complicated, etc.)
-
-

☺ Thank you for taking the time to complete this questionnaire ☺
We appreciate your participation!

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