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Indoor/Outdoor Wheelchair

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Abstract

Over 125,000 paraplegics in the United States require a wheelchair for transportation. Many of these people want the ability to travel safely over a variety of obstacles and thereby greatly increase their independence. This project developed an all-purpose wheelchair that operates as a standard wheelchair indoors, and competes with an all-terrain wheelchair outdoors. To accomplish this, necessary standard features and dimensions were retained for indoor operation. To improve mobility outdoors, the chair was modified to allow on-the-fly adjustment of the center of gravity to prevent tipping. Mountain bike tires were utilized to increase traction and optional ratcheting drive levers were included to provide a mechanical advantage for climbing steep hills. Field tests showed the prototype capable of extending the user's range on steeper slopes, over roots, through mud and grass while the standard chair had major difficulties with traction and tipping. Survey results indicate 85% of people prefer the prototype to a standard wheelchair regarding the advantages it provided in each test.

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1.0 Introduction

Globally, an estimated 100-130 million people with disabilities require the use of a wheelchair. In the United States alone 1.5 million people use manual wheelchairs (Kaye, Kang and LaPlante 2000). Wheelchair use is becoming even more common as the average lifespan increases. With new wheelchairs continually being designed, manual wheelchairs are expected to promote activity and independence (Cook and Polgar 2007). However, because standard wheelchairs are optimized for ADA (American with Disabilities Act) approved surfaces and slopes, they can limit one's ability to traverse different terrains and surfaces (Engel and Hildebrandt 1974).

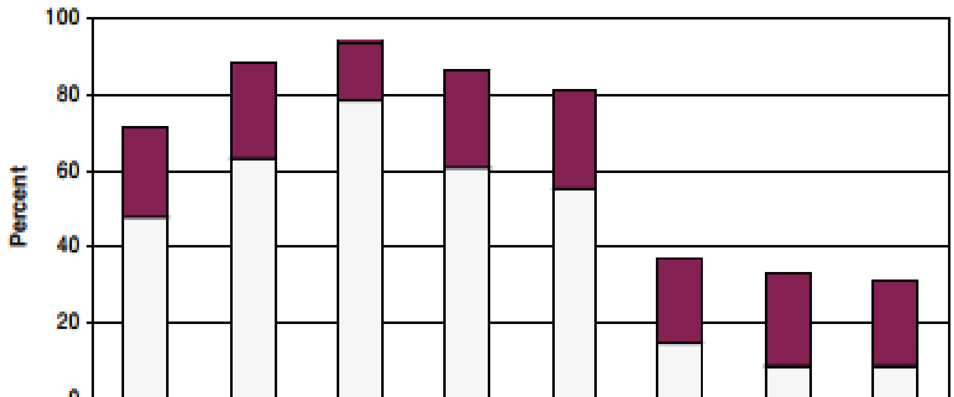
In 2003, 65-80% of wheelchair related injuries were caused by tipping and falling. Active, paraplegic wheelchair users do not want to be held back by their wheelchair's limitations and need a wheelchair that inspires confidence outdoors on surfaces that are not ADA approved (Xiang, Chany and Smith n.d.). To address this issue, many wheelchair users buy a secondary wheelchair intended for outdoor terrain and steep slopes. These wheelchairs are built with many additional features for outdoor function but are not designed to comply with ADA standards and are generally undesirable for a daily use wheelchair because of their higher weight, larger dimensions and lack of portability. Having two wheelchairs, one for indoor use and one for outdoors, is costly and inconvenient. There is a major deficiency in the market for those who desire a hybrid wheelchair that can maneuver through challenging outdoor surfaces while still retaining function within ADA standardized buildings.

The goal of this project is to design a manual wheelchair used by independent paraplegics that traverses challenging outdoor surfaces while maintaining the ability to access ADA standardized buildings.

2.0 Identification of Need

In 1869, the first wheelchair patent for a model with rear push wheels and small front casters was issued in the United States. Herbert Everest and Harry Jennings invented the first lightweight, steel-framed, collapsible wheelchair in 1932, setting the precedent for the design of most current manual wheelchairs (Mobility Scooters Otago 1999). Now, most manual wheelchairs are lightweight and collapsible. These wheelchairs greatly benefit the users who depend on their manual wheelchair in daily life.

Wheelchair users deal with a multitude of limitations. The largest limitation, Figure 1, is the ability to walk one-fourth of a mile (Kaye, Kang and LaPlante 2000). An average person walks 5,117 steps a day which is approximatetly two and a half miles (Bassett, et al. 2010). Of the next three top limitations, two out of three are required to be performed every day: standing and bending down. Those incapable of walking or standing may decide to use assistive devices.



	Lifting 10 lbs.	Climbing stairs	Walking 1/4 mile	Standing 20 mins.	Bending down	Reaching up or out	Grasping	Holding pen
■ Difficulty only	23.0	24.7	15.7	25.8	25.8	22.2	24.7	22.6
□ Unable	48.3	63.7	78.5	61.0	55.4	15.0	9.1	9.0

Figure 1: Proportion of Wheelchair Users with Functional Limitations, by degree and type of limitation, age 18 and above (Kaye, Kang and LaPlante 2000).

Many different injuries can lead to the need for a wheelchair. Approximately 250,000 Americans suffer from a spinal cord injury,

Table 1. Spinal cord injuries are commonly a result of a motor vehicle accident, falling, acts of violence, sports and recreation injuries, alcohol, and cancer. Motor vehicle accidents and falls are the leading causes of injuries at 35% and 25% respectively (Mayo Clinic Staff 2014).

The number of spinal cord injuries increases, on average, by 11,000 people each year. Fifty-two percent of those with spinal cord injuries are paraplegic and are capable of using a manual wheelchair (Matthew 2015). Paraplegia is defined as, “complete paralysis of the lower half of the body including both legs” (American Heritage Dictionary 2011).

Table 1: Paraplegia Causes and Function Loss (Hickey JV 1998). The left column indicates which vertebrae are injured. The right column discusses the function loss.

Paraplegia Causes and Function Loss	
T1-T6 Injuries	Loss of all motor and sensory function below the mid-chest region, including loss of motor function in the trunk muscles Some loss of voluntary respiratory function Loss of bowel and bladder function Full independence in a wheelchair and in managing urinary drainage and inserting suppositories Can achieve full-time employment and does not need major architectural changes in living quarters
T6-T12 Injuries	Loss of motor and sensory function below the waist No loss of respiratory function Loss of bowel and bladder control In addition to T1-T6 capabilities, complete abdominal, upper back, and respiratory control permit good sitting balance and wheelchair operation
L1-L3 Injuries	Loss of most motor function of the legs and pelvis, and loss of sensation in lower abdomen and legs Retention of knee jerk reflex No loss of respiratory function Loss of bowel and bladder control All T1-T12 capabilities
L3-L4 Injuries	Loss of motor and sensory function in portions of the lower legs, ankles, and feet No loss of respiratory function Loss of bowel and bladder control May achieve walking with braces
L4-S5 Injuries	Degree of motor function varies: Hip abduction and internal rotation, ankle dorsiflexion, and foot inversion possible in L4 - S1; foot eversion in L5-S1; knee flexion in L4-S2; plantar flexion and ankle jerk in S1-S2; bowel/bladder control in S2-S5 Sensory function in portions of lower leg: medial aspects of the foot in L5; lateral aspects of the foot in S1; posterior aspects of the calf/thigh in S2 No loss of respiratory function; may or may not have bowel/bladder control Can walk with braces and live relatively independently

Once a patient sees a physical therapist, he or she will eventually be fitted for a wheelchair depending on the injury type. At this time, those patients would need to apply for funding to cover the cost of their wheelchair. Medicare only covers 80% of the cost, leaving the patient with the remaining 20%. For this reason, the price needs to be within a reasonable range, especially since only 25% of those injured are on Medicare (University of Birmingham 1998). Currently, in the marketplace, a manual wheelchair user would have to spend around $160 out of pocket on a wheelchair (Karman 2014). To travel outdoors on steep slopes, grass, gravel or other rough terrains, a user would also have to buy an outdoor manual all terrain wheelchair, which means he or she would have to spend even more out of pocket. A wheelchair that can be utilized indoors and outdoors on all types of surfaces while costing the same as a standard manual wheelchair is desirable.

3.0 Background

When designing a product, it is important to know the user's abilities and limitations. These limitations can be grouped into two types of living, independent and assisted. However, each group is subject to the same types of wheelchair limitations. Knowing the limitations of standard wheelchairs, allow new designs to include features, which reduce the risk of common injuries.

3.1 Wheelchair Operators

Wheelchairs are designed to aid many different types of users. The users can be separated into two general categories: those capable of independent living and those who benefit from assisted living.

3.1.1 Independent Living

Section 7(15)(B) of the Rehabilitation Act defines severe disability as

> "An individual with a severe physical or mental impairment whose ability to function independently in the family or community or whose ability to obtain, maintain, or advance in employment is substantially limited and for whom the delivery of independent living services will improve the ability to function, continue functioning, or move towards functioning independently in the family or community or to continue in employment, respectively." (U.S. Government n.d.)

Local independent living centers provide independent living services to persons with severe disabilities. These services can include aid with finding accessible housing, support groups, and transportation (Fox-Quamme 2005). Many who are capable of independent living have suffered from a spinal cord injury causing them to become paraplegics.

3.1.2 Assisted Living

Assisted living can help an individual with a disability in a wide range of needs. The housing can range from a small house for one resident, to a large facility providing residence to hundreds (Assisted Living 2015). In order to be considered for assisted living, a person with a disability must require help with at least one of the activities of daily living (ADLs). These tasks include functional mobility, bathing, self-dressing, self-feeding, and the ability to use the restroom. Multiple tests are used to determine whether a person would benefit from assisted living. Some common scales are Katz ADL, Lawton IADL, and Bristol ADL. (Activities of daily living 2015). This project will focus on paraplegics who are capable of living independently with the use of a manual wheelchair.

3.2 Common Injuries from Wheelchair Use

Manual wheelchairs are operated by repetitive movement, which can lead to injury without careful operation. On average, a manual wheelchair user pushes his or her chair 2000 to 5000 times per day. Due to the large amount of activity, there can be frequent minor injuries such as friction burns and finger entanglement. However, these injuries are the best-case scenarios. Long-term injuries can develop from the repetitive motion. Hand and wrist arthritis, tendonitis, and carpal tunnel syndrome can result from long-term use (McGuire, Niccum and Quinonez n.d.). However, 50% of all injuries are accidental caused by unlocked brakes, tipping chairs, and unassisted transfers (Karman Healthcare n.d.). Many of these injuries could be prevented by having features added to their wheelchair or by a new type of wheelchair. If a user could go farther using the same applied force, then fewer pushes would be needed in a day, cutting down on the chance of friction burns, finger entanglement, arthritis, and other injuries.

4.0 Current Wheelchairs

4.1 Indoor Wheelchairs

Manual indoor wheelchairs have detailed specifications that must be followed in order to be considered fully functional while indoors. Many wheelchairs comply with the International Organization for Standardization (ISO) in addition to meeting the standards set by the American National Standards Institute (ANSI). If a wheelchair's specifications are within the ANSI wheelchair standards, it is implied that the operator should have no difficulty navigating standardized buildings. ANSI has been "working closely with the International Standards Organization (ISO) so that the ANSI standards will be essentially the same as those in other participating countries" to promote global compliance (McLaurin and Peter n.d.).

ADA standards refer to the requirements of the buildings and ANSI standards refer to the dimensional requirements of the chair. If a building meets all ADA standards, any ANSI approved chair should have no operational issues. If the chair exceeds one or more of the explicit universal standard dimensions, there is a possibility that the chair may encounter difficulty while maneuvering indoors. Existing wheelchair design specifications are based on ANSI and ADA requirements. Focused ADA specifications can be found in Table 43 in Appendix A: Wheelchair Propulsion test and ADA.

An ADA approved surface has several restrictions. "Most loose materials, including gravel will not meet these requirements unless properly treated to provide sufficient surface integrity and resilience" (United States Access Board 2014). This implies that any indoor surface such as linoleum or carpet, or outdoor pathway such as concrete, asphalt, and brick is easily traversable by any wheelchair if it is ADA approved. However, over time, an outdoor ADA approved surface can become weathered or damaged causing it to no longer be an ADA compliant surface. Cracks larger than half an inch will not comply with the ADA code.

To be considered fully functional in an ADA approved building, the wheelchair must be able to fit under a desk. The standard desk has a height of 30 inches (76cm). Though, for ergonomic reasons, "the proper height for a non-adjustable working surface is about 27.5 inches (floor to top of surface) (ANSI 1988)" (Salvendy 2001). With these standards in mind, the seat must be at a height so the wheelchair user can sit at the desk comfortably.

4.1.1 Current Standard Wheelchair Models

Indoor and outdoor wheelchairs can be difficult to classify. An indoor wheelchair can be referenced as a standard wheelchair but can also be used outdoors, on some terrains. Therefore, the outdoor wheelchairs can be referred to as all-terrain wheelchairs. The market for indoor wheelchairs is diverse. Each model meets the dimensional ANSI standards in addition to complying with the ADA standards for the surfaces it traverses. A chair should be no larger than "28 inches wide, 51 inches long and 43 inches high" (McLaurin and Peter n.d.). Since there is room for design variance within the ANSI standards, indoor wheelchair designs may focus on other elements such as weight, foldability, carrying capacity, or comfort. Table 2 compares design specifications of a small sample of indoor wheelchairs. All four wheelchairs are manually operated and meet ANSI specifications, while still featuring unique aspects. The Invacare Crossfire is in this table because of its structural similarity to standard indoor wheelchairs.

Table 2: Current Standard Wheelchair Specifications and Comparison (1800 Wheelchair 1997).

Wheelchair	Width (in)	Length (in)	Height (in)	Seat Height (in)	Weight (lbs.)	Capacity (lbs.)	Material	Foldability (Y/N)	Cost ($)	Rear Wheel Diameter (in)	Key Feature
Invacare Tracer EX2	24.5 - 28.5	32	36	17.5-19.5	36	250	Carbon Steel	Y	99	24	Best Price
Karman Ergo Flight Wheelchair	25, 27	32	36	18.5	19.5	220	T6 Aluminum	Y	689	20	Light weight, Ergonomic
Invacare Top End Crossfire All Terrain Wheelchair	22-28	33	30	16-21	19.5	250	Aluminum	N	2,519	25	Bike tires
Quickie QXI Wheelchair	25	33	38	17.5	29	265	Aluminum	Y	999	22	Highly Customizable

4.2 Outdoor Wheelchairs

Outdoor or all terrain wheelchairs are made for a myriad of different objectives and environments such as hiking trails, steep grades, and/or beaches. With these outdoor terrains as the focus, trying to bring the chairs indoors can often be very difficult or ineffective. Many cannot fit through doors, under desks or turn around within the required diameter, thus, making outdoor wheelchairs undesirable for users who traverse ADA approved buildings regularly.

4.2.1 Current Models of Outdoor Wheelchairs

There are very few standards for all-terrain wheelchairs, differing greatly from indoor wheelchairs that must pass through doorways, fit under desks and navigate ADA standardized buildings. However, many do have similar features that increase stability, mobility, and safety on non-ADA approved surfaces. For example, by using reinforced castor wheels or a third, reinforced wheel in the front or rear, users can overcome uneven surfaces while maintaining higher rolling speeds and greater stability. Many all-terrain wheelchairs implement mountain bike features for increased performance such as front and rear suspension for reduced vibrations or disk brakes for increased stopping potential (Engel and Hildebrandt 1974).

One example of this type of chair is the Invacare Top End Crossfire All Terrain Wheelchair, Figure 2. It is a rugged and capable manual wheelchair that is built to traverse a variety of surfaces. It utilizes 25-inch mountain bike wheels and tires that increase traction and roll speed as well as reinforced and enlarged castor wheels to help with stability. Finally, its frame design utilizes both aluminum and titanium to increase strength while keeping weight relatively low (19.5 lbs.) (Invacare 2013).

Figure 2: Invacare Top End Crossfire All Terrain Wheelchair (Invacare 2013).

The Mountain Trike, an off-road capable wheelchair, Figure 3, utilizes levers with a drivetrain to enable a mechanical advantage to the operator with each push. The levers also control steering and braking. The left lever arm has a cable pull system running to the rear wheel that is operated by rotating the grip left or right. Braking is done through a hydraulic disc brake system running from the levers to calipers that slow rotors attached to each driven wheel.

Figure 3: Mountain Trike (Mountain Trike 2015).

These components of the levers allow operators to control and move the chair without touching the wheels, Figure 4. Finally, to aid in comfort and reduce bumps, the Mountain Trike is equipped with three 100mm air-suspension shocks. These shocks are attached to the rear wheel and below the armrests between the frame and axle. The Mountain Trike accomplishes its goal of “exploring the countryside” very well but for a user wishing to use it daily, it may become very burdensome due to its size and weight (44.1lbs) (Mountain Trike 2015).

Figure 4: Drivetrain, Disc Brake (left) and Lever system (right) (Mountain Trike 2015).

4.3 Limitations

Although there are benefits of outdoor chairs, there are several major limitations that prevent users from having off-road capable chairs as his or her daily chair. Many cannot fit through doors, cannot fold or weigh too much to be lifted in and out of a car regularly (Engel and Hildebrandt 1974). This can limit the mobility of the user and his or her ability to travel independently with the chair. When in ADA approved buildings, the chairs are often cumbersome. However there are several outdoor chairs that could potentially overcome these limitations.

4.4 Indoor and Outdoor Wheelchairs

Although there are effective and successful indoor chairs and outdoor chairs, few products are useful in both settings. An indoor/outdoor wheelchair must compete functionally with the products on the market. The following chairs or attachments could be used in both indoor and outdoor environments.

4.4.1 Rio Mobility Dragonfly

The Dragonfly, Figure 5, is manufactured by Rio Mobility and is an attachment to a standard wheelchair that lifts the front two castors off the ground and supports the front of the chair with one larger front wheel. The device attaches to two points on each side of the wheelchair frame. The bottom connection on each side is a rigid connection and the top is connected via a pin and has a pneumatic cylinder to work as shocks. However, putting on the attachment requires the user to lift the front wheels entirely off the ground, which in general means the user must get completely out of the chair. The larger front wheel can traverse rough terrain more easily than with smaller castors and the steering of the single wheel helps with travel across lateral slopes.

Figure 5: Rio Mobility Dragonfly (Rio Mobility 2014).

The operator uses their arms in a bicycle like motion to turn the front wheel and propel the device. The handles are connected to a sprocket, which uses an exposed chain to turn the smaller sprocket on the front wheel. A handle mounted about halfway up the shaft activates the disc brake, slowing the device. The Dragonfly can be detached once the user is indoors and the wheelchair functions as a standard chair (Rio Mobility 2014).

4.4.2 Debug Beach Wheelchair

The Debug Beach Wheelchair, Figure 6, is a unique chair designed for use in loose sand. The large wheels allow the chair to sit on top of the surface of the sand rather than sinking in, and the increased contact patches effectively distribute the weight of the user. However, the chair requires an attendant to push it because it has no method for propulsion by the user.

Figure 6: Debug Beach Wheelchair (Debug Beach Wheelchair n.d.).

The rear suspension articulates 20 degrees for each wheel independently to allow the wheels to stay grounded if the surface is slanted or if traveling over ruts or bumps. The chair fits through a 36-inch doorway and has changeable wheels for different environments (Debug Beach Wheelchair n.d.).

4.4.3 Freewheel

The FreeWheel, Figure 7, is also an attachment, but the user propels the chair using the hand rims as a standard wheelchair. The front castors are lifted off the ground and the single inflatable front wheel supports the weight. Once again, putting this attachment on the wheelchair requires the user to be able to lift the front wheels meaning they may require assistance or another chair while attaching the FreeWheel.

Figure 7: FreeWheel (FreeWheel 2015).

The device makes the stance of the chair similar to the Dragonfly, but is much more compact and allows the user to propel the chair in the traditional way that entails grabbing the hand rims (FreeWheel 2015).

4.4.4 Wijit

The Wijit, made by Innovations Health, Figure 8, is a wheel that replaces the wheel on a current chair and is equipped with levers to provide a propulsion method that does not require the user to bend forward. The user is able to remain upright and push both levers, rather than grabbing the rims of the wheels and pushing down and forwards in the arc pattern.

Figure 8: Wijit (Innovations Health 2015).

Wijit can also be quickly adjusted to move forward or in reverse by twisting the handles. The Wijit activates internal gears located at the hub of the wheel in a fashion similar to a ratcheting socket wrench. One gear is present and during the forward setting, a spring-loaded bar engages the teeth and pushes the gear to drive the gear forward and then drags over freely when returning. If the bar is rotated via turning the handle, the bar is rotated in the opposite direction, engaging with the gear teeth pushing the gear backwards and dragging freely over the gear teeth when returning in the same manner. There is also a mechanical advantage created through the use of gears. The Wijit uses a ratio that increases distance per stroke, but a similar mechanism can be adjusted to provide more torque by decreasing the distance per stroke should that be required to climb a slope or move over an object such as a root (Innovations Health 2015).

4.4.5 SoftWheel

The SoftWheel, Figure 9, is a device that incorporates suspension to each of the rear tires by replacing the rigid spokes with shock absorbing compression cylinders. When the chair hits a bump, the cylinders on the bottom expand and those on the top compress so the entire wheel moves up or down in relation to the seat. This helps to alleviate the uneasy ride given by rolling over bumps, cracks, or uneven bricks. Outdoor riding is considerably more comfortable than without shocks and the shocks in the wheel could potentially provide a method of handling harsh terrain like gravel and rocks without adding a great deal of complexity or added features (Softwheel 2014).

Figure 9: SoftWheel (Fertig, Fertig and Fertig 2014).

4.5 Relevant Patents

4.5.1 US4098521A

This patent, Figure 10, is a wheelchair that can be adapted to pass through narrow openings. This works by adding an additional pair of casters underneath the seat of the wheelchair. When necessary, the assistant tips the wheelchair and removes each of the main drive wheels. The wheelchair is now supported by four casters and can fit through openings just barely wider than the user without the driven wheels extending laterally outward past the frame. This chair must be attendant propelled and the transition into narrow areas requires assistance, but fitting through small doorways is possible (Keith 1976).

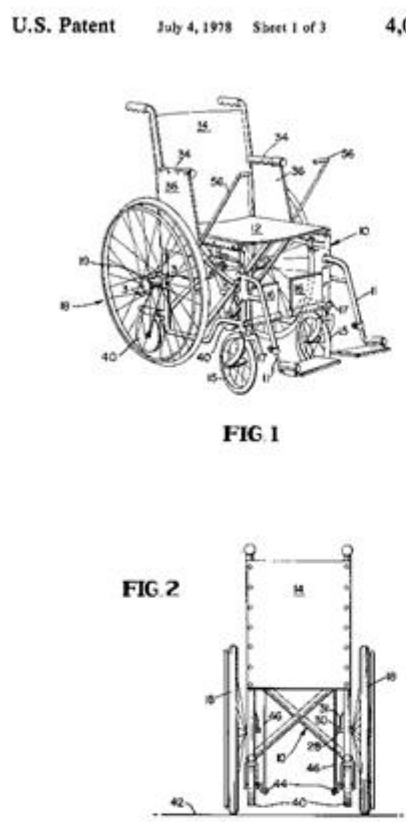


Figure 10: Wheelchair Adaptable for Narrow Openings (Keith 1976).

4.5.2 US20150115566A1

This patent details a manual All-Terrain Wheelchair that has two driven wheels in the standard position of a manual wheelchair and one centered in the front that freely turns. All of the wheels are wider than standard wheelchair tires to allow for travel on non-paved surfaces. The user propels the chair by grabbing the hand rim and pushing forward. The design is more stable than a standard chair due to its increased width and allows for easier travel over uneven surfaces due to an integrated suspension system. (Fertig, Fertig and Fertig 2014).

4.5.3 US3917312A

This patent, Figure 11, is for a wheelchair frame that operates both indoors and outdoors. The chair is similar to a transport chair because of its dimensions, but has wider wheels and a built in suspension system to handle bumps and other challenging terrain. The axles of the two rear wheels are rigidly mounted to the frame, but the front wheels are attached to an extended portion of the frame. The frame supporting the front wheels are subject to elastic deformation during use on rough surfaces and the shock is further dampened by a spring. This allows each of the front wheels to dip or move upward to contour to the surface it is on.

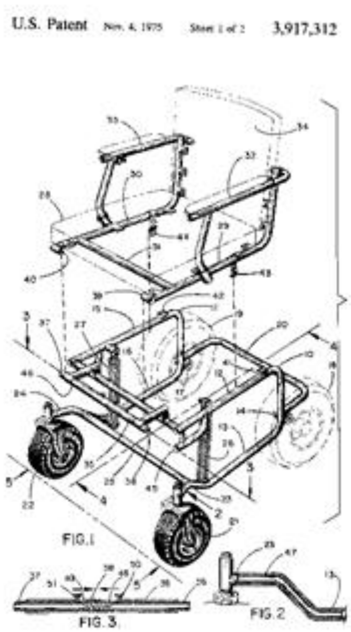


Figure 11: Wheelchair Frame with Suspension (Rodaway 1974).

The elastic deformation of the frame also allows the front of the frame to twist and have each wheel on different horizontal planes. The main feature of this chair is the ability to maintain ground contact with all of the wheels to provide more control and safety, but it requires an attendant to push the user (Rodaway 1974).

5.0 Assessing Users

To determine reasonable expectations for the target users, the group conducted research on user ability and skills tests. Testing published by Dalhousie University accurately assesses users and defines their capability. They are widely accepted tests and known as the Wheelchair Propulsion Test and Wheelchair Skills Test. Each test utilizes the user's own wheelchair to determine if they are effective with what they have or if an adjustment needs to be made.

5.1 Propulsion Test

The propulsion test, Figure 91 in Appendix A, measures the user's ability to push the chair 10 meters forward or backward. It records the number of pushes, distance per push and the pushing and return motion in order to assess the capabilities of the user. The test is used to measure the Derived Wheelchair-Propulsion Data, Figure 12. Some rows provide an opportunity to record observations that potentially optimize results when correct. The test was conducted with 58 diverse test subjects to test validity, reliability, and repeatability and has been determined to be inexpensive, quick and reliable. The averages in Figure 12 create a baseline of the manual wheelchair operator (Askari, et al. 2013).

WPT data (trial 1) (n=58)

Parameter	Data Type*	Values
Recorded data		
Able to successfully complete the 10m	n (%)	58 (100.0)
Direction of travel		
Forward	n (%)	57 (98.3)
Backward	n (%)	1 (1.7)
Limb monitored for cycle count		
Arm	n (%)	46 (79.3)
Leg	n (%)	12 (20.7)
Propulsion method		
2 hands	n (%)	37 (63.8)
1 hand	n (%)	0 (0.0)
1 hand and 1 foot	n (%)	8 (13.8)
2 hands and 2 feet	n (%)	4 (6.9)
2 hands and 1 foot	n (%)	3 (5.1)
1 hand and 2 feet	n (%)	1 (1.7)
2 feet	n (%)	4 (6.9)
1 foot	n (%)	1 (1.7)
Time (s)	Median (range)	15 (6–38)
Cycles	Median (range)	13.5 (2–41)
Hand—proper contact phases†	n (%)	19 (35.9)
Hand—proper recovery phases†	n (%)	4 (7.6)
Foot—proper contact phases‡	n (%)	11 (57.9)
Derived data		
Speed (m/s)	Mean ± SD	0.73±0.29
Push frequency (cycles/s)	Mean ± SD	0.98±0.30
Effectiveness (m/cycle)	Median (range)	0.74 (0.24–5.00)

* Mean and SD data are reported when the data were normally distributed; otherwise, the median value and range of values are reported.

† There were 53 hand propellers.

‡ There were 21 foot propellers, for whom data on the contact phases were missing for 2.

Figure 12: Wheelchair Propulsion Test Results (Askari, et al. 2013)

5.2 Skills Test

The Wheelchair Skills Test, Figure 13, is an assessment of a user that is concerned with their technical abilities. It deals with many factors such as strength, endurance, and balance. The test requires minimal set up, utilizes the user's current manual chair and takes about 30 minutes to administer. The scoring, Figure 14, is on a 0 to 2 scale with 2 being a pass, 1 being a pass with difficulty and a 0 being a failure.

Wheelchair Skills Test (WST) Version 4.2 Form
Manual Wheelchairs Operated by Their Users

Name of wheelchair user: ____________________

Tester: ______________ Date: ______________

#	Individual Skill	Capacity Score* (0-2)	Training Goal? (Y/N)	Comments
1	Rolls forwards (10 m)			
2	Rolls backwards (2 m)			
3	Turns while moving forwards (90°)			
4	Turns while moving backwards (90°)			
5	Turns in place (180°)			
6	Maneuvers sideways (0.5 m)			
7	Gets through hinged door			
8	Reaches high object (1.5 m)			
9	Picks object up from floor			
10	Relieves weight from buttocks (3 sec)			
11	Transfers to and from bench			
12	Folds and unfolds wheelchair			
13	Rolls 100 m			
14	Avoids moving obstacles			
15	Ascends 5° incline			
16	Descends 5° incline			
17	Ascends 10° incline			
18	Descends 10° incline			
19	Rolls across side-slope (5°)			
20	Rolls on soft surface (2 m)			
21	Gets over gap (15 cm)			
22	Gets over threshold (2 cm)			
23	Ascends low curb (5 cm)			
24	Descends low curb (5 cm)			
25	Ascends curb (15 cm)			
26	Descends curb (15 cm)			
27	Performs stationary wheelie (30 sec)			
28	Turns in place in wheelie position (180°)			
29	Descends 10° incline in wheelie position			
30	Descends curb in wheelie position (15 cm)			
31	Gets from ground into wheelchair			
32	Descends stairs			
	Total score:*	%		

* See score options and formula for calculating total score on page 2

1

WST 4.2 Form for Manual Wheelchairs operated by Their Users
Originally approved for distribution and use: April 3, 2013; Current version: May 24, 2013

Figure 13: Wheelchair Skills Test (Wheelchair Skills Program 2012)

Scoring Options for Individual Skills

Score	Score	What this means
Pass	2	Task independently and safely accomplished without any difficulty.
Pass with difficulty	1	The evaluation criteria are met, but the subject experienced some difficulty worthy of note.
Fail	0	Task incomplete or unsafe.
Not possible	NP	The wheelchair does not have the parts to allow this skill.
Testing error	TE	Testing of the skill was not sufficiently well observed to provide a score.

Formula for Calculating Total Scores

Total Capacity Score = sum of individual capacity scores/([32 – # of NP and TE scores] x 2) X 100%

Figure 14: Wheelchair Skills Test Scoring Options (Wheelchair Skills Program 2012)

Thirty of the test criteria were unanimously approved by the nine occupational therapists performing testing. The Center for Rehabilitation Outcomes Research at the Rehabilitation Institute of Chicago performed an independent review and trial of the skills test. They determined the test had an excellent reliability. The mean results of the test, out of 100, organized by location of the injury are the following:

Tetraplegia (C4-C8) = 72.1 ± 7.9

High paraplegia (T1-6) = 82.8 ± 9.1

Low paraplegia (T7-L2) = 84.0 ± 12.4

There are only slight differences between injury locations and the mean for all levels (C4-L2) combined is 80.7 ± 11.8 (Heinemann 2010). This test will be used to determine if a user is capable of using a manual wheelchair, and ultimately an Indoor/Outdoor wheelchair.

6.0 Design Specifications

The following design specifications state the requirements of the device and will be used to measure the success of our prototype. It can be assumed that any specifications referring to the device's function or capability are with a 195 lbs. person in the wheelchair (McDowell 2008). This provides an accurate result because it closely models an average user's weight. It can be noted that the wheelchair will have its maximum weight limit tested separately. Each specification is ranked between 1 and 3 depending on the level of importance and priority to the prototype and final design. Specifications marked with a (3), are regarded as a "must have" for the device. Specifications designated as a (2), are qualities or characteristics that it should have. These specifications would improve certain aspects of the device but are not required for operation or function. Finally specifications marked as a (1), are ones that would just be nice to have. They would be important for a final design but not to a functioning prototype.

6.1 Indoor Operation Requirements

1. The entire device must not exceed 51" in length (3). (ISO 7176-7: 1998)
    a. The ISO standard states that 51" is the maximum operable length while indoors. The shorter the length, the greater the maneuverability.
2. The entire device must not exceed 43" in height (3). (ISO 7176-7: 1998)
    a. The ISO standard states that 43" is the maximum operable height while indoors.
3. The entire device must be capable of an operable width of 28" (3). (ISO 7176-7: 1998)
    a. The ADA standard for a doorway is 32". The 28" width is an ISO standard that allows proper operational clearance through the average doorway.
4. The device must be equipped with wheel locks (3). (ISO 7176-7: 1998)
    a. Wheel locks are required by ISO. Wheel locks improve safety and increase stability while the wheelchair remains stationary.

6.2 Function

5. The device must be able to be operated solely by the user (3).
    a. The device must be transportable, adjustable, and operable without any assistance in order to allow the user independence.
6. The device must have driven wheels that are independent from each other (3).
    b. In order to minimize the turning radius, the driven wheels must be able to turn independently.
7. The chair must support a load of at least 250 lbs. (3).
    c. The 95th percentile of American men is 250 lbs. The device must be able to accommodate 95% of the population (Halls 2015).
8. The seat of the chair must not exceed 20" inches from the ground (3).
    d. Desk heights are a minimum of 28 inches according to ADA standards (Justice 2010). To allow the user to fit underneath the desk, the seat should allow enough clearance for the user's legs and the thickness of the tabletop.
9. The device must have a means of slowing down and stopping which is operable by the user (3).
    e. In order to travel over obstacles and slopes, the device must be capable of stopping with a user in the chair.

10. The device must be able to come to a complete stop within a distance of 10 ft. when traveling at a speed of 9.32 mph on an ADA approved surface (2).
    a. As per ISO 7176-7, wheelchairs have a safety rating for speeds up to 15 km/h (9.32 mph) and should be able to stop within safe distance on an ADA approved surface at this speed. Design Specifications 8-10 and 14 based on function pertain to ISO 7178-8: 1998

6.3 Size/Weight

11. The device must weigh 50 lbs. or less (3).
    a. In order for the device to compete with current models it must fall within the same weight class.
12. The device must not exceed 33" x 29" x 60" during transportation (3).
    a. In order for the device to not inhibit the user's independence, he or she must be able to fit the wheelchair in the backseat of their car. The device may have additional mechanisms that could potential increase length or height, thus the 60" is a reasonable measurement. This measurement was taken from a standard US four-door sedan.

6.4 Maintenance

13. The major components of the device must be assembled and disassembled through the use of common household tools (1).
    a. In order to optimize shipping, the device may need to be assembled upon arrival. Our device must be capable of assembly using only common household tools.
14. Part replacement must be conducted through the use of common household tools (2).
    a. To facilitate maintenance, any replaceable parts should be removable and capable of being reinstalled using common household tools.

6.5 Durability

15. Under normal indoor and outdoor operation, the device must last at least five years (2).
    a. When a chair is used for 8-12 hours a day, it is expected to last five years without replacement (SpinLife: Experts in Motion 2015). The indoor/outdoor wheelchair should at least meet the lifecycle of wheelchairs currently on the market.

6.6 Cost

16. The prototype cost should be less than $640 (3).
    a. This is the amount that is provided by WPI. A successful prototype must be manufactured with the granted funds.

6.7 Aesthetics

17. The wheelchair must have the option to have armrests (1).
    a. This allows the user to decide whether or not they want the armrests; every user has their own preference.
18. The wheelchair must have the option to have wheelie bars (1).

    a. This allows the user to decide whether or not they want the bars, every user has their own preference.

19. The user should be protected from dirt and debris that come from direct contact with the hand rim (2).
    a. Keeps the users hands and clothing, clean and out of harm's way.
20. The wheelchair should come in a variety of colors (1).
    a. Users are more inclined to buy a product if it is customizable.
21. The wheelchair must have a form of storage that can be accessible while seated (1).
    a. Most people carry valuables with them every day, such as phones and wallets. Currently, most users' use a backpack, which is hung on the back of their chair.
22. The user should have the option of attaching a cup holder to the side of their wheelchair (1).
    a. Since a wheelchair user has to use both of their hands to propel the wheelchair forward, they are not able to hold a drink. A cup holder can make carrying a drink more convenient when at a party or even around the house.
23. The user must have the option to have handles on the back of their wheelchair, which can be used for pushing the wheelchair and for holding a backpack (1).
    a. Users normally need to carry valuables and medical equipment with them, which is accomplished by carrying a backpack.
24. Safety labels must be present on the device and be visible (3).
    a. Proper device operation is displayed if the labels are clearly visible, which could prevent injury to the user or damage to the chair.

6.8 Environment

25. The device must be able to navigate no more than or up to 2" wide gaps/cracks from any direction (3).
    a. Standard mountain bike tires have a width 3" and should not be impeded by anything less than or equal to its width when traversing it from any direction. (Brown 2007) As per ADA Standards (302.3), surfaces cannot have cracks or gaps larger than 0.5".
26. The device must not be impeded by a ditch perpendicular to motion less than 6" deep and a width less than the radius of the driven wheels from any direction (3).
    a. As per ADA Standards (302.3), surfaces cannot have cracks or gaps larger than 0.5". However, the device must be able to overcome larger gaps and irregularities in outdoor surfaces. The numbers provided incorporate a larger variety surfaces that contain more imperfections or gaps than ADA approved surfaces.
27. The device must be able to navigate grassy terrains (4" length grass) (3).
    a. Warm and cool season grass is kept at most 4" long, usually (1-3"), and is regularly mowed during its peak season of growing (Bayer Advanced 2015).
28. The device must be operable in cold, winter conditions with temperatures as low as 0 degrees Fahrenheit (3).
    a. In order to make the wheelchair useful in areas subject to cold temperatures, the wheelchair must function properly in temperatures as low as 0 degrees. This is the lowest anticipated temperature that the user will be operating the chair in because the risk of frostbite or hypothermia greatly increases when the temperature dips below zero.
29. The device must be able to traverse walkways that have at least 2" of snow (3).

a. With regular plowing and shoveling, it is reasonable to say that in safe conditions there will be no more than 2" of snow on the ground. The user must be capable of traveling through this amount of snow.

30. The device must not tip when stationary and positioned transversely on a 25-degree slope (3).
31. The device must not tip when stationary and positioned longitudinally on a 25-degree slope (3).
    a. The device must follow ISO 7176 testing standards for static stability on the increased slope angle in order to allow access to a wider range of slopes and terrains. The device will be tested using sandbags weighted to 195 lbs. to model an average user and center of gravity.
32. The device must be able to navigate bumps, logs or rocks that lift one of the rear wheels up to 15 degrees above the other without tipping (3).
33. The device must be able to climb or descend slopes up to 15-degrees while maintaining stability (3).
    a. 25-degrees is at the high end of a beginner ski slope (0 to 30-degrees) and will be used as a measurable goal for stability tests. In addition, testing done at the University of Pittsburgh has determined both theoretically and experimentally that most wheelchairs have a tipping point between 20 & 30 degrees. (Rentschler 2002).
34. The device must be able to traverse 3/4" to 4" gravel or stone walkways (3).
    a. This covered a variety of common gravel path crushed stone sizes. (Braen 2013)
35. The device must be able to traverse Class 1 Hiking Trails (3).
36. The device must be able to travel over a log of at least a 4" diameter (2).
    a. Class 1 hikes have limited exposure to cliffs, steep grades and foot entrapments such as rocks or roots (14ers 2014). This class of trail provides a reasonable goal that the chair should be able to traverse with ease, greatly improving a person's mobility and independence outdoors. These specifications reflect outdoor operating environments that the device will be expected to be able to navigate effectively in order to accomplish the objectives set forward in the goal statement.

6.9 Safety

37. The device has no exposed sharp edges, pinch points, or foot/leg entrapments (3).
38. The user must not be exposed to potential hazards inflicted by the device when operating the device correctly (3).
    a. Keeping the user safe during use is critical. It also needs to keep the person safe who may be lifting the chair for transportation.
39. All mechanisms and wires present on the wheelchair must not interfere with the use of the chair (3).
    b. If an object interferes with the use of the chair and it moving parts, then it could damage the chair, resulting in high repair expenses for the user. Entanglement could cause the chair to suddenly stop moving, causing injury to the user.

6.10 Manufacturability

40. The device must be able to be fabricated using equipment available on WPI Campus (3).
41. The device must be able to be constructed and tested before April 21st, 2016 (3).

42. The device must be manufactured using materials or additional parts that are readily available and low-cost (satisfy budget requirements) (3).
    a. These specifications are set as a means to keep the project grounded in order for it to be finished on time. Additionally the design team must use the resources provided and from that, constraints of manufacturing and tooling are given. Any additional parts that must be ordered should be readily available.

6.11 User Capability Requirement

Subjects must use their own chair to accomplish these tasks to determine if they can effectively use the indoor/outdoor wheelchair. In each specification, WPT denotes a requirement derived from the Wheelchair Propulsion Test, and WST denotes a requirement derived from the Wheelchair Skills Test.

43. The user must be capable of traveling 2.62 feet/second as measured by the Wheelchair Propulsion Test (2).
44. The user must be capable of a push frequency of 1.1 cycles per second according to the Wheelchair Propulsion Test (2).
45. The user must be capable of an effectiveness of 2.66 feet/cycle according to the Wheelchair Propulsion Test (2).
    a. Design Specifications 43-45 have been determined based on the results of the wheelchair propulsion test. The numbers chosen represent users that score 10% higher than the average; a requirement to use an indoor/outdoor wheelchair. (WPT)
46. The user must be capable of turning 90° while moving forward (3).
47. The user must be capable of turning 90° while moving backwards (3).
48. The user must be capable of turning 180° in place (3).
    a. Design specifications 46-47 are defined as such because users must be able to accomplish this in order to navigate through a building or to conquer and/or avoid obstacles while outdoors. (WST)
49. The user must be capable of passing through a hinged door without contacting the door frame (3).
    a. The user must have enough dexterity and fine motor skills to be able to pass through a doorway without crashing in order to allow for safe travel through buildings. (WST)
50. The user must be able to reach an object 5 feet off the ground (1).
51. The user must be able to pick an object off of the floor (2).
    a. Design specifications 50-51 ensure that the user can utilize the chair as transportation, but effectively reach objects in their vicinity. This can be necessary to eat and prepare dinner, or for recreation such as playing toss with a ball. (WST)
52. The user must be able to relieve their full weight from their buttocks for 3 seconds (2).
53. The user must be capable of transferring themselves to and from a bench (2).
    a. Design specifications 38-39 are necessary if the user needs to transfer their body for reasons such as getting into a car or getting into bed. They must be able to lift their weight and transfer it in order to accomplish this independently. In addition, they must be able to readjust their bodies to a comfortable position should they become uncomfortable after an extended period of time. (WST)
54. The user must be capable of folding and unfolding their wheelchair (3).
    a. This ensures that the user can fold up their chair for transportation, and unfold it to get back into it once they reach their destination. (WST)

55. The user must be able to roll 300 feet without rest or over-exertion (3).
    a. The operator must be capable of traveling this distance in order to have adequate endurance. (WST)
56. The user must be able to avoid moving objects while traveling forward (3).
    a. In order to navigate through busy hallways, sidewalks or trails, moving objects such as pedestrians should be avoided. (WST)
57. The user must be capable of ascending a 10° incline on an ADA approved surface (3).
58. The user must be capable of descending a 10° decline on an ADA approved surface (3).
59. The user must be capable of rolling across a side slope of 5° (3).
    a. Design specifications 57-59 ensure that a user can move on slopes that are steeper than ADA approved surfaces in their current chair. Should the user pass these specifications, they should be able to meet or exceed the design specifications set for the indoor/outdoor wheelchair. (WST)
60. The user must be capable of rolling 2m on grass specified in Design Specification 27 (3).
61. The user must be capable of rolling 2m on carpet (3).
    a. Design specifications 60-61 ensure that the user is capable of traversing slightly challenging surfaces. This demonstrates control and a general awareness of how to move over outdoor terrain. (WST)
62. The user must be capable of moving over a 0.8in high threshold (3).
    a. Getting over door thresholds and transferring from one surface to another as well as going over small rocks or roots is required of the user. (WST)
63. The user must be capable of performing a stationary wheelie for at least 15 seconds (2).
    a. This requirement entails a great deal of agility and control. These qualities are required to operate the indoor/outdoor wheelchair effectively. (WST)
64. The user must be capable of getting into the wheelchair from the ground (3).
    a. This design specification requires the user to be able to get into his or her chair should an accident happen that throws them from their chair. The ability to return to an operating position on the seat is required in order to allow the user to independently travel on rough trails. (WST)

7.0 Ideation & Selection

Creating a final design was a multistep process. First, a morphological chart was created. This chart consists of functions to be considered for the preliminary concepts. To determine how stability is affected by the user's center of gravity, a parametric analysis was performed. The analysis tests the stability of a wheelchair in both the longitudinal and lateral direction when the user's center of gravity is shifted. With the results from the parametric analysis in mind, preliminary concepts were created. These concepts were broken into three major sections: stability, propulsion, and braking. From these concepts, six preliminary designs were created using functions from the morphological charts. To pick the top designs, a weighted decision matrix was created. The weighted design matrix led to two different designs. Zero order prototypes were created to show proof of concept and to compare the designs. After the comparison, one final design was selected.

7.1 Morphological Chart

In the ideation phase of design, it is important to use methods of brainstorming and creation to extract all ideas that can be incorporated into a final design. One method is the creation of a morphological chart. A morphological chart is used to generate solutions for multiple design functions. For each function, possible solutions were

7.1.1 Ranking Functions

The main functions of the Indoor/Outdoor wheelchair are Propulsion, Power Transmission, Stopping, Stance, Seat Position, Lateral Stability, Transportation and Storage, Suspension, Turning, and Longitudinal Stability. Each of the functions is described in Table 3.

Table 3: Description of Functions

Propulsion The manner in which the user translates force to the wheelchair, driving it in a desired direction.	**Stopping** The braking mechanism used to slow or stop the wheelchair during operation.	**Lateral Stability** The configurations that allow the device to traverse cross slopes without danger of tipping	**Longitudinal Stability** The configurations that allow the device to travel up and down slopes without tipping.
Power Transmission The manner in which the chair translates the force inputted by the user into useful motion.	**Stance** The number, relative size, and layout configuration of the wheels that contact the ground during operation.	**Transportation and Storage** The methods by which the device can be moved from location to location or put in a tight space when not in use.	**Turning** The way in which the device changes direction or moves in a direction other than forward or backward.
Power Transmission Mechanism The mechanism by which the user's force is translated to the wheels.	**Seat Position** The available axes that the seat or backrest can transition between.	**Suspension** The locations in which a suspension mechanism may be placed.	**Suspension Mechanism** The mechanical feature that directly absorbs the shock produced by traveling over uneven surfaces.

In order to rank each function in order of importance to the design, a function-ranking matrix (Pairwise comparison chart), Table 4, was created to compare the importance of each function to another. Each row represents the function being evaluated and each column represents the function it is being evaluated against. If the function in the row is more important than the one in the column, it receives a 1. If they are of equal importance a 0.5 is awarded. If the function in the row is less important than the one in the column, it receives a 0. The total is tallied up, and the relative rankings of each function are determined.

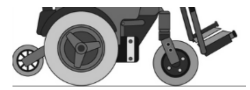
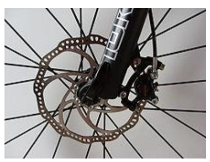
Table 4: Function Ranking Matrix. The color scale shows the most important features in green and the less important features in red.

	Propulsion	Power Transmission	Power Transmission Mechanism	Stopping	Stance	Seat Position	Lateral Stability	Transportation and Storage	Suspension Mechanism	Suspension	Turning	Longitudinal Stability	Total
Propulsion	0	1	1	0	0.5	1	0	1	1	1	0	0	6.5
Power Transmission	0	0	1	0	0	1	0	1	1	1	0	0	5
Power Transmission Mechanism	0	0	0	0	0	0	0	0	0	0	0	0	0
Stopping	1	1	1	0	1	1	0	1	1	1	1	0	9
Stance	0.5	1	1	0	0	1	0	0.5	1	1	0	0	6
Seat Position	0	0	1	0	0	0	0	0	1	1	0	0	3
Lateral Stability	1	1	1	1	1	1	0	1	1	1	1	0.5	10.5
Transportation and Storage	0	0	1	0	0.5	1	0	0	1	1	0	0	4.5
Suspension Mechanism	0	0	1	0	0	0	0	0	0	0	0	0	1
Suspension	0	0	1	0	0	0	0	0	1	0	0	0	2
Turning	1	1	1	0	1	1	0	1	1	1	0	0	8
Longitudinal Stability	1	1	1	1	1	1	0.5	1	1	1	1	0	10.5

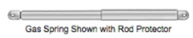
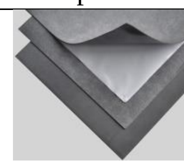
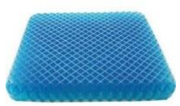
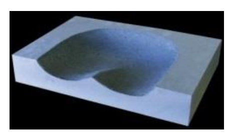
Once the order of importance was determined, the morphological chart,

Table 5, was put in that order and solutions were devised. Each solution has different advantages and disadvantages, but the order of the solutions from left to right is the most desired to the least desired. These were ranked based on factors such as function and feasibility.

Table 5: Morphological chart to aid in generating preliminary designs

Function	Solution						
Lateral Stability	 Lower Center of Gravity	 Camber	 Casters that Rotate Outward	 Wider Frame	 Wider Wheels		
Longitudinal Stability	 Extendable wheelbase	 Lengthened Wheelbase	 Lower Center of Gravity	 Additional rear Caster(s)			
Stopping	 Disc Brakes	 Rim Brakes	 Cantilever Brakes	 Coaster Brakes	 Grabbing Rims	 Wheel Locks	 Ground Contact
Turning	 Independent Wheels	 Rear Turning Wheel	 Front Turning Wheel				

Propulsion	 Drive Levers	 Hand Pedals	 Rims				
Stance	 Two Big Two Small	 Rear Tricycle	 Front Tricycle	 Four Equal Wheels			
Power Transmission	 Gearbox	 Single Speed	 Hand on Rims	 Multi Speed			
Transportation & storage	 Collapsible chair	 Backrest folds down	 Removable Wheels				
Seat Position	 Height Adjustable (Up & Down)	 Length	 Totally adjustable (both up & down and				

		Adjustable (forward & backward)	forward & backward				
Suspension	 Seat Suspension	 Compressible Spokes	 Rear Caster Suspension	 Front Caster Suspension			
Suspension Mechanism	 Mechanical Springs	 Gas Springs	 Vibration Dampening Material				
Power Transmission Mechanism	 Gearbox/lever system	 Belt	 Chain				
Seat (Accessory)	 Gel	 Breathable Mesh	 Form-Fitting				

Storage (Accessory)	 Under Seat	 Zipper Pockets	 Backpack Hooks	 Velcro	 Attachments		
Arm Rests (Accessory)	 Removable	 Foldable	 Swivel	 Non-Foldable			
Tip Sensor (Accessory)	 Accelerometer - 1st	 Plumb bob					
Tip Warning (Accessory)	 LED Warning - 1st	 Vibration Warning					

7.2 Parametric Analysis

Before starting to generate preliminary concepts, a parametric analysis was performed to determine how shifting a user's center of gravity and widening the base of the wheelchair affects the tipping angle of the wheelchair.

From the analysis, in Appendix B: Parametric Analysis, the longitudinal uphill tipping angle will be affected by changing the CG's horizontal distance from the rear wheel's point of contact and the height of the user's center of gravity.

When determining how the tipping angle is affected going downhill longitudinally using the height of the CG and the wheelbase, it is a reasonable assumption that changing the CG horizontal distance from the rear wheel contact point will have the same impact on the tipping angle.

Finally, the lateral tipping angle was analyzed. The group found that changing the track at different heights of CG would not have a greater impact on the tipping angle. For example, changing the track width "x" amount at seat height "y" will have the same effect as changing the track width "x" amount at seat height "z". Conversely, at any track width, changing the height of the CG will have the same effect on the tipping angle. This shows that the tipping angle of the chair is dependent on each factor individually. Thus, meaning that the track width and CG height have negligible effects on each other.

7.3 Preliminary Concepts

When generating design concepts, three categories were considered: stability, propulsion, and braking.

7.3.1 Stability

To improve stability, the tipping angle can be increased by lowering the user's center of gravity, moving the user's center of gravity forward to prevent rearward tipping, and/or widening the base of the wheelchair. Multiple designs were used to move the user's center of gravity: cambered wheels, unequal four bar linkage, and parallelogram linkage.

7.3.1.1 Cambered Wheels

Cambered wheels increase the stability of the wheelchair by increasing the lateral base of support of the wheelchair. The angle of the cambered wheels is limited by the width of a doorframe since increasing the wheel angle increases the width of the wheelchair. Other advantages along with disadvantages are listed in Table 6.

Table 6: Advantages and Disadvantages of Cambered Wheels (Landsman 2015)

Advantages	Disadvantages
• Places the push rims in a more ergonomic position for pushing. It is more natural to push down and outward • Forces are redirected to soften the ride • Protects the hands when pushing in tight areas • Makes turning quicker • Less strain on shoulders since the plane of the wheel is closer to that of the shoulder	• May add cost to the chair • Excessive camber may cause the wheels to rub against the armrest side panels or against the user • Diminished traction and uneven tire wear on conventional tire

7.3.1.2 Unequal Four Bar Linkage

The unequal four bar linkage design consists of different length links that move the seat and backrest of the chair together in order to move the CG forward and downward to improve stability. The linkage systems are shown in blue in Figure 9.The unequal four bar linkage utilizes two parallel four bar linkages, one on each side of the chair. The large links are longer than the small links. The seat base serves as the coupler link between the long and short rockers of the linkage. Figure 15 illustrates how the system will be mounted to a basic wheelchair frame.

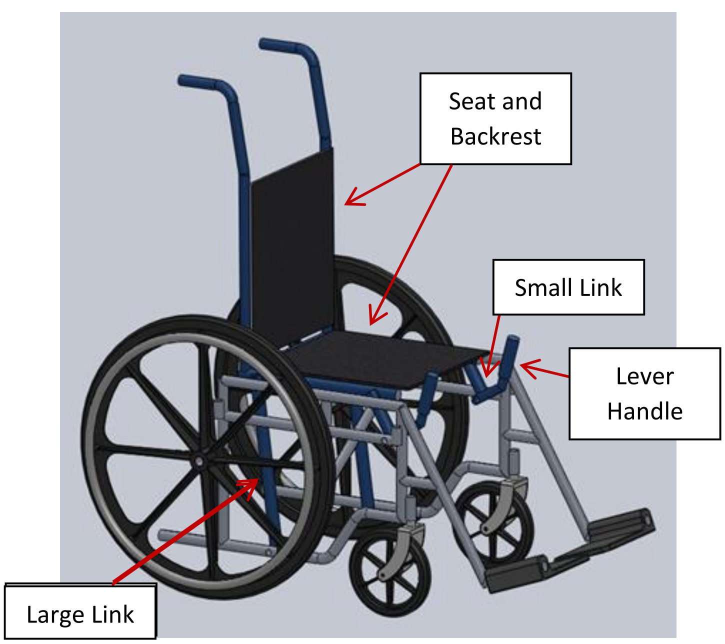


Figure 15: Unequal four-bar linkage consisting of two short links, two long links, two lever handles, a seat, and a backrest.

The indoor position of the linkage system is its furthest back position. This configuration places the seat in the standard position of an unmodified manual wheelchair. The backrest, mounted to the seat, will move with the seat as the linkage system is actuated. Figure 16 illustrate the indoor position and the links being used in the design.

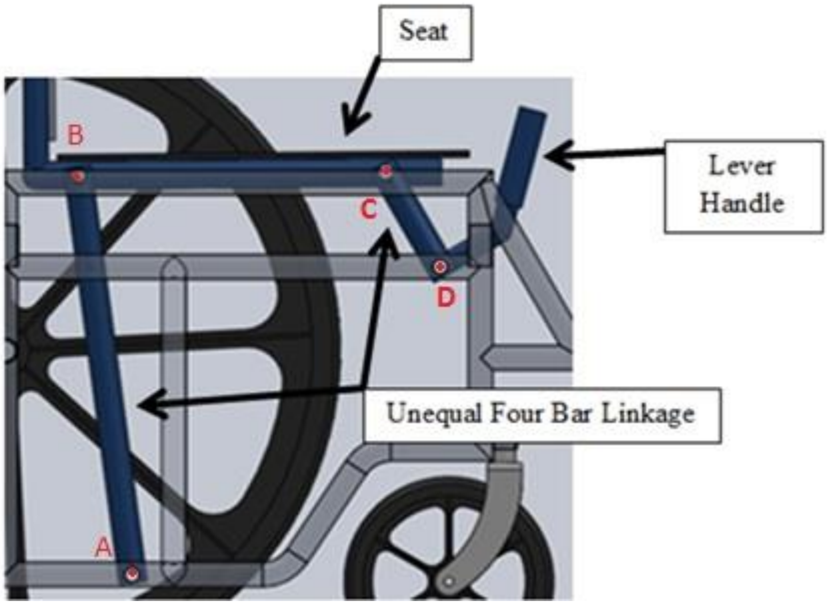


Figure 16: Close-up Side view Unequal Linkage in Indoor Position. The large link is from joint A to B and the small link is from joint C to D.

The longest link (AB) is attached to the bottom bar of the frame at joint A, which allows rotation. Joint B connects the longest link and the rear end of the seat. Then, the shortest link (CD) is attached to the frame at joint D and the seat front at C. The lever handle, a rigid extension of link CD, is used to rotate the whole linkage system forward to the outdoor position when the user pushes on the lever handles (Figure 17).

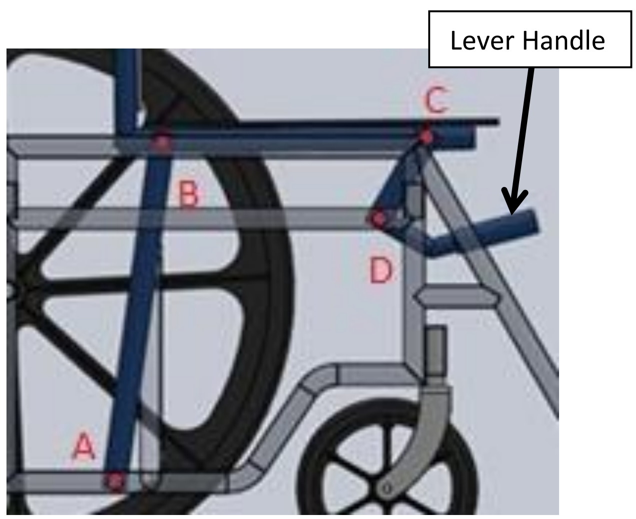


Figure 17: Side View of Unequal linkage wheelchair with the seat in the forward position.

To return to the indoor position, the user will grab on to the armrests and push backward on the seat. To limit the rotational motion of the links, rubber stops (not shown) will be mounted on the frame at appropriate positions to prevent the links from rotating further than desired.

7.3.1.3 Parallelogram Linkage

This design employs a parallelogram four bar linkage to move the seat forward and down. The parallelograms run parallel to the frame, so the drawing only shows the side of the parallelogram. In the upright position, the seat is functional for indoor use, Figure 18. The right armrest is not shown in order to clearly see the parallelogram mechanism. When the chair is used outdoors, the chair is moved to the forward position, Figure 19.

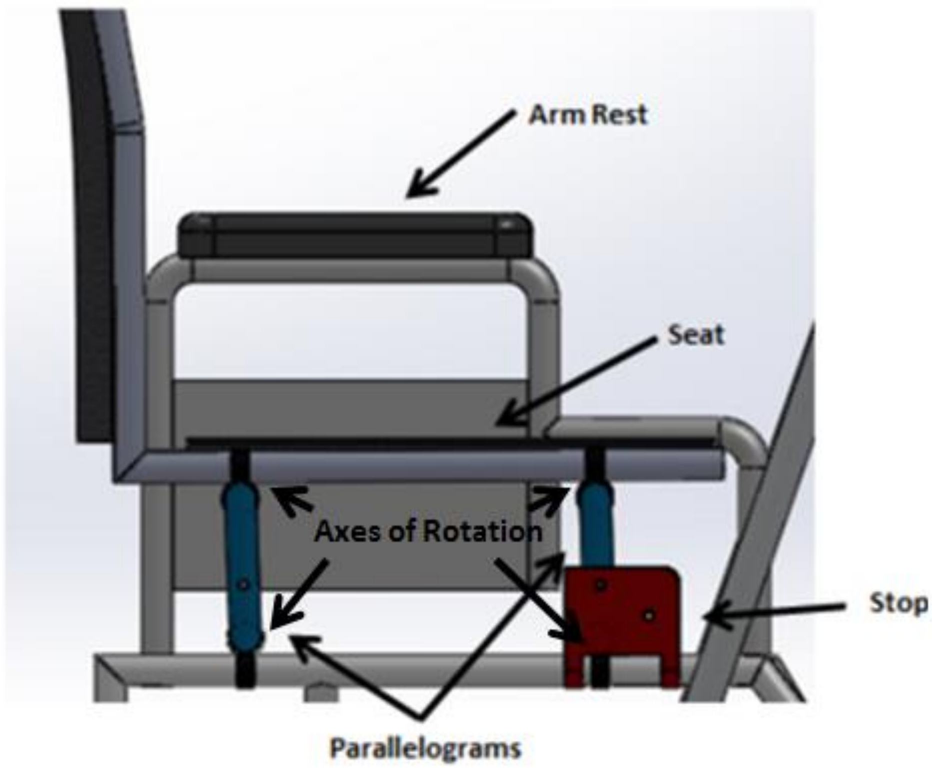


Figure 18: Side View of Parallelogram Mechanism in Indoor Position

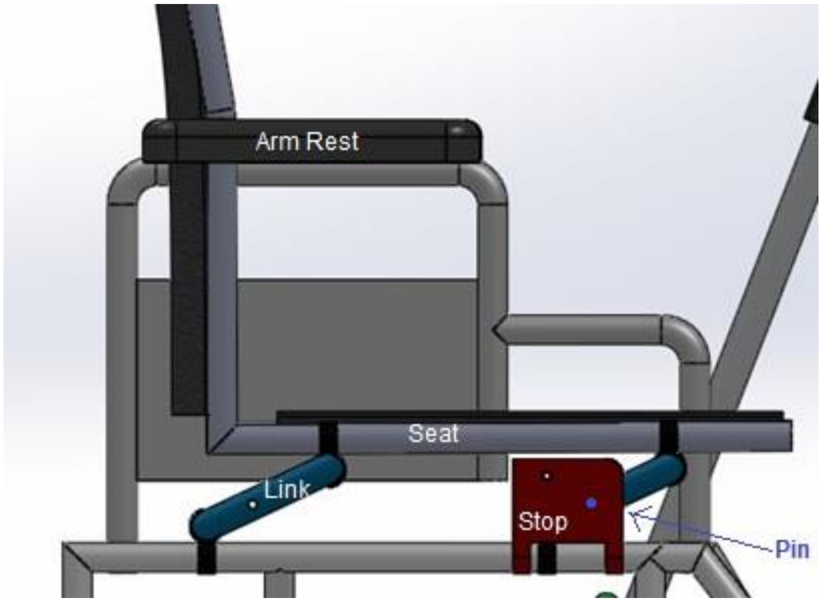


Figure 19: Side View of Parallelogram Mechanism in Outdoor Position

A lock, located at each front link, will keep the wheelchair's seat in its desired position. The lock uses a stop and a pin to keep the seat in its position. To transition from indoor to outdoor position, the user pulls a pin that passes through the parallelogram link and the stop. Both sides of the chair have identical pins and stops. The stop, Figure 20, is designed specifically for this application by providing a front contour to prevent the seat from tipping further forward, and a rear contour to prevent the seat from traveling too far backward. To change the seat's position, the user would support his or her body using the armrests, which are attached to the frame, and move the seat either by sliding forward to move to the outdoor position or by pushing on the backrest to move to the indoor position. In the forward position, the parallelograms are at a 25° angle from the horizontal and all of the weight is supported by the stop and linkage. Therefore the user is not required to support any weight while inserting the pins. When transitioning into the indoor position, the user does not have to hold their weight while inserting the pin since the parallelogram sits at a 95-degree angle from the horizontal. The black portions are where the front link of the parallelogram rests at each seat position. The sleeves at the bottom are to attach the stop to the frame of the wheelchair. Lastly, the small holes on the side are for a tethered, magnetic pin that locks the position of the parallelogram.

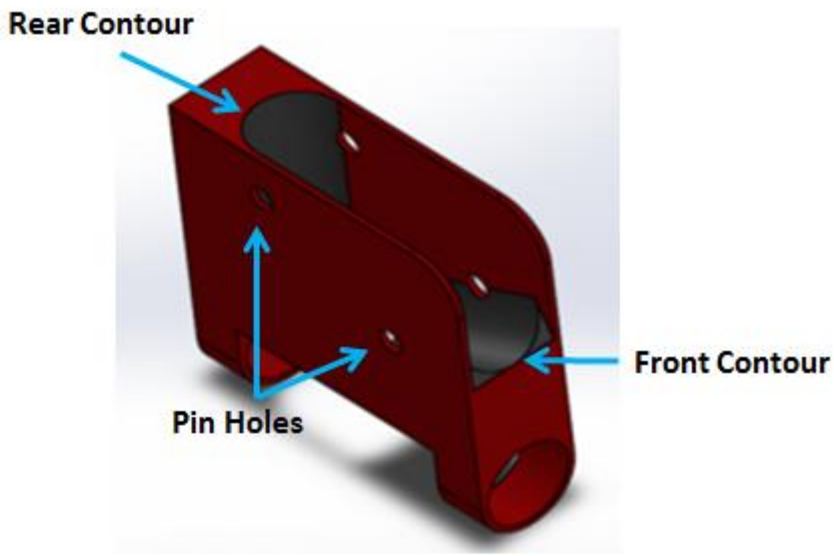


Figure 20: Stop for Parallelogram Mechanism that Holds the Wheelchair in the Indoor or Outdoor Positions

7.3.2 Propulsion

Different methods can be used to propel the chair. The mechanical advantage each design provides can be crucial to the success of the device. Also, the ease of operation is a considerable factor that can greatly affect a design. The positioning of the hands is important because it affects the ergonomic mechanics, force application, and comfort regarding grip and operational endurance.

7.3.2.1 Hands on Rims

Hands on rims propulsion is the simplest of all propulsion systems. It is the easiest to learn and maintain. When a person first starts to use a manual wheelchair, they are taught to propel themselves using hand rims. Therefore, using this propulsion system, the user would not have to learn a new method of propulsion. Additionally, since hand rims are so common, they are easy to replace with parts being readily available. While desirable in some ways, hands on rims may not be the most ergonomical and efficient method. This method of propulsion is desirable for its simplicity, adaptability, and reliability.

7.3.2.2 Drive Levers

Drive levers are capable of providing a mechanical advantage. The following design utilizes a drive lever paired with a ratchet and pawl assembly mounted on each rear axle. The drive lever is connected to the frame via pin joint A, and is connected to the coupler (green) via Ball Joint A, Figure 21.

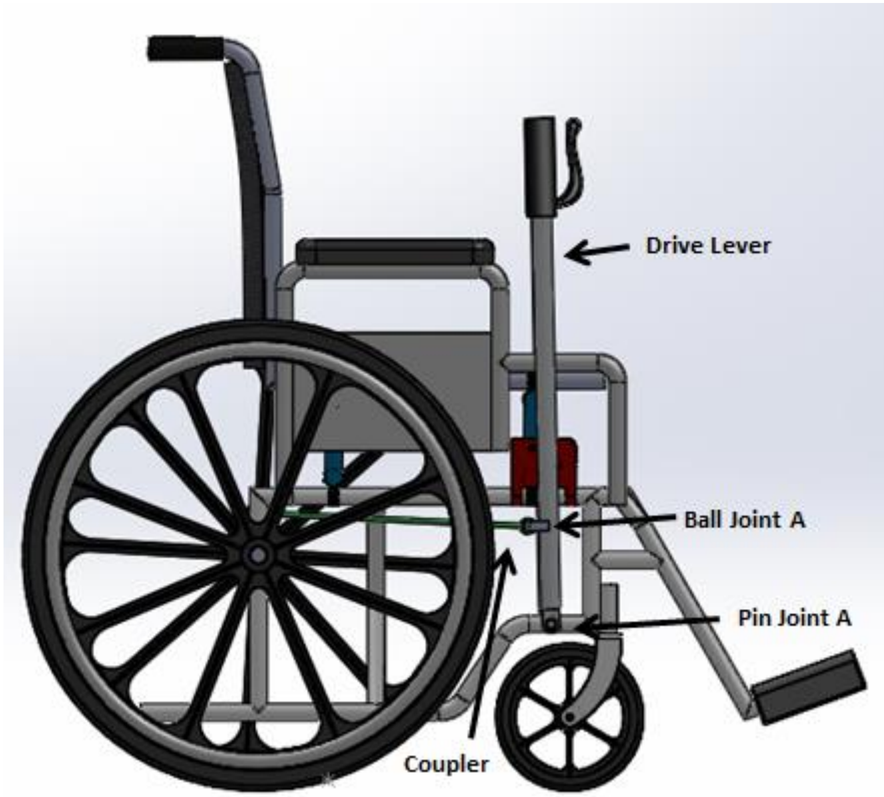


Figure 21: Side view of a drive lever propulsion system.

To more clearly show the power transmission, the rear wheels have been removed and the ratchet and pawl system on each side of the wheelchair is shown, Figure 22.

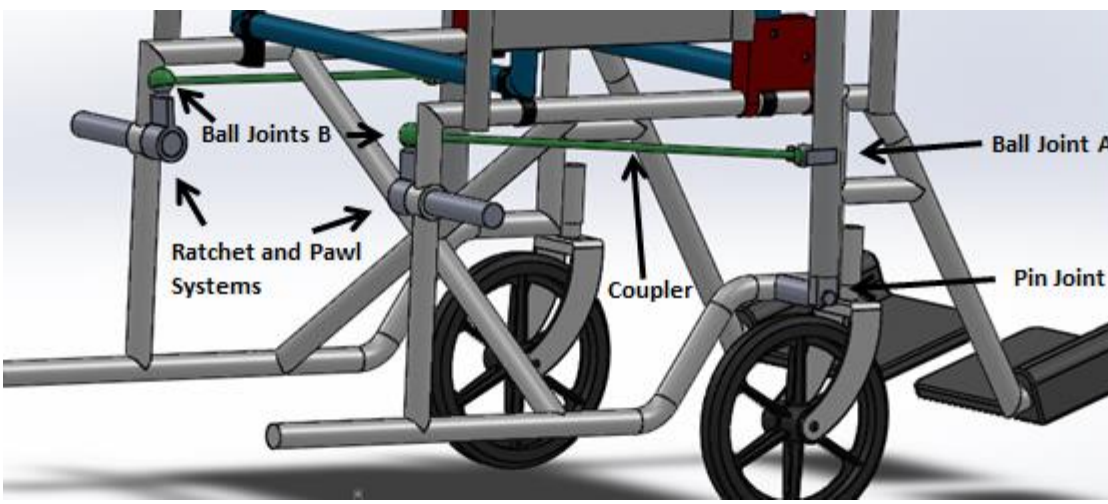


Figure 22: Close View of Propulsion System

When the drive levers are pushed, the force is transferred through Ball Joint A to Ball Joint B via the coupler. The ratchet and pawl system allows the motion to propel the chair forward and return to the original position when the drive levers are pulled backwards. The direction of the ratchet and pawl system can be controlled by a switch mounted at the top of the drive lever that changes which pawl is engaged to the ratchet (not shown). Each drive lever system is operated individually, allowing the chair to move forward or backwards and turn in any direction including pirouette.

7.3.2.3 Adjustable Levers

The drive levers are mounted by pin joint B directly to the frame, Figure 23. Many parts of the wheelchair have been removed and only one drive lever is depicted for simplicity. A reversible ratchet and pawl assembly is mounted to each wheel axle that works similar to a ratchet socket wrench that can be set to actively rotate one way, and passively rotate the other. When the drive lever is pushed forward (away from the user), it moves the coupler forward and activates the ratchet and pawl assembly. When the drive lever is pulled backwards (toward the user), the coupler follows the same path but passively returns the pawl to its original position.

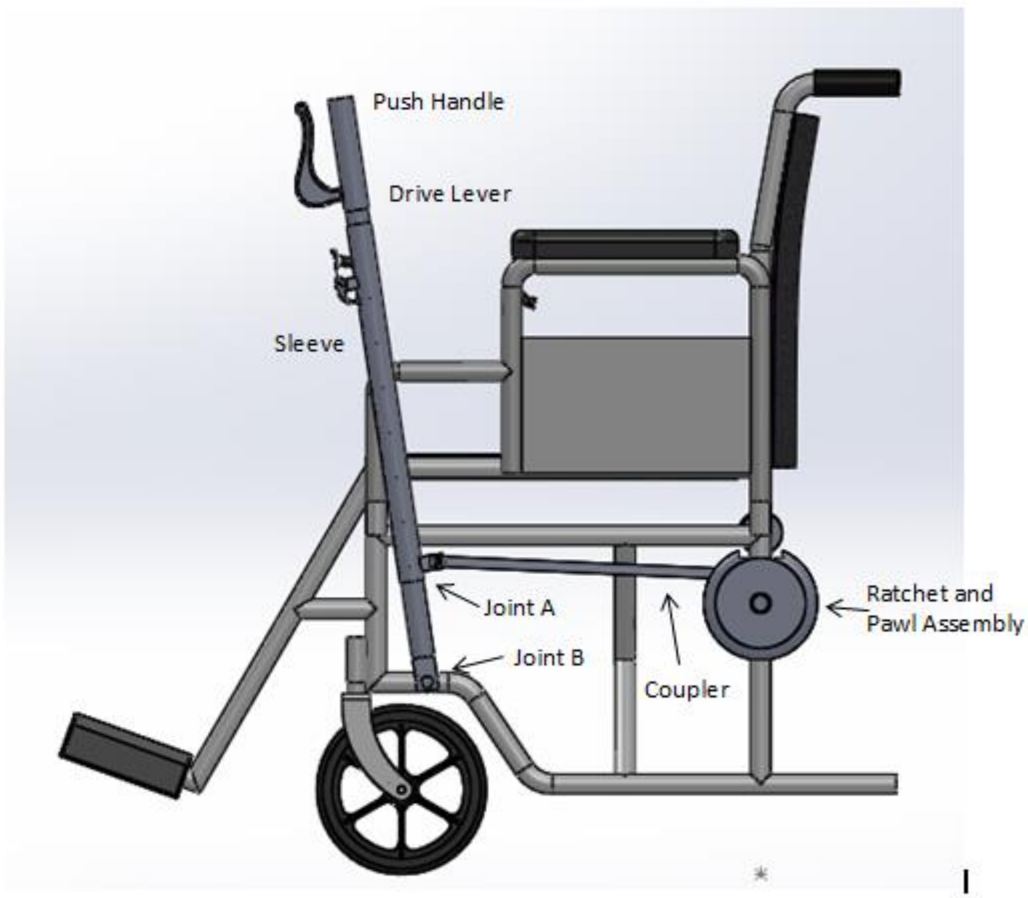


Figure 23: Side View of Adjustable Drive Lever Design

The mechanical advantage of the linkage can be changed by sliding the sleeve up and down the drive lever. This is done by squeezing the sleeve handle, which removes the locking pin from the notches in the drive lever, Figure 24. The handle moves up and down with the sleeve. When the sleeve handle is released, the spring loaded locking pin slides into a notch and sets the location. At the sleeve's top position, the ratchet and pawl system will rotate more with each stroke. At the bottom position, the ratchet and pawl system rotates less with the same stroke of the handle, increasing the mechanical advantage.

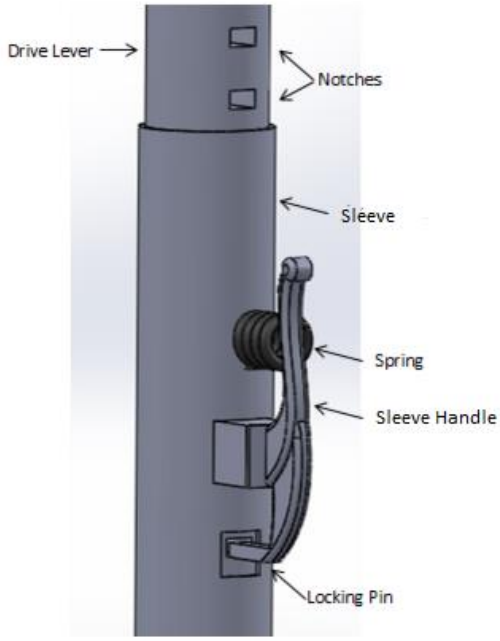


Figure 24: Close up of Drive Lever Sleeve used to Adjust Drive Lever Mechanical Advantage

In order to analyze the mechanical advantages possible with this design, 24 in. long drive levers were assumed to be mounted with a maximum horizontal stroke of 12 in. The locations of pin joint A were estimated to be between 4 and 12 in. from pin joint B. Although the drive lever will move in an arc, a horizontal distance at the minimum and maximum points along the drive lever will be compared to the stroke of the drive lever grip as a close estimate of the ratio of the input to output, Figure 25.

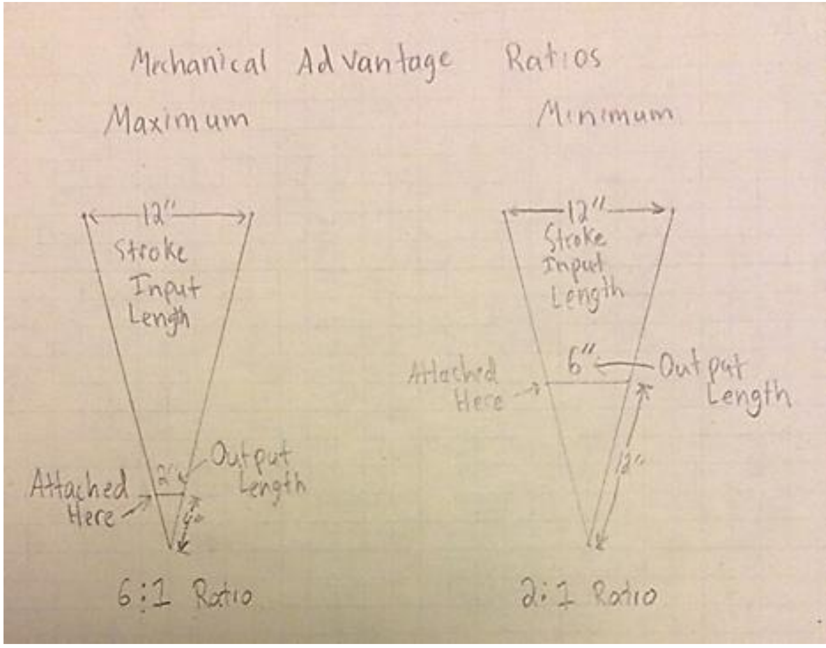


Figure 25: Analysis of Mechanical Advantage Dependent on Lever Arm Length

When the bar is mounted 4 in. from the pin joint, the output length is 2 in., which yields a 6:1 mechanical advantage. When the bar is mounted 12 in. from the pin joint, the output length is 6in., which yields a 2:1 mechanical advantage. This range is large enough for a user to be able to conquer many outdoor obstacles, but may not be ideal for traversing over flat surfaces because maintaining a mechanical advantage can decrease the speed of the system. Adjustable levers are desirable when considering versatility and adjustable mechanical advantages. However, the manufacturability may create complex challenges.

The handle at the top of the drive lever will have an easily accessible brake handle in addition to a drive switch on top. The drive switch will use a cable system to change the direction of the ratchet and pawl system forward, neutral, or reverse. The idea will look similar to Figure 26.

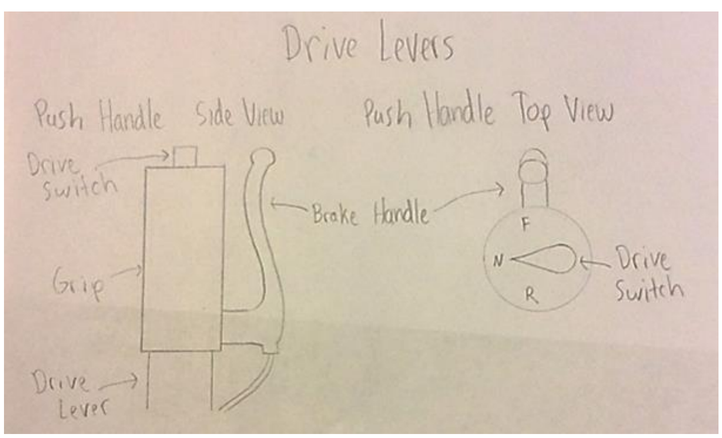


Figure 26: Drive Lever Handle used to Adjust Gears and Brake

7.3.3 Braking

The final design category is braking. Braking is crucial, as it directly relates to the safety of the operator. Two types of braking systems were considered, disc brakes and cantilever brakes, Table 7. After considering the advantages and disadvantages of these braking systems, it was decided that disc brakes would be used on all designs that have an added braking system.

Table 7: Advantages and Disadvantages of Disc Brakes and Cantilever Brakes (Road Bikes: Rim Brakes vs. Disc Brakes 2015)

Disc Brakes	Cantilever Brakes
Advantages • Strong stopping power in all weather conditions • Easily modulated power • Little strength needed to engage • Unaffected by warped rims • No rim wear and tear	Advantages • Easy installation • Less stress on spokes • Less maintenance
Disadvantages • Hard to install • More stress on spokes • Requires a rotor mounted to the wheel	Disadvantages • Takes time to engage • Severely affected by weather • Wear and tear on rims • Affected by water and mud

7.4 Preliminary Designs

Features described in the Preliminary Concepts section of this document were combined to create six preliminary designs.

7.4.1 Design One

The first design uses three features: unequal four bar linkage, cambered wheels, and hand rims. The unequal for bar linkage moves the seat forward to increase uphill longitudinal stability. The cambered wheels will increase the lateral stability. The propulsion method for this design is hand rims.

7.4.2 Design Two

This design utilizes only the unequal four bar linkage to change the center of gravity in a horizontal direction, which increases longitudinal stability. Hand rims will remain the means of propulsion in this design.

7.4.3 Design Three

The third design consists of the unequal four bar linkage to increase longitudinal stability and a drive lever system used for propulsion.

7.4.4 Design Four

Design four consists of two features: unequal four bar linkage and adjustable drive levers. The unequal four bar linkage will increase the longitudinal stability when traveling uphill. The adjustable drive levers will allow for optional mechanical advantages along with a new way to propel the wheelchair.

7.4.5 Design Five

The fifth design uses the parallelogram four bar linkage and drive levers. The parallelogram four-bar linkage moves the center of gravity forward and down which increases stability both longitudinally and laterally. The drive levers allow the choice between using the drive levers or the hand rims for propulsion.

7.4.6 Design Six

Finally, design six utilizes two features: parallelogram four bar linkage and adjustable drive levers. The parallelogram four-bar linkage will increase the longitudinal and latitudinal stability of the wheelchair while the adjustable drive levers provide a mechanical advantage during propulsion.

7.5 Assessing Preliminary Designs

7.5.1 Weighted Decision Matrix 1

Several factors must be included in the weighted decision matrix. The factors for the indoor / outdoor wheelchair are:

Function – The ability for the chair to accomplish tasks involved with conquering obstacles such as doors and narrow hallways indoors and slopes, rocks and grass outdoors.

Safety - The ability for the chair to mitigate risk of injury or other dangers to the user regarding tipping and physical hazards such as pinch points, sharp edges, and foot entrapment.

Ease of Use - The effort required to utilize the device's features.

Manufacturability - The ability to make a working prototype of the device with the given resources and allotted time.

Durability - The ability for the device to endure normal use for several years without excessive wear or unreasonable maintenance.

To determine the best designs, the designs are ranked on these factors that differentiate a successful design from an unsuccessful one using a weighted decision matrix. In order of importance the factors are Function, Safety, Ease of Use, Manufacturability, and Durability. These factors must be weighted based on relative importance. The weights of the factors are presented in Table 8 and described in the following paragraphs.

Table 8: Weights of Each Factor

Factor	Function	Safety	Ease of Use	Manufacturability	Durability
Weight	30%	30%	18%	15%	7%

First, function and safety are tied as the most important because safety is not important if function is not achieved and vice versa. These factors are the most important which led them to account for a combined 60% of the total. Less important than those two factors is the ease of use, giving it a weight of 18%. If a device is not easy to operate, regardless of its capabilities, it may prevent people from purchasing the device. Based on the time, money, and available resources of this project, manufacturability is the next most important factor, giving it a weight of 15%. It is likely that a corporation would put manufacturability as a lower weight, possibly below durability, but for this project it is an important factor. If a successful prototype cannot be built, a lack of proof of concept leaves possibilities for failure. The next most important factor is durability, giving it a weight of 7%. Similarly, durability for this project may not be a driving factor, but certainly should be included. The wheelchair will take the place of two wheelchairs; an indoor and an outdoor wheelchair, meaning the use will be considerably more than a normal wheelchair. During full-scale production, durability will be crucial, but for this project it is a less important factor.

Within some factors are sub-factors that further define the ranking criteria in the weighted decision matrix. The sub-factor weights must add up to the weight of the factor they pertain to. The breakdown of each sub-factor can be found in Table 9, Table 10, Table 11, Table 12, and Table 13

Table 9: Function Sub-Factor Breakdown

Function 30% Total			
Sub-Factor	Turn Radius	Stopping	Propulsion
Weight	10%	12%	8%

Function is broken down into Turn Radius, Stopping and Propulsion. Turn radius is measured as the furthest point from the center of rotation when in indoor operation. This is important for moving through buildings, giving it a weight of 10%. Next is stopping, 12%, because of the need to be able to control the speed of the wheelchair and be able to stop within a reasonable distance. The last sub-factor is propulsion, which is concerned with how the user moves the wheelchair. If he or she cannot move the wheelchair efficiently, it will not be an effective design.

Table 10: Safety Sub-Factor Breakdown

Safety 30% Total			
Sub-Factor	Lateral Stability	Longitudinal Stability	Physical Hazards
Weight	12%	12%	6%

Safety is broken down into 3 sub-factors: Lateral Stability, Longitudinal Stability and Physical Hazards. Lateral and longitudinal stability are very important factors for safety because tipping can cause users to fall out of their chair and lead to injury. They are weighted equally because of the importance not tipping in either direction is of equivalent value. Additionally any design features or mechanisms must not be hazardous such as a sharp edge, pinch point or foot entrapment.

Table 11: Ease of Use Sub-Factor Breakdown

Ease of Use 18% Total			
Sub-Factor	Portability	Transfers	Indoor / Outdoor Transition
Weight	4%	6%	8%

The most important sub-factors for Ease of Use are the wheelchair's transition from indoor to outdoor configurations. The transition is a crucial component of the project and warrants a rating of 8%. It deals with the difficulty of the modifications, if any, which must be made to the device when changing from indoor to outdoor operation and vice-versa. The Transfers sub-factor is concerned with the ease of relocating the user to and from the device. Portability is the device's ability to be transported. This is important because the user is considering the size of his or her own car when selecting a wheelchair.

Table 12: Manufacturability Sub-Factor Breakdown

Manufacturability 15% Total			
Sub-Factor	Cost	Part Availability	Processes
Weight	5%	5%	5%

The Cost sub-factor is concerned with the cost of manufacturing the prototype. It is important to keep to the budget to ensure construction of the prototype. Part Availability is the ability to get the necessary components in a timely manner. Processes are the methods of manufacturing that must be used for components of the device. Each of these sub-factors is equally important in achieving a successful prototype, giving 5% to each.

Table 13: Durability Sub-Factor Breakdown

Durability 7% Total		
Sub-Factor	Useful Life	Repair
Weight	5%	2%

Useful life is the longevity of the device under normal use. This is important to ensure that the user does not have to regularly purchase new wheelchairs, giving it 5%. Repair is the difficulty to fix certain components of the device. This is less important than making a durable wheelchair that will last several years.

7.5.1.1 Scale Ranking Description

Each design was evaluated for each sub-factor on the weighted decision matrix rubric. The weight decision matrix allows each design to be ranked for effectiveness. The ranking was completed on a scale from one to five, with five being the best. Each rank within the scale was given a form of evaluation.

The function rubric is found in Table 14. The turning radius was evaluated on the amount of space in inches the wheelchair took up while turning. The maximum wheelchair that falls within the design specifications is 51” long x 28” wide, which gives it a turning radius of 29” if it can pirouette. The turning radius will increase if a wheelchair is not capable of a pirouette. A rank of 1 is assigned if the device has a turning radius greater than 40", which would be too large for indoor navigation. A rank of 2 is assigned if the device has a turning radius between 35” and 40". A rank of 3 is given if the device has a turning radius between 30" and 35". A rank of 4 is given if the device has a turning radius between 25" and 30". Finally, a rank of 5 is given if the device has a turning radius of less than 25" (a common radius for daily use chairs).

Stopping was ranked based on the distance it takes to stop when traveling 10 mph. This is determined both by the type of brake and the tires contacting the ground. If a device can come to a complete stop from 10 mph within a distance of 3 feet, it will be given a rank of 5. If the device stops within 6 feet, it should be given a 4. A rank of 3 should be given if the device can stop within 9 feet. A rank of 2 should be given if the device can stop within 12 feet. Lastly, a rank of 1 should be given if the device travels further than 12 feet without stopping.

The propulsion sub-factor is ranked based on whether or not the design has a mechanical advantage. Ratios are not taken into consideration at this stage because of the similarity of the propulsion systems. Designs with no advantage will be given a rank of 1. Designs with a fixed mechanical advantage are given a rank of 3. Designs with variable mechanical advantage are given a rank of 5.

Table 14: Function Rating Rubric

Scale	Factor		
	Function		
	Turn Radius	Stopping	Propulsion
1	>40 in.	<15 ft.	No Mechanical Advantage
2	>35 in.	<12 ft.	
3	>30 in.	<9 ft.	One Set Mechanical Advantage
4	>25 in.	<6 ft.	
5	<25 in.	<3 ft.	Multiple Mechanical Advantages

The Safety rubric is found in Table 15.Physical hazards, lateral stability and longitudinal stability are all covered under safety.

Table 15: Safety Rating Rubric

Scale	Factor		
	Safety		
	Lateral Stability	Longitudinal Stability	Physical Hazards
1	Tipping Angle less than 15 Degrees	Tipping Angle less than 15 Degrees	Frequent risk of foot entrapment, pinching, or exposure to sharp edges
2	Tipping Angle between 15 and 18 Degrees	Tipping Angle between 15 and 18 Degrees	
3	Tipping Angle between 18 and 21 Degrees	Tipping Angle between 18 and 21 Degrees	Frequent risk of foot entrapment, pinching, or exposure to sharp edges
4	Tipping Angle between 21 and 24 Degrees	Tipping Angle between 21 and 24 Degrees	
5	Tipping Angle is above 24 Degrees	Tipping Angle is above 24 Degrees	No risk of foot entrapment, pinching, or exposure to sharp edges

The Ease of Use rubric is found in Table 16, covering portability, transfer, and indoor/outdoor transition.

Table 16: Ease of Use Rating Rubric

Scale	Factor		
	Ease of Use		
	Portability	Transfers	Indoor/Outdoor Transition
1	>33"x29"x60" and >50 lbs	External Assistance Required	> 2 Minutes
2	≤33"x29"x60" or <50 lbs		> 1 Minute 30 Seconds
3	≤33"x29"x60" and <50 lbs	No Assistance Required; Normal Transfer	> 1 Minute
4	≤27"x23"x54" or <40 lbs		> 30 Seconds
5	≤27"x23"x54" and <40 lbs	Features to aid transfer built into Device	No Change

The Durability rubric is found in Table 17, which includes repair and useful life.

Table 17: Durability Rating Rubric

Scale	Factor	
	Durability	
	Repair	Useful Life
1	Non repairable by user	Less than 2 years of normal use
2	Extensive experience required	2 to 3 years of normal use
3	Some experience required to repair	4 to 5 years of normal use
4	Minimal experience required to repair	5 to 7 years of normal use
5	No experience required to repair	Greater than 7 years of normal use

Finally, a manufacturability rubric covering cost, part availability, and processes is found in Table 18.

Table 18: Manufacturability Rating Rubric

Scale	Factors		
	Manufacturability		
	Cost	Part Availability	Processes
1	>$750	At least one custom part required	Completely manufactured by 3rd party
2	< $750		Some 3rd party assistance required
3	< $650	At least one part requires shipping but no custom parts are required	Manufactured at WPI with specialty assistance
4	< $550		Manufactured at WPI with standard assistance
5	< $450	All parts can be obtained locally	Manufactured by project group

With every sub-factor having a determined scale and ranking associated with it, each design was evaluated using this initial weighted decision matrix.

7.5.2 Weighted Decision Matrix 2

After the initial weighted decision matrix, there was need for restructure and updates in order to better critique the top designs. Several of the sub factors were structured in a way that provided very little variance in ranking between designs and were unhelpful in differentiating between alternatives. Starting with the function factor, all designs received a 5 for turning radius and nearly all received a 4 for stopping. This result is primarily because all preliminary designs can pirouette and most utilize disc brakes for stopping. For the updated weighted decision matrix, the group decided to eliminate the turning radius and stopping sub factors. Function is now solely propulsion and it is weighted at 15% allowing for more distributed weight throughout the matrix. The remaining 15% was divided among the Safety, Ease of Use and Durability factors Table 19, Table 20, Table 21.

Table 19: Updated Safety Sub-Factor Breakdown

Safety 35% Total			
Sub-Factor	Lateral Stability	Longitudinal Stability	Physical Hazards
Weight	14%	14%	7%

Table 20: Updated Ease of Use Sub-Factor Breakdown

Ease of Use 25% Total			
Sub-Factor	Portability	Transfers	Indoor / Outdoor Transition
Weight	4%	6%	15%

Table 21: Updated Durability Sub-Factor Breakdown

Durability 10%		
Sub-Factor	Useful Life	Repair
Weight	7.00%	3.00%

The most important sub-factor for Ease of Use is the wheelchair's transition from indoor to outdoor. The transition is a crucial component of the project and warrants a higher rating of 15%. Nearly every design received a 4 for this category because each was able to change operation modes in less than 1 minute. To improve the usefulness of this category, the rubric rankings are now based on 15-second intervals from 0 to 60 seconds instead of 30-second intervals from 0 to 2 minutes.

With the changes made, the group completed a second weighted decision matrix that provided more definitive results. With the redistributed weights and factors removed the completed weighted decision matrix determined 3 preliminary designs to further analyze, Table 22.

Table 22: Weighted Decision Matrix. The color scale shows the best designs in green and the low scoring designs in red.

Factors	Propulsion	Safety			Ease of Use			Durability		Manufacturability			Total
Weights	15.0%	35.0%			25.0%			10.0%		15.0%			100
Sub-Factors		Longitudinal Stability	Lateral Stability	Physical Hazards	Portability	Transfers	I/O Transition	Useful Life	Repair	Cost	Part Availability	Processes	
Weights	15.0%	14.00%	14.00%	7.00%	4.00%	6.00%	15.00%	7.00%	3.00%	6.00%	6.00%	6.00%	88.00%
Design 1	1	3	5	3	3	3	2	3	3	3	3	3	52.4
Design 2	1	3	3	3	3	5	2	4	4	4	5	5	57.2
Design 3	3	4	3	3	2	1	3	3	3	4	1	5	53.6
Design 4	5	3	3	1	2	1	3	1	1	2	1	1	42.8
Design 5	3	4	4	3	2	1	3	3	3	3	1	3	61.8
Design 6	5	4	4	1	2	1	2	1	1	2	1	1	48.4

7.6 Zero Order Prototypes

Two zero-order prototypes were built to further understand the requirements for operating the seat adjustment mechanism. This process drew the group closer towards determining the final design. These prototypes both functioned and tested well with a member of the team as the operator.

7.6.1 Parallelogram Linkage

This zero order prototype is the Parallelogram Linkage design, Figure 27. With the parallelogram linkage, the CG is moved forwards and downward in order to increase the stability, as shown by the parametric analysis. In this case, the stop is the small block, shown by arrows, under the side of the seat. Note that this is not the intended location for the final design, but a simple solution for the zero order prototypes. The final design has stops that lock the links at their desired angles.

Figure 27: Zero order parallelogram linkage. Left: Indoor resting position. Right: Ideal position for outdoor use. The arrows point to the stops.

7.6.2 Unequal Four Bar Linkage

This zero order prototype is the Unequal Four Bar Linkage design, Figure 28. This design moves the center of gravity forward, which increases the longitudinal stability. The stops, shown by arrows, prevent the large link from over rotating. These stops are effective in regard to the prototype; for the final design, the stops would use a design, which is not as bulky. Also, as described earlier in the document, this design would feature two lever handles. For this prototype, lever handles were not created. Even without the handles, the team was able to operate the prototype with ease.

Figure 28: Unequal four-bar linkage. Left: Indoor position. Right: Ideal position for outdoor use. The arrows point to the stops.

8.0 Final Design

The final design includes three main elements that improve an Indoor Wheelchair's stability, propulsion, and braking. After considerable analysis, the final design incorporates the parallelogram linkage; drive levers, and disc brakes. Each design element described earlier requires modifications. The alterations were sparked by deeper analysis. As problems arose, appropriate changes to the design were made to compensate for potential issues and resulted the final CAD model.

An Invacare wheelchair was modified to incorporate the design, adding: a propulsion system, a braking system, and a linkage system to increase stability. Figure 29 and Figure 30 show the final design of the wheelchair.

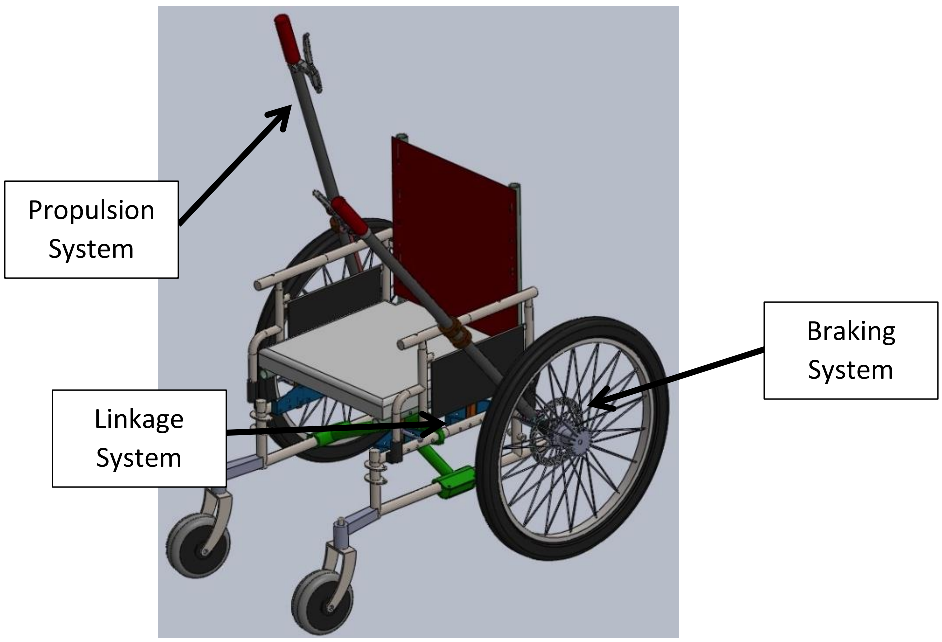


Figure 29: Complete design consisting of a propulsion system, braking, and linkage system.

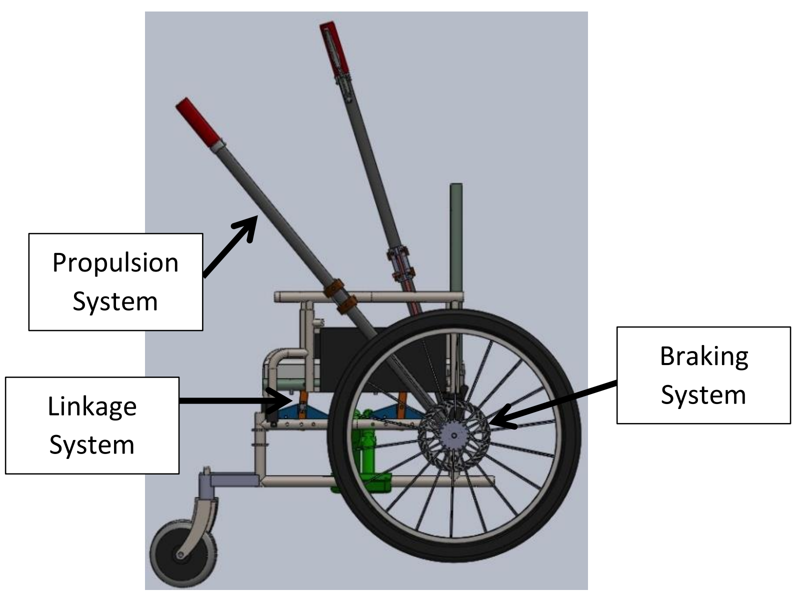


Figure 30: Side view of complete design.

A mountain bike tire is be utilized for each rear wheel with a disc brake rotor attached to the inside of each wheel, Figure 31. The caliper for the disc brake is located at the bottom of the disc brake.

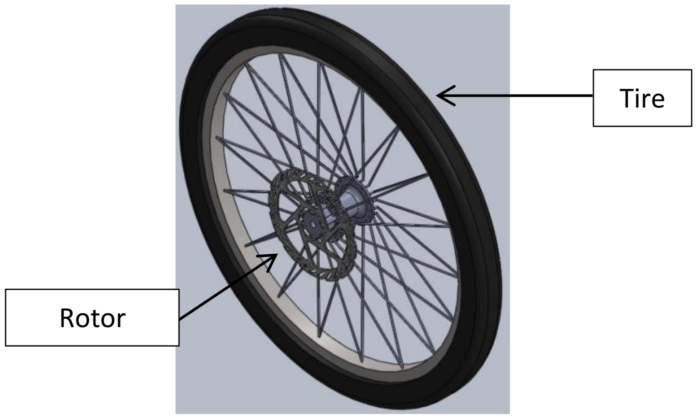


Figure 31: A new tire for better traction, and a disc brake of better stopping.

The propulsion system is attached to the hub of the wheel, Figure 32.

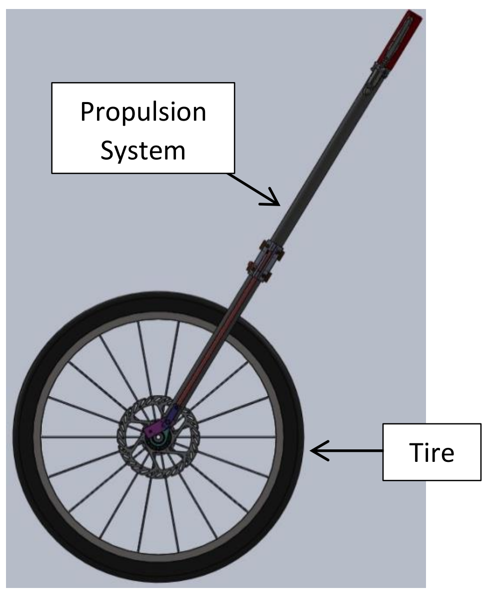


Figure 32: The tire and disc brakes has a propulsion system attached to it.

The propulsion system is made up of six key parts: a grip, brake handle, lock, links, ratchet, and connector to the wheel hub. The grip creates an idea spot for the user to propel the system from. The lock keeps the propulsion system in its desired position. When locked in the down position, the propulsion system is in forward. When the lock is in the top slot, the propulsion system is in reverse.

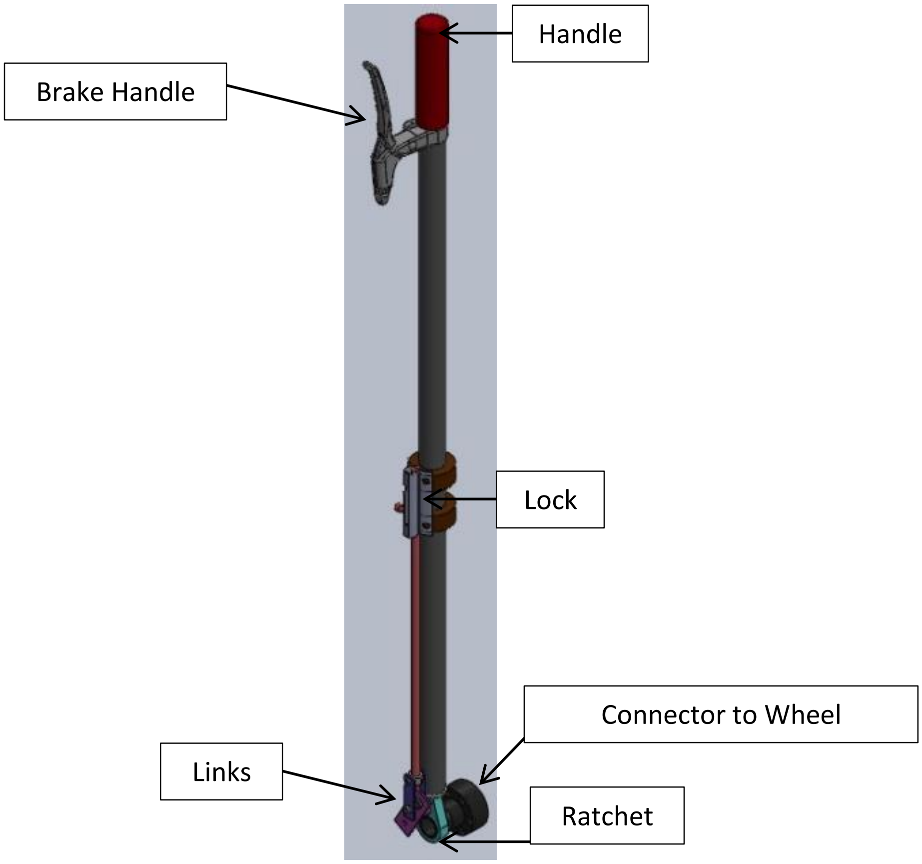


Figure 33: Propulsion system consisting of a lock, links, and a ratchet.

The ratchet is the main part of the propulsion system. Attached to one side of ratchet is a socket and round connector, which are welded together. The socket and round connector then attach to the wheel hub. On the other side of the ratchet is a linkage system. The link system allows the ratchet to switch between forward and reverse.

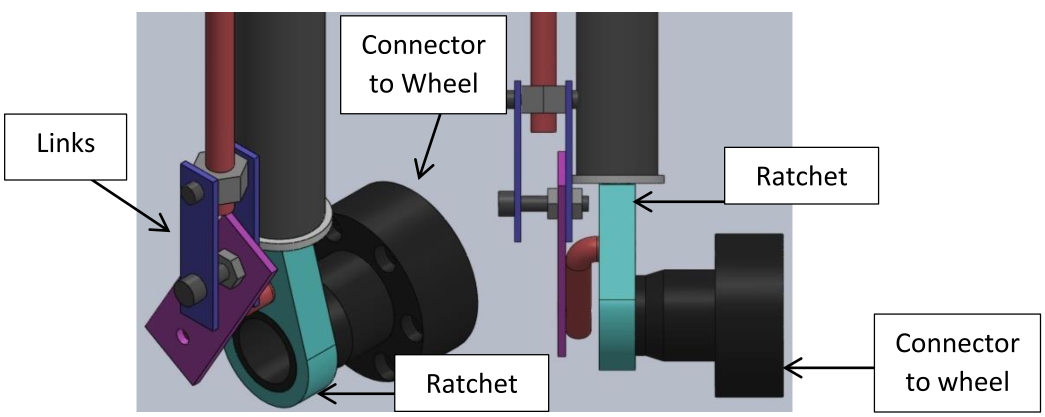


Figure 34: View of the ratchet and links from the propulsion system.

In order to move the wheelchair, a reversible hand ratchet is attached to the hub of the wheel. Two ratchets were purchased, one for each axle. The purchased ratchets were Hand Ratchet, Spline, Non-Slip SAE Ratcheting Combination Wrench found on Grainger, Figure 35.

Figure 35: Grainger Ratchet used for propulsion.

To keep the ratchet from sliding side to side, a spacer is rested between the frame and the ratchet and a socket was inserted into the ratchet. The axel runs through the socket, which also runs through the wheel hub and wheelchair frame, Figure 36.

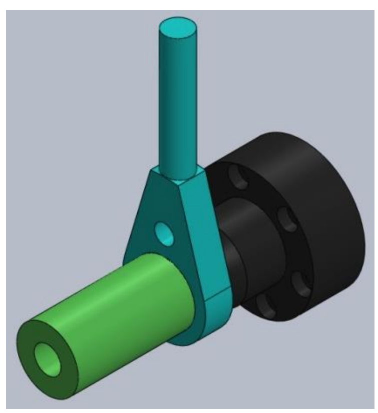


Figure 36: Configuration of the ratchet on the axle.

The inner mechanics of the ratchet must be modified to allow the reversing mechanism to be adjustable at a location a distance away from the axle to make it more accessible. In order to do this, it is important to look at how the purchased internal ratchet system works. The top cover has been removed to more clearly show how the system works, Figure 37.

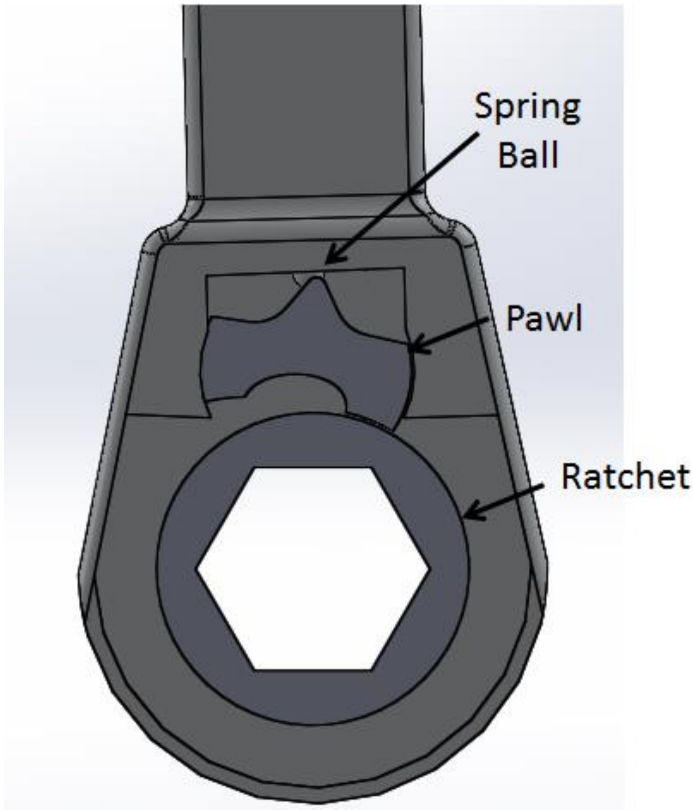


Figure 37: Inside Mechanism of Ratchet and Pawl

The ratchet is the interface that attaches to the socket that is mounted around the axle. Fine teeth are located on the entire round exterior of the ratchet. The pawl has teeth that engage with the teeth on the ratchet. The direction that the ratchet can actively push is controlled by which side of the pawl is engaged to the ratchet. The thumb switch on the opposite side of the ratchet head rotates the pawl, not shown. The spring ball keeps the pawl locked in one direction until the user switches it. To make the thumb switch capable of adjustment from a location closer to the handle, the pawl has a hole drilled and tapped. A rod with a 90° bend was screwed into this hole and glued to prevent rotation after it is fastened and is effectively a switch extender, Figure 38.

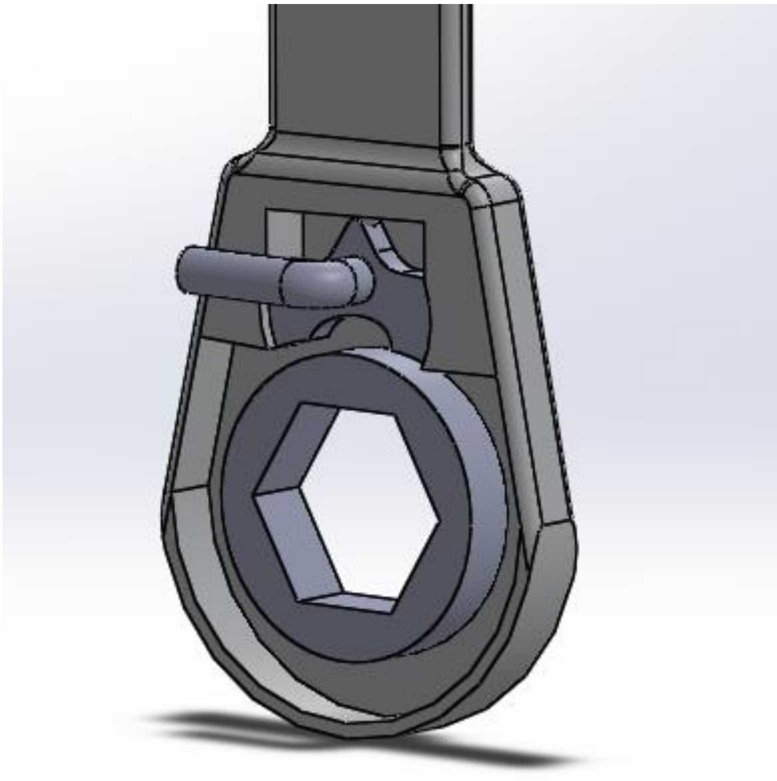


Figure 38: Extended Switch Configuration

The seating system,Figure 39, was recreated to allow for a folding system when being transported and a ridgid system when being used.

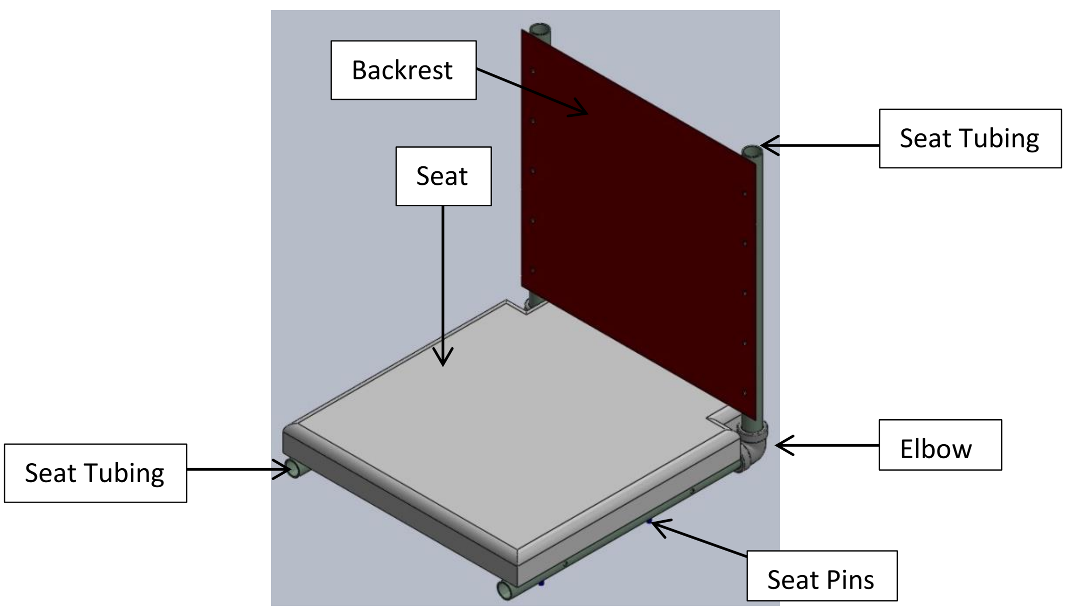


Figure 39: Isometric view of the seat and seat frame.

The seat frame and backrest are made from tubing being attached to an elbow fitting then attached to tubing again, Figure 40. Using tubing rather than a solid rod allows for a lighter mechanism.

The seat is attached to pins to allow for the seat to be removed. The pins run from the seats and through the seat tubing. The holes in the seat tubing help to keep the seat from moving but also ensure the chair does not close on itself. The seat also connects to a linkage system, Figure 41.

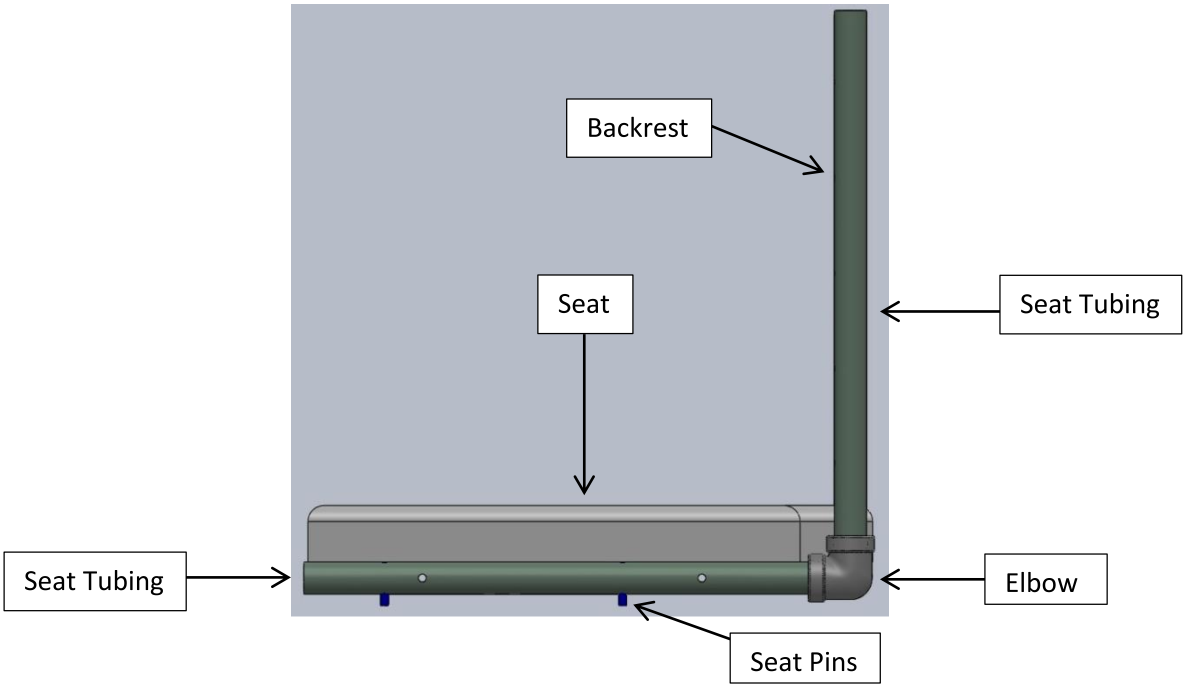


Figure 40: Side view of the seat and seat frame.

The linkage system is connected to the frame of the seat, Figure 41. A round pin connects them; this allows the links to rotate while keeping the seat level.

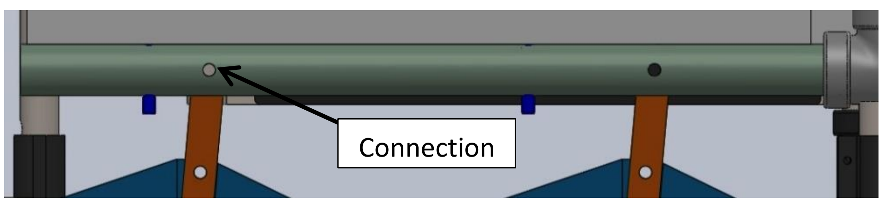


Figure 41: Connection between the links and the seat frame.

When the seat and links are in the indoor position, Figure 42, the links are just past 90 degrees. Being past 90 degrees allows the user sit on the seat while inserting the pin. If the links where at 90 degrees, the seat may fall forward while the user tries to put pins in.

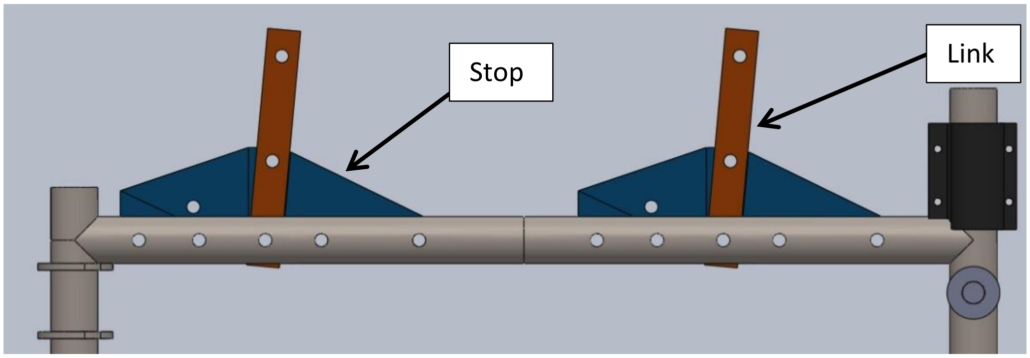


Figure 42: Links in the indoor position.

To transfer to outdoor mode, the pins on both sides are pulled out, then the user pushes forward using the armrests. The linkage system can rotate forward, moving the seat down. After reaching the stop, the links are reinserted. With the links completely on the stop, Figure 43, the user is in the desired mode for outdoor use.

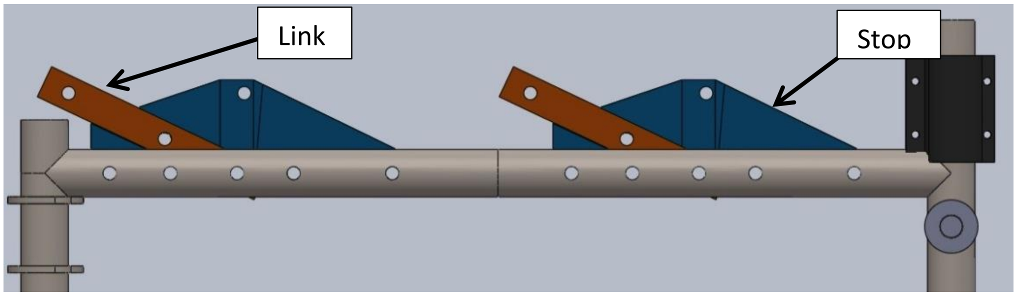


Figure 43: Links in the outdoor position.

The stops are very important for the design, Figure 44. There are four stops on the wheelchair, two on each side.

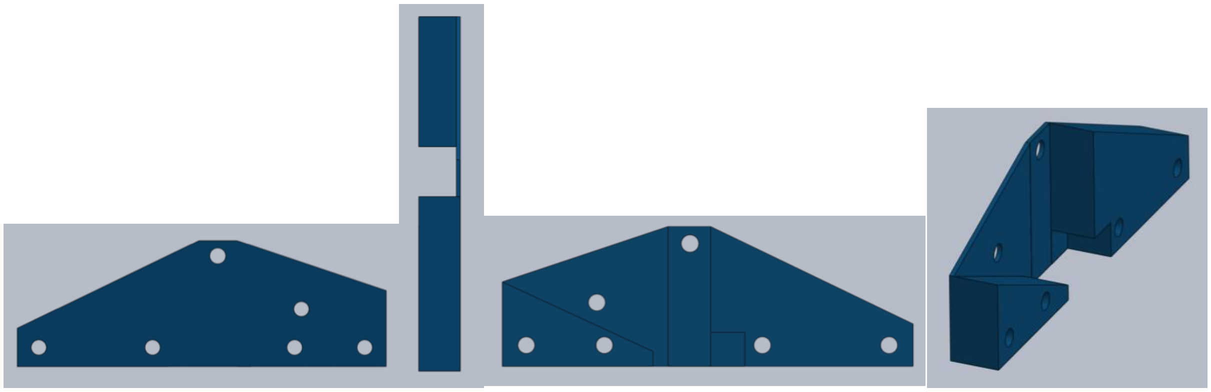


Figure 44: Back, Bottom, Front, and Isometric view of the stop.

The linkage system needs a way to lock the link when in both the outdoor position and the indoor position. To lock the links, a pin locator was designed. The locator was attached to the link, Figure 45.

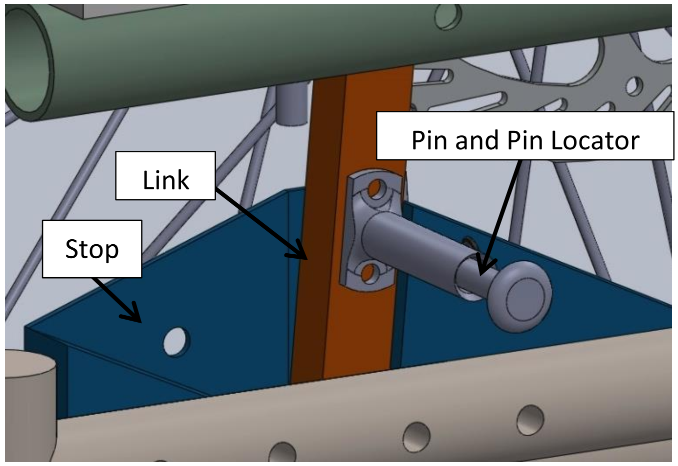


Figure 45: Pin locator is attached directly to the link.

A pin is located inside of the pin locator, Figure 46. The pin is slid forward to lock the link in place. Then the pin is pulled out of the stop so the link can move.

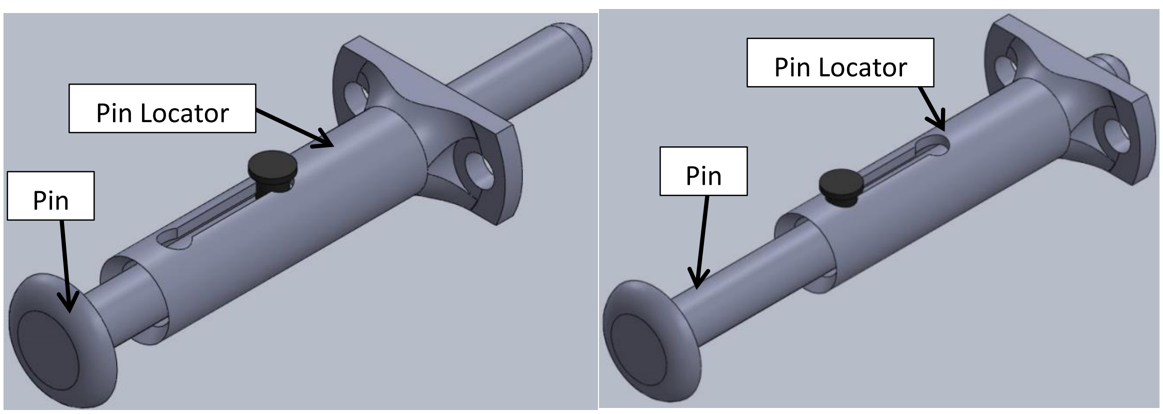


Figure 46: Left: Pin engaged, locking the pin in place. Right: Pin disengaged, seat is free to move.

On either side of the wheelchair are armrests, Figure 47. The armrests are important to the design since the user uses the armrests when changing from the seat from the outdoor to indoor mode.

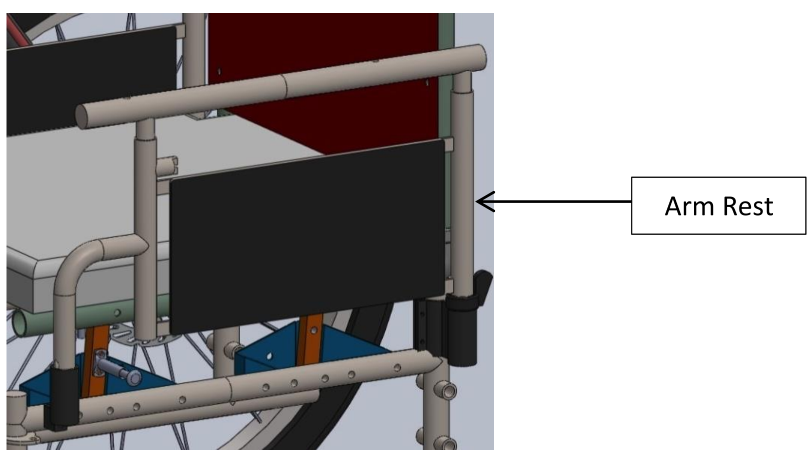


Figure 47: Seat in indoor mode showing the location of the armrests and armrest connectors.

9.0 Analysis of Final Design

This section aims to determine the validity of the final design and determine any critical dimensions. Three design parameters were determined by conducting various analyses: the required material and dimensions of the links, the ideal angle for the links to rest when in outdoor position to allow ease of transition to the indoor position, and the requirements of the propulsion system. The analysis determined that the design was feasible if the critical dimensions are met or exceeded. Detailed calculations can be found in Appendix C: Mathcad Calculations.

9.1 Transition Force

The transition from indoor operation to outdoor operation requires the user to use the armrests to lift him- or herself off of the seat and push backwards against the backrest. The seat was modeled in SolidWorks and a Free Body Diagram was created based on the dimensions and properties, Figure 48. The seat and links are modeled as two-dimensional members because the activation force required is the only value that is desired for this study.

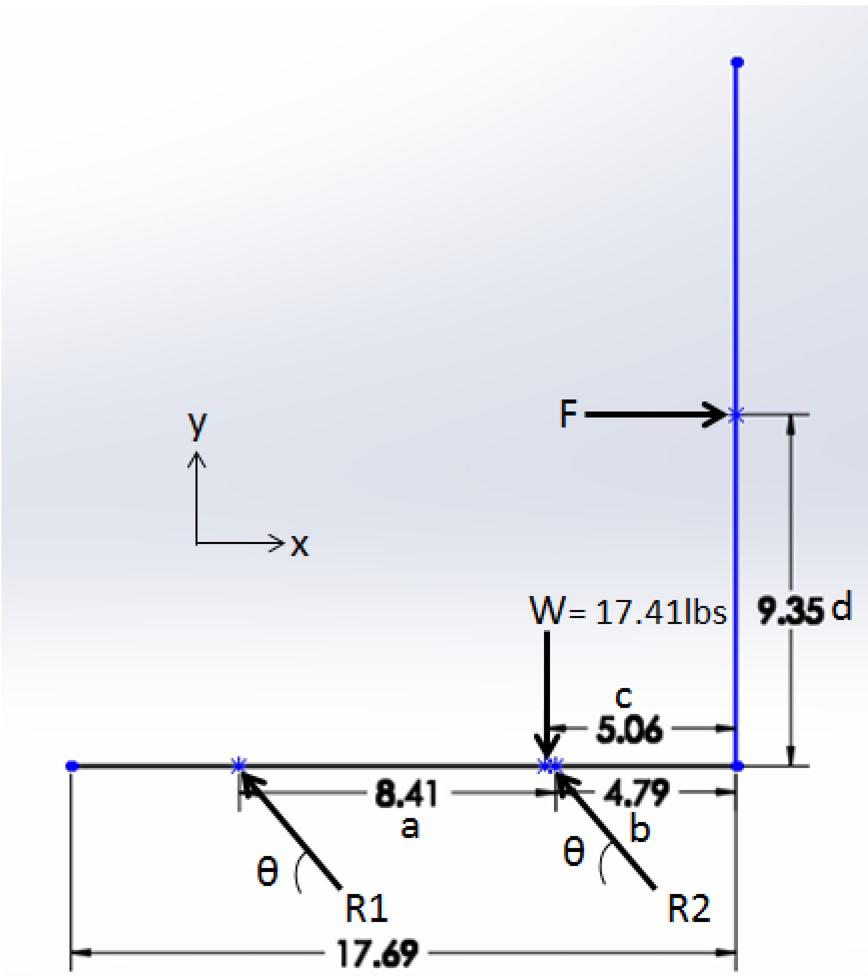


Figure 48: Seat Free Body Diagram

Table 23: Variables Describing Forces on Seat

F	The force applied by the user. This acts completely on the x-axis halfway up the backrest.
W	The force due to the weight of the seat. It is applied vertically in the plane of the center of mass as found in SolidWorks. This was found to be 17.4 lbs.
R1	The reaction force applied by the front link of the seat mechanism.
R2	The reaction force applied by the rear link of the seat mechanism.
S	Intersection of Seat and Backrest

Three independent equations were produced to solve for the three unknowns: F, R1, R2. The summation of the forces in the X direction, the summation of the forces in the Y direction, and the summation of moments about point S were utilized. The equations were inputted to Mathcad and the "find" function was used to find solutions. It solved the forces at each angle Theta. At 25 degrees, the horizontal force required to move the seat back F = 37.34 lb.

The equations solved for the forces at each individual angle, theta. Then the calculation was repeated for angles ranging from 10° to 90° to determine a curve for the horizontal force F required vs. link angle, Figure 49.

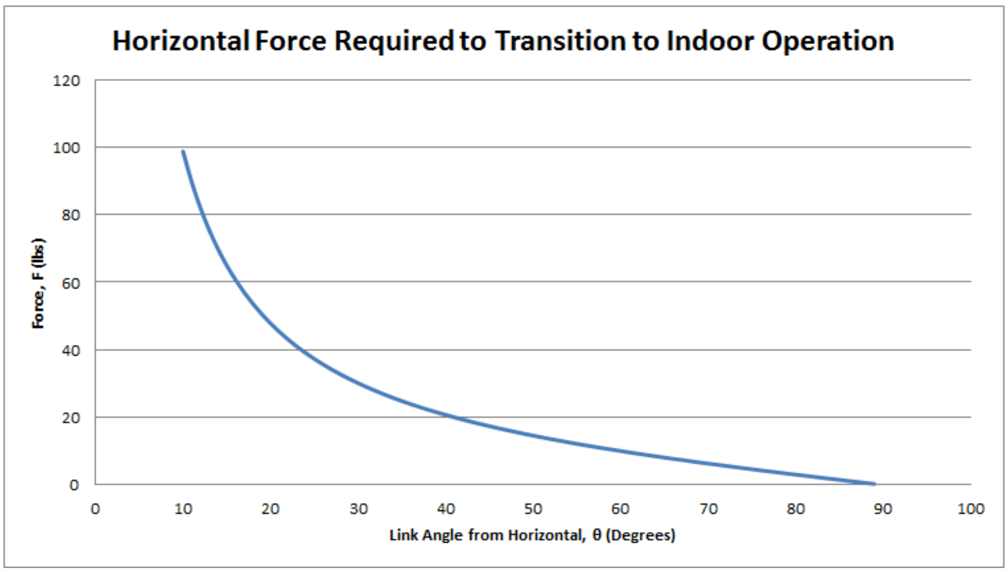


Figure 49: Link Angle from Horizontal vs. Horizontal Force Applied by User

To choose the best value of theta, the slope (degrees per lb.) of Figure 49 was graphed in Figure 50 and further analyzed.

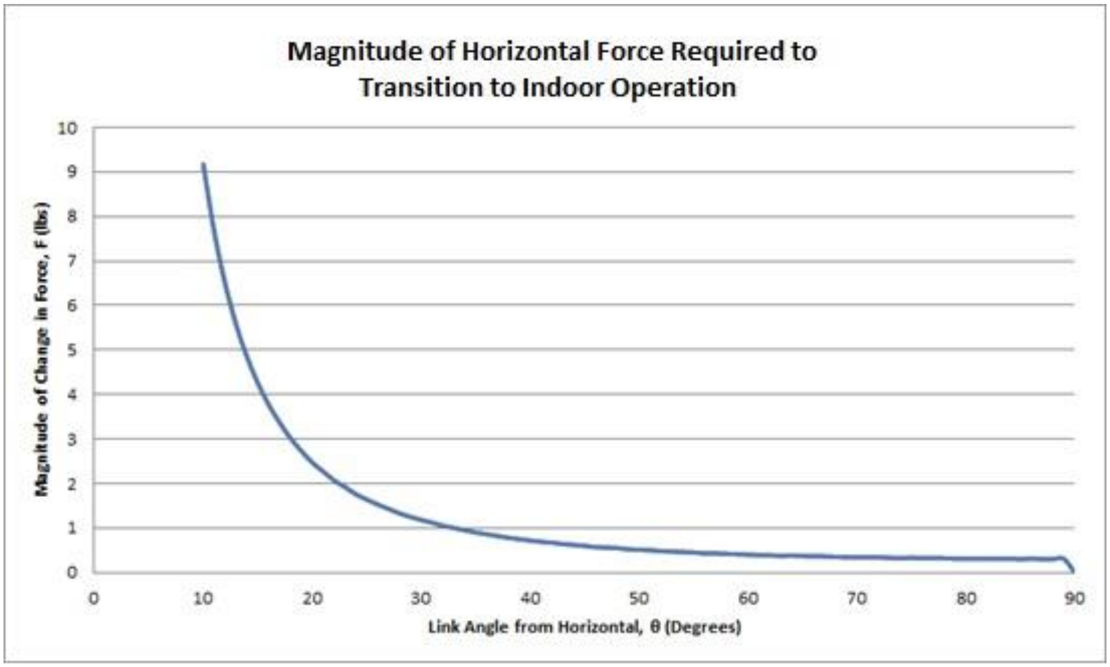


Figure 50: Link Angle in Outdoor Position vs. Magnitude of Change in Force Required to Transition to the Indoor Positon.

The change in force required to transition to indoor position is a magnitude exponentially based on the angle of the link. In other words, for each change in the link's positional degree, the magnitude of the force required to move the seat back is exponentially related. Therefore, the best angle to choose is where the graph begins to reach a horizontal asymptote. The value selected as the minimum link angle is 25°. This is the angle that the links will rest on the stopper in the outdoor position. The link will rotate from this angle to the indoor position (91°). This angle requires a modest force and allows the mechanism to move the center of gravity downward 1.48 in. and forward 3.17 in. which are both significant changes to lower the risk of tipping.

The force on the links was calculated from the weight of the user combined with the weight of the seat. This data was used to determine the necessary material properties of the links to prevent failure using a force and stress analysis. The goal of the analysis was to yield a safety factor of 5 under the worst-case scenario. Assuming the user is seated against the backrest, the center of gravity used from the anthropometric study completed earlier is 7.49 in. from the back of the seat. Figure 51 shows a dimensioned free body diagram of the linkage and seat in the outdoor (lowered) position.

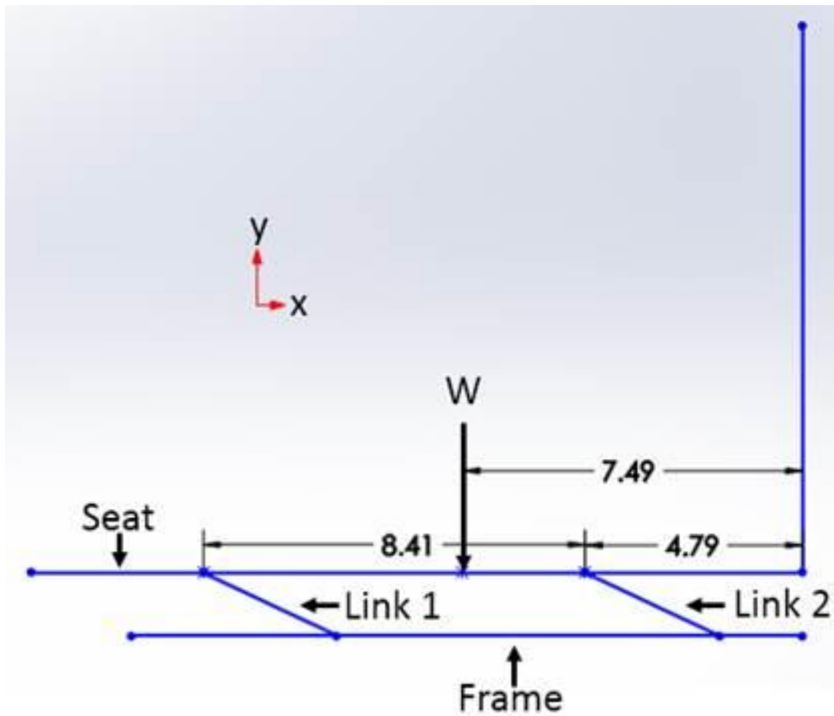


Figure 51: FBD: W position analysis

In the outdoor position, the links rest at 25 degrees above the horizontal as the transitional analysis showed to be the optimal angle for capable transition. Understanding the W force is not equidistant from each link, Mathcad calculations in Appendix C: Mathcad Calculations explain the exact force on each link. The rear link receives/handles the most force: FL2= 202lbf. A more focused FBD, Figure 52, illustrates the forces on one link within the stopper housing.

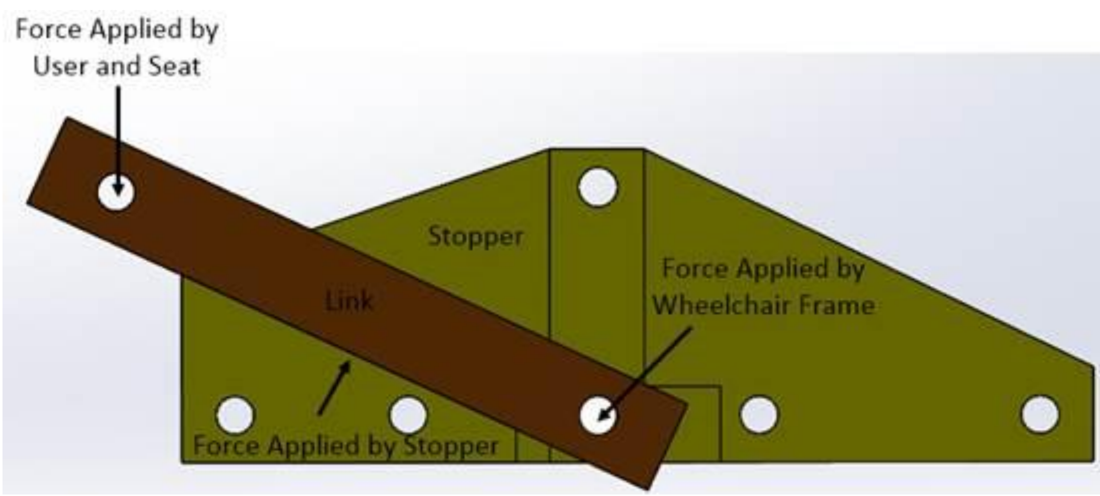


Figure 52: FBD on CAD Model

The stopper provides a distributed load, but for safety analysis, a concentrated load depicted as R1 in Figure 53 was used to test the strength of the material used in the link.

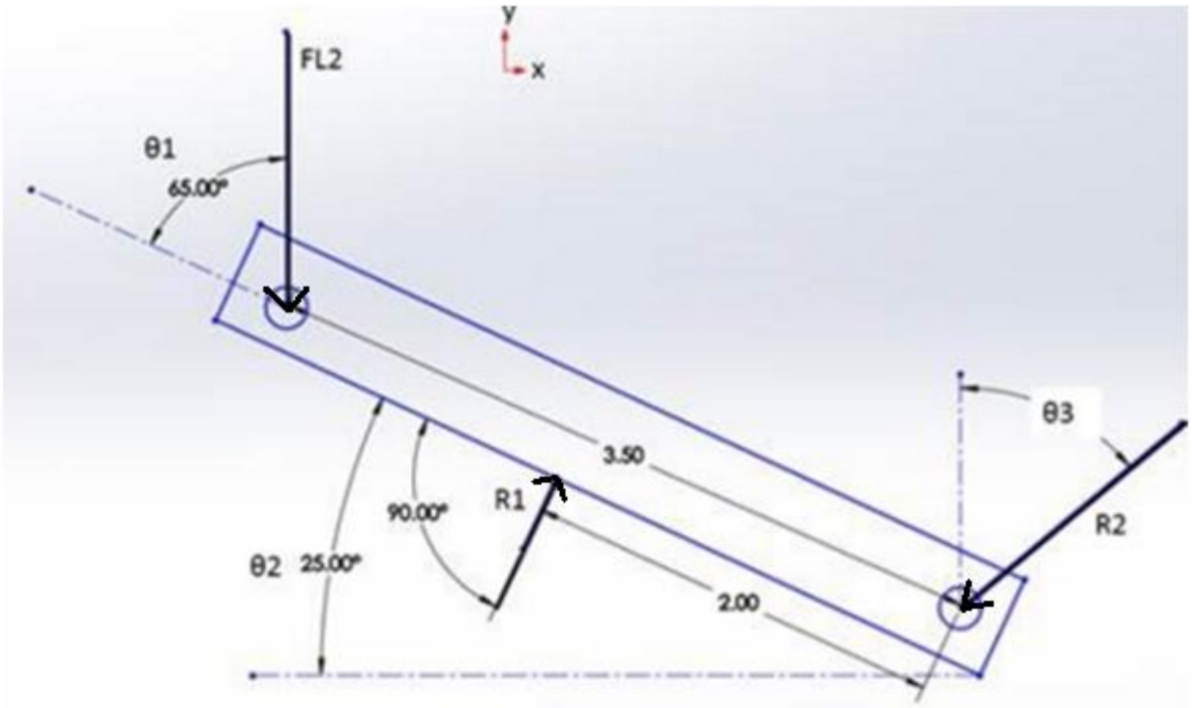


Figure 53: FBD on Link

F_{L2}	Force applied on link due to user's weight plus the weight of the seat
Θ_1	Direction of F_{L2}
R_1	Force applied on link due to the stopper
Θ_2	Direction of R_1
R_2	Force applied on link due to the pin attached to the wheelchair frame
Θ_3	Direction of R_2

Table 24 Variables Describing Forces on Individual link

The Mathcad formulas and results can be found in Appendix C: Mathcad Calculations. Considering the required safety factor of 5.00, the maximum shear stress allowed to the AISI 1090 Steel is 15.6ksi. Compared to the predicted applied shear stress of 8.44 ksi, the material will withstand worst-case scenario force conditions with a safety factor of 5.00.

9.2 Propulsion Failure Threshold Testing

The propulsion mechanism was tested to ensure that the design would withstand any potential forces applied by the user during normal operation. This test loaded the mechanism until failure to determine the weakest element and how much force it was able to withstand. If the torque is significantly larger than that which a human can produce, the test determines that the proposed prototype is successful as designed. Testing protocols were created and detailed in Appendix E: Propulsion System Failure Testing Protocols

9.2.1 Procedure

With all those participating in a designated safe location, 10 lb. weights were added to the bucket one at a time. A piece of scotch tape was applied over the entire length of the readout of the spring gauge. The indicator ripped the scotch tape as it moved down and this was used to determine the maximum force. Using the length of the lever arm, the maximum torque applied before failure was calculated. This measurement was compared to the maximum torque a user can produce using the drive levers in the proposed final prototype.

9.3 Propulsion Mechanism Failure Analysis Results

Max Torque: 231 ft-lb (77 lb. applied to a 3ft lever arm)

The force gauge shows a reading of 82 lb. however 5 lb. must be subtracted due to the design of the indicator, Figure 54. The red indicator removed the tape with the bottom of the slide, but the actual reading is at the top. The full length of the indicator spans 5 lbs.

Figure 54: Force Gauge Reading

The mechanism was subjected to a gradually increasing force that caused failure in the connection between the steel sheet and the aluminum wheel hub at a force of 77 lbs. The point of failure can be seen at arrow A in Figure 55.

Figure 55: Fracture point of propulsion system (drive lever not pictured).

While the bolts failed in shear and the hub split in crack propagation, the weld and ratchet system showed no signs of failure, Figure 56. As can be seen at points A and B, there was no damage to the weld or the teeth of the socket. The wrench has been rated for 800 ft-lb of torque and our test did not exceed 250 ft-lb.

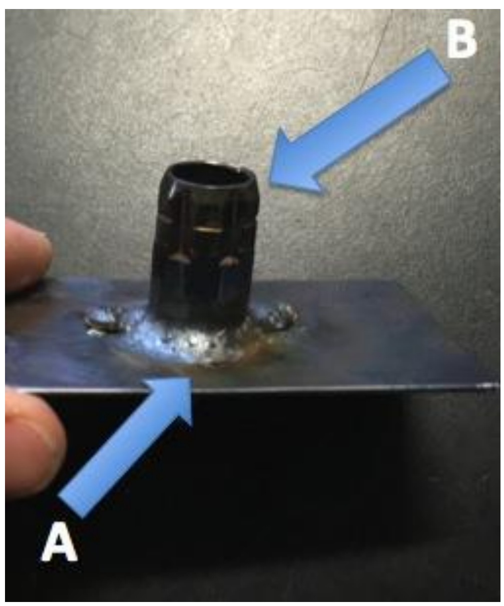


Figure 56: Steel plate welded to socket where drive lever connects

9.3.2 Discussion

This test confirmed that the socket wrench and weld would not be the probable modes of failure in the design. In the final design, there are 2 additional bolts between the steel part and the wheel hub to strengthen this connection. The hub on the final design is also stronger and thicker than the model used in the test.

The maximum force a user can apply during operation is approximately 400N, or 90 lbf (Winter, et al. 2010). The drive lever will be 30 inches in length, applying 225 ft-lbf. of torque to the wheel hub. Our test determines that the design will withstand this amount of torque. However, to account for fatigue and impact loading, a stronger wheel hub and additional and more robust screws will be utilized on the wheel in the final prototype, Figure 57. The wheel hub will be thicker and wider. The screws will have a larger diameter, screw into threads, rather than self-tapping screws, and the number will be increased from 4 to 6.

Figure 57: Comparison of Test hub (A) to final design hub (B)

9.4 Propulsion System Requirement Analysis

In order to determine the maximum torque that will be applied to the propulsion system, the worst-case scenario will be considered. This will occur when the device encounters an obstacle that is too tall for the wheelchair to climb, causing slippage of the rear wheels. The surface with the largest coefficient of friction will apply the maximum torque before slipping. This maximum required torque value to create slip will be used in the determination of the propulsion system design.

It should be noted that the maximum curb height that the chair can climb is dependent on the friction between the wheel and the surface on which the wheelchair is located. There is a curb height that the wheelchair can climb that would require the same amount of torque as would cause slipping. However, a lower curb would require less torque and a higher curb would not be mountable because slip would occur first. Therefore, the maximum torque applied would occur at slippage and at this maximum curb height, but for the simplicity of calculation, the torque required to cause slip will be considered.

The surface with the highest coefficient of friction that the device will encounter is dry asphalt. It has a coefficient of friction of 0.9 (Toolbox 2016). This analysis will simulate a wheelchair slipping on a dry asphalt road. This analysis assumes the weight of the person is 250 lb. and the weight of the wheelchair is 50 lb. The FBD is Figure 58.

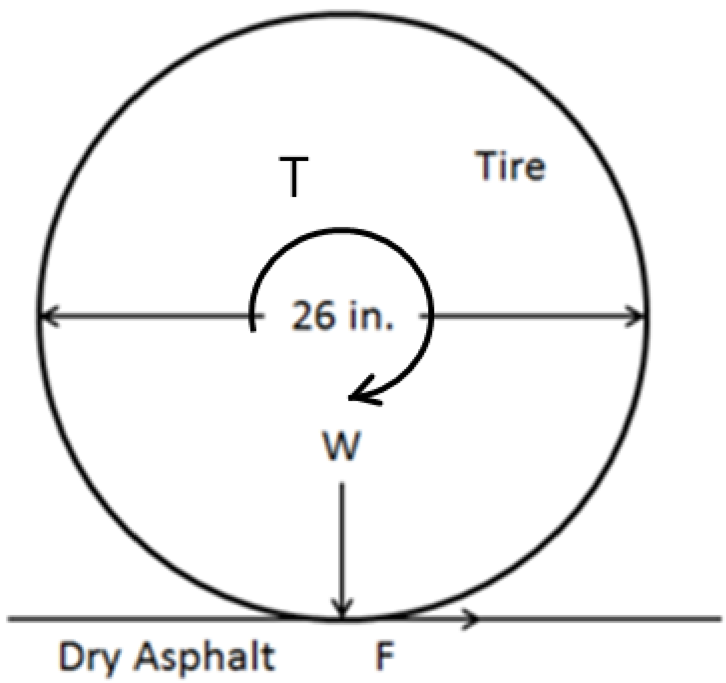


Figure 58: Free body diagram of wheel on dry asphalt

W Weight Applied by User and Wheelchair
F Friction Force
T Torque Applied by User

$W_{total} := 250lbf + 50lbf = 300\,lbf$

Assume the total weight is ditributed evenly between both rear wheels

$$W := \frac{W_{total}}{2} = 150\,lbf$$

$\mu := 0.9$

$F := W \cdot \mu = 135\,lbf$

The torque is the Force multiplied by the distance to the wheel hub

$D := 26in$

$$T := F \cdot \frac{D}{2} = 146.2\ \ lbf \cdot ft$$

9.4.1 Results of Torque

It is clear that the maximum torque that could be applied, in the worst-case scenario, is less than 150 ft-lbf. The physical configuration tested failed at 228 ft-lbf, giving it a current Safety Factor of 1.56. With a more robust configuration in the final prototype, the factor of safety is higher.

10.0 Manufacturing

Following the completion of the kinematic and stress analyses of the final design and ordering of parts, the manufacturing process began. An Invacare standard wheelchair was supplied by WPI, which served as the foundation for the prototype. Several modifications were made to the frame along with the addition of new machined parts. Work was conducted in the Washburn Labs Machine Shop as well as in the Rehabilitation Lab.

10.1 Modifications

The first step in the manufacturing process was to modify the side support frames of the wheelchair. The original side frames were very similar to the modified piece, as the only change was the lowered relocation of the main support bar. The bar needed to be lowered to accommodate the linkage system. If the support bar remained where it was originally, then the seat would have been raised 3 inches higher due to the linkage system. A higher seat would not allow the user to access tables or desks without hitting them. A lower bar allows the seat to remain at its original height with the links in the upright position.

The upper horizontal support bar was removed with a vertical band saw and replaced with a new ¾ inch diameter pipe in a lowered position 4.5 inches. Shown in Figure 59, is the new placement of the upper horizontal indicated in the red box. The new pipe was welded in place and later drilled with a drill press so the linkage and stopper system could be mounted to it. Ten ¼ inch holes were measured from the rear, centered, punched and then drilled.

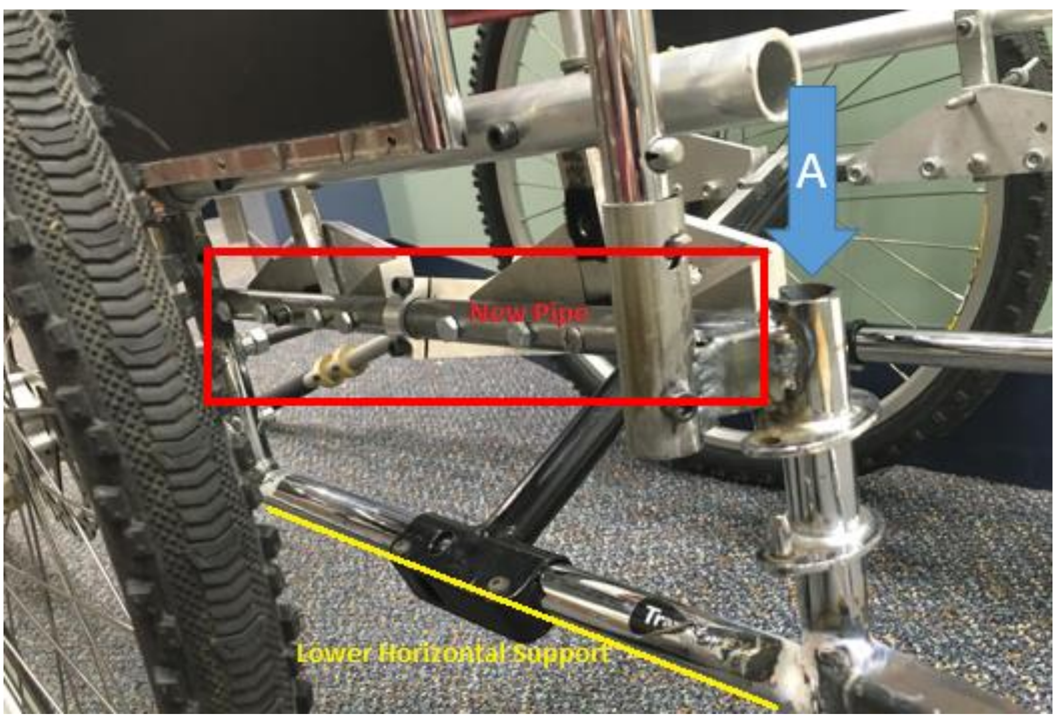


Figure 59 Modified Wheelchair Frame

For added seat clearance, the vertical bars were cut just above the new upper horizontal bar (Point A in Figure 59). The wheelchair armrest had to be modified due to the added width of the chair and removal of rear armrest holders. New holders, Figure 60, were welded to the frames with a 1 inch rectangular, steel tube standoff to prevent interference with the seat and linkage systems. Finally holes at point 'B' were drilled in the holder cylinders so that the armrest pins could lock in place during operation. All sharp edges were removed with the grinder, and welds were dropped and weight tested.

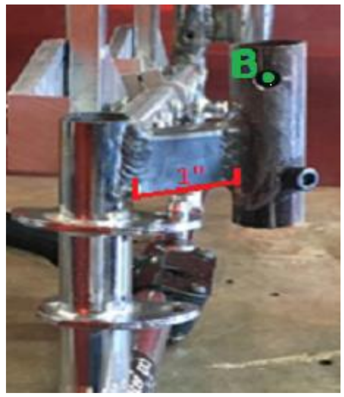


Figure 60: Modified Armrest Holder for Left Side

Finally, due to the use of the mountain bike wheels as rear wheels, there was a need for a longer wheelbase and larger diameter castor wheel to prevent tipping forward when in the outdoor mode. The headsets that held the castor forks to the frame were sawed off the chair frame and re-welded with a 4 inch long rectangular steel pipe, Figure 61. This extended the wheelbase and raised the front end of the wheelchair, greatly improving its longitudinal stability in both indoor and outdoor modes.

Figure 61: Modified Castor Headset location

10.2 Folding Mechanisms

In order to allow the wheelchair to fold, the scissor style folding mechanism had to be altered. Initially, the mechanism was connected directly to the seat, and folded in as the wheelchair was folded. The black pieces were cut with a vertical band saw, removing the clamps that connected the bars to the seat Figure 62.

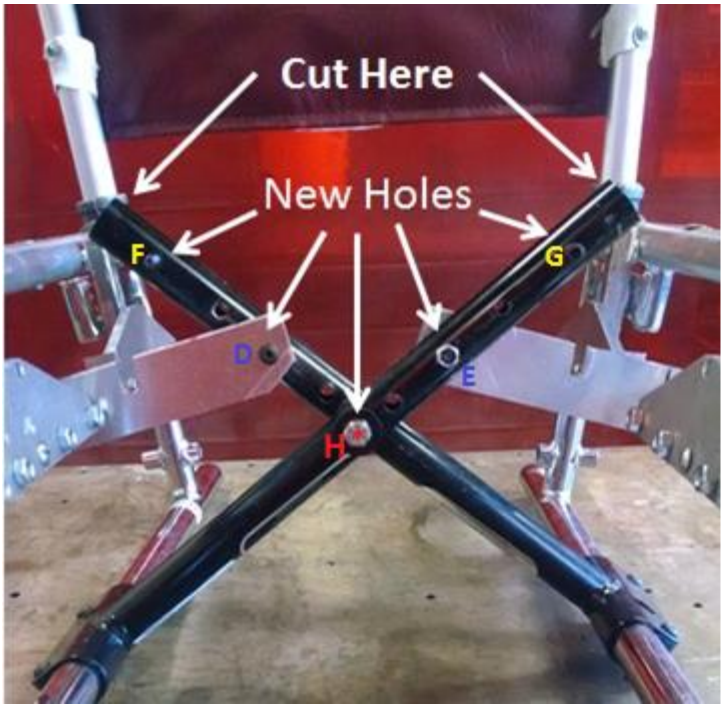


Figure 62: Modified Folding Mechanism

Two rectangular links, Figure 63, were machined on a Minimill, one for each side of the folding mechanism. The small hole on the right is a ¼ inch diameter and the slot has a slightly larger width, allowing the pins to slide into place at the toggle position. The ¾ inch hole on the left is to be attached to the wheelchair frame. The line through this hole denotes where the part was cut with the vertical band saw. This allows the rectangular link to mount on the upper horizontal support beam. The part drawing with dimensions can be found in Appendix D: Drawings of Prototype.

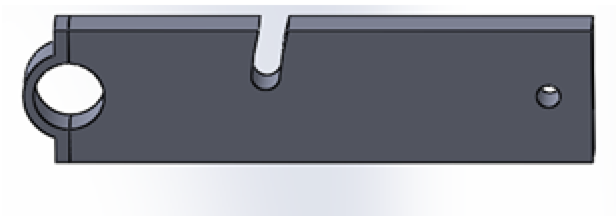


Figure 63: Rectangular Link in Folding Mechanism

Once machined and cut, a drill press was used to drill holes A & B, Figure 64, into the shoulders of the clamp part and a hand tap was used to thread the holes. This allows the clamp to be put onto the wheelchair frame and then screwed into the rectangular link.

Figure 64: Attachment of the Rectangular link and Clamp to the Frame (Right Side)

The other side of the rectangular link is bolted to the folding mechanism through the new holes D & E, from Figure 62: Modified Folding Mechanism, Figure 62. The lower hole in each pipe is the new location of the main pivot H, Figure 62, was not modified, and instead were bolted to the new rectangular link. The uppermost holes on each black pipe, labeled F & G from Figure 62 are a ¼ inch in diameter and a ¼ inch bolt was inserted as a pin that will rest in the slot machined into the rectangular link. The pin and the slot can be seen in Figure 65 black tube, a nut was secured to prevent the pin from moving (not shown).

Figure 65: Pin and Accepting Slot

The pin rests in the slot when the wheelchair is completely unfolded. This puts the folding mechanism in the toggle position and prevents the side frame members from bowing outward. Figure 66 is a view of the mechanism when it is completely unfolded.

Figure 66: Completely Unfolded View

The lower inside corners of the machined rectangular links interfered with one another, which restricted the wheelchair's full folding potential. These corners were cut off using a hacksaw to prevent the obstruction (Figure 67).

Figure 67: Remedial Cut of Machined Part (Rectangular Link)

The user can now grab each side frame member and fold the device, Figure 68. There is a slight outward tilt of the seat back when the chair is folded. Since the cut to the rectangular link was made, the device can now fold to a size that now 3 inches smaller than before. The new folding system can fold up to enough for storage in the back seat of a car, meeting Design Specification 12.

Figure 68: Completely Folded Position

10.3 Link System

The Linkage System consists of four links and four stoppers. The four links were cut to 4 inch lengths from two bars of ½ x 5/8 x 8 inch rectangular aluminum stock. Then, ¼ inch holes were drilled in each link using the mini mill CNC machine with chamfers on the holes used for the pins. Following the links, stoppers were machined from two bars of ¾ x 2 x 12 inch rectangular aluminum stock. After cutting each piece of stock into two 6 inch long pieces, the stock was fixed in the mill and ¼ inch holes were drilled. The stopper was removed and bolted to a sacrificial piece of aluminum scrap. The scrap was used to prevent tools from hitting the vice during the contouring operation that created the resting positions for the links. After the parts were finished they were de-burred and edges were chamfered to reduce the friction during transition, Figure 69. Note only three stoppers are shown, but four were machined.

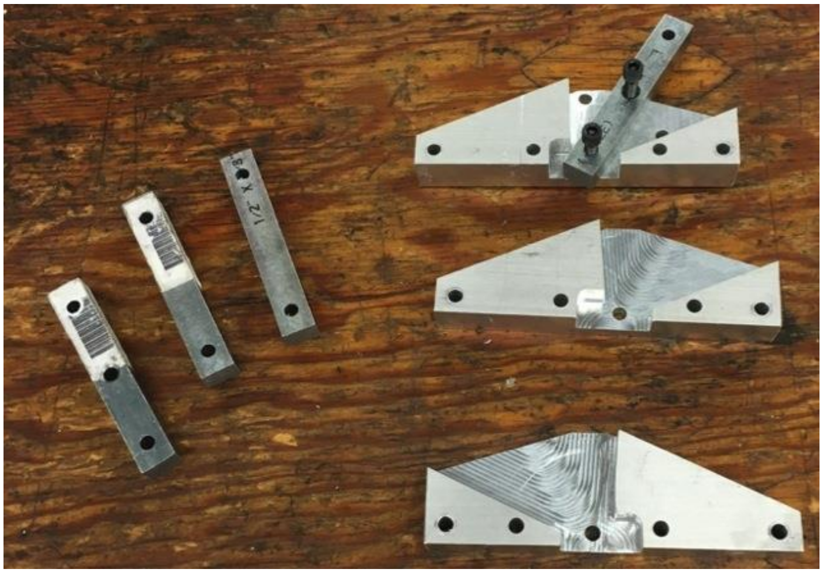


Figure 69: Machined Links and Stoppers

With all parts machined, links and stoppers were bolted to the upper horizontal support bars of the wheelchair frame. Small 1/16 inch thick washers were added between the links and the support bars to alleviate some horizontal pressure on the links. This enabled smoother transitions between indoor and outdoor positions.

10.4 Seat Assembly

The seat was constructed from 1 inch aluminum tubing, steel threaded elbows, a repurposed cushioned seat, and the original wheelchair seat back. The tubing was cut using a hacksaw to 16 and 17 inch lengths and then 7/8 inch threads were die cut into one end of each of the 4 tubes. The pieces were then threaded into the elbows and the 16 inch tubes were marked and punched at the locations where they would be bolted to the links of the linkage and stopper system. The group then drilled ¼ inch holes into the pipe perpendicular to the vertical plane in the center of the tube using the drill press.

Next, ¼ inch holes were drilled into the plywood of the cushioned seat and pins were pressed through fitted. Following the seat construction, 5/8 inch holes were drilled into the top of the 16 inch tubes (S1 – S4, Figure 71) for the seat assembly to fit the seat's pins. Press-fit brass locators were fit in the 5/8 inch holes in order to assist the user in finding the pinholes when placing the seat in the assembly, Figure 70. With these pieces prepared, the seat frame tubing was bolted to the links, gorilla glue was added to the threads of the elbows and the seat was placed in the pinholes.

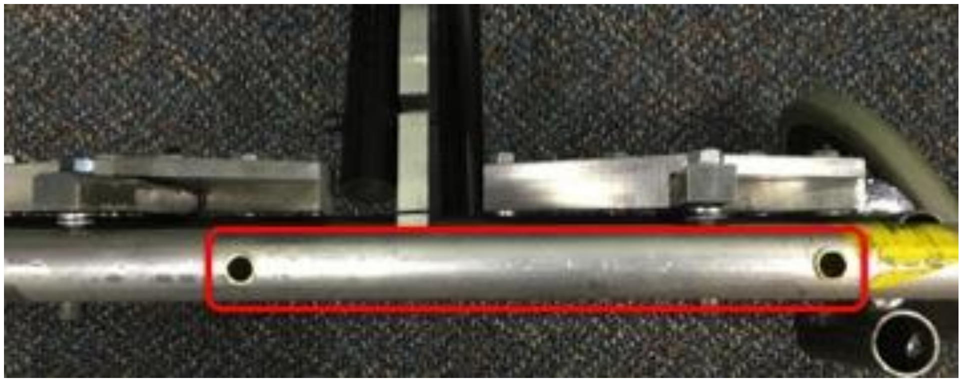


Figure 70: Press Fit Brass Locators on Right Seat Frame (top view)

Finally the seat back was attached with an elastic band as a means to not inhibit the folding mechanism when it causes the frame to no longer be parallel. The bands were bolted on to the seat frame and then again bolted to the seat back, Figure 71 and Figure 72.

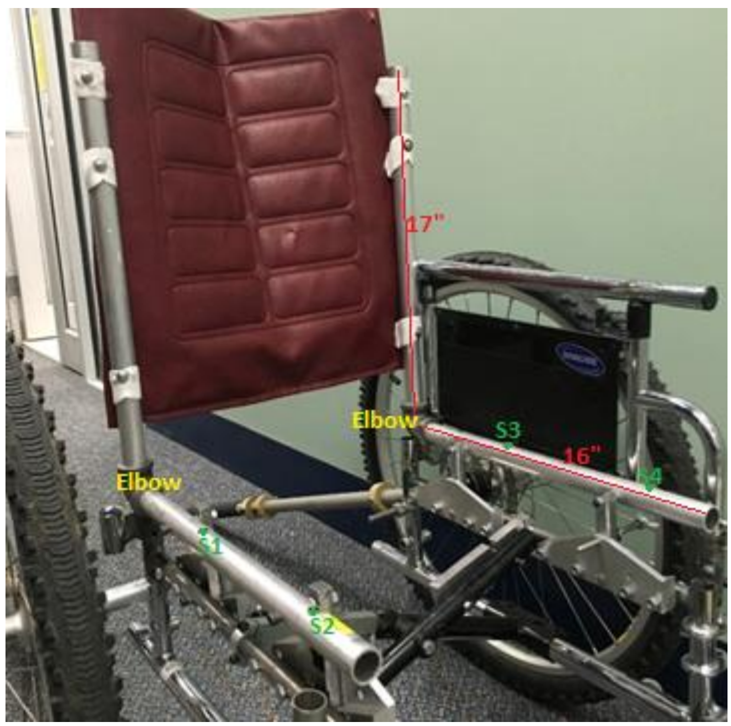


Figure 71: Seat Frame and Seat Back Mounted on Wheelchair

Figure 72: Seat Mounted on Seat Frame and Wheelchair

10.5 Propulsion System

The drive lever system is broken down into 3 subassemblies, which include the ratchet device, driver lever, and shifting mechanism. The ratchet device consists of a ¼ inch pull-through socket welded to a steel piece that will be bolted to the mountain bike wheel, Figure 73(Socket not shown). The socket was centered on wheel hub with a bolt and spacer fixture then welded to the steel piece.

Figure 73: Steel Piece Bolted to Wheel hub and Disc Brake Rotor

The drive lever subassembly involved a modified steel socket wrench, a machined aluminum bushing and 1 inch diameter aluminum tubing. The wrench used for the ratchet mechanism was disassembled and then reassembled with a bent ¼ inch steel rod to replace the original shifting latch. The steel rod was bent using a torch, hammer and vice then later cut to proper length for the shifting mechanism shown in Figure 74.

Figure 74: Bent Shifting Rod Inserted into Wrench

To attach the lever arm to the wrench, the handle of the socket wrench was cut with a hacksaw where the diameter began to taper. Then, using a die, 7/16 inch threads were cut into the handle. Next, the bushings were machined in the lathe using simple contouring and drilling operations. After the machining, they were clamped in the vice and the center hole was tapped with a 7/16 inch tap so the wrench handles could be threaded into the bushing. The bushings were press fit into the aluminum tubing and tig-welded at the lip for added strength for the wrenches threaded into place.

The final subassembly was the shifting mechanism. It required 2 links and a straight shifting rod attached to the bent shifting rod (Figure 75) in order for the assembly to properly shift. The bent rod was attached to a thin metal link (A) and then 2 thin metal links (B & C) were cut to length and drilled to size 10-32 screws. The links were then connected to the straight shifting rod that runs vertically through an oversized bolt (OB). The straight rod was able to move the links up and down while still being able to rotate about its axis. The shifting rod must rotate in order to lock in gear. To compensate for the bent shifting rod being offset 0.5 inch from the drive lever tubing, wooden standoffs were cut using large circle drill bits in the drill press. The team felt confident that the wood would be sufficient for a prototype but recommends the potential use of a different material if/when recreating the device. Six standoffs with a 1 inch ID and 1.5 inch OD were cut and attached with 10-32 set screws. The holes were predrilled to prevent splitting.

Figure 75: Ratchet and lower end of Drive Lever

With the linkage assembled, the slot latch and slotted guide were lined up and screwed on to the standoffs, Figure 76. With the slot latch and slotted guide attached, the distance required to shift was measured and then equivalent extra material at the bottom of the slot latch was removed in order to enable the drive levers to be in the forward position at the bottom of the slot latch, Figure 76. The diameter of a 10-32 bolt was added to this measurement to accommodate the bolt threaded into the straight shifting rod used to move the mechanism up and down, Figure 77.

Figure 76: Shifting Mechanism in Forward Position

Figure 77: Shifting in Reverse Position

10.6 Brakes

The disc brake is on the wheel hub and the brake calipers were mounted to the wheelchair frame in an unobstructed location. To do this, a small metal plate intended to hold the brake calipers was welded to the end of a 7/16 inch axle stock. The axle was press fitted into the lower axle slot in the wheelchair frame. The position of the caliper on the plate was then located to meet the disc brake and

¼ inch holes were drilled. To finalize the assembly, the axle was welded in place and the brake calipers were mounted to the small metal connection plate.

10.7 Final Assembly

With armrests in the corrected position, final assembly began by cutting each axle and die cutting 7/16 inch threads on each side. The wheel bearings were replaced with 7/16 inch ID roller bearings that were press fit into each wheel hub. The ratchet device subassembly was then bolted to each wheel with the disc brake rotors and the drive lever system was mounted on to each ratchet device. The wheels and connected propulsion systems were mounted on the axles and bolted to the chair frame. An aluminum spacer was mounted between the frame and the drive lever on each side to prevent the socket wrench from disengaging the welded socket. Figures 37-41 show the completed sub-assemblies of the wheelchair coming together to complete the final prototype.

Figure 78: Propulsion System Assembly

The next figure shows the wheel assembly mounted on the wheelchair frame.

Figure 79: Propulsion System Bolted to Wheelchair Frame

Finally, the chair is displayed from a side view in both indoor and outdoor seating positions.

Figure 80: Side View of Wheelchair in Indoor Position

Notice the difference in the seat’s position in regards to the wheelbase and height from the ground.

Figure 81: Side View of Wheelchair in Outdoor Position

Figure 82: Final Assembly of Wheelchair

11.0 Testing

This section describes each testing protocol that was carried out in order to determine the success of the device. Design specification testing isolates and tests individual aspects of the prototype and compares them against expected results of a successful device. Field-testing involves performance in a real world environment. It outlines a testing path that incorporates many obstacles in the terrain that a user might struggle with while using a standard wheelchair. The tester navigated the path to determine if the prototype is effective in a realistic scenario.

11.1 Design Specification Testing

To determine if the final prototype is successful, it must be compared against the design specifications previously established. Each specification will be marked with a Pass or Fail. Passing critical design specifications is required for deciding if the prototype is a success. The protocols can be found in Appendix E: Propulsion System Failure Testing Protocols

This test was set up with the same configuration as the propulsion system in the final prototype. This determined feasibility of the design in regards to system failure.

To be tested:

- Potential failure modes of the system
- Maximum torque applied before failure
- Part that fails first (ratchet, lever arm, weld connections, wheel spokes, hub)

Materials:

- Spring Gauge (with tape covering the indicator to give a maximum force reading)
- 10 lb. Weights
- Bucket
- Rope
- Wheel
- Socket
- Ratchet Wrench
- Clamps or Equivalent

Setup:

1. Using self-tapping screws, a steel plate was attached to the wheel hub and then a pass through socket was welded onto the steel plate, Figure 100.

Figure 100: Wheel with Welded Steel Plate and Socket.

This simulated the final prototype, which had a steel piece onto which the steel socket was welded. The wheel that was used for the prototype is shown in Figure 101.

Figure 101: Wheel that was used for Final Prototype.

Although different shapes, the steel piece screwed to the hub is what the socket will be welded to. The similarity between the intended prototype wheel and the tested wheel provides an accurate representation of the wheel hub and this allows for destructive testing on a wheel that will not be needed for the final prototype.

2. The test wheel was secured to a table in a horizontal orientation. Torque was applied so it was fastened in a way to prevent rotation. This was done by clamping the wheel directly to the

table edges and creating a perimeter around the other edges to prevent it from lifting up or spinning, Figure 102.

Figure 102: Wheel Clamped to Table.

3. The ratchet was connected to the outside of the lever arm via hose clamps. A metal tube was used as the lever arm. A hole was drilled 36 inches from the center of the ratchet for the spring gauge, which was attached in later steps, Figure 103.

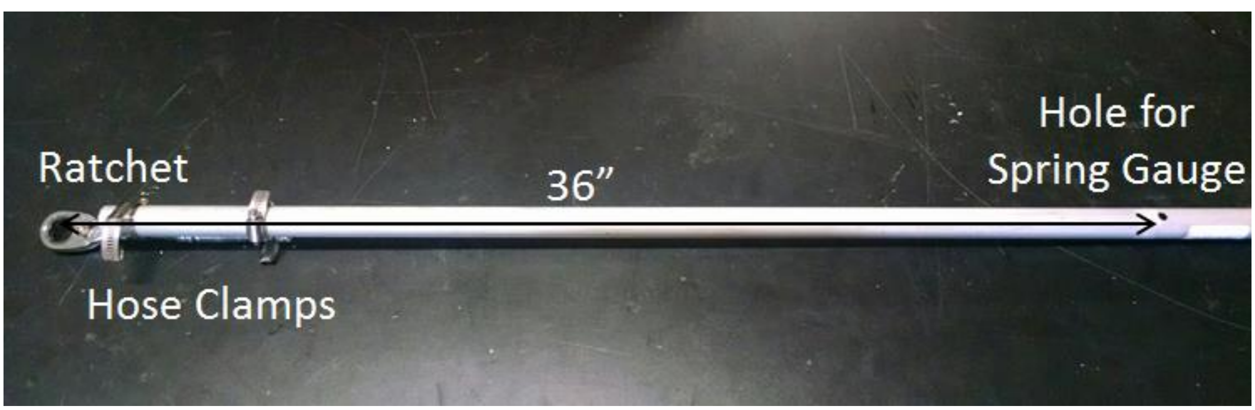


Figure 103: Ratchet attached to Lever Arm.

4. The ratchet was connected to the socket that is mounted to the wheel hub. An additional piece of plywood was added to support the weight of the lever arm due to the orientation of this test. The final

prototype will have the wheel in a vertical orientation, so this will not be a factor. Supporting the lever arm in this way makes it a more realistic test. The spring gauge was connected to the lever at the hole that was drilled earlier, Figure 104.

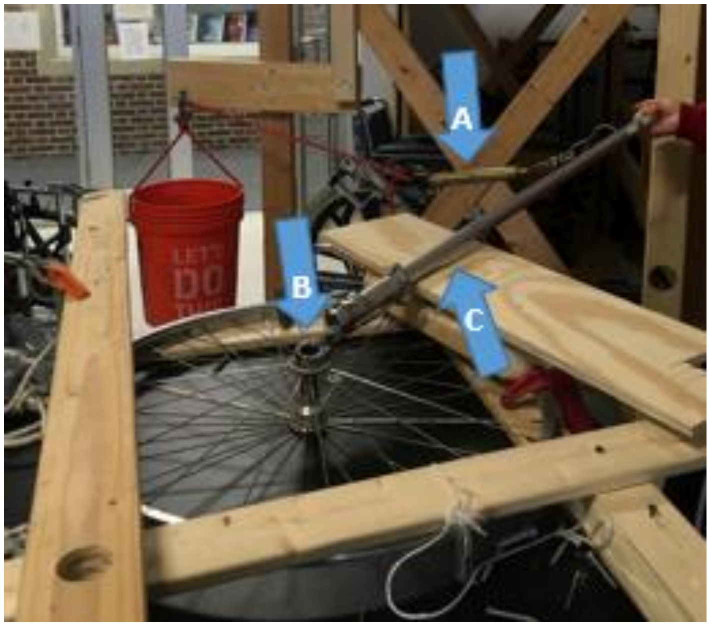


Figure 104: Lever Arm attached to Socket.

A	The Spring Gauge attached to the lever arm
B	Ratchet attached to the socket
C	Wood piece supporting lever arm weight

5. The other side of the spring gauge was attached to a rope that leads to a pulley system with a bucket on the other end that weights can be put in, Figure 105.

Figure 105: Pulley and Weight Bucket Configuration.

A is the pulley. B is the bucket to hold the weights. The metal bar inside of the bucket prevents the rim from collapsing under the weight.

Appendix F: Design Specification Testing.

Table 25 displays the results of the performance based design specification tests. These prove the device's ability to effectively satisfy the design constraints with regards to usability and functional aspects.

Table 25: Performance Design Specification Results

Indoor Operation		Function		Size/Weight		Environment	
Pass		**Pass**		**Pass**		**Pass**	
Fail		**Fail**		**Fail**		**Fail**	

Table 26 displays the results of the production based design specification tests. These specifications are concerned with the quality and manufacture of the device.

Table 26: Production Design Specification Results

Cost		Aesthetics		Maintenance		Manufacturability		Safety	
Pass		**Pass**		**Pass**		**Pass**		**Pass**	
Fail		**Fail**		**Fail**		**Fail**		**Fail**	

11.2 Field Test

A specific test path was laid out in Institute Park to incorporate natural terrain, obstacles, and slopes, Figure 83 and described in Table 27.

Figure 83: Testing path through Institute Park (Google Maps)

These elements will help test each design specification, Table 27. At any point along this path or nearby, special tests can be conducted to ensure thorough and reliable testing. This path also assumes the operator is a fully capable user and can pass all wheelchair skills tests.

Table 27: Description of each zone and which design specifications the zone tests.

Zone	Description	Design Specification Tested
1	ADA approved walkway, uphill, Possible Snow	4, 5
2	Loose Gravel	1, 2, 10
3	Lateral Stability test slope 15 degrees, large tree roots	8, 12
4	Downhill testing Slopes 10-20 degrees	6, 7, 9, 11
5	Thick Grass, Flat, potential mud	3
6	Uphill testing slopes 10-20 degrees	6, 7, 9, 11
7	Mostly level grassy terrain	3

12.0 Results

The design team completed a series of tests on the prototype that showed very conclusive and showed that the prototype wheelchair overcomes several of the limitations of using a standard indoor chair. It was tested indoors and was able to pass all ANSI standards as well as the original design specifications. The following includes the objectives and results for each of the tests conducted by the project team.

12.1 Design Specification Testing

Each design specification was tested using Table 28. Of the 42 design specifications, the prototype passed 35 of the design tests. Two design specifications were unable to be tested due to time constraints. These design specifications were "The device is able to traverse a Class 1 Hiking Trail" and "Under normal indoor and outdoor operation, the device must last at least five years."

Table 28: Completed Design Specification Testing

Design Specification Testing			
Design Specification	**Test Steps**	**Expected Result**	**Pass/Fail**
Indoor Operation Requirements Design Specification Tests The tests in this section should be performed with the device in the indoor position			
1	1. With the drive levers in the down position, measure the horizontal distance between the front most and rear most point of the device.	The device does not exceed 51 inches in length.	P 51 inches
2	1. With the drive levers in the up position, measure the vertical distance between the lowest point and highest point of the device.	The device does not exceed 43 inches in height.	F 49 inches
3	1. Measure the horizontal distance between the left most and right most points of the device as viewed by the user.	The device does not exceed 28 inches in width.	F 29 inches
4	1. Visually verify that wheel locks are present on the device and engage the wheel when activated.	Wheel locks are present and engage the wheel in the locked position.	F Not Present
Function Design Specification Tests			

5	1. No outside help and no use of the tester's legs are allowed for this test. The user must remain on seat of the device for steps 2 – 7. 2. Move the seat from the indoor position to the outdoor position by using the arm rests to lift and pull the seat forward. 3. Move the seat from the outdoor position to the indoor position by using the arm rests to lift and push on the seat backrest. 4. With the propulsion system in the forward direction, push both drive levers to propel the wheelchair forward at least 10 feet on an ADA approved surface. 5. Put one of the drive levers into reverse and leave the other in forward and use both drive levers to turn the device at least 90°. 6. Reverse the direction of both drive levers and use both drive levers to turn at least 90° in the opposite direction as step 5. 7. Put both drive levers in reverse and use the drive levers to move backwards at least 10 feet on an ADA approved surface. 8. Transfer from the device to another seat or equivalent. 9. Remove the seat from the device and fold the frame. 10. Unfold the frame and replace the seat.	All features of the device can be operated solely by the user including the seat adjustment, propulsion, and folding.	P
6	1. Verify that the device can pirouette by	The device can pirouette.	P

	using one drive lever in forward and one drive lever in reverse.		
7	1. With the seat in the indoor position, place 250 lbs. onto the seat in any configuration. 2. Repeat Step 1 with the seat in the outdoor position.	The device can support a load of 250 lbs.	P
8	1. While in the indoor position, measure the vertical distance from the lowest point of the device to the surface of the seat.	The seat does not exceed 20 inches from the ground.	P 19.5 inches
9	1. In the indoor position, move the wheelchair by either have another person manually pushing it or use of the drive levers. 2. While moving, activate the brake handle on the drive lever until the device comes to a stop.	The device has a means of slowing down and stopping.	P
10	1. While in the indoor position, push or propel the device on an ADA approved surface at least 14 feet per second. 2. Verify the speed by using a video camera with a backdrop displaying distances. Use frames per second to determine the speed traveled just before braking. 3. Activate the brakes and measure the distance traveled from first activating the brakes until coming to a complete stop as verified by the video.	The device is capable of coming to a complete stop within a distance of 10 feet when traveling at a speed of 14 feet per second.	P 4 feet 6 inches
Size/Weight Design Specification Tests			

The following tests should be performed with the device in the indoor position.			
11	1. Weigh the entire device on a scale.	The device weighs 50 lbs. or less.	F 52.6lbs
12	1. Remove the seat and fold the frame. 2. Measure the dimensions of the folded frame in a manner in which they would be placed into the back seat of a car.	The device is less than 30 x 29 x 60 inches during transportation.	F 38x23x51
Maintenance Design Specification Tests			
13	1. Obtain a wrench set, pliers, screwdrivers and a hammer. These are the only tools allowed for this test. 2. Unscrew the bolts holding on each axle and remove each axle. 3. Remove the brake handle from each drive lever. 4. Remove each wheel with drive lever attached. 5. Unscrew the screws at the inside of each wheel hub that supports the disc brake and drive levers. 6. Undo the bolt that holds each front caster and remove both casters. 7. Replace all components of the device.	The major components of the device are capable of being assembled and disassembled with common household tools.	P
14	1. Test 13 is indicative of the success of this Test. If Test 13 passes, the same procedure with new parts instead of the old could also be executed, meaning it satisfies this requirement and no further testing is required.	Part replacement can be conducted using only common household tools.	P
Durability Design Specification Tests			
15	1. Due to the time constraints, this design	N/A	N/A

	specification cannot be tested.		
Cost Design Specification Tests			
16	1. Add up the costs of all parts that make the prototype.	The parts required for prototype construction cost less than $640.	P
Aesthetics Design Specification Tests			
17	1. Attach armrests to the wheelchair. 2. Remove the arm rests from the wheelchair.	The wheelchair has the option to have armrests.	P
18	1. Attach wheelie bars to the frame of the wheelchair frame. 2. Remove the wheelie bars from the wheelchair frame.	The wheelchair has the option to have wheelie bars.	P
19	1. Visually verify that operation of the device does not require touching the wheel.	The user is protected from dirt and debris that come from direct contact with a wheel.	P
20	1. Verify that portions of the wheelchair have the ability to accept paint.	The wheelchair can be produced in a variety of colors.	P
21	1. Visually verify that the wheelchair has the option for storage either underneath the seat or at another location.	The wheelchair has storage that is accessible while seated,	P
22	1. Verify that a portion of the frame or armrest has the possibility of attaching a cup holder to it.	The user has the option of attaching a cup holder to the side of the wheelchair.	P
23	1. Use the handles attached to the seat back to push the wheelchair.	The user has the option to have handles on the back of the wheelchair.	P
24	1. Visually verify safety labels are present at any potential dangerous part of the	Safety labels are present and visible.	F

	wheelchair.		
Environment Design Specification Tests The following tests should be performed with the device in the outdoor position.			
25	1. Find a crack or gap at least 30 inches long and between 1.5 and 1.6 inches wide. 2. While operating the wheelchair, pass over the crack with a perpendicular approach. 3. Pass over the crack at an approximate 45° angle. 4. Pass parallel over the crack so that one wheel of the device is completely covering the width of the crack.	The device is able to navigate at least 1.5 in. wide gaps or cracks from any direction.	P
26	1. Find or create a ditch 6 inches deep, 30 inches long, and 13 inches wide. 2. While operating the wheelchair, pass through the ditch from a perpendicular approach.	The device is not impeded by a ditch less than 6 inches deep and less than one radius of the driven wheel wide.	P
27	1. While operating the wheelchair, pass through grass at least 4 inches tall.	The device is able to navigate grassy terrains with grass up to 4 inches tall.	P
28	1. Verify that no parts of the device are significantly affected by temperatures as low as 0° F.	The device must be operable in cold, winter conditions with temperature as low as 0° F.	P
29	1. Propel the wheelchair on a walkway covered with at least 2 inches of snow.	The device can traverse a walkway that has at least 2 inches of snow.	P
30	1. Place the device on a piece of plywood and load the seat with 250 lbs. of sand	The device does not tip when stationary and	P 25-30 degrees

	bags or equivalent, while attempting to evenly distribute the load. 2. Engage the wheel locks. 3. Using a car jack, slowly lift either the left or right side of the plywood until the chair begins to tip. 4. Measure the maximum angle before tipping with an inclinometer.	positioned transversely on a 25° slope.	
31	1. Repeat Test 30 but lift the front of the plywood. 2. Repeat Test 30 but lift the rear of the plywood.	The device does not tip when stationary and positioned longitudinally on a 25° slope.	P
32	1. Use a double sided ramp (one with a peak and a down slope on each side), or equivalent, that is a height sufficient to tilt the wheelchair transversely to a 15° angle when one wheel is at the peak and the other is on the ground. 2. Propel the wheelchair to have one of the wheels pass over the ramp and down the other side while the other wheel remains on the ground.	The device is able to navigate bumps or rocks without tipping that lift one wheel up to create a 15° angle.	P
33	1. Propel the wheelchair up a slope of at least 15°. 2. Return down the same slope.	The device must be able to climb and descend up to 15° slopes while maintaining stability.	P
34	1. Propel the device over at least a ¾ inch gravel or stone walkway.	The device is able to traverse at least ¾ inch gravel or stone walkways.	P
35	1. Use the device on a class 1 hiking trail for 1000 feet without getting stuck or	The device is able to traverse a Class 1 Hiking	N/A

	tipping.	Trail	
36	1. Propel the wheelchair over a log at least 4 inches in diameter.	The device is able to travel over a log at least 4 inches in diameter.	P
Safety Design Specification Tests The following tests should be performed with the device in the indoor position.			
37	1. Visually verify that the device has no exposed sharp edges, pinch points, or foot/leg entrapments.	The device has no exposed sharp edges, pinch points, or foot/leg entrapments.	P
38	1. During testing, verify that no discomfort or injury is being inflicted to the tester. This demonstrates the safety of the device under correct operation.	The user is not endangered when operating the device correctly.	P
39	1. Visually verify the routing of all cables and wires are done to mitigate risk and do not interfere with operations of the chair. 2. Visually verify all moving mechanisms cannot interfere with operations of the chair.	All mechanisms and wires do not interfere with the use of the chair.	P
Manufacturability Design Specification Tests			
40	1. Verify that all manufacturing was completed on the WPI Campus .	All manufacturing was completed on the WPI campus.	P
41	1. Verify the date of completion of the prototype and testing.	The device was constructed and tested before April 21st.	P
42	1. Verify the lead-time on any purchased material did not exceed one week and that no individual part cost more than $200.	All materials required for manufacturing were readily available and low-cost.	P

The prototype passed every function, environment, cost, aesthetics, maintenance, manufacturability, and safety design specification test, Table 29 and Table 30.

Table 29: Performance Design Specification Results

Indoor Operation		Function		Size/Weight		Environment	
Pass	1	**Pass**	6	**Pass**	0	**Pass**	11
Fail	3	**Fail**	0	**Fail**	2	**Fail**	0

Table 30: Production Design Specification Results

Cost		Aesthetics		Maintenance		Manufacturability		Safety	
Pass	1	**Pass**	8	**Pass**	2	**Pass**	3	**Pass**	3
Fail	0	**Fail**	0	**Fail**	0	**Fail**	0	**Fail**	0

Indoor operation mainly focused on the overall dimensions of the prototype. The prototype had a length of 51 inches, height of 49 inches, and width of 29 inches. The length passed the test since the expected results was for the device to not exceed 51 inches in length. However, the height and width failed since the device did exceed 43 inches and 28 inches, respectively.

Environment testing passed all of the expectations for the design. The device traversed 4 inches of snow, which is two inches more than required. The device may be able to handle deeper snow but due to weather conditions, this could not be tested. Stability of the prototype on steep slopes was of high interest. The design specification state the device should not tip when stationary and positioned transversely on a 25-degree slope, or longitudinally on a 25-degree slope. To test these specifications, the prototype was positioned on a board and lifted using jacks for testing.

12.1.1 Static Slope Testing

The prototype was positioned on an adjustable slope and the forward, backward and side tipping angles were measured, Table 31. The goal of the test was to determine how much the prototype improved the standard tipping angle of wheelchair. As a control and comparison, an ADA approved ramp or slope can be no more 5 degrees. The chair was able to remain upright in the forward (Figure 84) and backward (Figure 85) position up to 30 degrees and up to 24 degrees in the sideways position.

A standard wheelchair was also tested, confirming the advantages of the prototype in the rear and lateral tipping directions. However, the prototype did not show much advantage when tipping forward. The test still showed success with the backwards testing of the prototype being 3x better than the standard indoor chair.

Table 31: Tipping Degrees

Direction	Prototype	Standard
Forward	30 Degrees	28 Degrees
Backward	30 Degrees	10 Degrees
Lateral	24 Degrees	19 Degrees

Figure 84: Static Forward Tipping Test Setup

Figure 85: Static Backward Tipping Test Setup

12.2 Park Course Testing

The prototype and a standard wheelchair provided by WPI Health Services were operated through the test course to see a direct comparison on a variety of slopes, surfaces, and obstacles. The prototype proved exceptionally stable and competent in various aspects of the course, while the standard wheelchair was prone to tipping and lacked traction and maneuverability. The prototype was more efficient and required less energy from the user to traverse slopes and ascend inclines. The user in the standard wheelchair was considerably more tired after long inclines both on sidewalks and in grass.

The user in the prototype was able to safely navigate declines and could fully stop and rest on slopes with the brakes. The outdoor mode of the prototype increased stability and gave the user more confidence on higher degree slopes. The brakes allowed the user to steer and handle the wheelchair without grabbing the dirty wheels. The hands and clothes of the user in the standard wheelchair were also noticeably dirtier than those of the prototype user. The drive levers kept the user's hands and clothing away from the wheels, an unexpected benefit of not using the hand rims.

In conclusion, the performance of the prototype definitively passed all requirements in all zones of the test course. The prototype moved through each zone in less than half the time it took the standard wheelchair too. The prototype easily navigated the course’s slopes ranging between 10 and 20 degrees that caused the standard wheelchair user to tip. The standard wheelchair user had to shift his weight several times to wheelie over a root or maneuver himself through mud or gravel. The prototype user felt much safer and did not need to move his body weight around to overcome obstacles, different slopes or surfaces.

12.3 User Feedback Testing

12.3.1 Feedback Testing Protocols:

Goal: To compare the device with a standard indoor wheelchair by testing the standard functions of each chair. The data found will provide the group with relevant information regarding any benefits or drawbacks of the prototype outdoors and on slopes.

Participants will be chosen at random and given an instructional manual as to how to use the device's functions being tested. Prior to the tests beginning, participants will be evaluated to ensure they can safely operate the device. All mechanism, bolts, fasteners, and edges on the devices will be checked prior to testing as well, to prevent failure or injury. Group members will monitor tests.

12.3.1.1 Position transition

Goal: To discover the user's capability of transitioning from indoor position to outdoor position and then back again.

Procedure:

After reading the Instructions describing the Transition process, the participants will be asked to transition down and up using the linkage system. Each transition (up and down) will be timed separately. Afterwards, the participant will be asked to fill out the survey in regards to the interface and ease of use.

12.3.1.2 Folding Mechanism

Goal: To compare the ease of folding and storing the chairs

Procedure:

After reading the Folding mechanism section of the instruction manual for the prototype wheelchair, participants will be asked to fold and unfold each wheelchair. They will be timed and following the test, the chairs will be folded again and participants will be asked to lift and insert each chair into the rear seat of a car. They will again be timed and following the completion of this test, asked to fill out a survey comparing function and ease of use of each chair's ability to fold.

12.3.1.3 Grass Propulsion

Goal: To compare the prototype and a standard wheelchair in the ease of propulsion. Specifically, the ease of propulsion in grass when traveling forward and then traveling backwards will be compared.

Procedure:

After reading the instructions manual for propulsion and shifting, the participants will be asked to switch the propulsion system from forward to reverse, then reverse to forward. Next the user will be asked, using the drive levers, to propel the wheelchair forward across the flat grass for 20 feet, turn 180° and return to the starting line; this task will be timed. Then the participant will use a standard wheelchair to repeat the test. After every task has been completed, the participant will complete a survey about each task they completed.

12.3.1.4 Ramp/Hills

Goal: To compare the prototype to a standard wheelchair in the ease of traveling up an ADA approved ramp.

Participants will begin in a standard wheelchair at the bottom of the ramp in front of Alumni Gym. They will propel themselves up the ramp and will be timed from the moment they begin until they reach the top of the ramp. The ramp consists of a 53 foot ramp, a 180-degree turn on a landing, and another 39 foot ramp. Testing will then be repeated with the prototype using only the hand rims. It will then be repeated one more time using the prototype drive levers. After the testing, the participant will complete a survey about the task they completed.

12.3.2 Results of User Tests

12.3.2.1 Grass Testing

Seven subjects tested a standard wheelchair using the hand rims, the prototype with hand rims, and the prototype with drive levers on grass. When asked which wheelchair they preferred for travel on grass, six of seven people preferred the prototype. Additionally, the raw data collected by the project group can be found in Table 32.

Table 32: Raw Data of the Grass Test

Tester	Standard Wheelchair	Prototype Hand Rims	Prototype Drive Levers
1	47 seconds	33 seconds	69 seconds
2	33 seconds	31 seconds	42 seconds
3	23 seconds	21 seconds	30 seconds
4	40 seconds	37 seconds	38 seconds
5	62 seconds	33 seconds	52 seconds
6	28 seconds	27 seconds	47 seconds
7	45 seconds	30 seconds	45 seconds
Average	**39.7**	**30.3**	**46.1**
Std Deviation	**13.17**	**5.1**	**12.3**

12.3.2.1a Determining if the Data is Statistically Significant

Standard Wheelchair vs. Prototype with Hand Rims on Grass

A non-normal distribution of the participants' times will be assumed for this test. A Wilcoxon test, which compares the median values of two sample sets to determine the statistical significance was used (Boston University School of Public Health 2016). A α value of 0.05 will be considered statistically significant for this one-tailed test with a hypothesis that the prototype with hand rims is faster than the standard wheelchair on grass. To determine if the data between the standard wheelchair and prototype with hand rims are statistically different, a Wilcoxon test was performed. The information is in Table 33.

Table 33: Determination of Statistical Significance of Standard Wheelchair vs. Prototype with Hand Rims on Grass

Critical α value	Sample Size	Critical W	Resultant W	Significant?
0.05	7	3	0	Yes

The data showed a significant difference between the prototype with hand rims and the standard wheelchair, indicating that the prototype with hand rims is faster than the standard wheelchair for travel on grass.

Prototype with Hand Rims vs. Prototype with Drive Levers on Grass

The same procedure was repeated for the prototype with hand rims and the prototype with drive levers, Table 34. If the data are not statistically different, the drive levers will be considered the same speed as hand rims on grass. If the data are significantly different, drive levers will be considered to be slower than hand rims.

Table 34: Determination of Statistical Significance of Prototype with Drive Levers vs. Prototype with Hand Rims

Critical α value	Sample Size	Critical W	Resultant W	Significant?
0.05	7	3	0	Yes

The data show that drive levers are slower than hand rims. Later in this document, the investigation to how much slower the drive levers are than hand rims, and if the mechanical advantage of the drive levers are enough to offset the slower times will occur.

12.3.2b Analysis

The first investigation will be the comparison of the prototype with hand rims to the standard wheelchair on grass. It is clear that the times of the prototype with hand rims showed a smaller standard deviation implying that it is more reliable and repeatable regardless of the user. The standard chair on the other hand, had a large standard deviation and in general, only users with experience were able to travel quickly and most struggled. Figure 86 shows the two times of each test for each person.

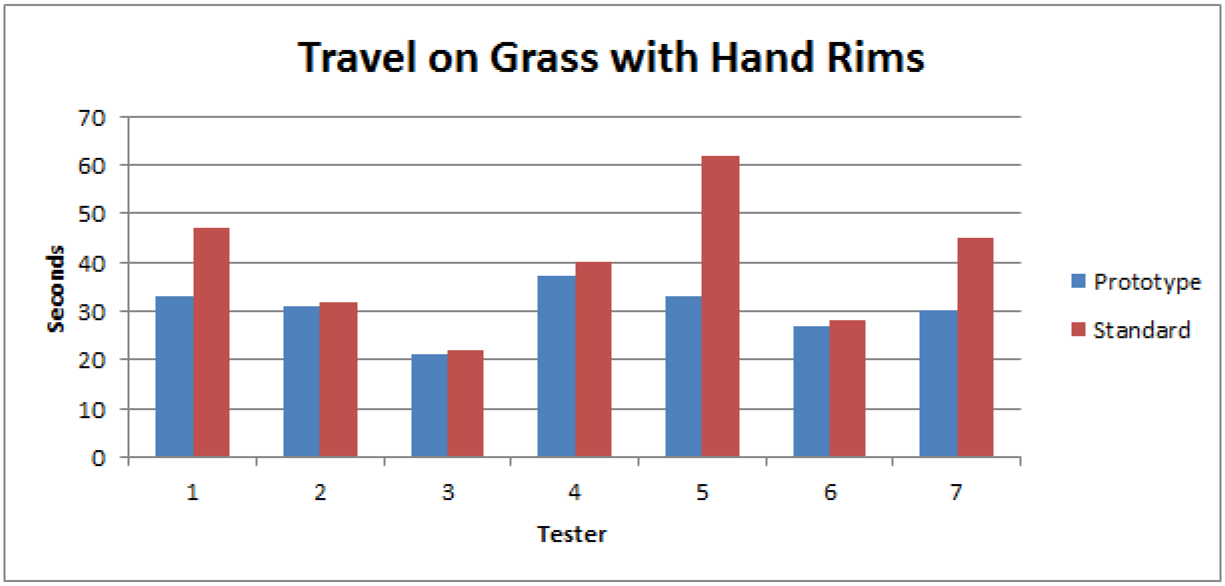


Figure 86: Graphical Comparison of Tester's Time with the Prototype Hand Rims and Standard Wheelchair

The comparison from person to person negates the confounding factors such as physical variation of each tester, test weather, and experience in a wheelchair. Every test subject was able to travel on grass faster with the prototype. Improvement of times for every tester indicates that the prototype was more effective at traveling on grass. A numerical comparison of the times in standard wheelchair and the prototype with hand rims can be seen in Table 35.

Table 35: Numerical Comparison of the Times in the Standard Wheelchair and Prototype of Each Tester

Tester	Standard Wheelchair	Prototype Hand Rims	Percent Faster
1	47 seconds	33 seconds	42%
2	32 seconds	31 seconds	3%
3	22 seconds	21 seconds	5%
4	40 seconds	37 seconds	8%
5	62 seconds	33 seconds	88%
6	28 seconds	27 seconds	4%
7	45 seconds	30 seconds	50%
		Average	**28.6%**

This is a definitive result that is indicative of the success of the prototype. To further reinforce the result, more testing should be completed. Ultimately, 6 out of 7 testers preferring the prototype over the standard wheelchair indicates that the prototype is superior for travel on grass.

The next comparison is between the prototype using hand rims and the prototype using drive levers. The large standard deviation of the drive lever times, much like the standard wheelchair on grass indicates that there is a distinct learning curve. Some users struggled with the drive levers while others were able to travel quickly.

It is clear that drive levers took a longer time, but the additional mechanical advantage was expected to slow the wheelchair down to increase torque. The mechanical advantage provided by the wheelchair is anywhere from 2-3 times that of the hand rims depending on where the user's hands are on the drive levers. On average, the drive levers are 1.5 times slower but the drive levers provide an average mechanical advantage of 2.5, which indicates the increased mechanical advantage, is beneficial. Another method of visualizing this can be seen in Figure 87. It would be expected that drive levers are 2.5 times slower than hand rims, assuming the same stroke length provided by the user. The black line in the graph represents the ratio of 2.5:1 time ratio between the prototype with drive levers and the prototype with hand rims.

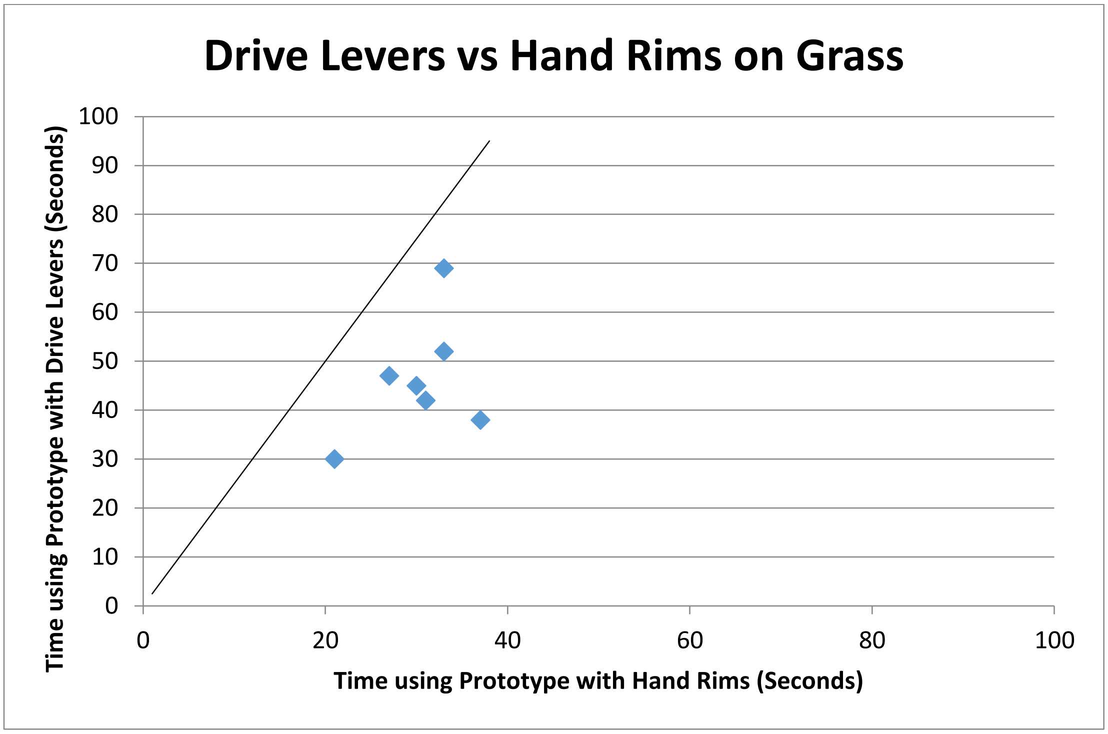


Figure 87: Drive Levers vs. Hand Rims on Grass to Determine Efficacy of Drive Levers

Each data point that falls below the line indicates that the user was able to travel faster than two times slower. Frequency of stroke was not measured and cannot be assumed to be the same but assuming a similar amount of effort input can be. This is because all users were all reasonably fit and above average in terms of upper body strength. Thus, with seven of seven people provided data points below this line, it indicates that each tester benefitted from the drive levers. For travel on grass, the prototype is superior based on user preference and performance.

12.3.2.2 Ramp Testing

Six subjects were tested on the ramp with a standard wheelchair, the prototype using the hand rims, and the prototype using the drive levers. When asked which wheelchair they preferred for travel on slopes, five of six people preferred the prototype. The raw data can be found in Table 36.

Table 36: Raw Data of the Ramp Test

Tester	Standard Wheelchair	Prototype Hand Rims	Prototype Drive Levers
1	34 seconds	33 seconds	78 seconds
2	46 seconds	55 seconds	110 seconds
3	32 seconds	27 seconds	47 seconds
4	30 seconds	31 seconds	72 seconds
5	27 seconds	28 seconds	60 seconds
6	26 seconds	31 seconds	67 seconds
Average	**32.5**	**34.2**	**72.3**
Std Deviation	**6.6**	**9.5**	**19.5**

12.3.2.2a Determining if the Data are Statistically Significant

Standard Wheelchair vs Prototype with Hand Rims up the Ramp

A non-normal distribution will be evaluated for this test and a Wilcoxon test was once again used. A α value of 0.05 will be considered statistically significant for this one-tailed test with a hypothesis that the prototype with hand rims is faster than the standard wheelchair up the ramp. To determine if the data between the standard wheelchair and prototype with hand rims is statistically significant, a Wilcoxon test was performed. The information is in Table 37.

Table 37: Determination of Statistical Significance of Standard Wheelchair vs. Prototype with Hand Rims on Grass

Critical α value	Sample Size	Critical W	Resultant W	Significant?
0.05	6	2	8	No

The data are not statistically different. The prototype with hand rims and the standard wheelchair are equivalent in time for travel up the ramp.

The same procedure was then repeated for the prototype with hand rims and the prototype with drive levers. The information is in Table 38.

Table 38: Determination of Statistical Significance of Prototype with Drive Levers vs. Prototype with Hand Rims

Critical α value	Sample Size	Critical W	Resultant W	Significant?
<0.05	6	2	0	Yes

It is statistically significant that the drive levers are slower than the hand rims up a ramp. Later in this document the investigation to how much slower the drive levers are than hand rims, and if the mechanical advantage of the drive levers are enough to offset the slower times.

12.3.2b Analysis

The first study will be to compare the standard wheelchair to the prototype with hand rims. Once again the analysis will compare each person to avoid confounding factors. The data shows that the prototype was slightly slower, and showed a higher standard deviation. This is potentially due to the prototype being heavier which affects users of varying ability differently. Figure 88 is a graphical display of the times for each tester.

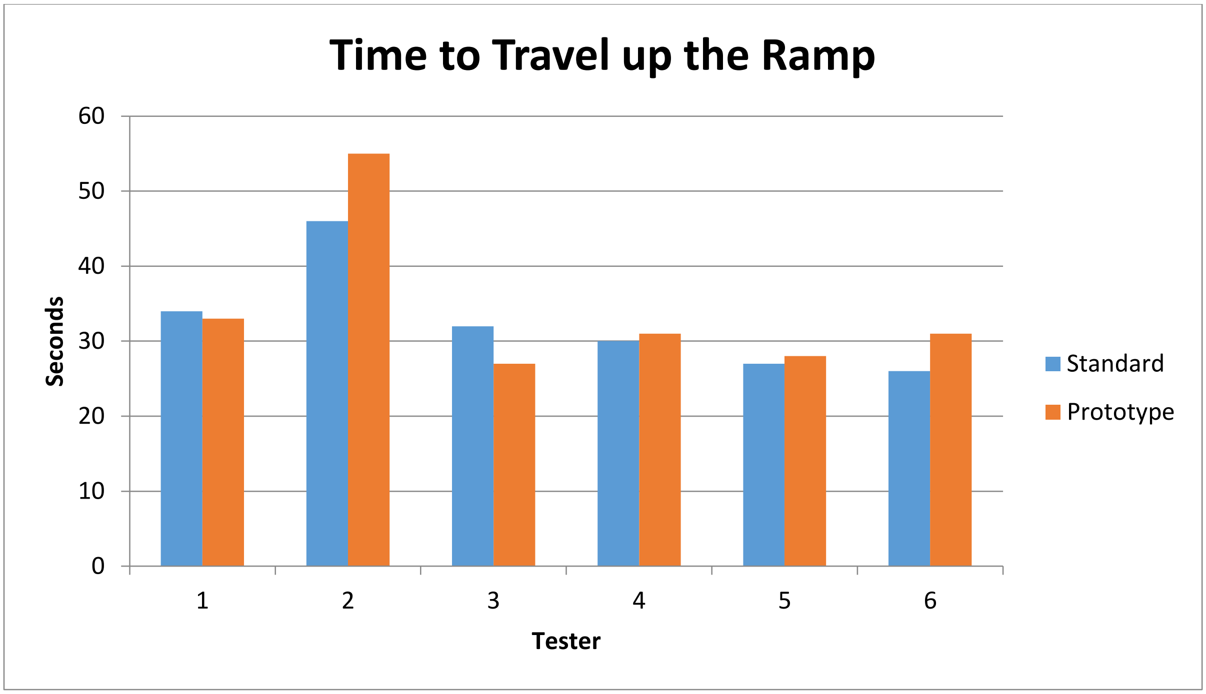


Figure 88: Graphical Comparison of Tester's Times of the Standard Wheelchair vs. the Prototype Hand Rims

Two people were faster with the prototype and four slower, but the times were not statistically significantly different. The numerical comparison of each tester can be found in Table 39 for reference only.

Table 39: Numerical Comparison of Tester's Ramp Climbing Times of the Standard Wheelchair vs. the Prototype Hand Rims

Tester	Standard Wheelchair	Prototype Hand Rims	Percent Faster
1	34 seconds	33 seconds	3%
2	46 seconds	55 seconds	-16%
3	32 seconds	27 seconds	19%
4	30 seconds	31 seconds	-3%
5	27 seconds	28 seconds	-3%
6	26 seconds	31 seconds	-16%

Although the time in each wheelchair to climb the ramp is statistically equivalent, users frequently stated feeling safer in the prototype. With the standard wheelchair, the front casters often lifted off of the ground and the wheelchair nearly tipped backwards. The wheels of the prototype remained firmly on the ground throughout the entire test. With optimization to reduce weight of the indoor outdoor wheelchair, it could potentially be faster and safer for travel up ramps. Five out of six testers prefer the prototype to the standard wheelchair, making the prototype superior for travel up ramps.

The next comparison is between the prototype with hand rims and prototype with drive levers up the ramp.

As expected, the drive levers are slower than the hand rims up a ramp, but only by 2.1 times. After each test, the users noted being significantly less tired after using the drive levers. With more practice, drive levers can be used more quickly and more effectively and are also beneficial for travel up longer ramps. Once again, a graph was created to test the benefits of the drive levers, Figure 89. The black line in the graph represents the ratio of 2.5:1 time ratio between the prototype with drive levers and the prototype with hand rims. While it has no statistical relevance, it is a valuable reference for comparing drive levers and hand rims while climbing a ramp.

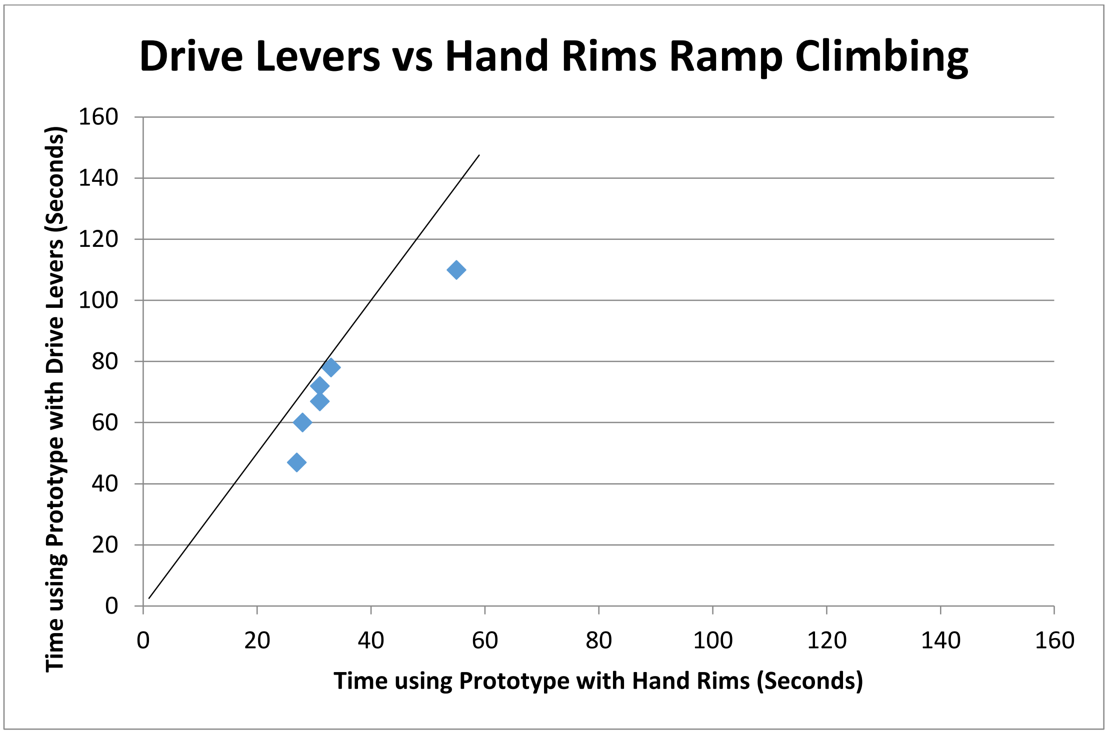


Figure 89: Prototype with Drive Levers vs. Prototype with Hand Rims for Ramp Climbing

Six out of six testers produced data points below the line, meaning that each tester benefitted from the use of drive levers.

12.3.2.3 Folding

The time it takes to fold the prototype was also compared to the time it took to fold a standard wheelchair. The raw data are in Table 40.

Table 40: Folding Test Raw Data

Tester	Standard Wheelchair	Prototype
1	3 seconds	5 seconds
2	3 seconds	5 seconds
3	10 seconds	12 seconds
4	2 seconds	4 seconds
5	3 seconds	5 seconds
6	7 seconds	2 seconds
7	4 seconds	3 seconds
Average	**4.6**	**5.1**
Std Dev	**2.9**	**3.2**

Although the prototype takes longer and has a slightly larger range, the times are tested for statistical significance. The data to test the significance is in Table 41. A normal distribution will be evaluated. A p value of greater than 0.05 would indicate the null hypothesis is true, that the wheelchairs are equivalent in folding.

Table 41: Determination of Statistical Significance of Folding Each Wheelchair

Desired p value	Variance	t-score	Degrees of Freedom	Resultant p value
> 0.05	2.31	1.30	12	0.109

The p value of 0.109 indicates for all intents and purposes, the time to fold each wheelchair is equivalent. A Wilcoxon test was performed to further solidify this conclusion should the data not be normally distributed. The information is in Table 42.

Table 42: Wilcoxon Test to Determine Statistical Significance of Folding Each Wheelchair

Critical α value	Sample Size	Critical W	Resultant W	Significant?
0.05	7	3	12	No

12.3.2.4 Transitioning Test

Each tester was timed when transitioning from Indoor to Outdoor and Outdoor to Indoor, and all times were less than 10 seconds. Therefore, the following analysis will investigate the ease or difficulty that each tester reported. Each tester was asked to rank the ease or difficulty of transitioning on a scale of 1 to 5, 1 being easy and 5 being difficult and their responses are shown in Figure 90.

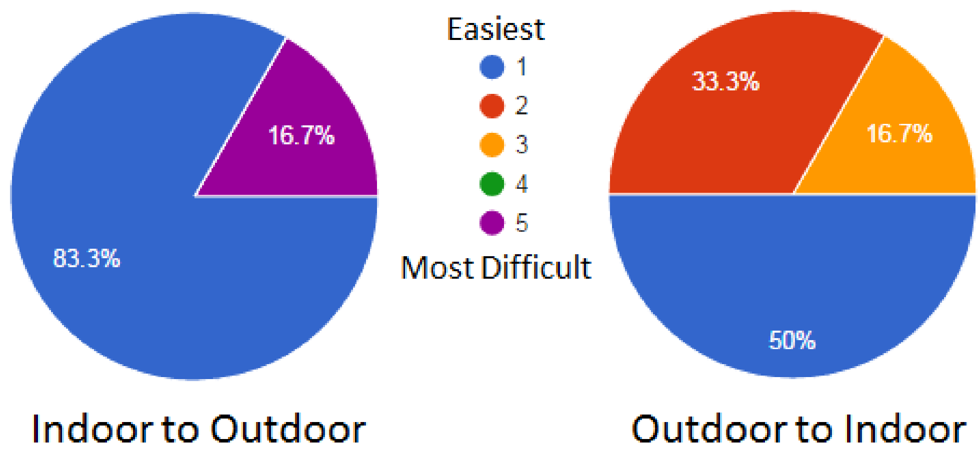


Figure 90: Ease/Difficulty of Transitioning from One Position to the Other

Each test subject was capable of transitioning from one position to the other with relative ease despite one person from Indoor to Outdoor experiencing difficulty. This was caused by an issue with reinserting the pin to lock the link in place and is considered an anomaly. Transitioning from Outdoor to Indoor was more challenging, as expected, because the user must lift his or her weight, but still easy overall. An active manual wheelchair user would most likely have a stronger upper body and be able to transition without difficulty.

12.3.3 User Feedback Testing Discussion

Results showed that the prototype with hand rims is faster on grass than the standard wheelchair. Although the prototype with drive levers is slower, for most people the mechanical advantage makes the device easier for travel on grass. Data from the Wilcoxon tests statistically showed the performance of the prototype and testers' remarks regarding the prototype confirms the benefits of the drive levers while on grass.

The prototype with hand rims and the standard wheelchair allow the user to travel up the ramp at the same speed, but feedback from testers showed that the prototype is easier, safer, and confidence inspiring. The drive levers were 2.1 times slower but the stability of the chair and mechanical advantage make up for the added time. With future improvements to the wheelchair, it is possible and likely that the times could be improved with reduced weight and improved gearing.

Finally, the time to fold the prototype is the same as the time to fold the standard wheelchair, proving that the added mechanism does not hinder lower priority tasks such storage and transport. Transitioning from position to position was also completed by all testers with relative ease, confirming the parametric analysis and anthropometric study results done prior to manufacturing and testing.

13.0 Conclusion

The design and development of the indoor/outdoor wheelchair was successful and exposed many weaknesses present in standard indoor wheelchairs in today's market. Standard indoor wheelchairs are ideal on ADA-surfaces but fall short when taken off of ADA-surfaces. Standard wheelchairs struggle on grass, mud, and steep slopes.

A wheelchair was designed to operate in an ADA standardized building while still being able to be utilized outside on non-ADA surfaces. A new seat system was added. The seat has the option to be completely removed, allowing for a rigid frame when being used and a collapsible frame when not being used. The seat's frame attaches to a linkage system, which was also a part of the design. The seat allows for two positions: indoor and outdoor. When in the indoor position, the seat sits at a standard height for manual wheelchairs. The linkage system then rotates the seat forward and down to be in the outdoor position. A new propulsion system was also added to the wheelchair. The system used a reversible ratchet and pawl as its driving mechanism. The ratchet can be switched between forward and reverse to allow the user to travel backwards and pirouette. The new propulsion system and linkage system are the key features to the prototype.

The prototype not only has the potential to extend the user's independence to higher degree slopes and more rugged surfaces, but it can also increase confidence on ADA approved ramps and around campus. Users felt more confident that they would not tip and were able to push hard while on grass with the increased traction of the mountain bike tires. Many evaluators did complain of the bulkiness and it not being as fast as the standard indoor chair on the ramp tests. Using lighter materials could potentially increase maneuverability and allow the user to achieve similar speeds as the indoor wheelchair on ADA surfaces. In conclusion, the project team successfully addressed all initial objectives, recently filed for a provisional patent and is currently looking to the future to expand upon and improve the device. The team hopes this device can one day be readily available and have significant impact on those who require the use of a wheelchair.

14.0 Future Work

While great strides were made in increasing the stability and propulsion of a wheelchair, there is still much room for continuation and improvement. Testing of the chair's tipping angles on a static slope showed that rear and lateral tipping angles had increased, but forward tipping was not greatly affected by the relocation of the center of gravity. This shows that descending a slope of at least 15 degrees in the prototype still produces a high percentage chance of tipping forward. Finding a more optimal location for the outdoor position in relation to the front casters may prove successful in significantly increasing the forward tipping angle.

Feedback from the independent testers showed a desire for an improved seat design. Testers remarked that the use of sliding tracks might speed up insertion or removal of the seat. The group also saw several issues with the propulsion system and suggests a redesign of the shifting or ratcheting system. The prototype had several interference issues and because of it, a better tolerance or machined system may be an adequate solution as well. Testers also suggested a better mechanical advantage so they could achieve a higher speed. They mentioned that reduced torque would be worth a higher flat ground speed if it were kept at one speed. However, implementing a multi-speed system could solve this problem without sacrificing torque for steep slopes or surfaces with high coefficients of friction.

There were reoccurring issues with the brakes and removal of the wheels was time consuming and difficult. A redesign of the interface between the brake rotor and caliper is advisable. There were issues with misalignment and the axle bending slightly under heavier testers causing the rotor to also deform. This caused uneven wear on the rotors, reduced power and inconsistent braking. It is recommended that a thicker or stiffer material be used for the axle as well. Braking was found to be an important factor for control and is desirable when outdoors.

It is recommended that a new prototype be built and not from an existing wheelchair. A prototype can be much lighter and efficient if it is not restricted by an existing chair’s design. Finally, testing done by more subjects, especially those who are paraplegic is desirable. Every student who used the prototype was able bodied and therefore potentially overlooked possible flaws or hazards for users who are paraplegic. These users could produce much different data and comment on new problems due to the limited or increased use of different muscle groups. While the project was successful, there is still much to be built off of and improved upon in the future.

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Appendix A: Wheelchair Propulsion test and ADA

Wheelchair Propulsion Test (WPT)© Version 1.0 Form

Subject # : ____________________. Date: ___________. Time: ___________Test # ___

Recorded Data*	
1. Able to successfully complete the 10m distance?	Yes ☐ No ☐
2. Direction of travel	Forward ☐ Backward ☐
3. Limbs contributing to propulsion, steering or braking (tick all that apply)	Left: Hand ☐ Leg ☐ Right: Hand ☐ Leg ☐
4. Limb monitored for timing propulsion cycles (tick one limb)	Left: Hand ☐ Leg ☐ Right: Hand ☐ Leg ☐
5. Time (to nearest second)	______ s
6. Total number of propulsive cycles (to nearest full cycle)	______ cycles
7. If using one or more hands for propulsion in the forward direction, during the *contact phases*, did the subject generally begin the contact between the hands and the hand-rims behind the top dead center of the rear wheel?	Yes ☐ No ☐ Not applicable ☐
8. If using one or more hands for propulsion in the forward direction, during the *recovery phases*, did the subject generally use a path of the hands that was predominantly beneath the hand-rims?	Yes ☐ No ☐ Not applicable ☐
9. If using one or more *feet for propulsion* and going forward, did the subject make initial foot contact with the knee flexed less than 90° from full extension and finish with the knee flexed more than 90° (or the opposite if going backward)?	Yes ☐ No ☐ Not applicable ☐
10. Comments: (e.g., position on seat, trunk and arm posture, hand grip, foot contact, consistency, need for training, footwear, equipment worn, wheelchair issues)	

Derived Wheelchair-Propulsion Data*	
1. Speed: 10m / ______ # seconds =	______ m/s
2. Push frequency (cadence): _____ # cycles / ______ # seconds =	______ cycles/s
3. Effectiveness: 10m / _____ # cycles =	______ m/cycle

*Directions on next page.

Tester signature: ____________________ Tester name (print): ________________

Figure 91: Wheelchair Propulsion Test (Wheelchair Skills Program 2012)

Table 43: ADA specifications (Justice 2010)

ADA Specifications	Measurement
Doorway Width	32 inches
Ramp Slope	1:12
Allowable floor gaps	< 0.5 inches

Appendix B: Parametric Analysis

The following analysis compares the effects of changing the COG, track and wheelbase on the Chair's Tipping angles. The group evaluated the longitudinal and lateral tipping angles while the chair is stationary, climbing and descending.

Setup

A wheelchair was standardized in order to perform the study Figure 92 and Figure 93. The weight of the wheelchair is 26lbs.

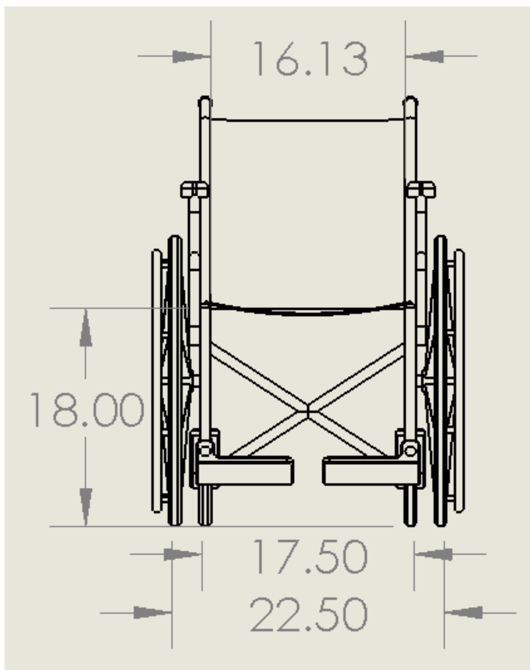


Figure 92: Front View of the Wheelchair Used, with Dimensions

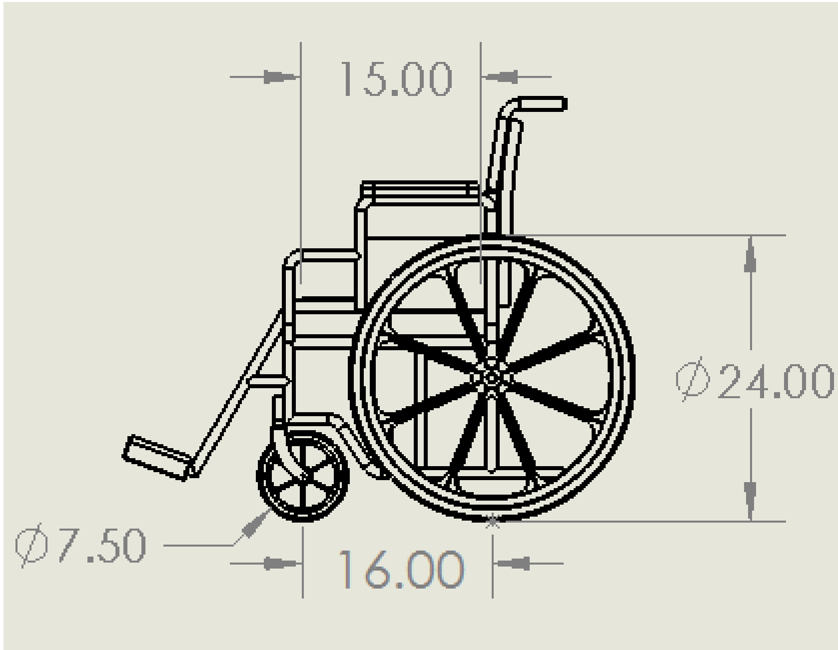


Figure 93: Side View of the Wheelchair Used, with Dimensions

A model of a person was retrieved from Grabcad and used to allow the correct weight distribution of an average male weighing 195lbs, Table 44.

Table 44: Weight Distribution for 195lb. male (Leva 1996)

Weight Distribution								
Body Part	Head	Trunk	Upper Arm	Lower Arm	Hand	Thigh	Lower Leg	Foot
Percent Weight	6.68%	42.57%	2.55%	1.38%	0.56%	14.78%	4.81%	1.29%

The model was placed in the seat in a normal position and the location of the combined center of gravity of the wheelchair and the model, relative to the midpoint between the rear wheel contact points was calculated, Figure 94.

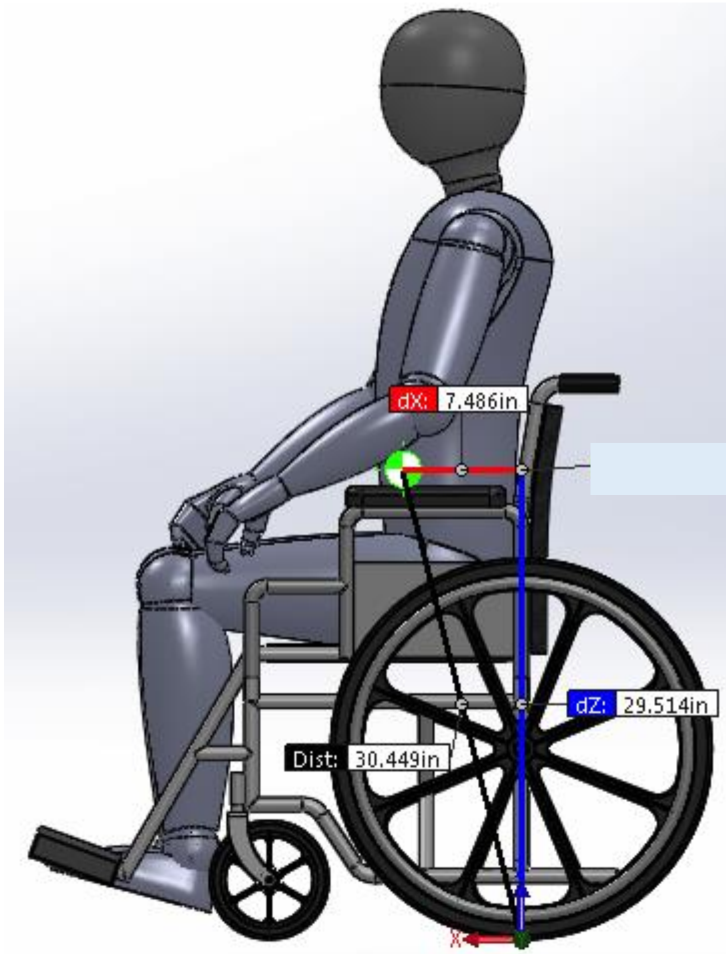


Figure 94: Human Model in Standard Wheelchair, Side View (Grabcad.com)

Method

In order to determine how the position of the user's center of gravity, the wheelbase and the width of the track affect the longitudinal and lateral stability, the tipping angle of the a wheelchair was evaluated. First, the uphill longitudinal tipping angle was evaluated by changing the height of the center of gravity, H, and the horizontal distance from the rear wheel contact point with the ground to the CG, L. Next, the downhill longitudinal tipping angle was calculated by changing the height of the seat, the wheelbase, and the horizontal distance from the rear wheel contact point with the ground to the CG, L. Finally, the lateral tipping angle was assessed by changing the track width and the seat height. A reasonable range for each variable was selected, Table 45.

Table 45: Operating Ranges for Each Dimension Changed

Dimension	Wheelbase, L+L2 (in)	CG Height, H (in)	CG Forward Distance From Axle, L (in)	Track (in)
Range	16 - 24	26 - 30	6 – 12	20 – 34

Longitudinal Tipping Angle

In order to assess the factors affecting longitudinal stability, a free body diagram was created to display the relevant dimensions for the tipping angle, Figure 95.

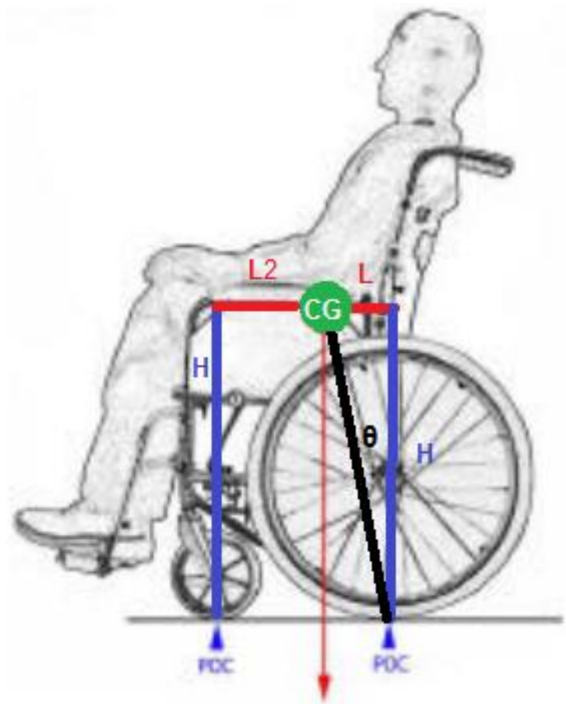


Figure 95: FBD of Longitudinal Stability, where H is the Height of the Center of Gravity, L is the Distance of the CG from the rear Wheel Axle and L+L2 is the Wheelbase

Longitudinal stability was broken into two parts, uphill and downhill. Uphill stability is affected by the user's center of gravity (CG) location. The tipping angle is calculated using the location of the CG. Figure 96 shows the CG located at a length 'L' horizontally from the rear wheel point of contact, and a certain height 'H'. The following equation that solves for theta expresses the angle at which the wheelchair will tip when traveling uphill:

$$\theta = \tan^{-1}\left(\frac{L}{H}\right) \quad \text{(Eq. 1)}$$

The uphill longitudinal tipping angle can be increased by lowering the user's center of gravity and/or shifting the user's center of gravity forward, Figure 96.

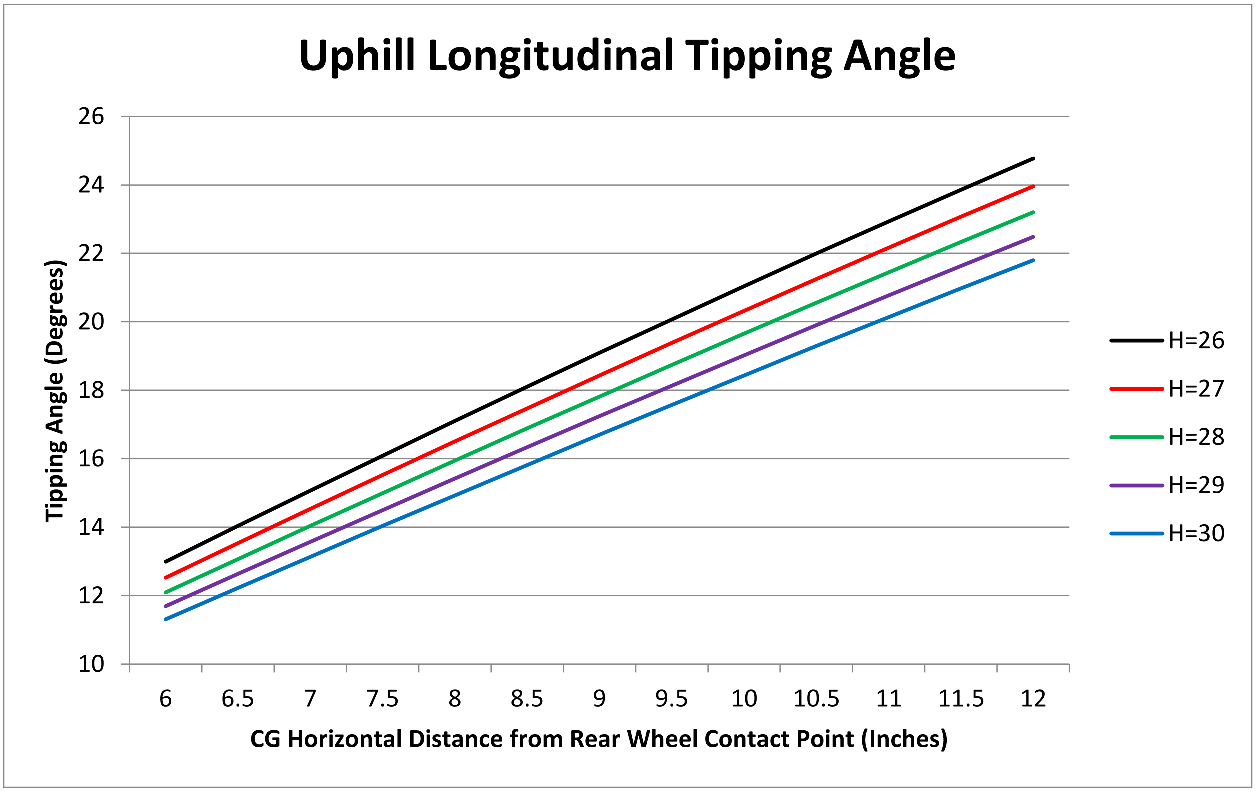


Figure 96: Uphill longitudinal tipping angle.

In a reasonable operating range, shifting the user's center of gravity horizontally and vertically does not directly affect each other. If the height is changed, while the horizontal center of gravity remains the same, the tipping angle changes slightly but it is not significant enough to make a substantial difference to a design. Likewise, the distance between each line, Figure 96, is essentially equivalent meaning that changing the height at any given CG horizontal distance will have the same impact on the tipping angle.

Downhill stability is affected by the user's CG location and the wheelchair's wheelbase. The distance 'L2' is the distance between the CG and the front wheel's point of contact.

$$\theta = tan^{-1}(\frac{L2}{H}) \quad \text{(Eq. 2)}$$

The downhill longitudinal tipping angle can also be increased by lowering the user's CG or lengthening the wheelbase, Figure 97.

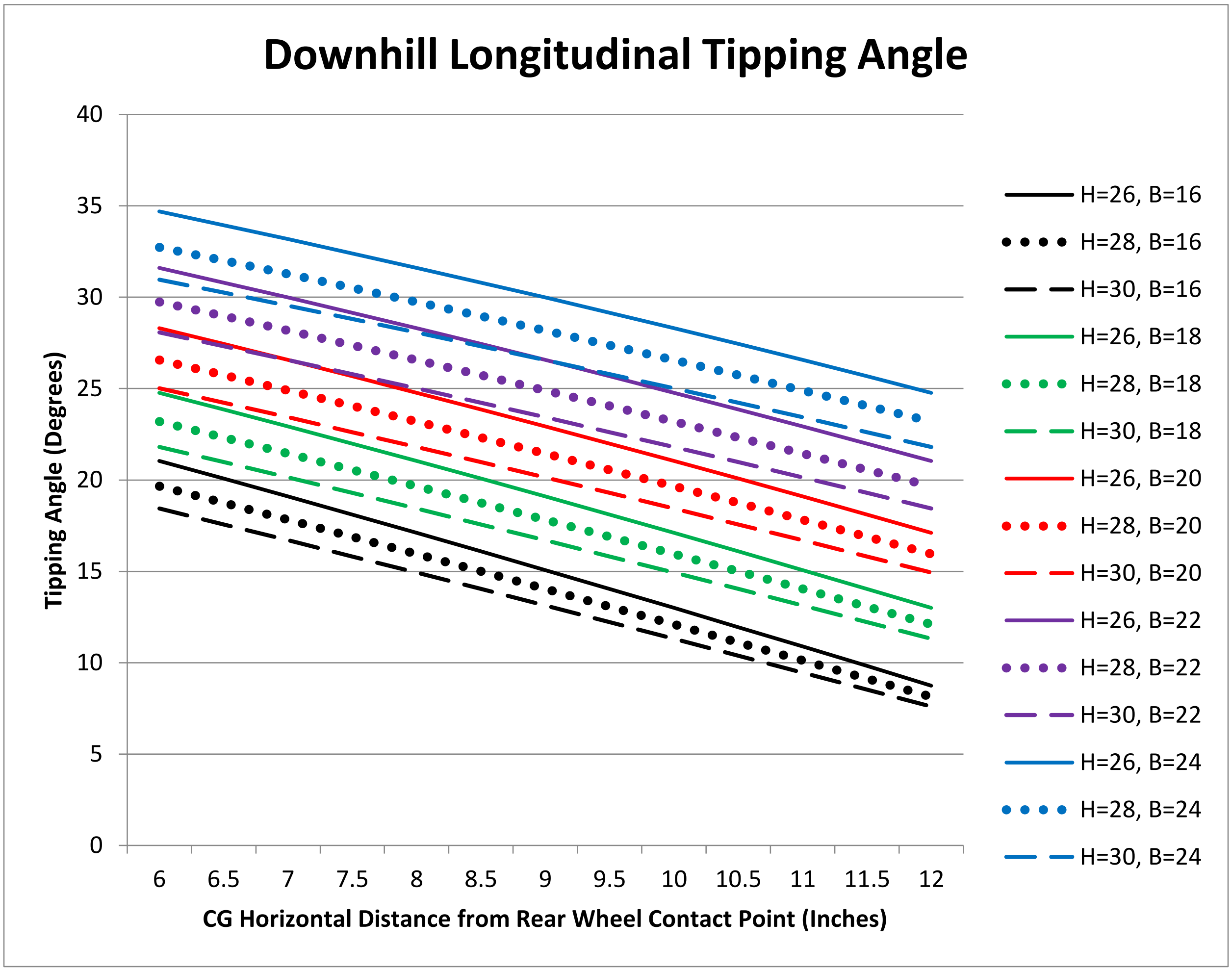


Figure 97: Downhill longitudinal tipping angle.

Within the specified range, moving the CG forward, lengthening the wheelbase and changing the height are not strongly dependent. With the height of the seat or wheelbase changed, the horizontal distance (in inches) of the system's CG from the backrest is slightly more sensitive to change. However, the change is not significant enough to make a substantial difference to a design.

Lateral Tipping Angle

A free body diagram was also created to display the relevant dimensions for lateral stability, Figure 98

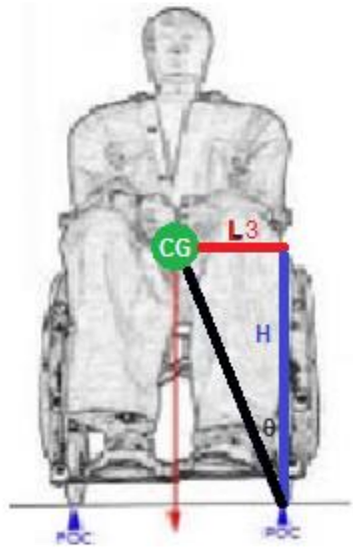


Figure 98: FBD for Lateral Stability, where L3 is half the width of the track, and H is the height of the center of gravity.

Lateral Stability is affected by the height of the CG and the wheelchair's track width. The same method is used to find the tipping angle in the lateral direction:

$$\boldsymbol{\theta = tan^{-1}\left(\frac{L3}{H}\right)} \text{ (Eq. 3)}$$

To compare the effects of changing the height of the seat and the track width vs. the tipping angle, a graph was created, Figure 99. If the user's CG is lowered and/or the track width is widened, then the tipping angle increases.

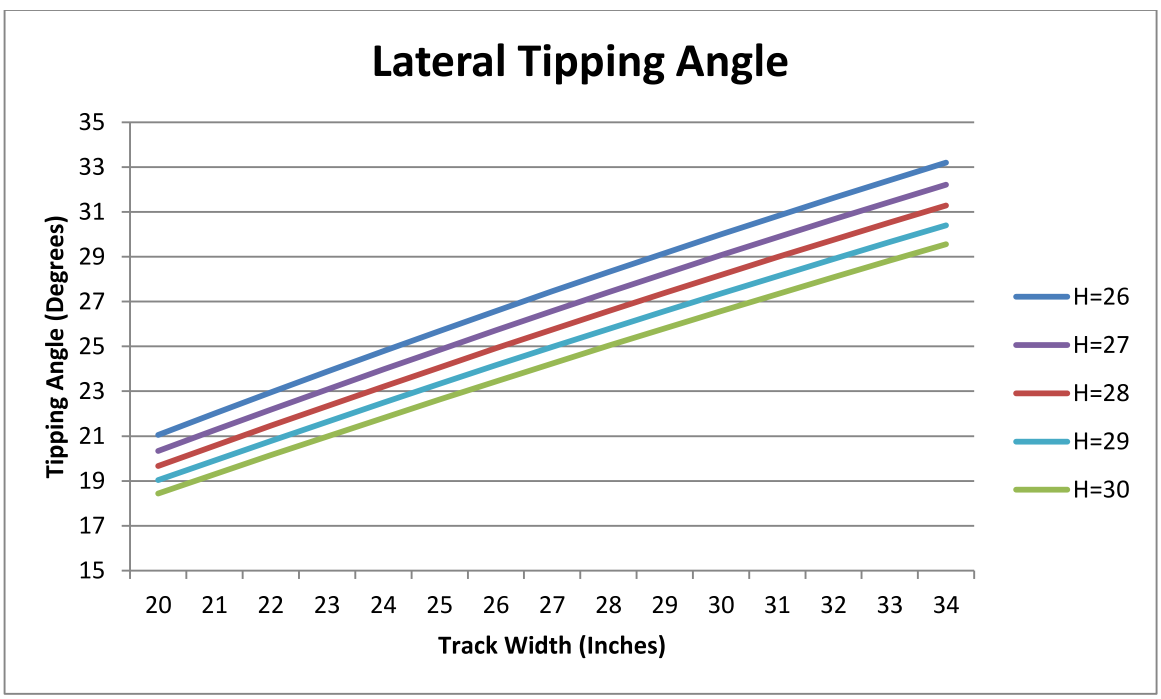
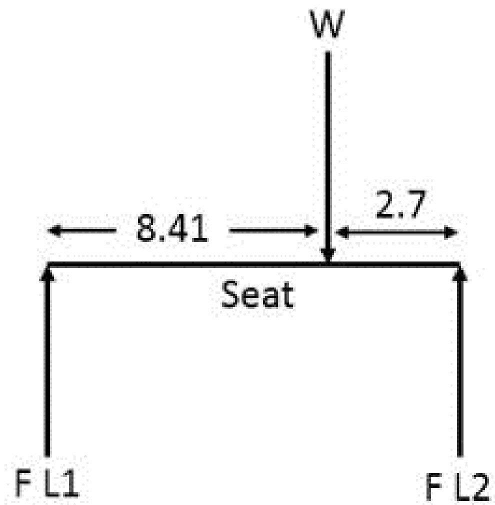


Figure 99: Lateral Stability Tipping Angle. The angle is affected by the width of the track and the height of the center of gravity.

In the selected range, the track and the height of the center of gravity are independent for the purpose of this application. This analysis determined that all variables are independent and do not affect the sensitivity of one another. Therefore, when designing, the largest possible change of any variable will always produce a maximum change in tipping angle.

Appendix C: Mathcad Calculations

The following calculations and sketches determine maximum stresses on the chair, links and stoppers used to determine safety factors, dimensions and materials.



Calculations (Mathcad):

When there is no weight on the chair (user is transitioning chair back to upright position)

$W_1 := 17.41 lbf$

When there is weight on the chair (user is using chair in lowered position)

$W_2 := 250 lbf + W_1$ $\quad\quad\quad W_2 = 267 \cdot lbf$

$F_2 := 0 lbf$

Given

$F_{L1} + F_{L2} - W_2 = 0$ sum of the forces in the y direction

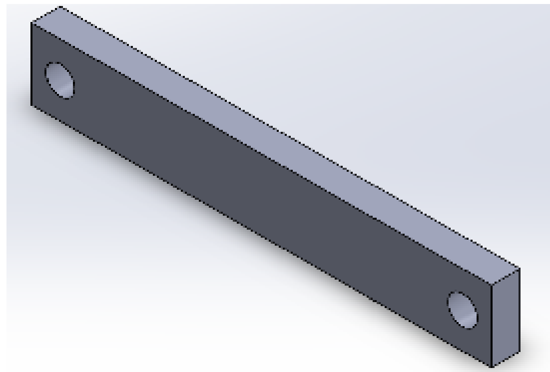
$-W_2 \cdot (8.41 in) + F_{L2} \cdot (11.11 in) = 0$ sum of the moments about the front pin

$\begin{pmatrix} F_{L1} \\ F_{L2} \end{pmatrix} := Find(F_{L1}, F_{L2})$ $\quad\quad\quad \boxed{F_{L1} = 65 \cdot lbf}$

$\boxed{F_{L2} = 202 \cdot lbf}$

Assumed Dimensions and Material (Mathcad):

$l := 4in$



$h := .625in$

$d := .25in$

$thick := 0.50in$

Using AISI 1090 Steel

Yield strength

$S_y := 78ksi$

Safety factor

$SF := 5$

$S_{max} := \frac{S_y}{SF}$ $S_{max} = 15.6 \cdot ksi$

$I := \frac{(thick \cdot h^3)}{12}$ $I = 0.01 \cdot in^4$

$c := 0.5 \cdot h$ $c = 0.313 \cdot in$

Force Calculations (Mathcad):

Known Values:

$F_{L2} := 202\,lbf$

$\theta_1 := 65 \cdot \frac{\pi}{180} = 1.13$

$\theta_2 := 25 \cdot \frac{\pi}{180} = 0.43$

Find R_1 and R_2

Guess

$R_1 := 1\,lbf$

$R_2 := 1\,lbf$

$\theta_3 := 1\,deg$

Given

$R_1 \cdot \sin(\theta_2) - R_2 \cdot \sin(\theta_3) = 0$ sum of the forces in the x-direction

$-F_{L2} + R_1 \cdot \cos(\theta_2) - R_2 \cdot \cos(\theta_3) = 0$ Sum of the forces in the y-direction

$-R_1 \cdot 2 + F_{L2} \cdot \sin(\theta_1) \cdot 3.5 = 0$ Sum of the moments

$\begin{pmatrix} R_1 \\ R_2 \\ \theta_3 \end{pmatrix} := \mathrm{Find}(R_1, R_2, \theta_3)$

$R_1 = 320. \quad lbf$

$R_2 = 161. \quad \cdot lbf$

$\theta_3 = 776. \quad \cdot deg$

$\theta := \theta_3 - 720\,deg = 56. \quad \cdot deg$

Bending Stress Calculations (Mathcad):

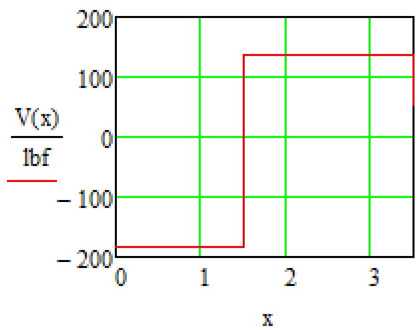
Singularity functions

$S(x,z) := if(x \geq z, 1, 0)$

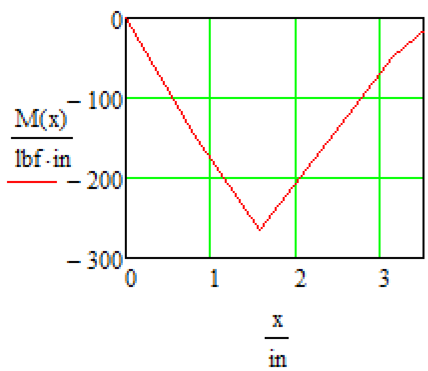
$V(x) := -F_{L2} \cdot \sin(\theta_1) \cdot S(x,0) + R_1 \cdot S(x,1.5) - R_2 \cdot \cos(\theta_3) \cdot S(x,3.5)$

$M(x) := -F_{L2} \cdot \sin(\theta_1) \cdot S(x,0in) \cdot (x - 0in)^1 + R_1 \cdot S(x,1.5in) \cdot (x - 1.5in)^1 - R_2 \cdot \cos(\theta_3) \cdot S(x,3.5in) \cdot (x - 3.5in)^1$

Shear Diagram



Moment Diagram



$M_{max} := M(1.5in) \qquad M_{max} = -274.6 \quad lbf \cdot in$

$\sigma_{crit} := \frac{-M_{max} \cdot c}{I} \qquad \sigma_{crit} = 8.4 \quad ksi$

$Success_{\sigma} := \begin{vmatrix} \text{"YES"} & \text{if } \sigma_{crit} < S_{max} \\ \text{"NO"} & \text{if } \sigma_{crit} \geq S_{max} \end{vmatrix} \qquad Success_{\sigma} = \text{"YES"}$

Tear Out Stress Calculations (Mathcad):

$$\sigma_{tear} := \frac{267lbf}{(h - d)\cdot thick} = 1.4 \quad ksi$$

$$Success_{tear} := \begin{cases} \text{"YES"} & \text{if } \sigma_{tear} < S_{max} \\ \text{"NO"} & \text{if } \sigma_{tear} \geq S_{max} \end{cases} \qquad Success_{tear} = \text{"YES"}$$

$$M(x) := -F_{L2}\cdot \sin(\theta_1)\cdot S(x, 0in)\cdot (x - 0in)^{-} + R_1\cdot S(x, 1.5in)\cdot (x - 1.5in)^{-} - R_2\cdot \cos(\theta_3)\cdot S(x, 3.5in)\cdot (x - 3.5in)^{1}$$

MathCad:

Known

$a := 8.41in \qquad b := 4.79in \qquad c := 5.06in \qquad d := 9.35in$

$\theta := 25 \qquad W := 17.41lb$

$$\theta_{deg} := \theta \cdot \frac{\pi}{180}$$

Solve

Guess

$R_1 := 1lb \qquad R_2 := 1lb \qquad F := 1lb$

Given

$$0 = -R_1\cdot \cos(\theta_{deg}) - R_2\cdot \cos(\theta_{deg}) + F$$

$$0 = R_1\cdot \sin(\theta_{deg}) + R_2\cdot \sin(\theta_{deg}) - W$$

$$0 = R_1\cdot \sin(\theta_{deg})\cdot (a + b) + R_2\cdot \sin(\theta_{deg})\cdot b - W\cdot c + F\cdot d$$

$$ans := find(R_1, R_2, F) \rightarrow \begin{pmatrix} -96.8 \\ 138.0 \\ 37.3 \end{pmatrix}$$

$R_1 := ans_0 \qquad R_2 := ans_1 \qquad F := ans_2$

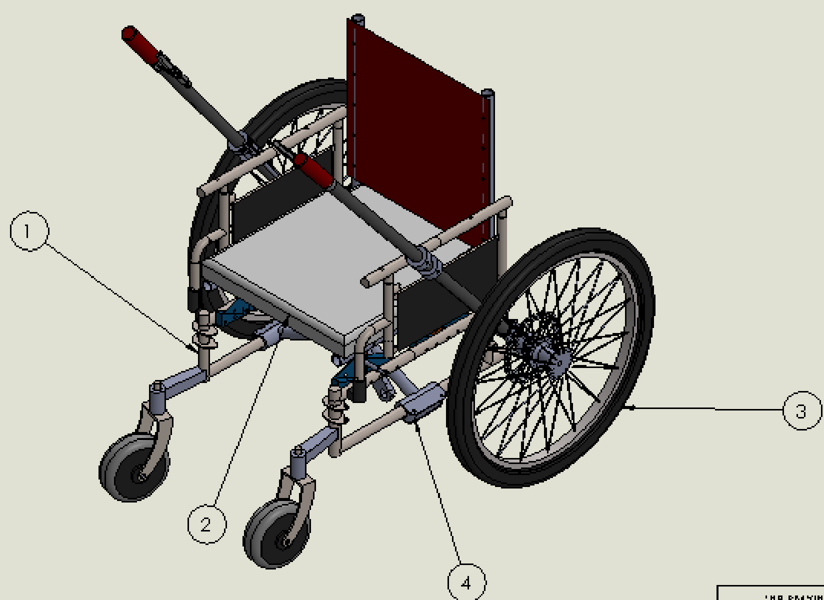
Results

$F = 37.3 \quad lb \qquad R_1 = -96.8 \quad lb \qquad R_2 = 138 \quad lb$

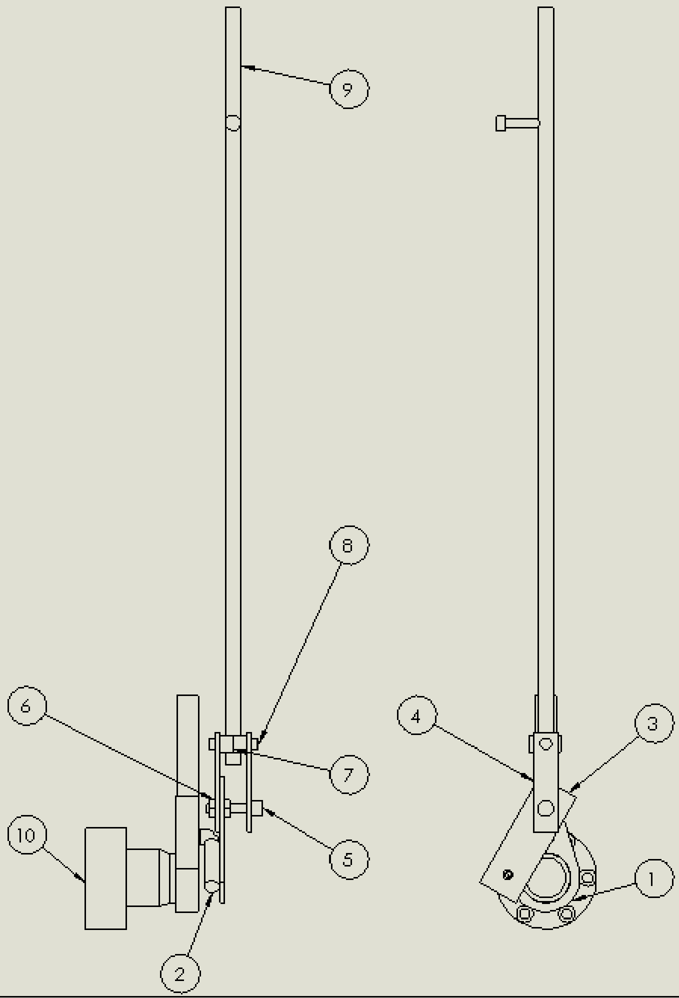
Appendix D: Drawings of Prototype

SYM	REVISION DESCRIPTION	DATE	BY

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10-0	Right of Wheelchair	1
2	6-0	Seat Assembly	1
3	7-0	Left of Wheelchair	1
4	9-0	Folding Mechanism	1

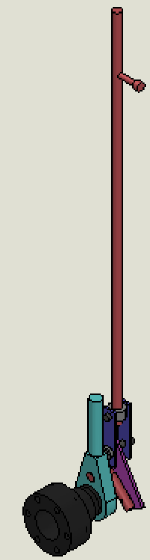


MATERIAL:		WC@WPI.EDU 100 Institute Rd Worcester, MA 01609
PROCESS:		
DRAWN BY E.M.S DATE 03/01/2016		TITLE/DESCRIPTION: Full Assembly
CHECKED BY DATE		PART NO. 1 2 - 0
APPROVED BY DATE		SCALE 1:8 REVISION X SHEET 1 OF 57



SYM	REVISION DESCRIPTION	DATE	BY

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1-6	Ratchet, From Socket to Bent Rod	1
2	1-4	Shifting Mechanism Bent Rod, From Link B to Ratchet	1
3	1-3	Shifting Mechanism Link B, From Link A to Bent Rod	1
4	1-2	Shifting Mechanism Link A, From Rod to Link B	2
5	1-8	4.8mm Screw	1
6	1-7	4.80 ID Nut	2
7	1-9	7.90 ID Nut	1
8	1-10	3.15mm Screw	2
9	1-1	Shifting Mechanism Rod, From Link A to Lock Bolt	1
10	1-5	Socket Welded to Chain Piece, From Ratchet to Axle	1



DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	.X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-.12DEG	ANGLES +/-.12DEG

MATERIAL:
PROCESS:

DRAWN BY: EJM.S DATE: 03/01/2016
CHECKED BY: DATE:
APPROVED BY: DATE:

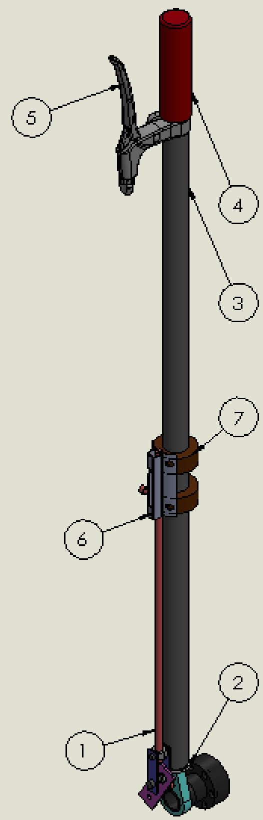
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609

TITLE/DESCRIPTION
Shifting Mechanism

PART NO. 1 - 0

SCALE: 1:5 REVISION: X SHEET: 2 OF 57

SYM	REVISION DESCRIPTION	DATE	BY



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1-0	Shifting Mechanism	1
2	2-1	Bushing, From Drive Lever to Ratchet	1
3	2-2	Drive Lever Tubing, To Bushing	1
4	2-3	Grip, To Drive Lever Tubing	1
5	2-4	Brake Handle, To Drive Lever Tubing	1
6	2-5	Bolt Lock, From Drive Lever Tubing to Shifting Mechanism	1
7	2-6	Wooden Spacers, From Drive Lever to Lock Bolt	2

MATERIAL:

PROCESS:

WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	.X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-1/2 DEG	ANGLES +/-1/2 DEG

DRAWN BY: E.M.S DATE: 03/01/2016

CHECKED BY: DATE:

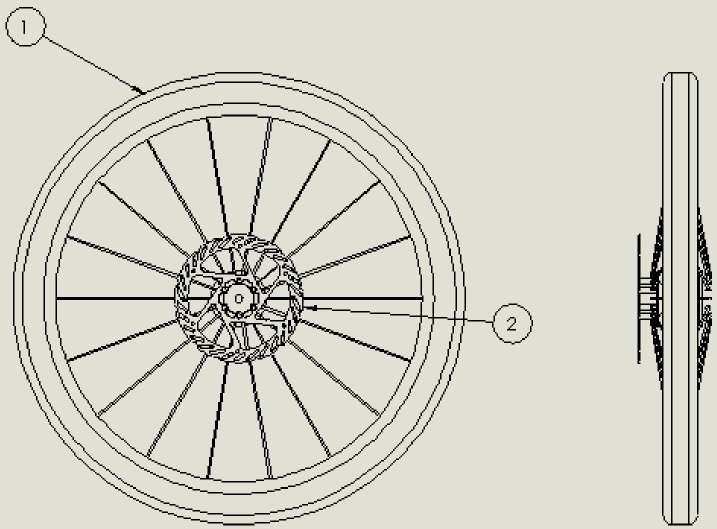
APPROVED BY: DATE:

TITLE/DESCRIPTION: Propulsion System

PART NO. 2 - 0

SCALE: 1:4 REVISION: X SHEET: 3 OF 57

SYM	REVISION DESCRIPTION	DATE	BY



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	3-1.	Bike Tire	1
2	3-2	Disc Brake, From Wheel to Propulsion System	1

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MATERIAL:

PROCESS:

WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	.X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-.1/2DEG	ANGLES +/-.1/2DEG

DRAWN BY: E.M.S DATE: 03/01/2016

CHECKED BY: DATE:

APPROVED BY: DATE:

TITLE/DESCRIPTION

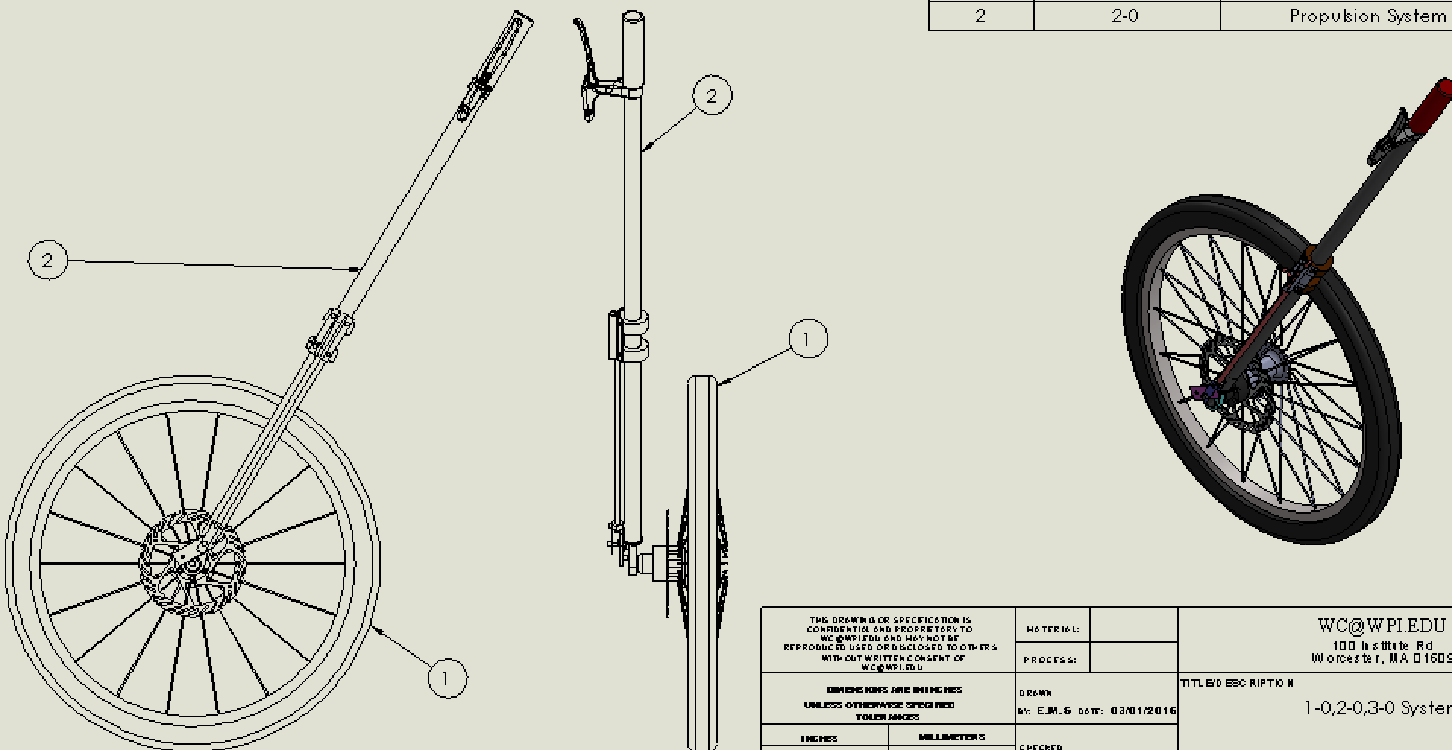
Wheel System

PART NO. 3 - 0

SCALE: 1:5 REVISION: X SHEET: 1 OF 57

SYM	REVISION DESCRIPTION	DATE	BY

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	3-0.	Wheel System	1
2	2-0	Propulsion System	1



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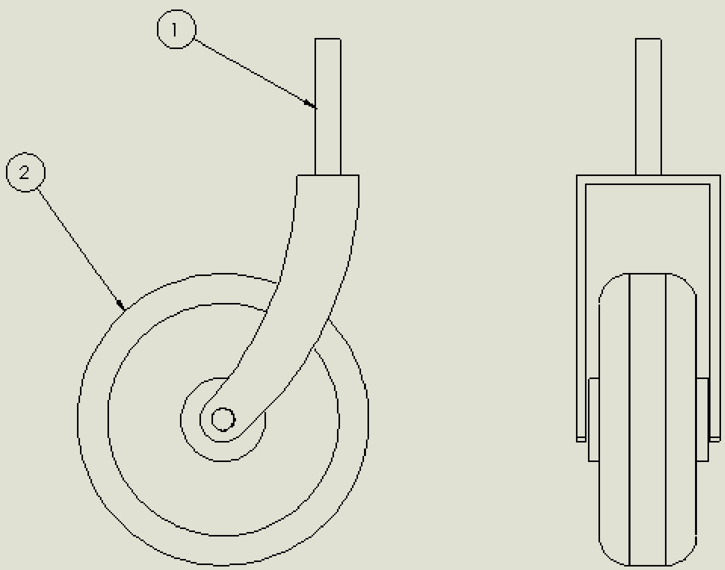
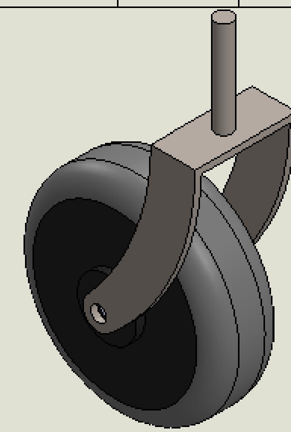
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES	DRAWN BY: EJM.G DATE: 03/01/2016	TITLE/DESCRIPTION: 1-0,2-0,3-0 System	
INCHES / MILLIMETERS .X +/-.030 / .X +/-.7 .XX +/-.010 / .X +/-.3 .XXX +/-.005 / .XX +/-.1 ANGLES +/-.12DEG / ANGLES +/-.12DEG	CHECKED BY: DATE:	PART NO. 4 - 0	
	APPROVED BY: DATE:	SCALE: 1:6	REVISION: X · SHEET: 5 OF 57

SYM	REVISION DESCRIPTION	DATE	BY





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	5-1	Caster Frame, From Frame to Caster Wheel	1
2	5-2	Caster Wheel, On Caster Frame	1

Note: Any caster assembly which fits the wheelchair frame can be used.

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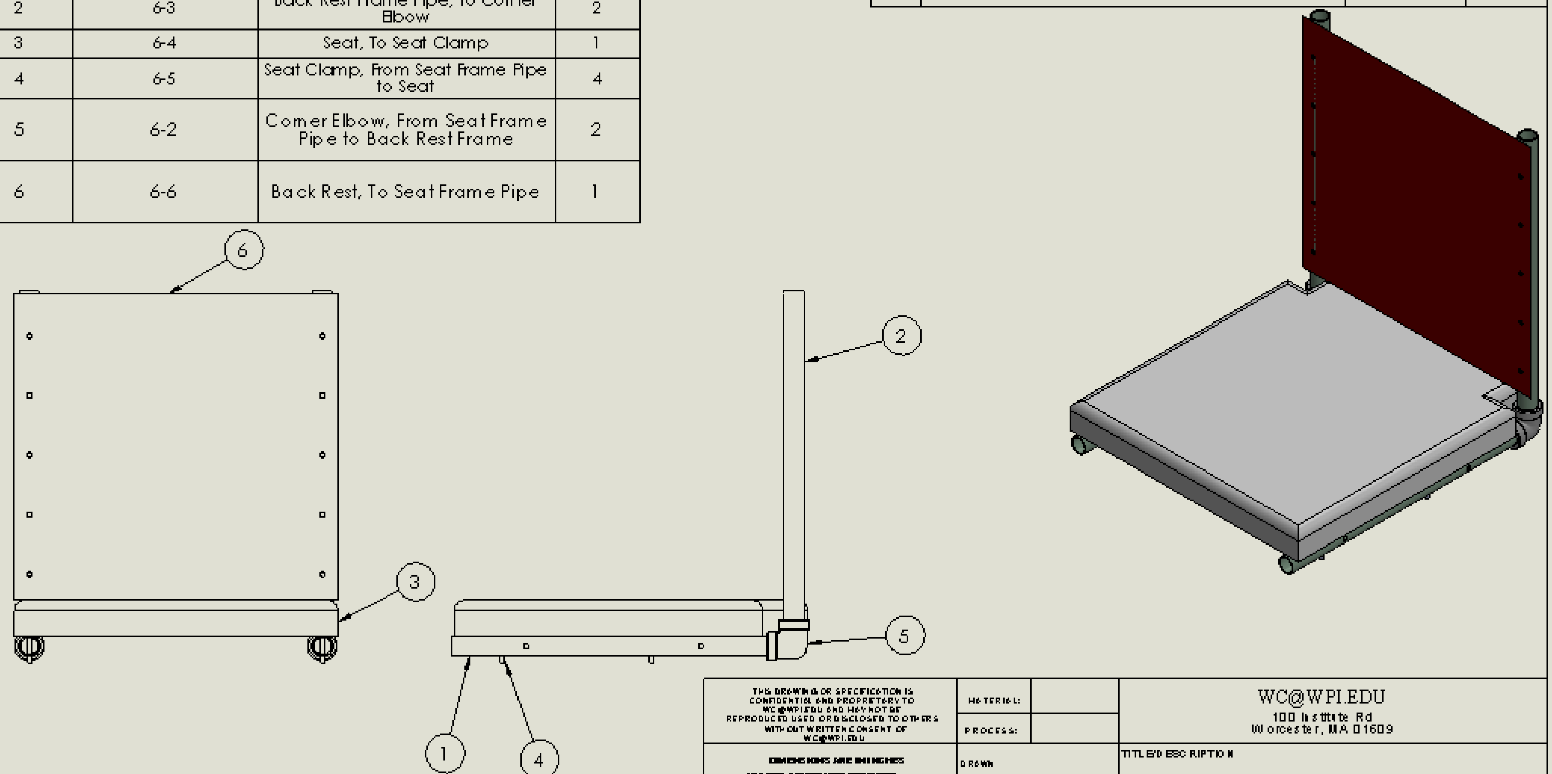
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES	DRAWN BY: EJM.6 DATE: 03/01/2016	TITLE/DESCRIPTION: Caster Assembly	
INCHES: .X +/-.030, .XX +/-.010, .XXX +/-.005, ANGLES +/-.1/2DEG	CHECKED BY: DATE:	PART NO. 5 - 0	
MILLIMETERS: .X +/-.7, .X +/-.3, .XX +/-.1, ANGLES +/-1/2DEG	APPROVED BY: DATE:	SCALE: 1:2	REVISION: X	SHEET: 6 OF 57

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6-1	Seat Frame Pipe, From Corner Elbow to Seat Clamp	2
2	6-3	Back Rest Frame Pipe, To Corner Elbow	2
3	6-4	Seat, To Seat Clamp	1
4	6-5	Seat Clamp, From Seat Frame Pipe to Seat	4
5	6-2	Corner Elbow, From Seat Frame Pipe to Back Rest Frame	2
6	6-6	Back Rest, To Seat Frame Pipe	1

SYM	REVISION DESCRIPTION	DATE	BY



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DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	.X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-.1 2DEG	ANGLES +/-.1 2DEG

MATERIAL:

PROCESS:

DRAWN BY: E.M.S DATE: 03/01/2016

CHECKED BY: DATE:

APPROVED BY: DATE:

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100 Institute Rd
Worcester, MA 01609

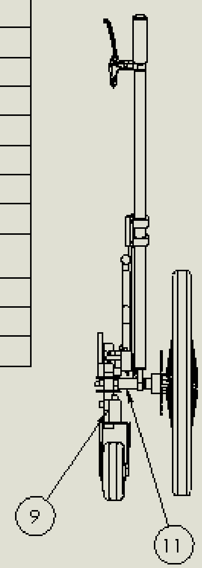
TITLE/DESCRIPTION
Seat Assembly

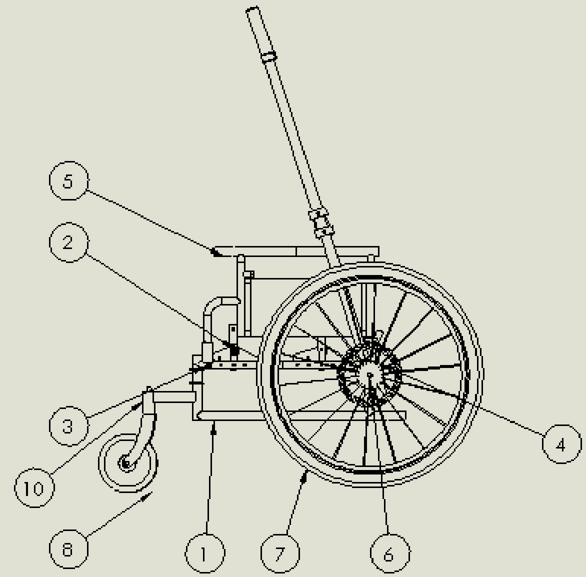
PART NO. 6 - 0

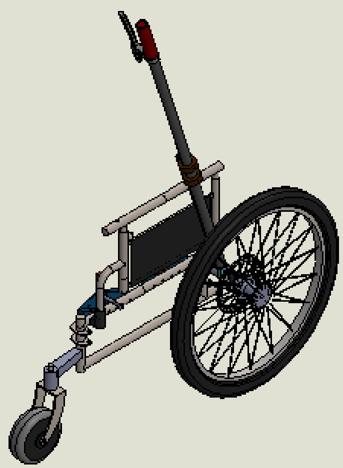
SCALE: 1:5 REVISION: X SHEET: 7 OF 57

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	7-1	Left Frame	1
2	7-3	Link, To Stop	2
3	8-2	Front Arm Rest Holder, From Arm Rest to Frame	1
4	8-1	Rear Arm Rest Holder, From Arm Rest to Frame	1
5	8-0	Left Arm Rest Assembly	1
6	7-4	Wheel Axle, From Frame to 4-0	1
7	4-0	1-0, 2-0, 3-0 System	1
8	5-0	Caster Assembly	1
9	5-3	Caster Extention	1
10	5-4	Caster Bearing Holder	1
11	7-5	Spacer	1
12	10-2	Right Stop, From Right Frame to Link	2
13	13-3	Pin Locator, to Stop	1
14	13-1	Pin to Stopper	1
15	13-2	Pin Screw, to Pin	1

SYM	REVISION DESCRIPTION	DATE	BY







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DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	.X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-.1/2DEG	ANGLES +/-1/2DEG

MATERIAL:
PROCESS:

DRAWN
BY: E.M.S DATE: 03/01/2016

CHECKED
BY: DATE:

APPROVED
BY: DATE:

WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609

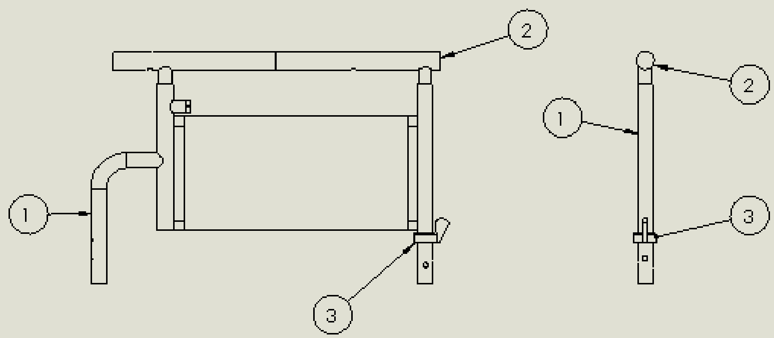
TITLE/DESCRIPTION
Left of Wheelchair

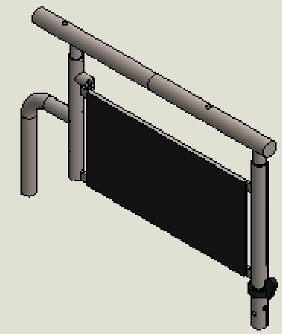
PART NO. 7 - 0

SCALE: 1:10 REVISION: X SHEET: 8 OF 57

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	8-3	Left Arm Rest Side Panel, From Holders to Arm Rest Frame	1
2	8-4	Arm Rest Frame, From Arm Rest Padding to Arm Rest Side Panel	1
3	8-6	Arm Rest Black Clip, To Arm Rest Side Panel	1

SYM	REVISION DESCRIPTION	DATE	BY





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MATERIAL:

PROCESS:

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100 Institute Rd
Worcester, MA 01609

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	.X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-.1/2DEG	ANGLES +/-1/2DEG

DRAWN BY: E.M.S DATE: 03/01/2016

CHECKED BY: DATE:

APPROVED BY: DATE:

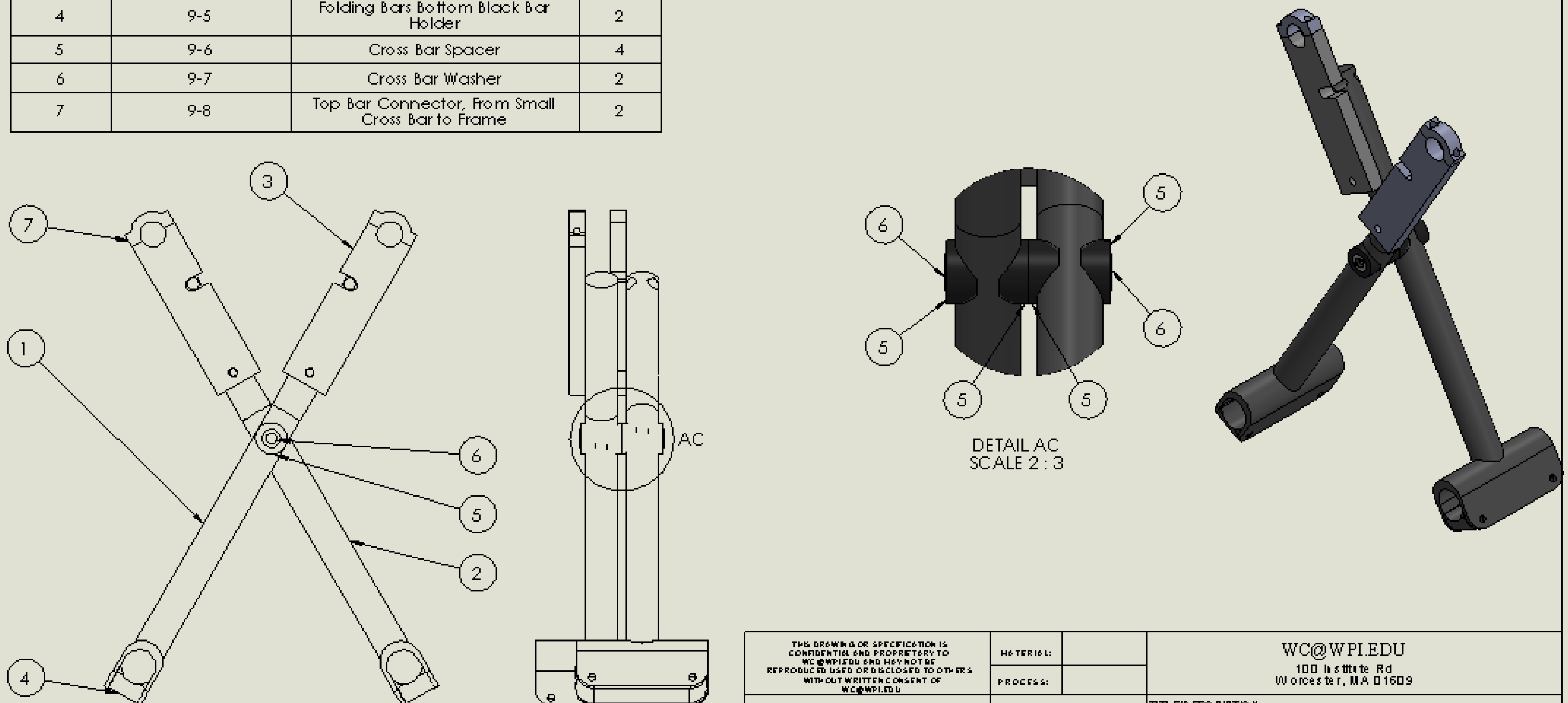
TITLE/DESCRIPTION: Left Arm Rest Assembly

PART NO. 8 - 0

SCALE: 1:5 REVISION: X SHEET: 9 OF 57

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	9-1	Cross Bar Large Bar Front	1
2	9-2	Cross Bar Large Bar Back	1
3	9-3	Cross Bar Small Bar	2
4	9-5	Folding Bars Bottom Black Bar Holder	2
5	9-6	Cross Bar Spacer	4
6	9-7	Cross Bar Washer	2
7	9-8	Top Bar Connector, From Small Cross Bar to Frame	2

SYM	REVISION DESCRIPTION	DATE	BY



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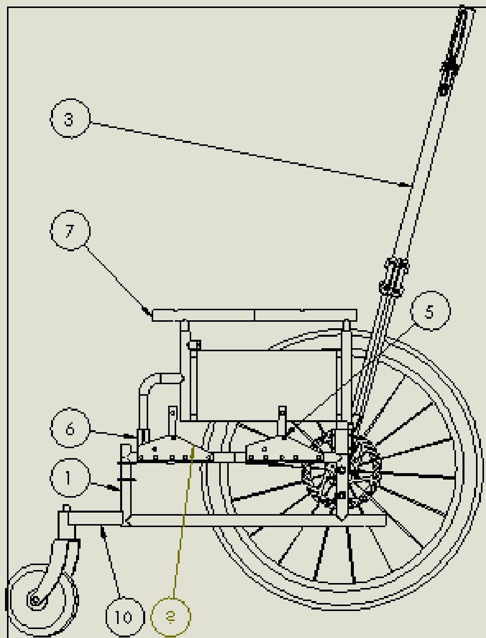
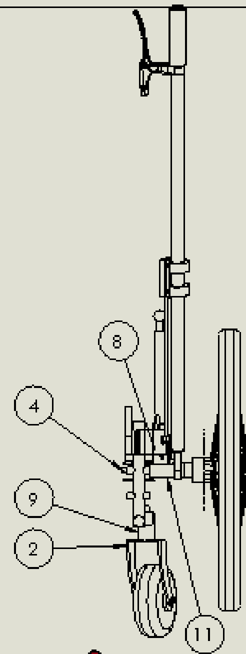
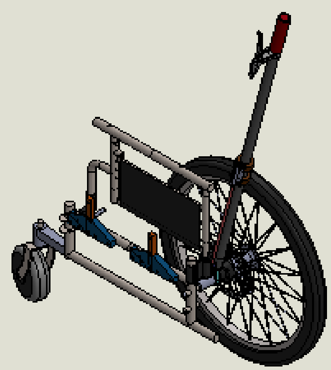
	PROCESS:		
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES	DRAWN BY: EJM.S DATE: 03/01/2016		TITLE/DESCRIPTION Folding Mechanism
INCHES / MILLIMETERS	CHECKED BY: DATE:		PART NO. 9 - 0
.X +/-.030 / .X +/-.7			
.XX +/-.010 / .X +/-.3	APPROVED BY: DATE:		
.XXX +/-.005 / .XX +/-.1			
ANGLES +/-.1 DEG / ANGLES +/-.1 DEG			SCALE: 1:3 REVISION: X SHEET: 10 OF 57





SYM	REVISION DESCRIPTION	DATE	BY

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10-1	Right Frame	1
2	5-0	Caster Assembly	1
3	4-0	1-0, 2-0, 3-0 System	1
4	7-4	Wheel Axle, From Frame to 4-0	1
5	7-3	Link, To Stop	2
6	8-2	Front Arm Rest Holder, From Arm Rest to Frame	1
7	11-0	Right Arm Rest Assembly	1
8	8-1	Rear Arm Rest Holder, From Arm Rest to Frame	1
9	5-4	Caster Bearing Holder	1
10	5-3	Caster Extention	1
11	7-5	Spacer	1
12	7-2	Left Stop, From Left Frame to Link	2
13	13-3	Pin Locator, to Stop	1



MATERIAL:

PROCESS:

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Worcester, MA 01609

TITLE/DESCRIPTION

Right of Whelchair

DRAWN

CHECKED

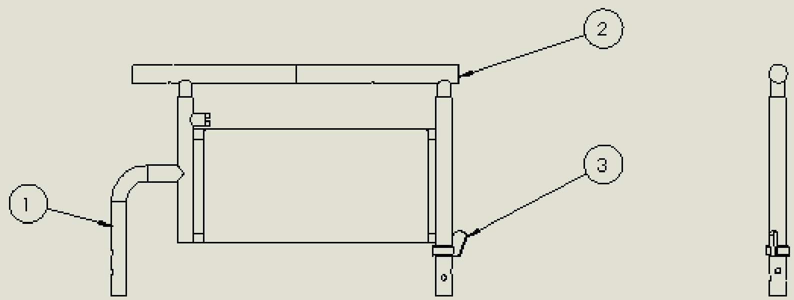
APPROVED

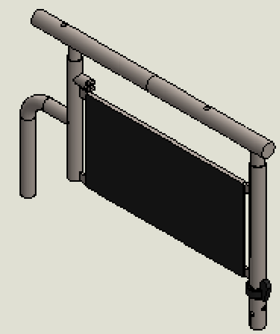
PART NO. 1 0 - 0

SCALE 1:8 REVISION X SHEET 11 OF 57

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	11-1	Right Arm Rest Side Panel, From Holders to Arm Rest Frame	1
2	8-4	Arm Rest Frame, From Arm Rest Padding to Arm Rest Side Panel	1
3	8-6	Arm Rest Black Clip, To Arm Rest Side Panel	1

SYM	REVISION DESCRIPTION	DATE	BY





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DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-.1 2 DEG	ANGLES +/-.1/2 DEG

MATERIAL:

PROCESS:

DRAWN BY: EJM.G DATE: 03/01/2016

CHECKED BY: DATE:

APPROVED BY: DATE:

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100 Institute Rd
Worcester, MA 01609

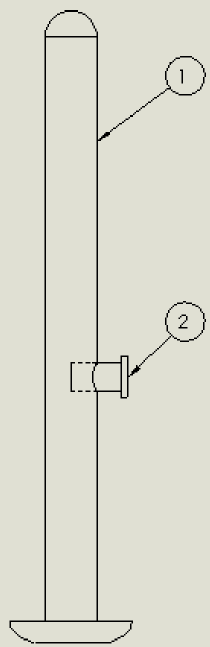
TITLE/DESCRIPTION
Right Arm Rest Assembly

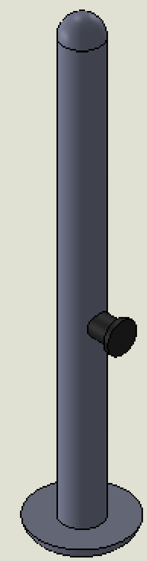
PART NO. 1 1 - 0

SCALE: 1:5 REVISION: X SHEET 12 OF 57

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	13-1	Pin to Stopper	1
2	13-2	Pin Screw, to Pin	1

SYM	REVISION DESCRIPTION	DATE	BY





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DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES

INCHES	MILLIMETERS
.X +/-.030	X +/-.7
.XX +/-.010	.X +/-.3
.XXX +/-.005	.XX +/-.1
ANGLES +/-.1/2 DEG	ANGLES +/-.1/2 DEG

MATERIAL:

PROCESS:

DRAWN BY: EJM.S DATE: 02/24/2016

CHECKED BY: DATE:

APPROVED BY: DATE:

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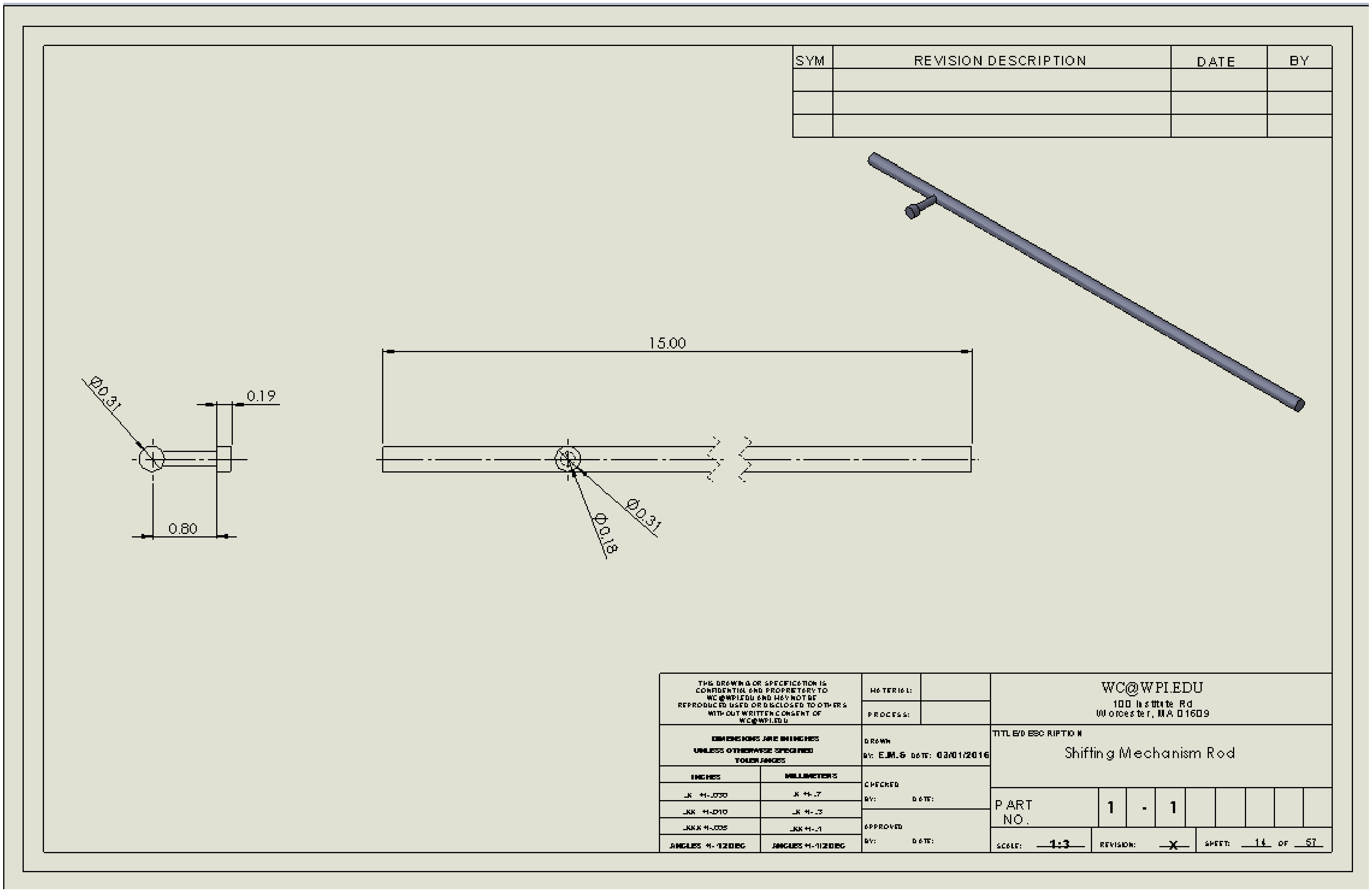
100 Institute Rd
Worcester, MA 01609

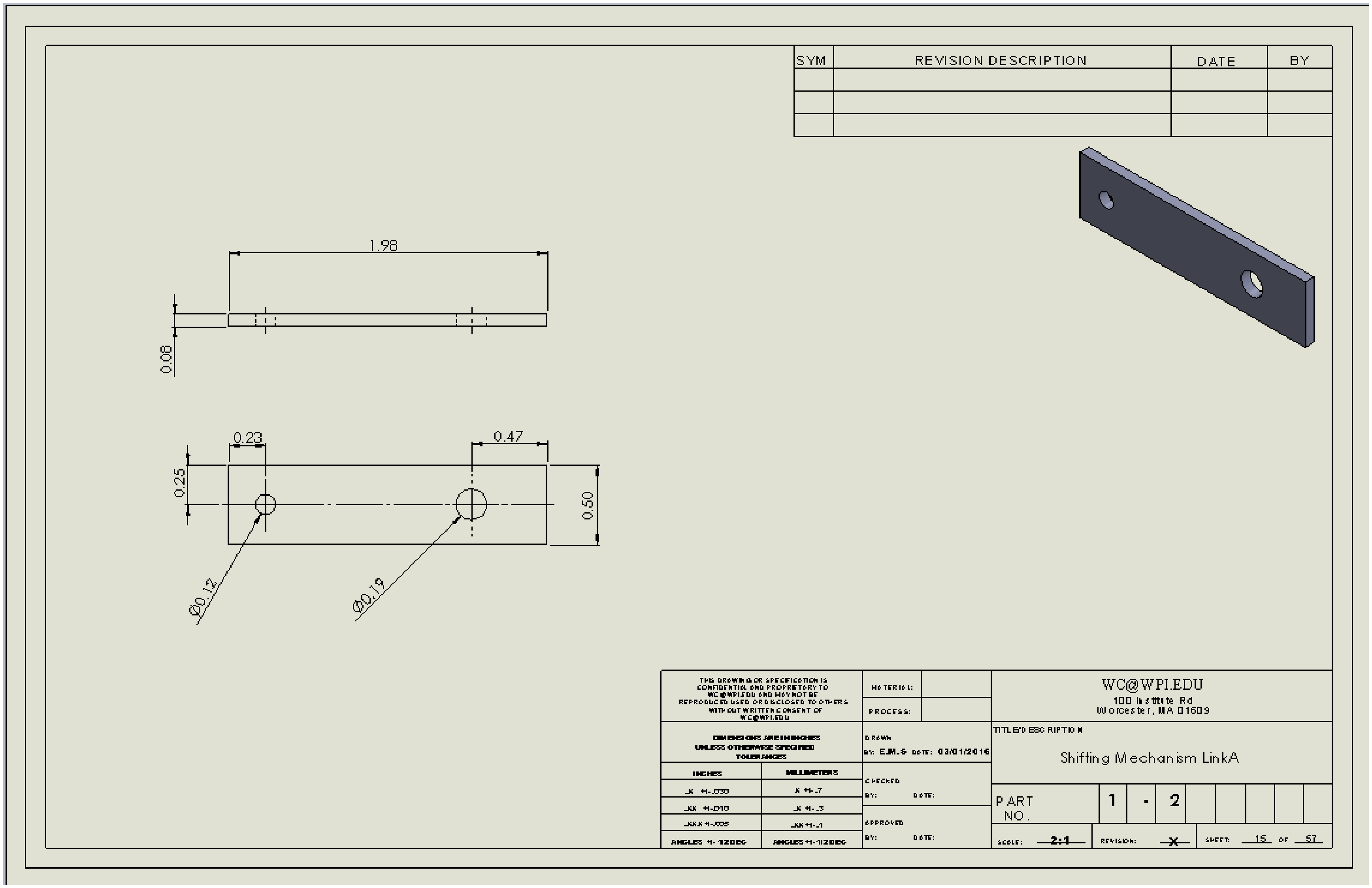
TITLE/DESCRIPTION
Pin Assembly

PART NO. 1 3 - 0

SCALE: 1:1 REVISION: X SHEET: 13 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
15.00
Ø0.31
0.19
0.80
Ø0.31
Ø0.18
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Shifting Mechanism Rod
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
MATERIAL:
PROCESS:
DRAWN
BY: EJM.6 DATE: 03/01/2016
CHECKED
APPROVED
PART NO.
1 - 1
SCALE: 1:3
REVISION: X
SHEET: 14 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
1.98
0.08
0.23
0.47
0.25
0.50
Ø0.12
Ø0.19
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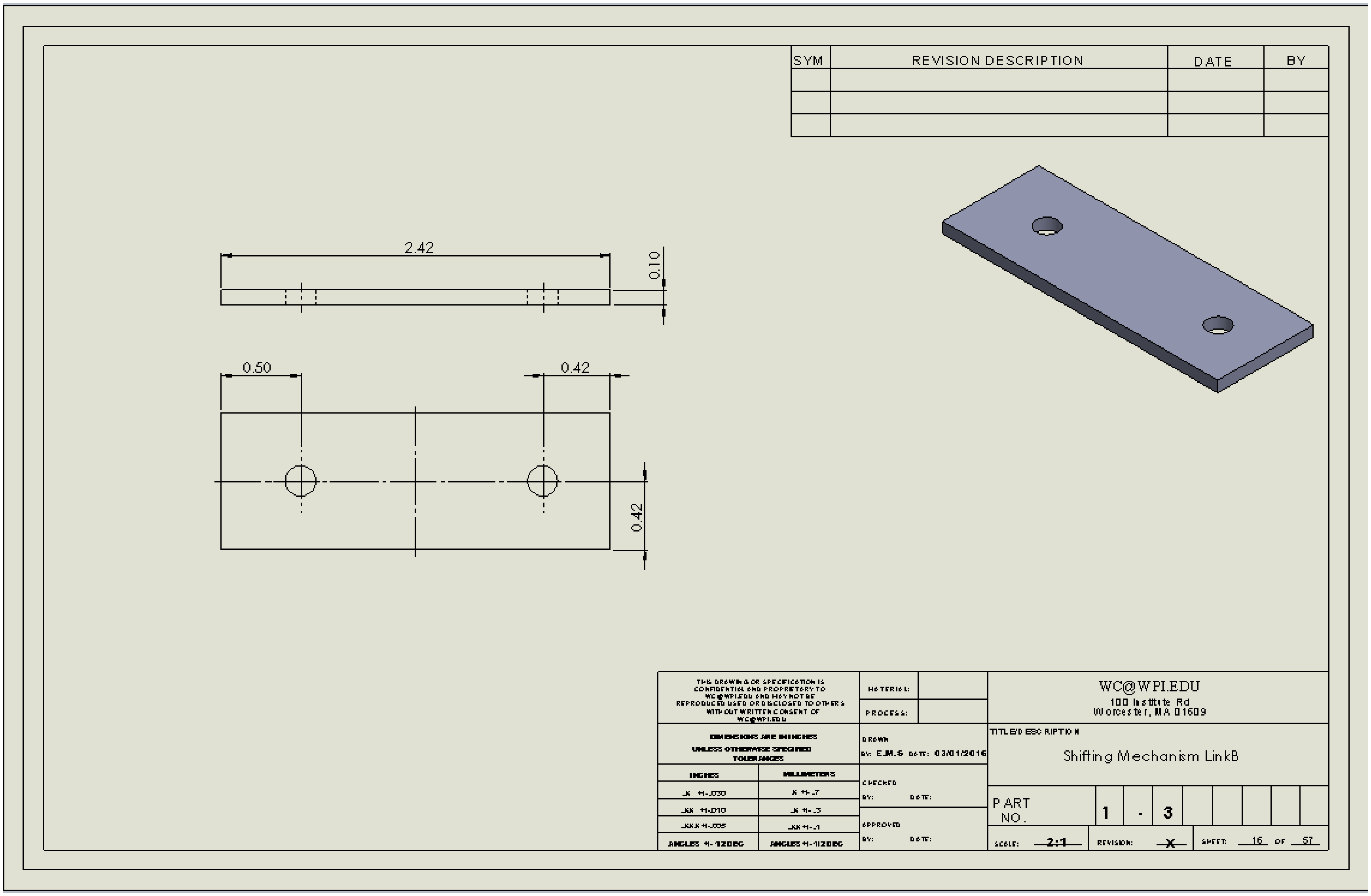
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2 DEG
MATERIAL:
PROCESS:
DRAWN
BY: EJM.G DATE: 03/01/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Shifting Mechanism LinkA
PART NO.
1 - 2
SCALE: 2:1
REVISION: X
SHEET: 15 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
2.42
0.10
0.50
0.42
0.42
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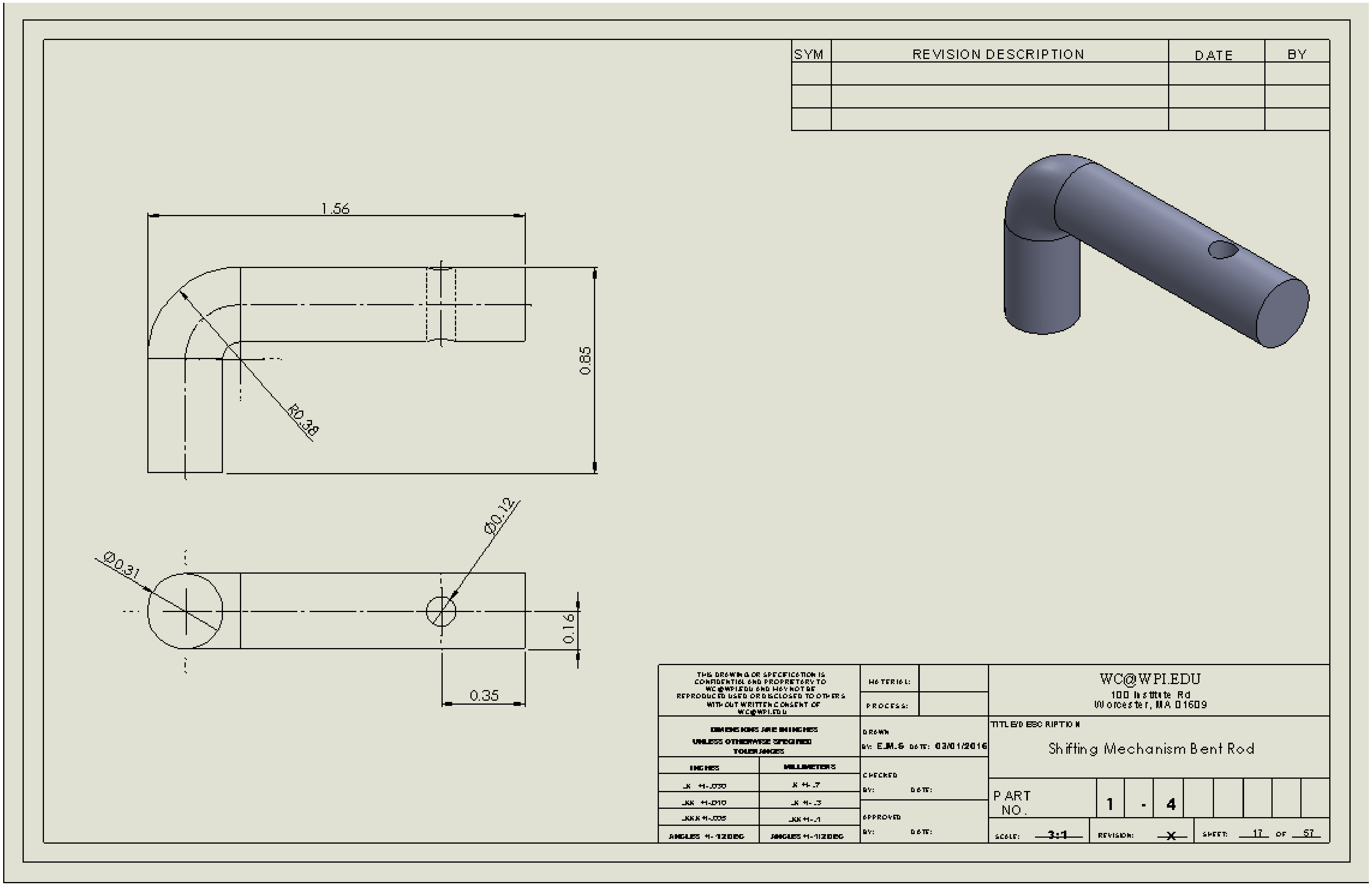
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: E.M.S DATE: 03/01/2016
TITLE/DESCRIPTION
Shifting Mechanism LinkB
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
1 - 3
SCALE: 2:1
REVISION: X
SHEET: 16 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
1.56
0.85
R0.38
Ø0.12
Ø0.31
0.16
0.35
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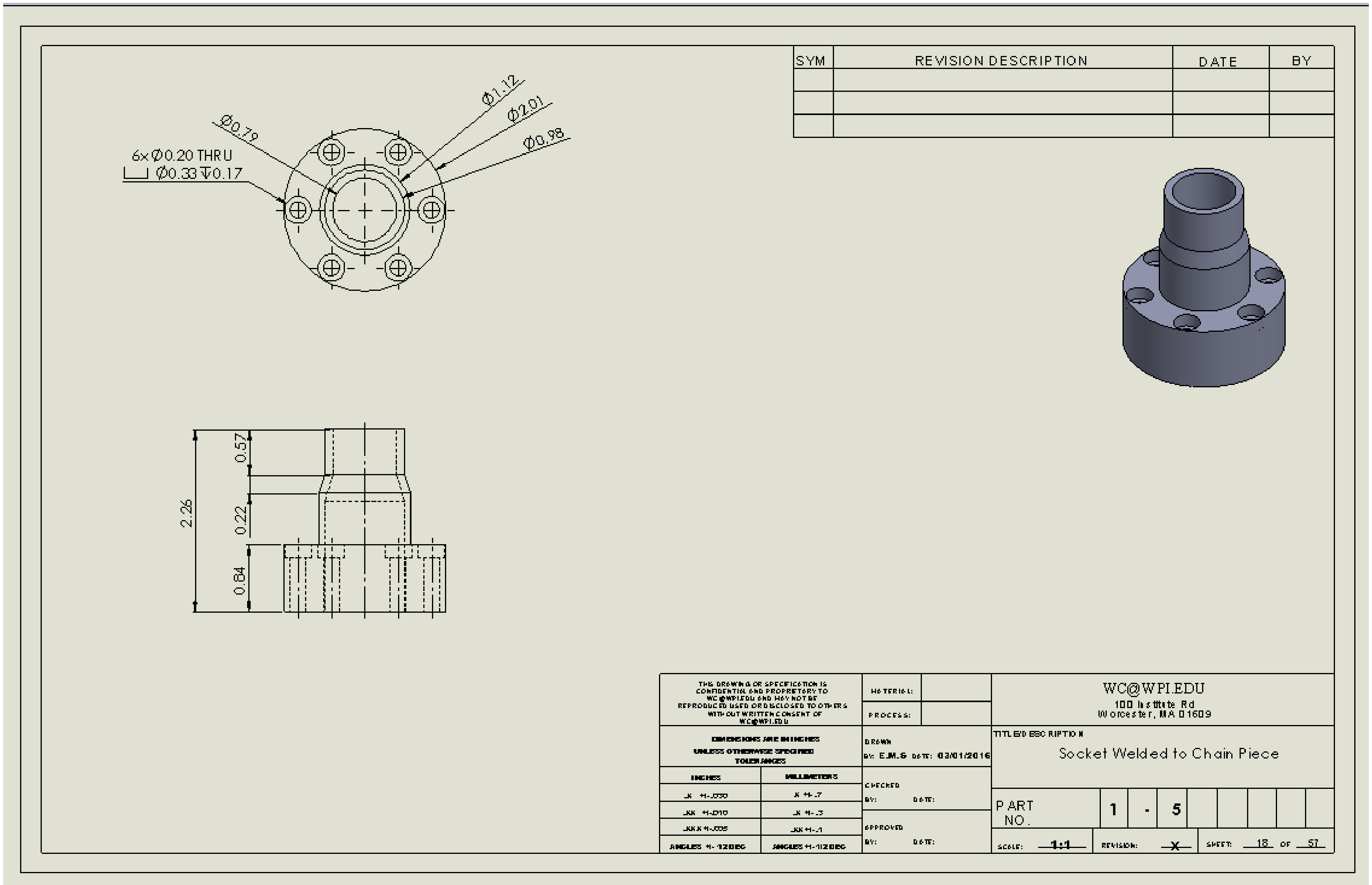
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2DEG
MATERIAL:
PROCESS:
DRAWN
BY: E.M.S DATE: 03/01/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Shifting Mechanism Bent Rod
PART NO.
1 - 4
SCALE: 3:1
REVISION: X
SHEET: 17 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
Ø1.12
Ø2.01
Ø0.98
Ø0.79
6×Ø0.20 THRU
⌴ Ø0.33 ↧0.17
0.57
0.22
2.26
0.84
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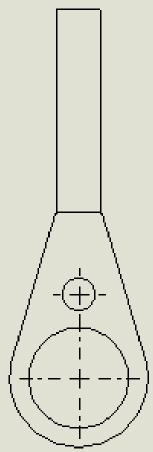
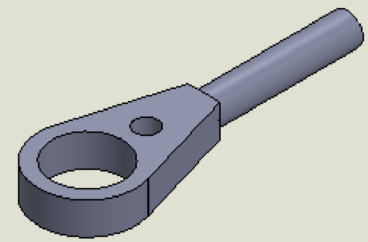
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2 DEG
DRAWN
BY: EJM.G DATE: 03/01/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Socket Welded to Chain Piece
PART NO.
1 - 5
SCALE: 1:1
REVISION: X
SHEET: 18 OF 57

The ratchet comes from Home Depot. Model Number: HUVTHRU28PC

SYM	REVISION DESCRIPTION	DATE	BY





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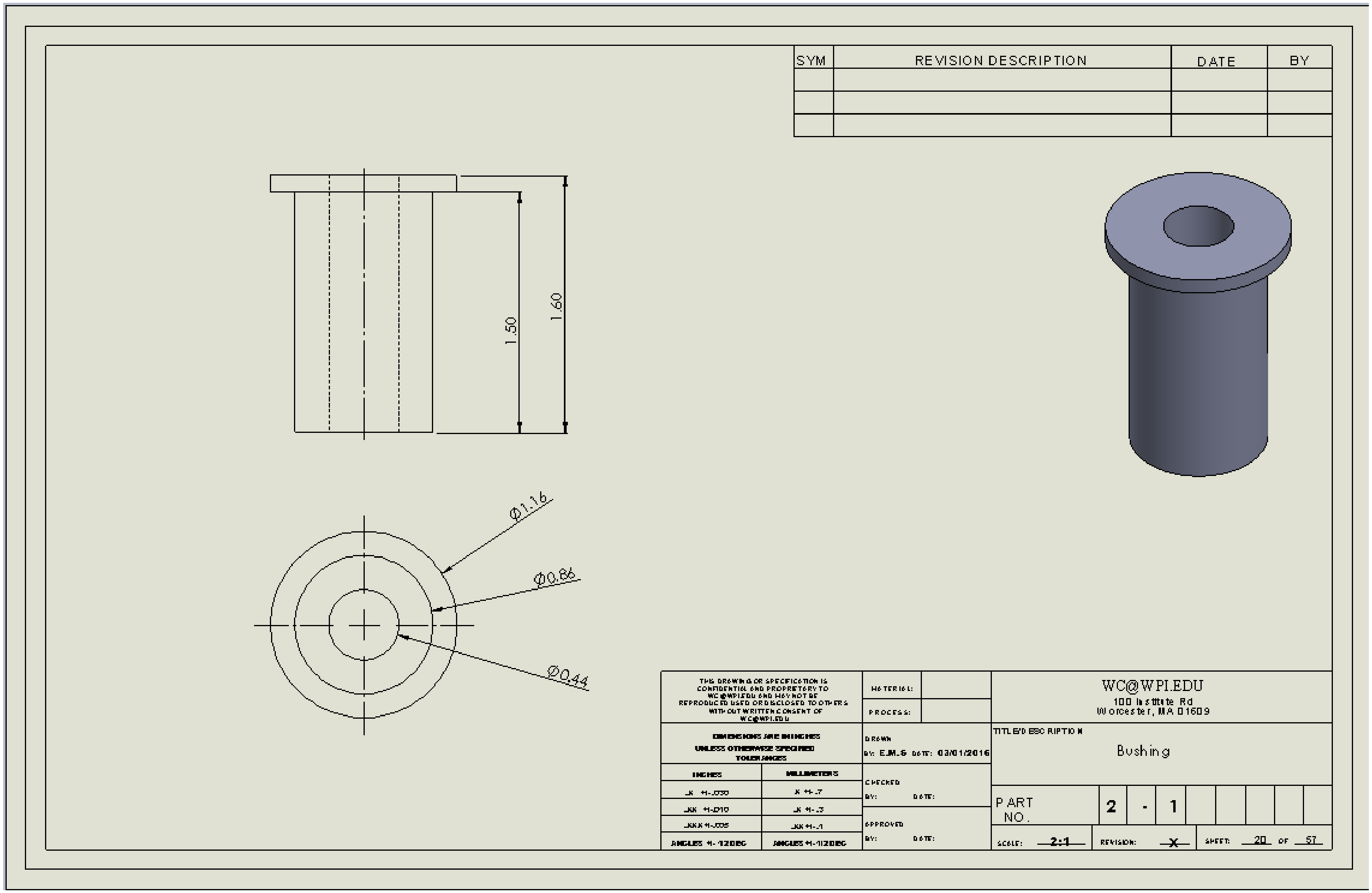
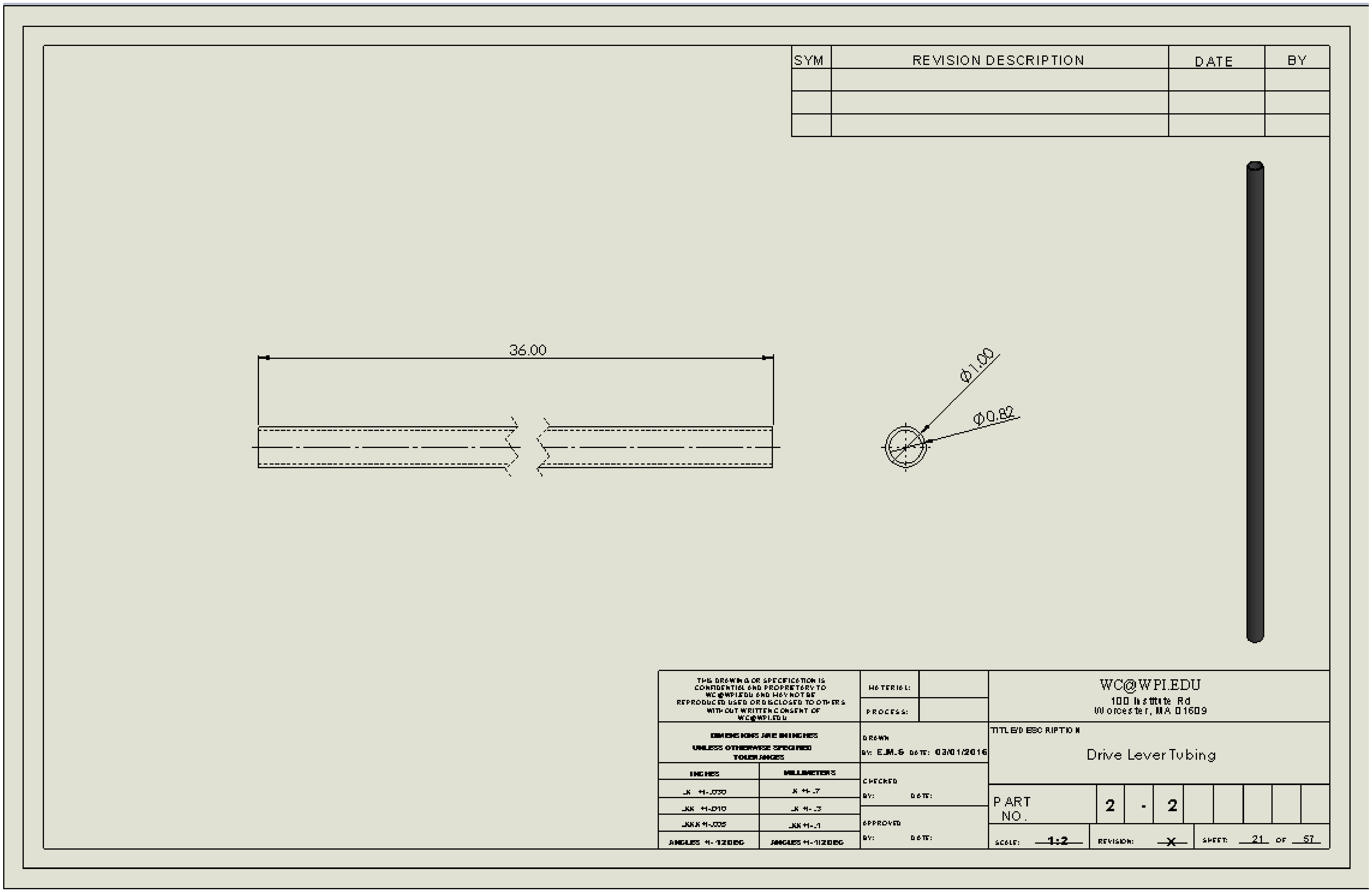
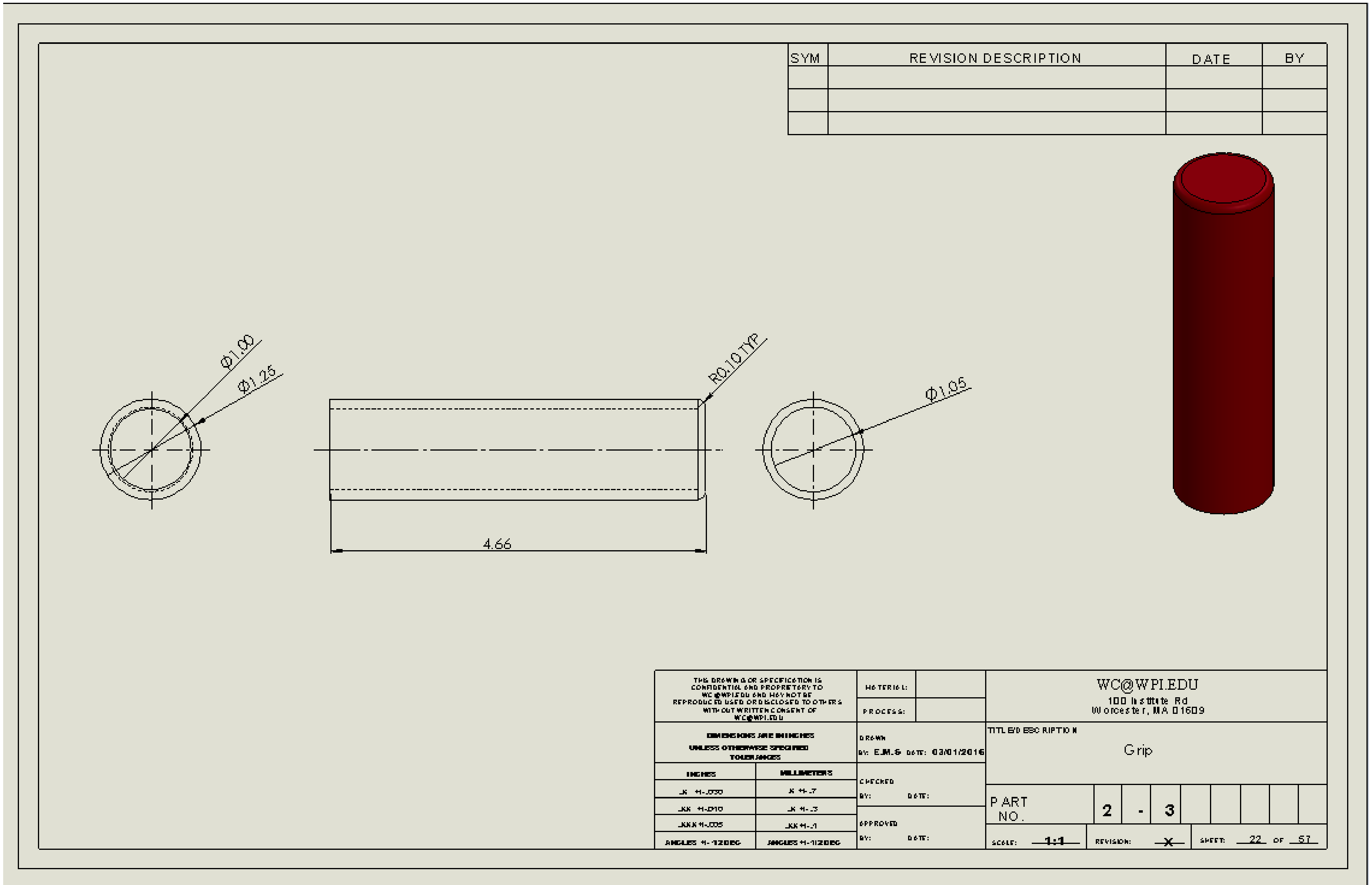
		PROCESS:		
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES		DRAWN BY: E.M.S DATE: 03/01/2016		TITLE/DESCRIPTION Ratchet
INCHES	MILLIMETERS	CHECKED BY: DATE:		PART NO. 1 - 6
.X +/-.030	.X +/-.7			
.XX +/-.010	.X +/-.3			
.XXX +/-.005	.XX +/-.1	APPROVED BY: DATE:		
ANGLES +/-1/2DEG	ANGLES +/-1/2DEG			SCALE: 1:1 REVISION: X SHEET: 19 OF 57

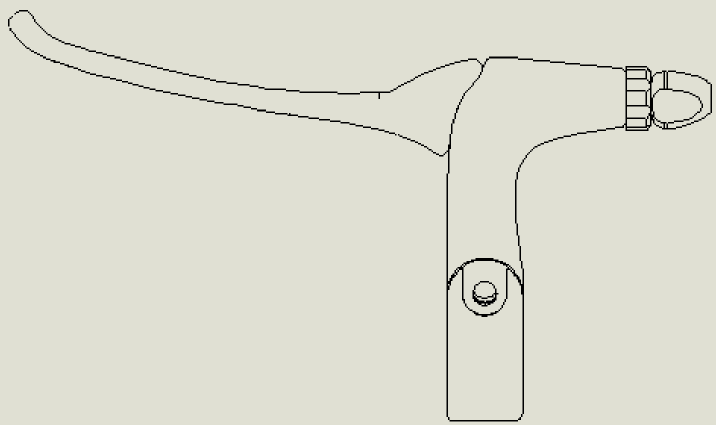

SYM
REVISION DESCRIPTION
DATE
BY
1.50
1.60
Ø1.16
Ø0.86
Ø0.44
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: EJM.S DATE: 03/01/2016
TITLE/DESCRIPTION
Bushing
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
2 - 1
SCALE: 2:1
REVISION: X
SHEET: 20 OF 57

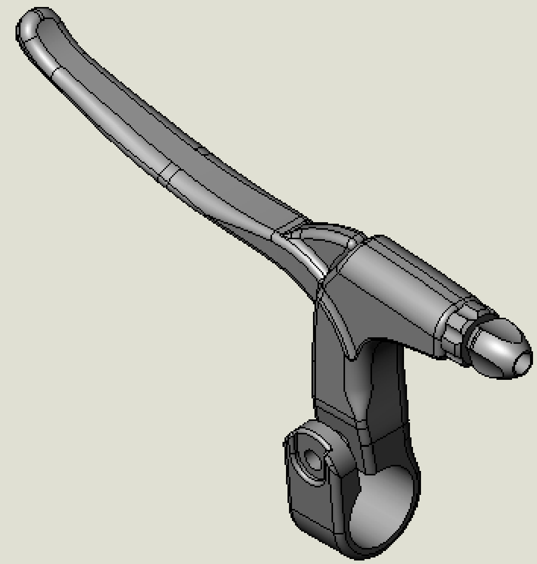

SYM
REVISION DESCRIPTION
DATE
BY
36.00
Ø1.00
Ø0.82
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: EJM.G DATE: 03/01/2016
TITLE/DESCRIPTION
Drive Lever Tubing
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
2 - 2
SCALE: 1:2
REVISION: X
SHEET: 21 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
Φ1.00
Φ1.25
R0.10 TYP
Φ1.05
4.66
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
.X +/-.030
.X +/-.7
.XX +/-.010
.X +/-.3
.XXX +/-.005
.XX +/-.1
ANGLES +/-.1/2DEG
ANGLES +/-1/2DEG
MATERIAL:
PROCESS:
DRAWN
BY: E.M.G DATE: 03/01/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Grip
PART NO.
2 - 3
SCALE: 1:1
REVISION: X
SHEET: 22 OF 57

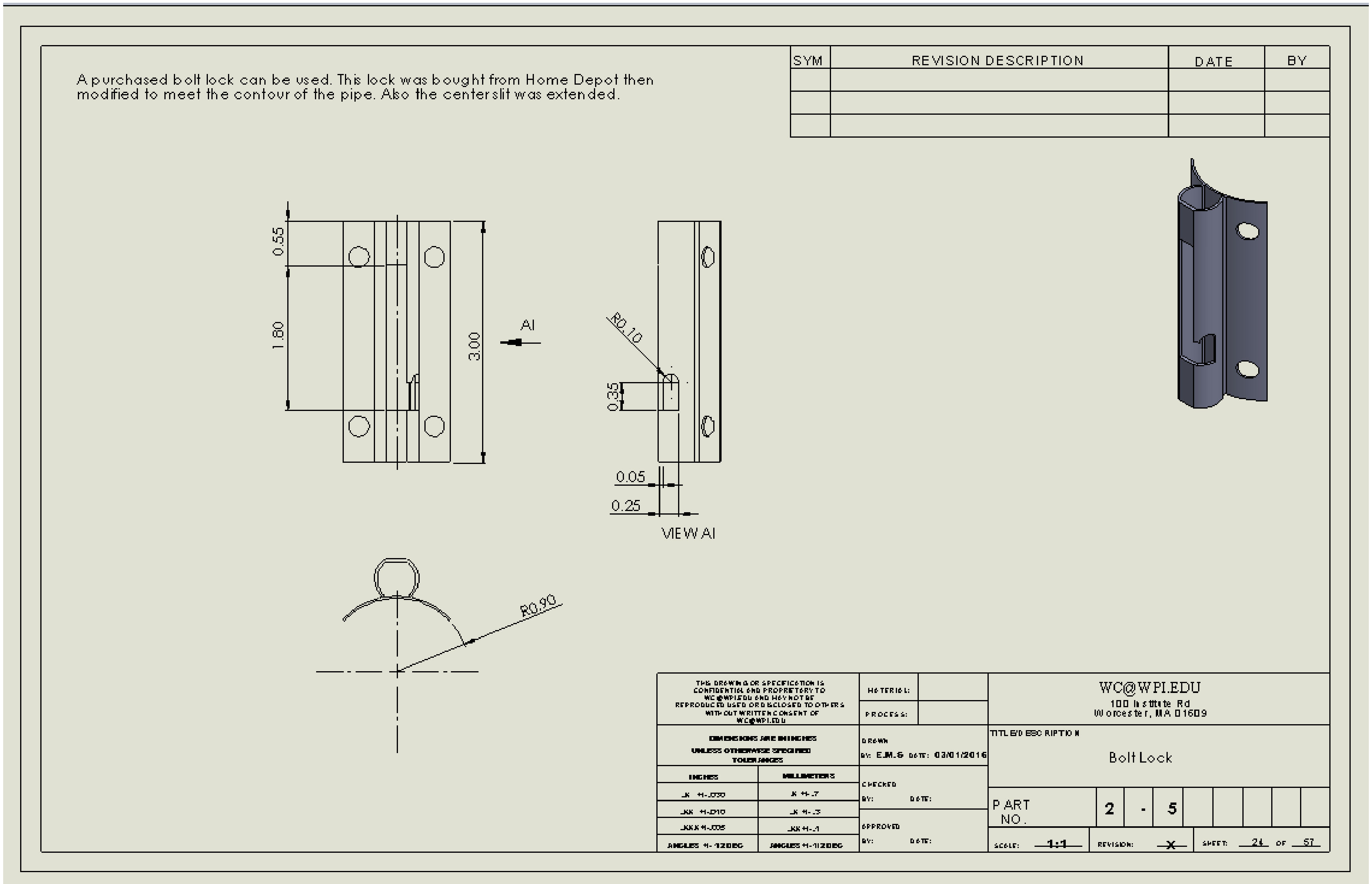
Any Bicycle brake handle which can be connected to a cable can be used.

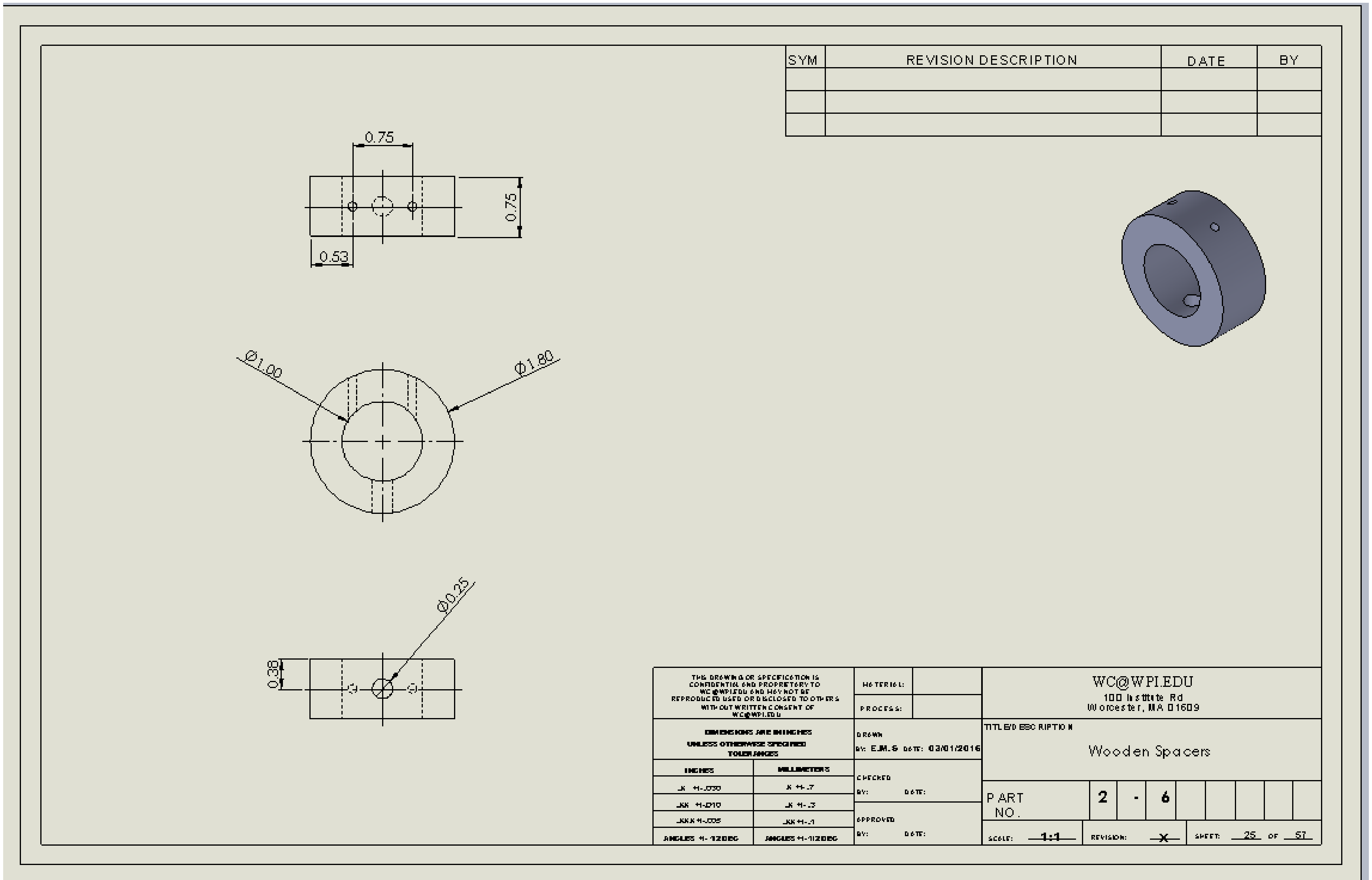
SYM	REVISION DESCRIPTION	DATE	BY

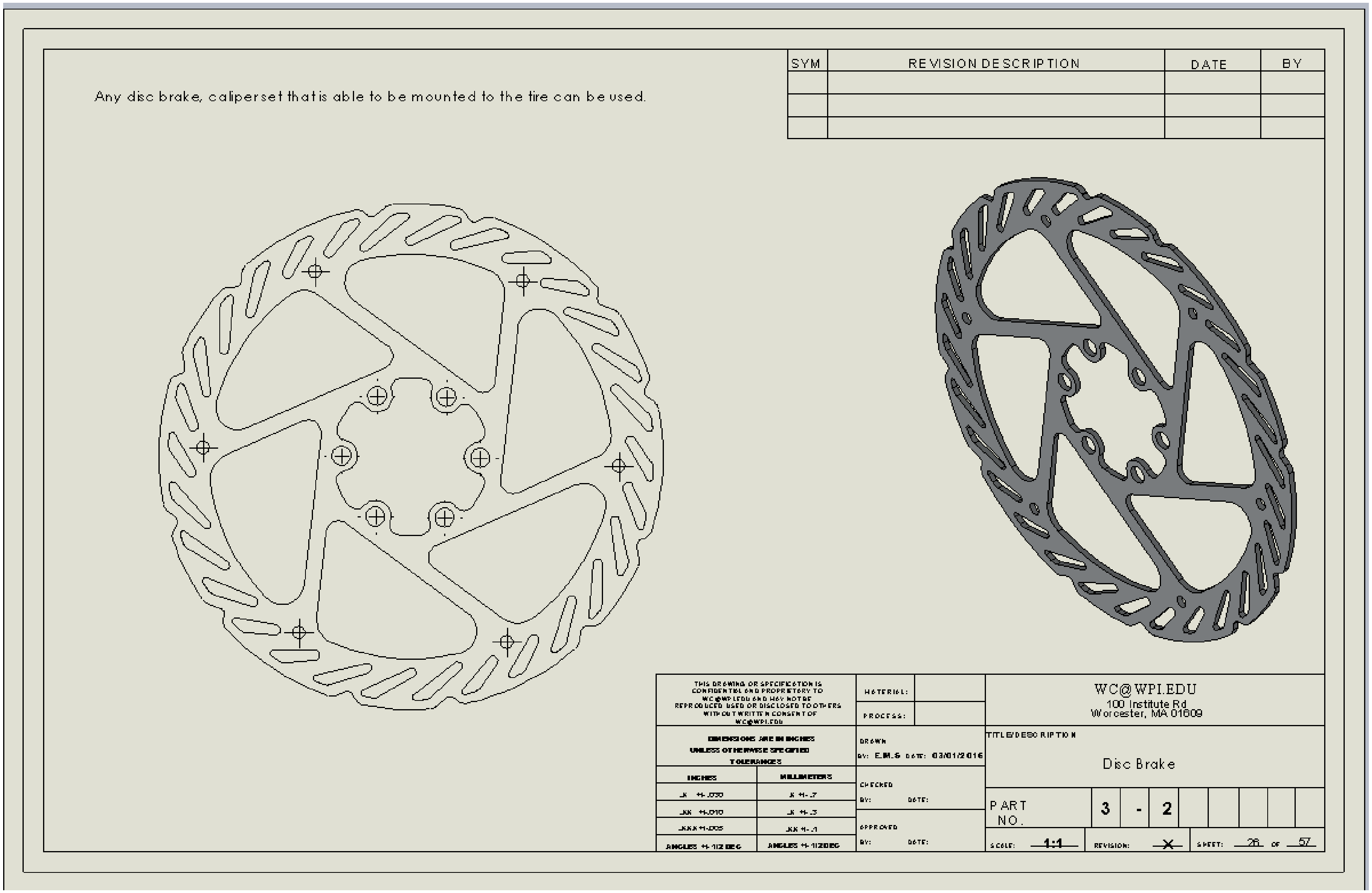


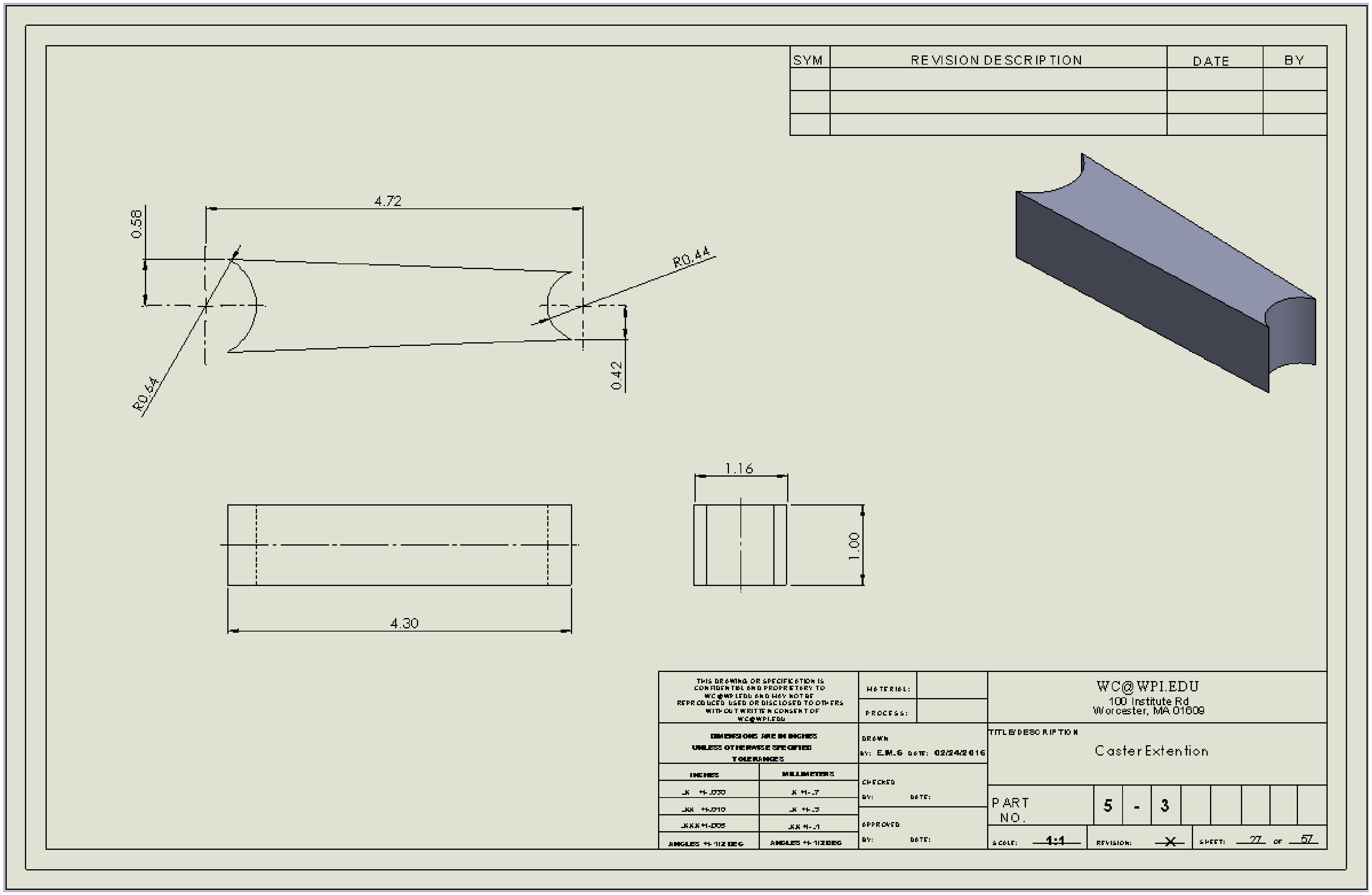


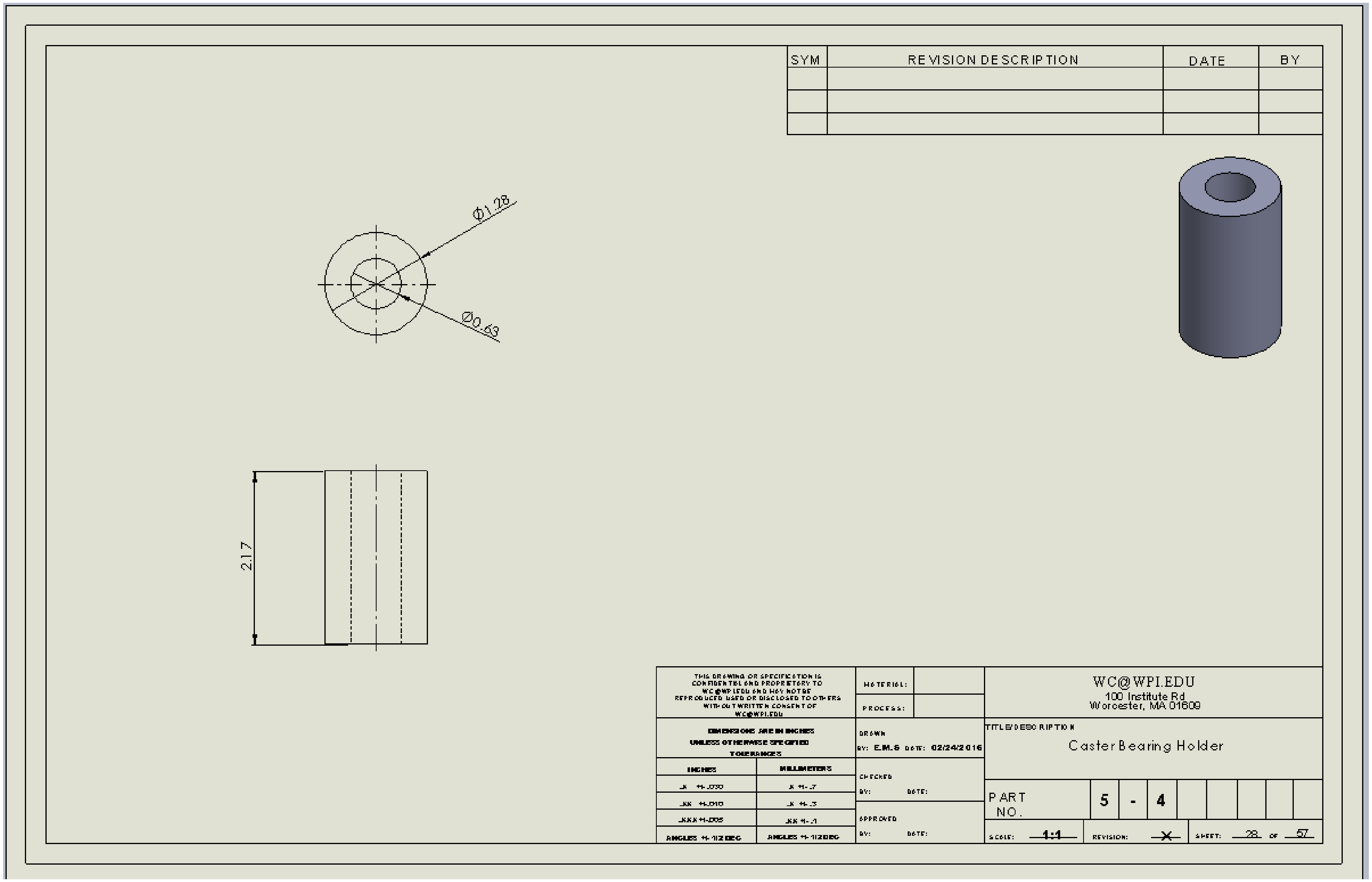
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU	MATERIAL: / PROCESS:		WC@WPI.EDU 100 Institute Rd Worcester, MA 01609
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES	DRAWN BY: EJM.S DATE: 03/01/2016		TITLE/DESCRIPTION: Brake Handle
INCHES	MILLIMETERS	CHECKED BY: DATE:	PART NO. 2 - 4
.X +/-.030	.X +/-.7		
.XX +/-.010	.X +/-.3	APPROVED BY: DATE:	
.XXX +/-.005	.XX +/-.1		
ANGLES +/-1/2DEG	ANGLES +/-1/2DEG		SCALE: 1:1 REVISION: X SHEET: 23 OF 57

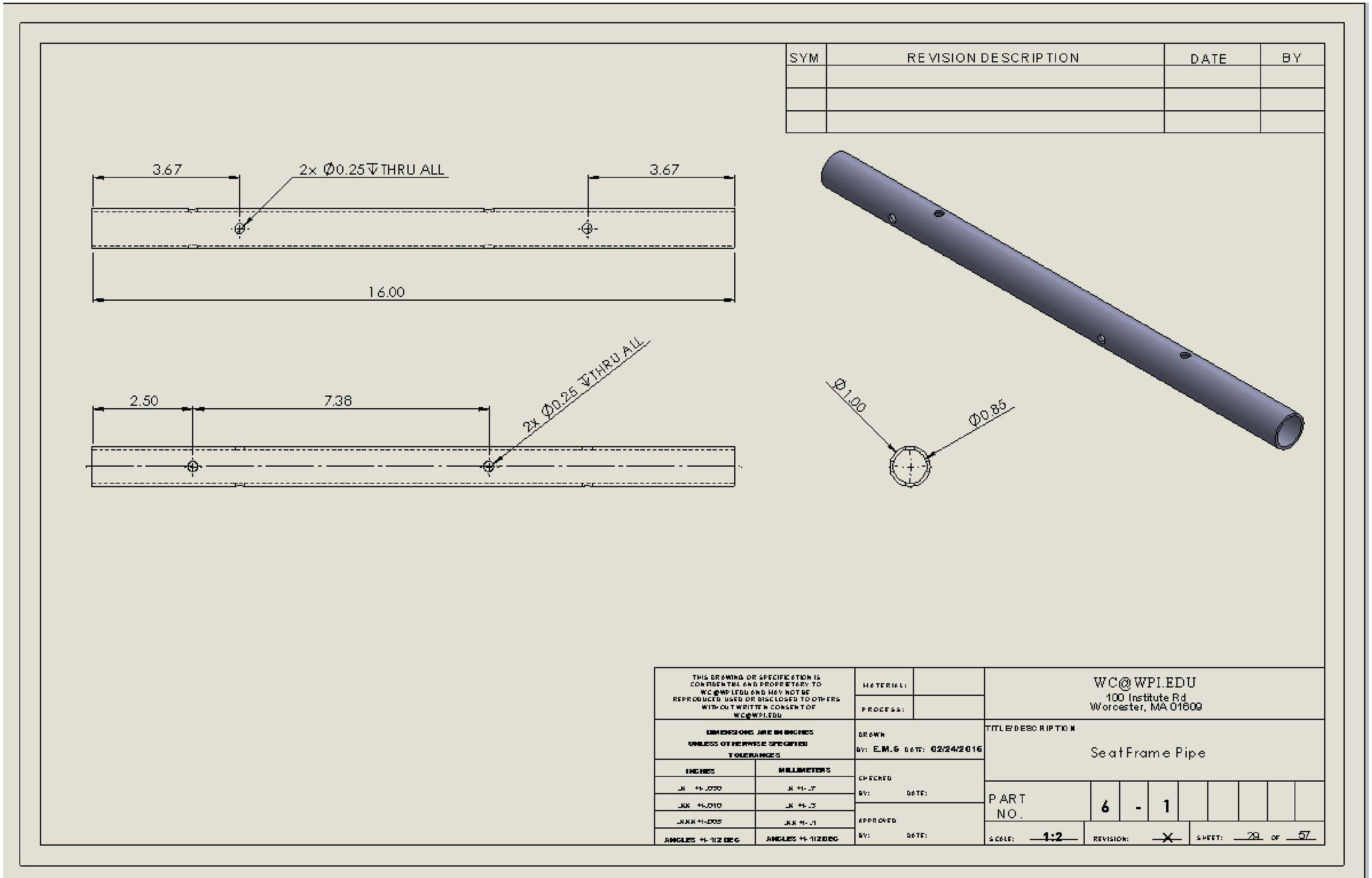

A purchased bolt lock can be used. This lock was bought from Home Depot then modified to meet the contour of the pipe. Also the centerslit was extended.
SYM
REVISION DESCRIPTION
DATE
BY
0.55
1.80
3.00
AI
R0.10
0.35
0.05
0.25
VIEW AI
R0.90
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: EJM.S DATE: 03/01/2016
TITLE/DESCRIPTION
Bolt Lock
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
2 - 5
SCALE: 1:1
REVISION: X
SHEET: 24 OF 57
ANGLES +/- 1/2DEG

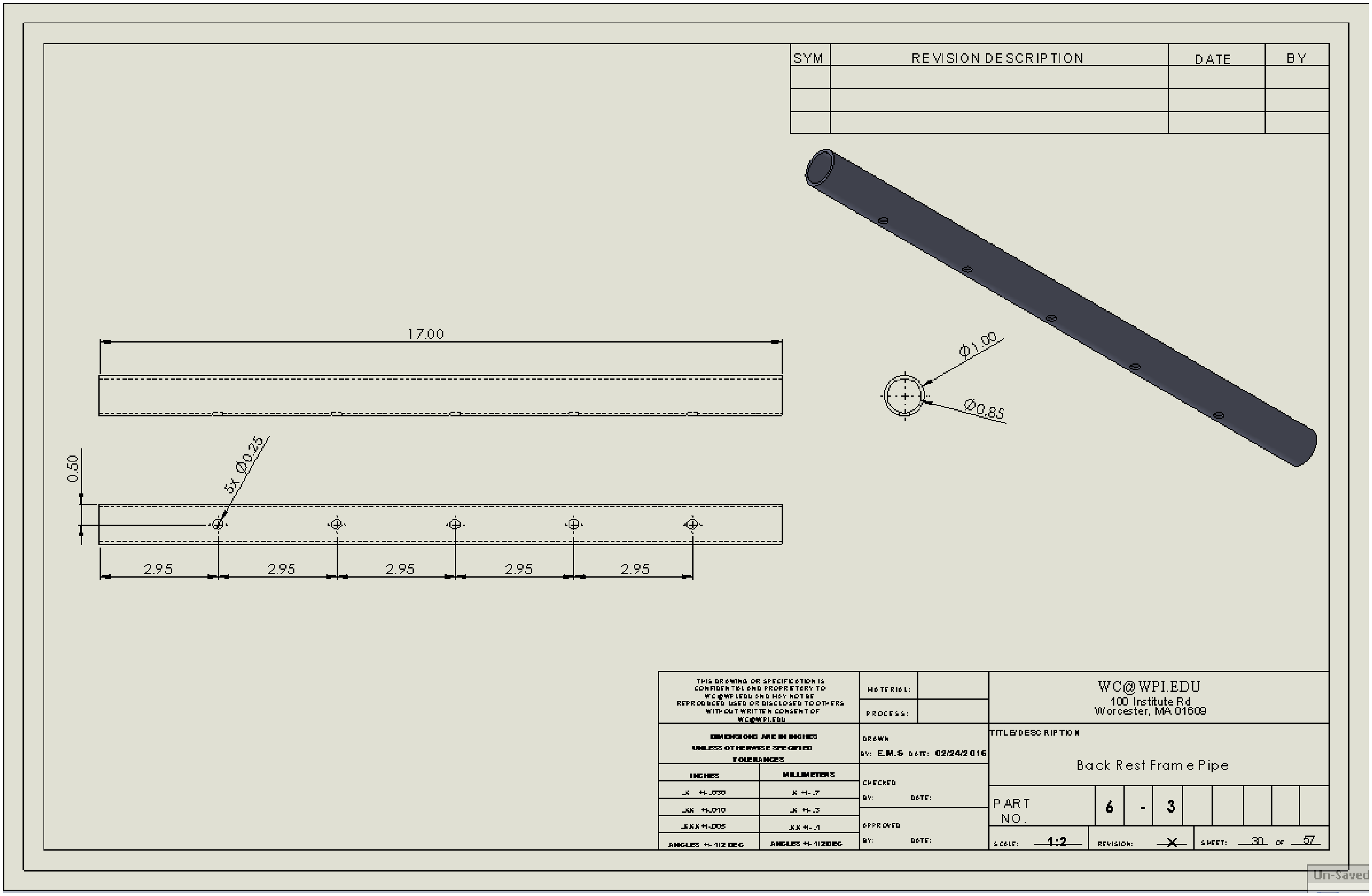

SYM
REVISION DESCRIPTION
DATE
BY
0.75
0.75
0.53
Ø1.00
Ø1.80
Ø0.25
0.38
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
.X +/-.030
.X +/-.7
.XX +/-.010
.X +/-.3
.XXX +/-.005
.XX +/-.1
ANGLES +/-.1/2 DEG
ANGLES +/-.1/2 DEG
DRAWN
BY: E.M.S DATE: 03/01/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Wooden Spacers
PART NO.
2 - 6
SCALE: 1:1
REVISION: X
SHEET: 25 OF 57

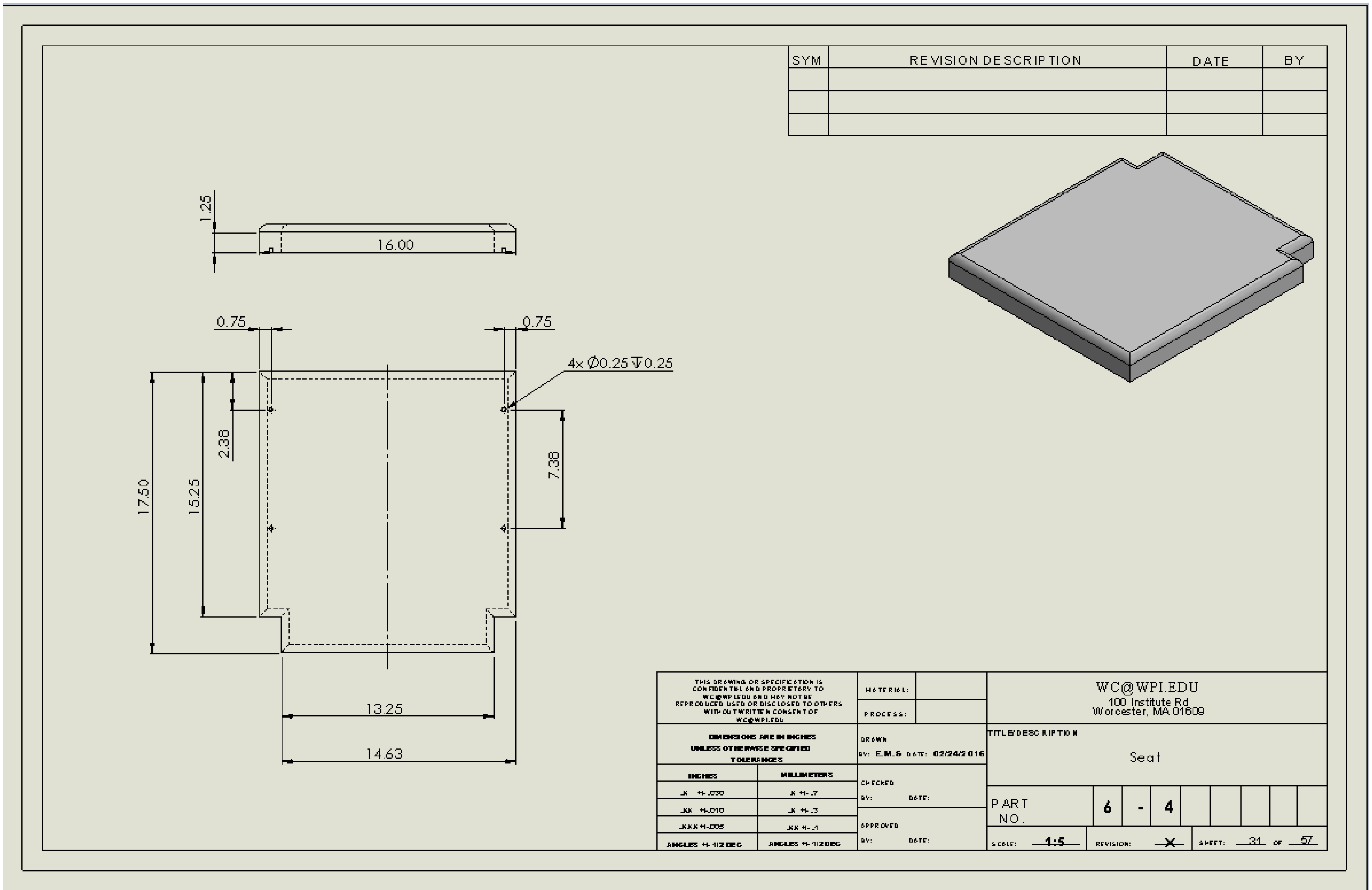

SYM
REVISION DESCRIPTION
DATE
BY
Any disc brake, caliperset that is able to be mounted to the tire can be used.
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED, USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
.X +/-.030
.X +/-.7
.XX +/-.010
.X +/-.3
.XXX +/-.005
.XX +/-.1
ANGLES +/- 1/2 DEG
ANGLES +/- 1/2 DEG
DRAWN
BY: E.M.S DATE: 03/01/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Disc Brake
PART NO.
3 - 2
SCALE: 1:1
REVISION: X
SHEET: 26 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
4.72
0.58
R0.44
R0.64
0.42
1.16
1.00
4.30
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
DRAWN
BY: E.M.S DATE: 02/24/2016
TITLE/DESCRIPTION
Caster Extention
INCHES
MILLIMETERS
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
5 - 3
SCALE: 1:1
REVISION: X
SHEET: 27 OF 57

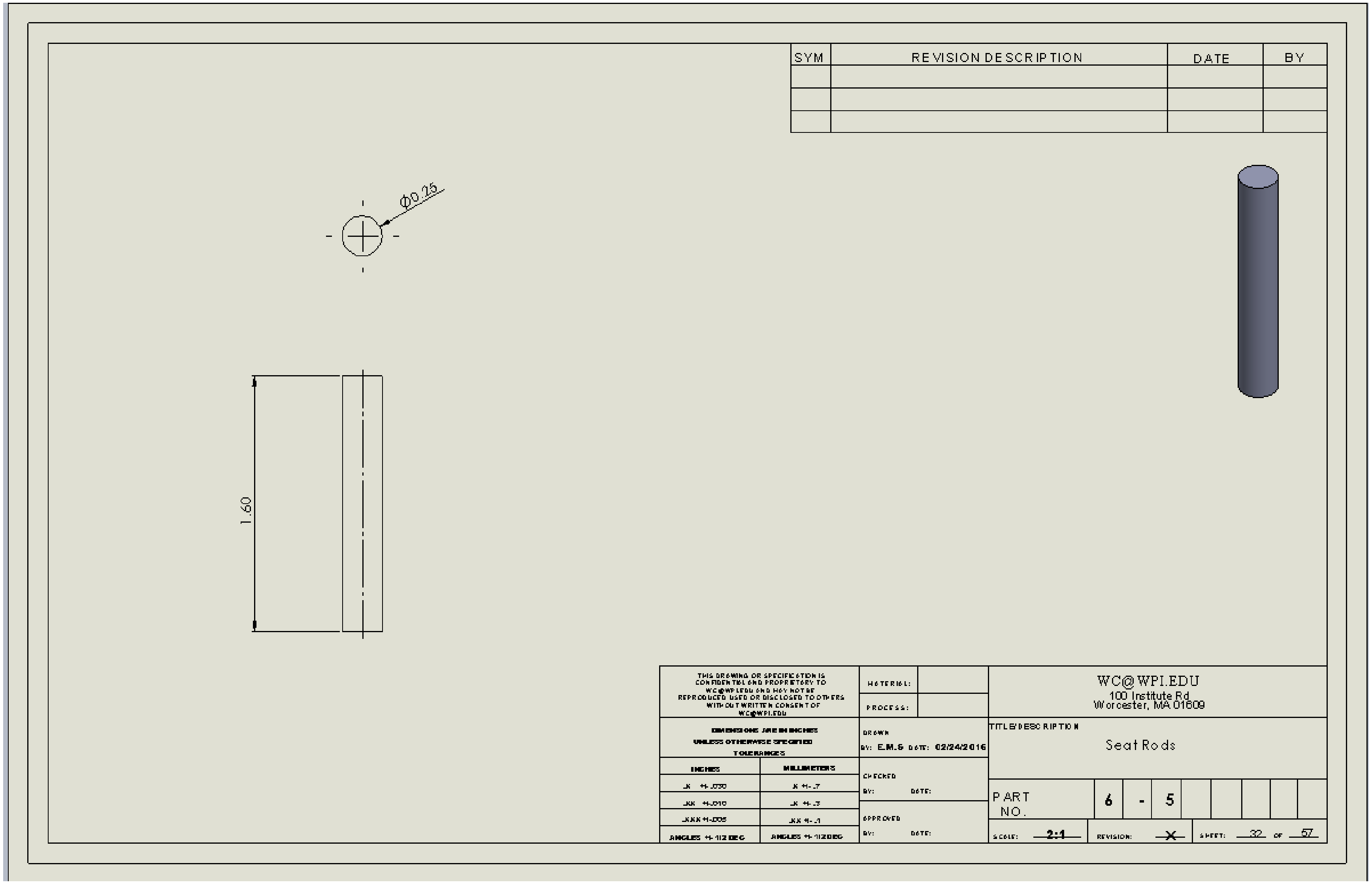

SYM
REVISION DESCRIPTION
DATE
BY
Ø1.28
Ø0.63
2.17
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: E.M.S DATE: 02/24/2016
TITLE/DESCRIPTION
Caster Bearing Holder
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
5 - 4
SCALE: 1:1
REVISION: X
SHEET: 28 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
3.67
2x Ø0.25 ⊽ THRU ALL
3.67
16.00
2.50
7.38
2x Ø0.25 ⊽ THRU ALL
Ø1.00
Ø0.85
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: E.M.S DATE: 02/24/2016
TITLE/DESCRIPTION
Seat Frame Pipe
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
6 - 1
SCALE: 1:2
REVISION: X
SHEET: 29 OF 57

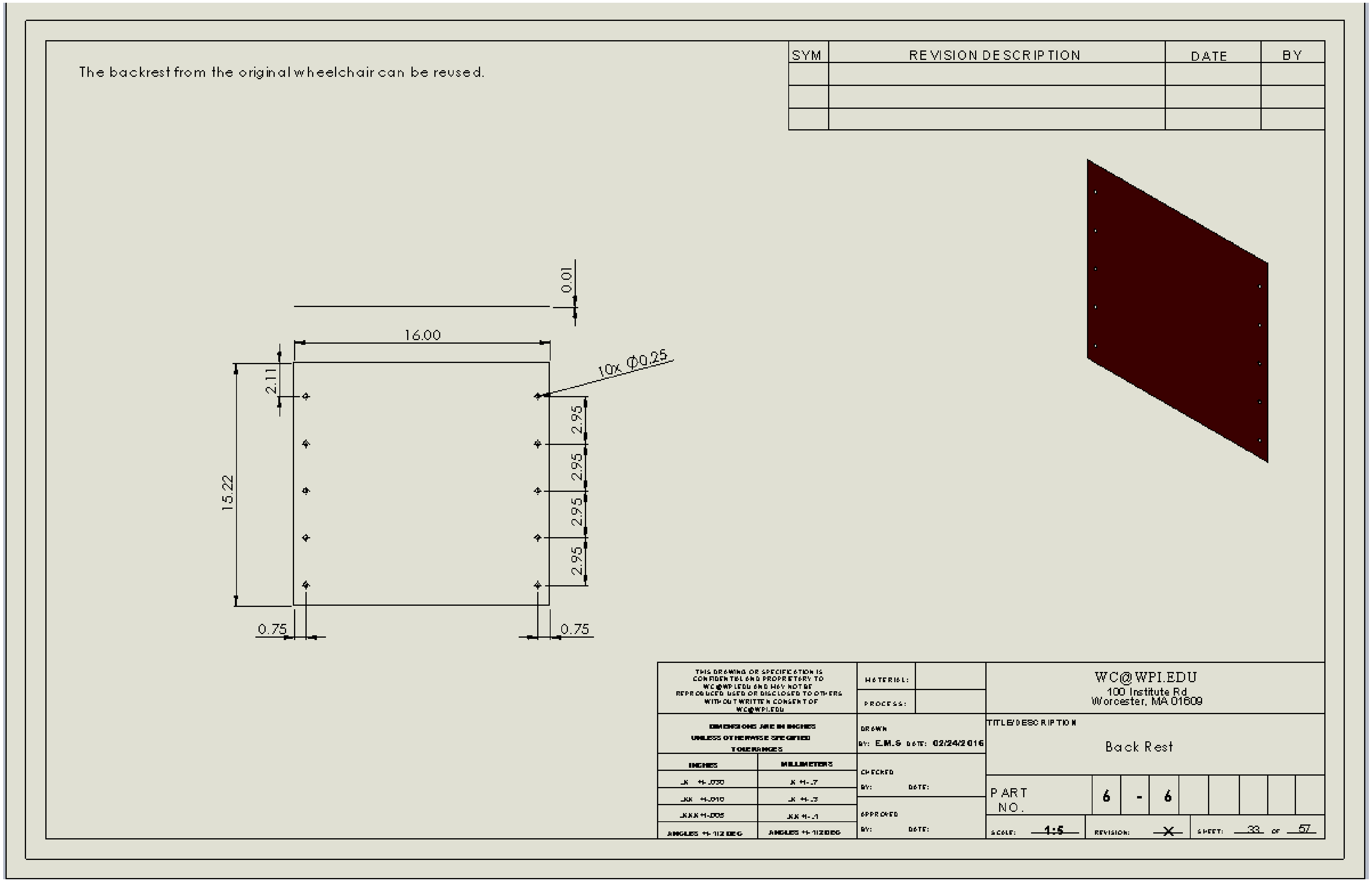

SYM
REVISION DESCRIPTION
DATE
BY
17.00
Ø1.00
Ø0.85
0.50
5X Ø0.25
2.95
2.95
2.95
2.95
2.95
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Back Rest Frame Pipe
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
APPROVED
PART NO.
6 - 3
SCALE: 1:2
SHEET: 30 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
1.25
16.00
0.75
0.75
4x Ø0.25 ↧0.25
17.50
15.25
2.38
7.38
13.25
14.63
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
MATERIAL:
PROCESS:
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
TITLE/DESCRIPTION
Seat
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
APPROVED
PART NO.
6 - 4
SCALE: 1:5
REVISION: X
SHEET: 31 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
Φ0.25
1.60
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2 DEG
ANGLES +/- 1/2 DEG
MATERIAL:
PROCESS:
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Seat Rods
PART NO.
6 - 5
SCALE: 2:1
REVISION: X
SHEET: 32 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
The backrest from the original wheelchair can be reused.
0.01
16.00
10x Ø0.25
2.11
15.22
2.95
2.95
2.95
2.95
0.75
0.75
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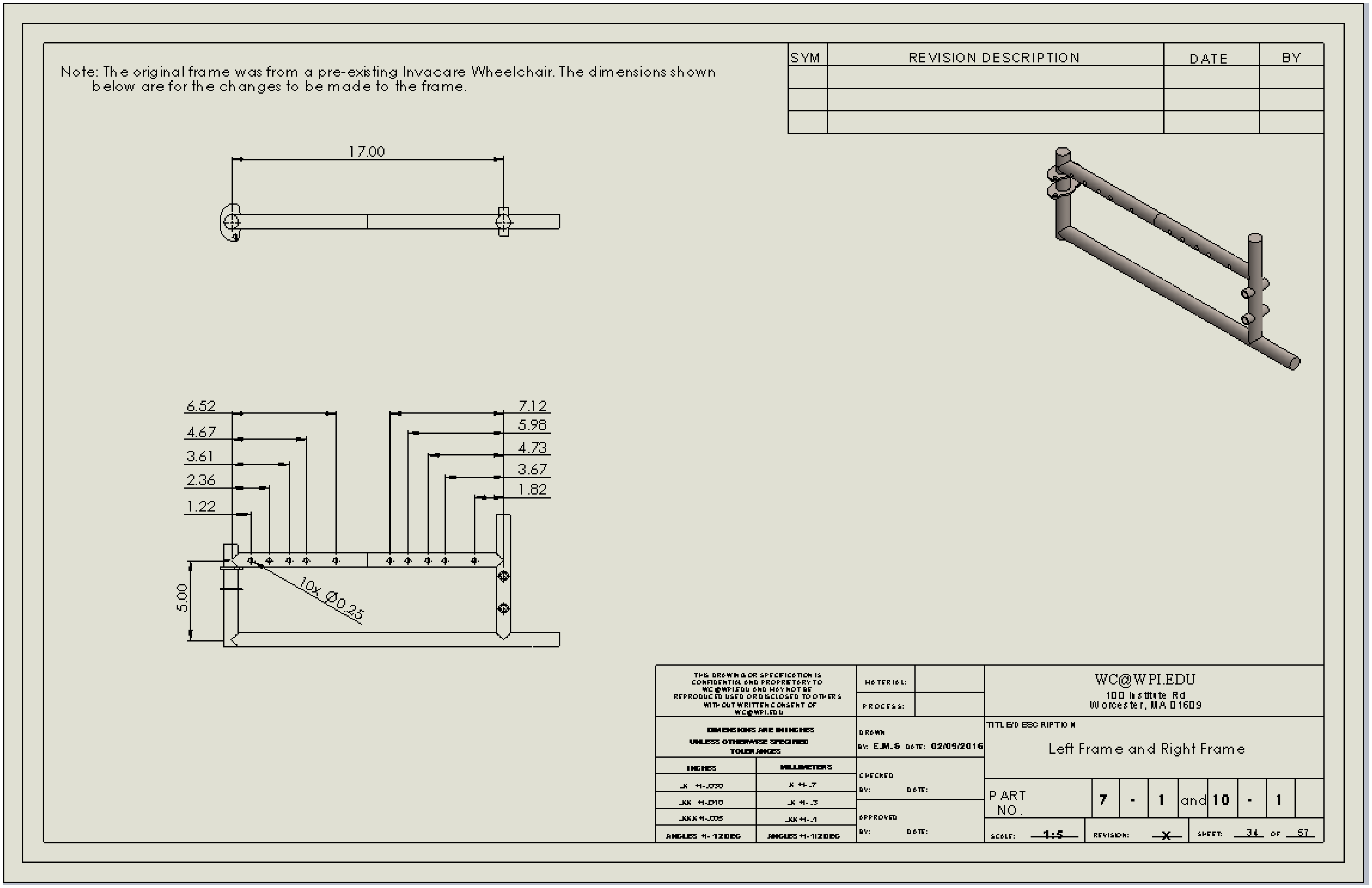
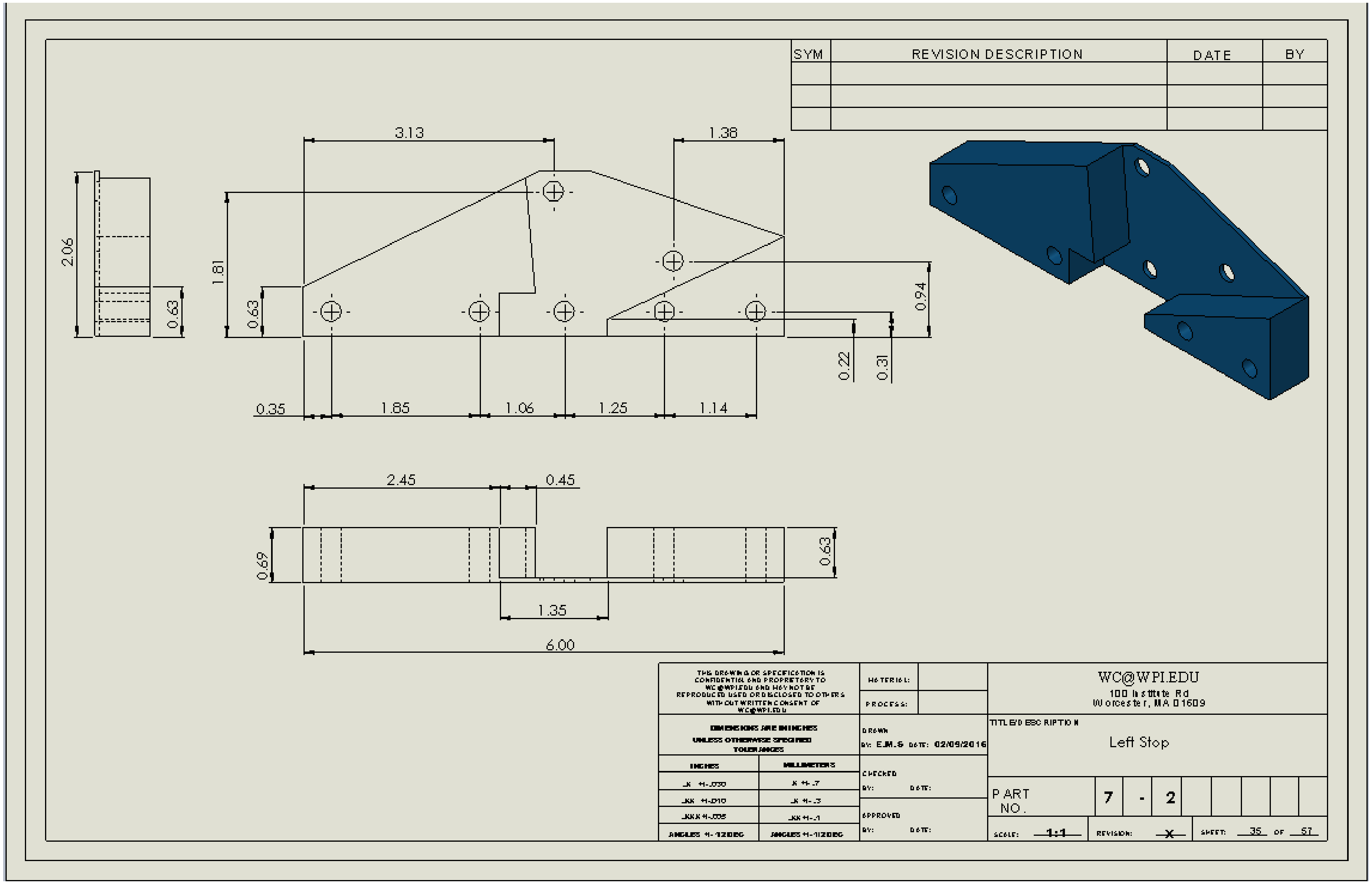
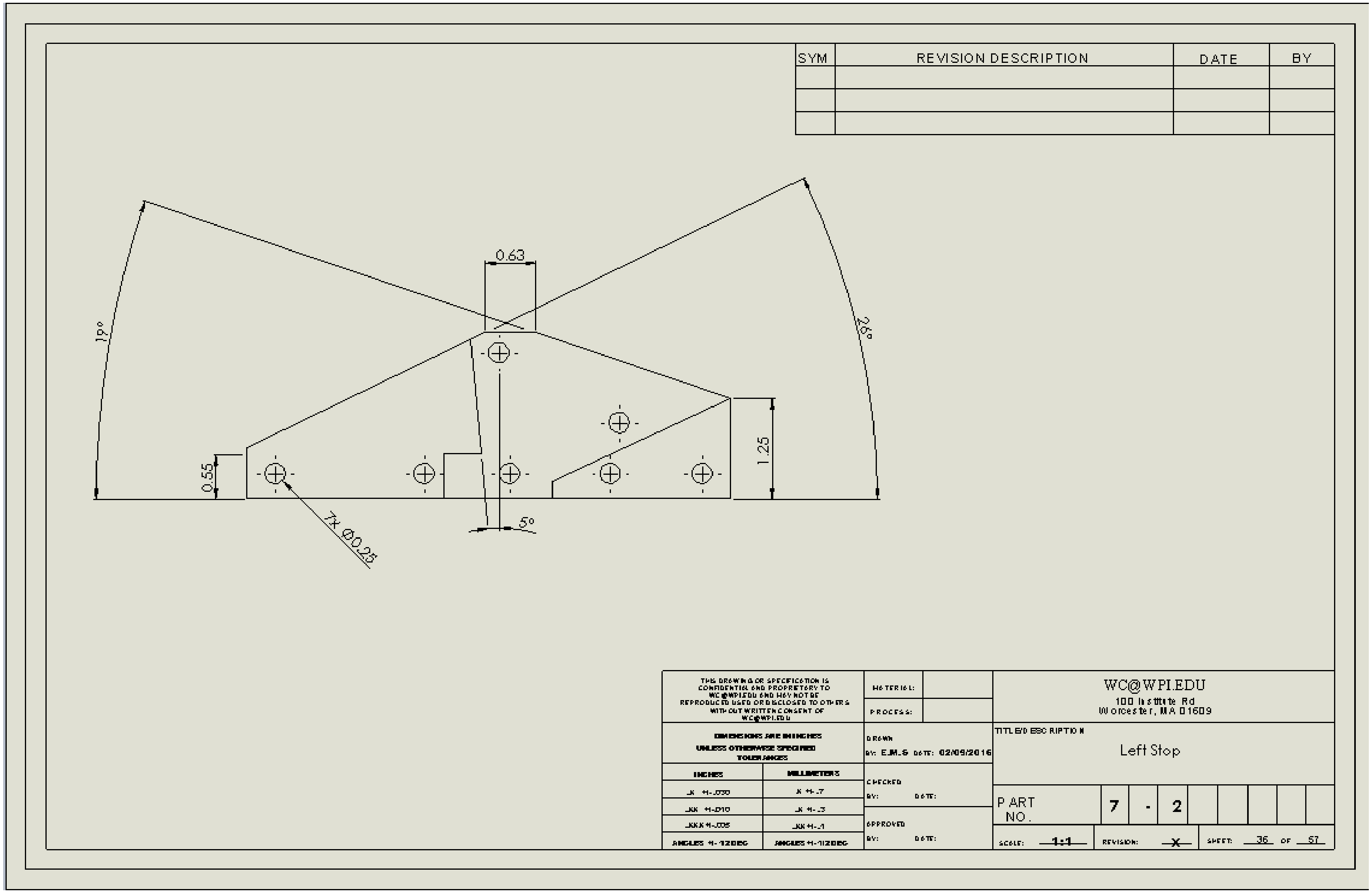
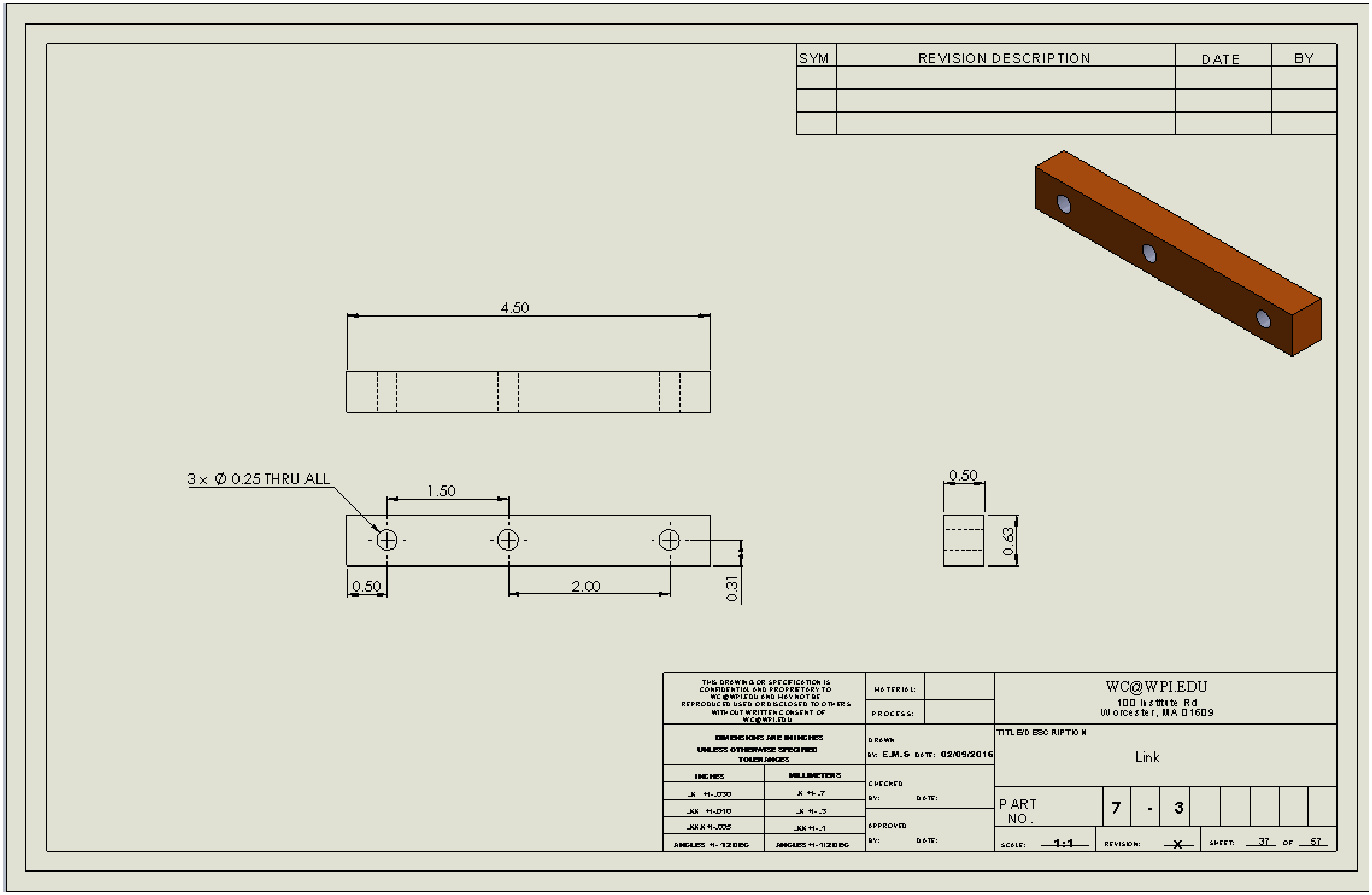
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
DRAWN
BY: E.M.S DATE: 02/24/2016
TITLE/DESCRIPTION
Back Rest
INCHES
MILLIMETERS
CHECKED
BY: DATE:
PART NO.
6 - 6
APPROVED
BY: DATE:
ANGLES +/- 1/2 DEG
ANGLES +/- 1/2 DEG
SCALE: 1:5
REVISION: X
SHEET: 33 OF 57



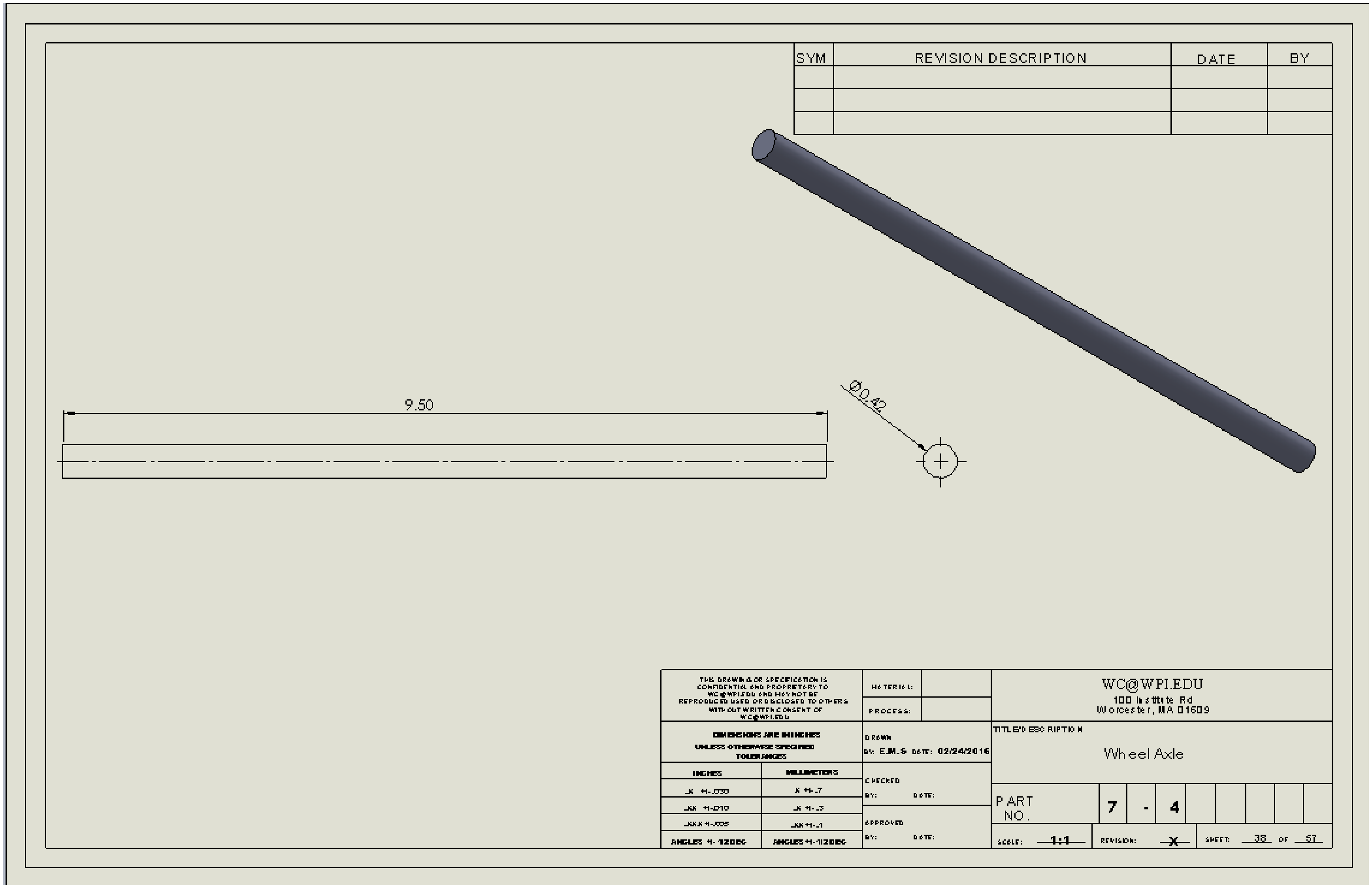
Note: The original frame was from a pre-existing Invacare Wheelchair. The dimensions shown below are for the changes to be made to the frame.
SYM
REVISION DESCRIPTION
DATE
BY
17.00
6.52
4.67
3.61
2.36
1.22
7.12
5.98
4.73
3.67
1.82
5.00
10x Ø0.25
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2 DEG
MATERIAL:
PROCESS:
DRAWN
BY: EJM.S DATE: 02/09/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Left Frame and Right Frame
PART NO.
7 - 1 and 10 - 1
SCALE: 1:5
REVISION: X
SHEET: 34 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
3.13
1.38
2.06
1.81
0.63
0.63
0.94
0.22
0.31
0.35
1.85
1.06
1.25
1.14
2.45
0.45
0.69
0.63
1.35
6.00
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
.X +/-.030
.X +/-.7
.XX +/-.010
.X +/-.3
.XXX +/-.005
.XX +/-.1
ANGLES +/-.12DEG
ANGLES +/-.12DEG
DRAWN
BY: EJM.G DATE: 02/09/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Left Stop
PART NO.
7 - 2
SCALE: 1:1
REVISION: X
SHEET: 35 OF 57

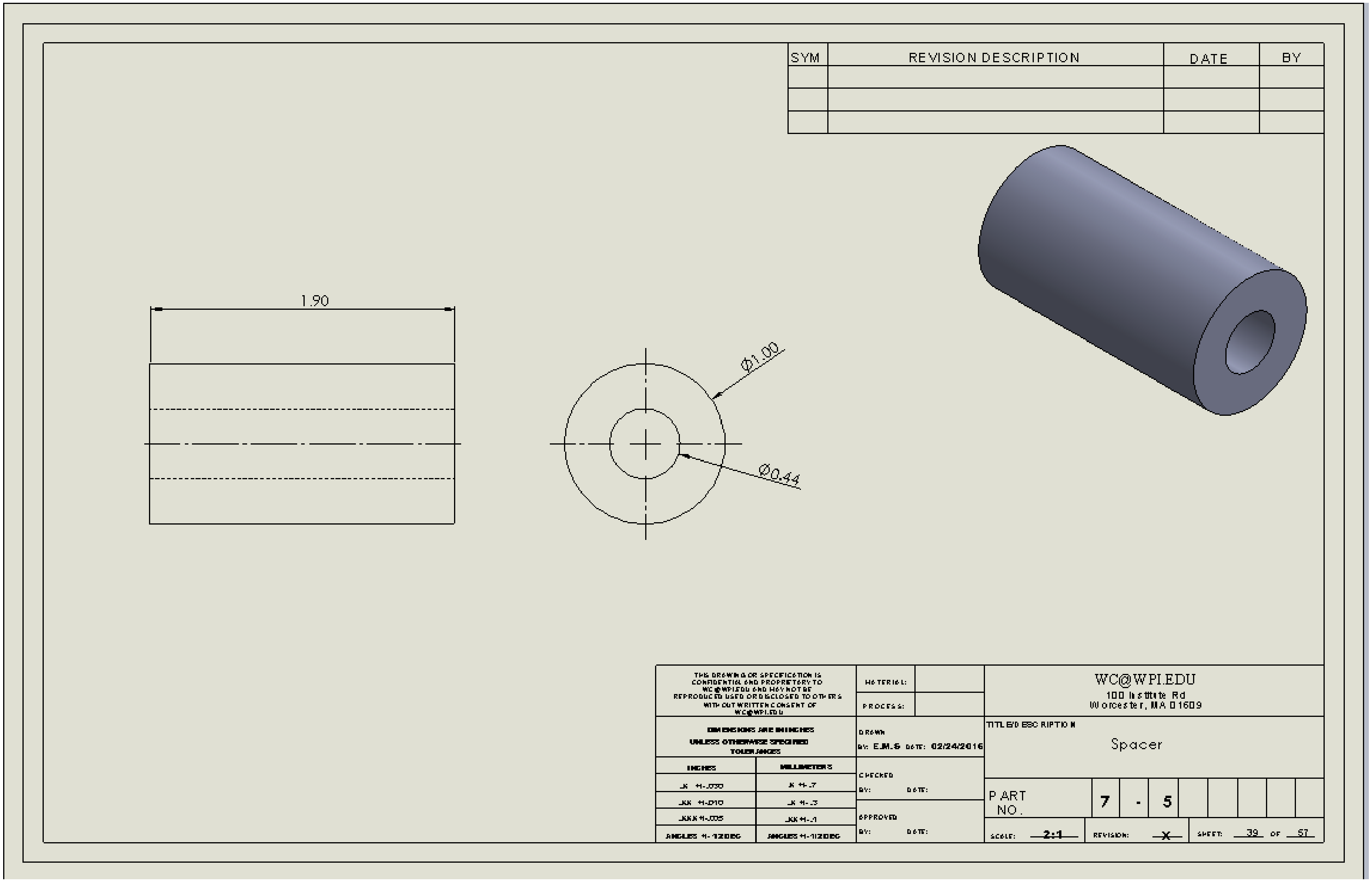

SYM
REVISION DESCRIPTION
DATE
BY
0.63
19°
26°
0.55
1.25
7x Ø0.25
5°
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2 DEG
DRAWN
BY: EJM.S DATE: 02/09/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Left Stop
PART NO.
7 - 2
SCALE: 1:1
REVISION: X
SHEET: 36 OF 57

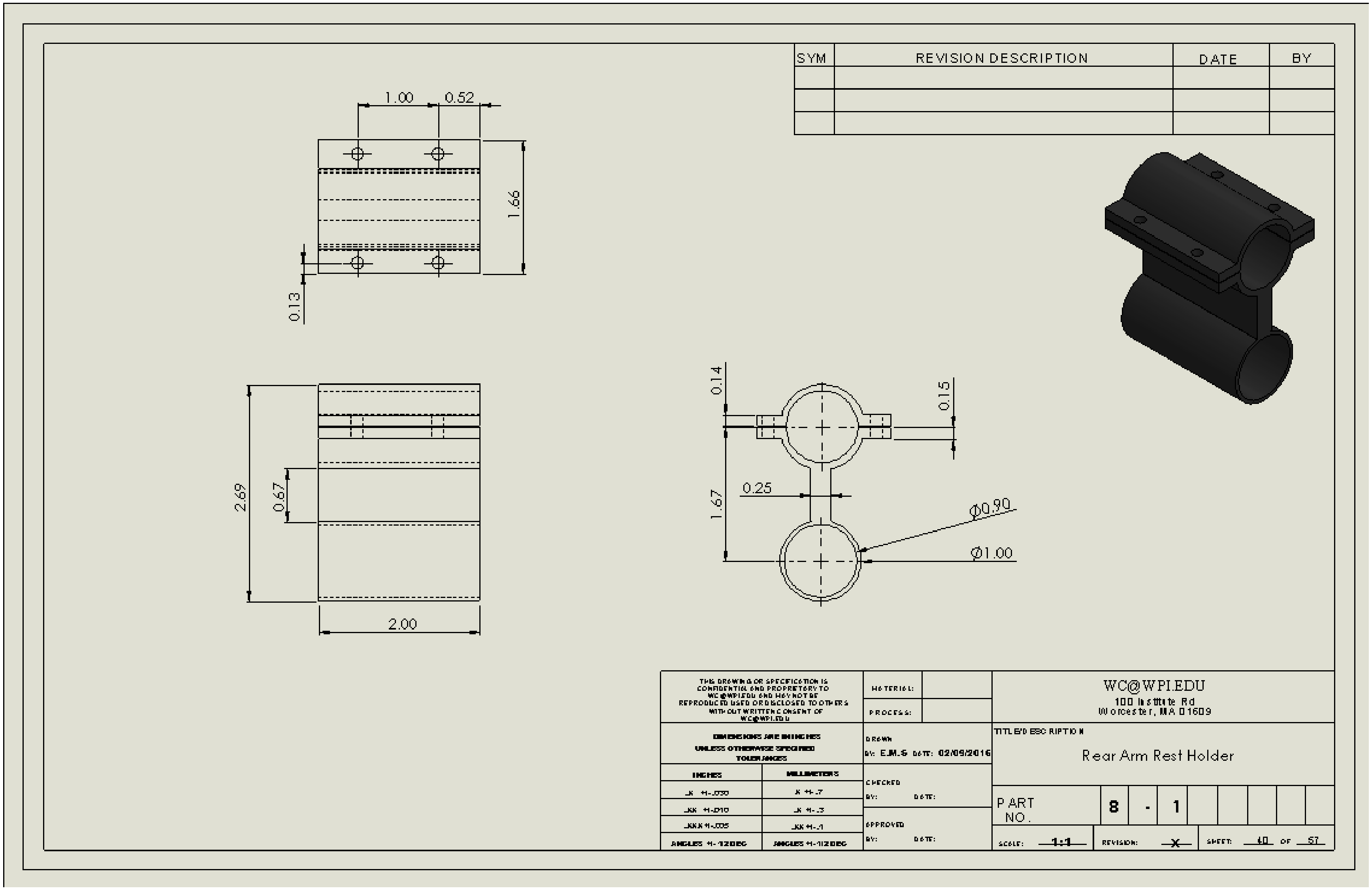


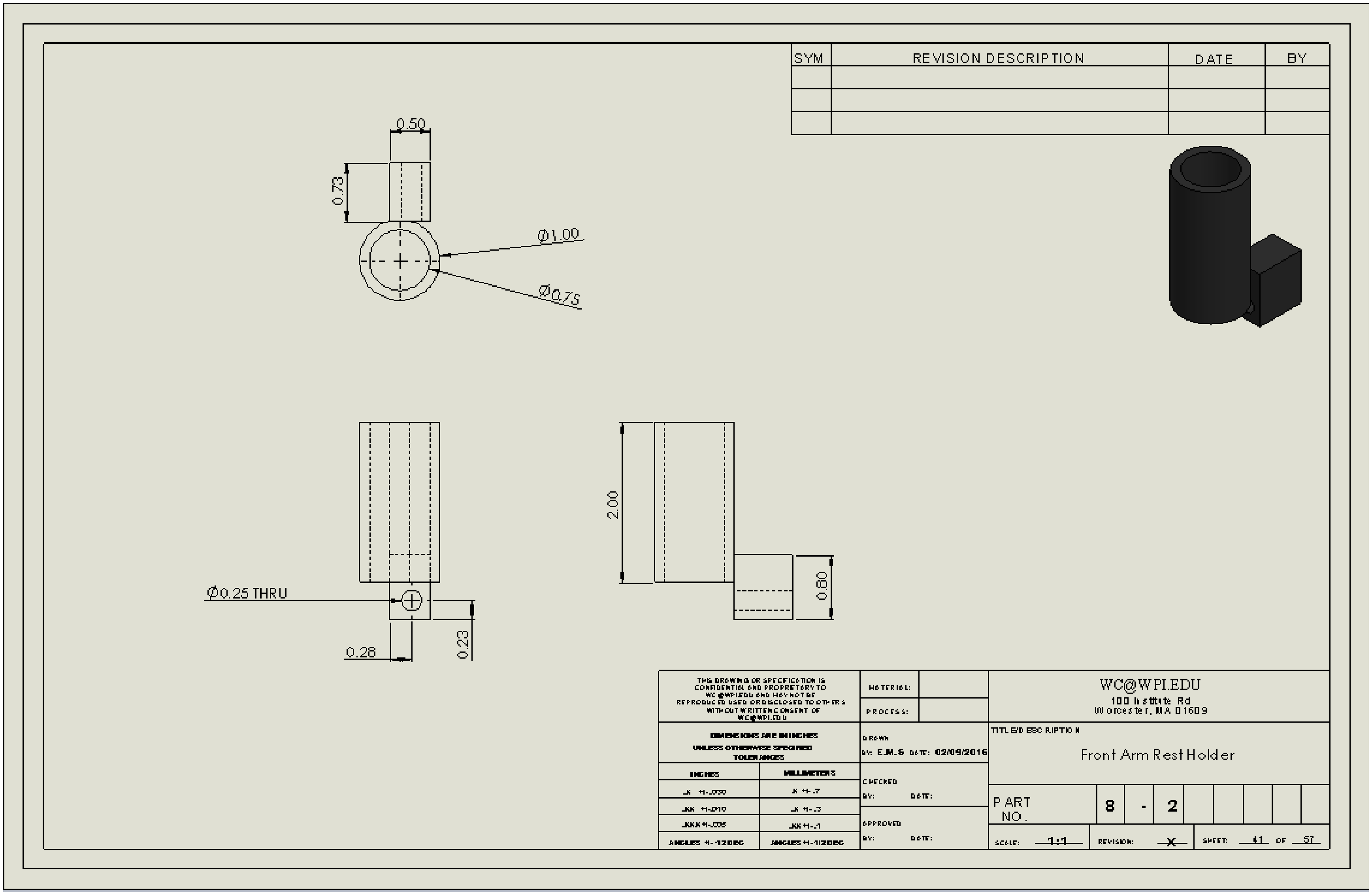
SYM
REVISION DESCRIPTION
DATE
BY
4.50
3x Ø 0.25 THRU ALL
1.50
0.50
2.00
0.31
0.50
0.63
THIS DRAWING OR SPECIFICATION IS CONFIDENTIAL AND PROPRIETARY TO WC@WPI.EDU AND MAY NOT BE REPRODUCED USED OR DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF WC@WPI.EDU
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES
INCHES
MILLIMETERS
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DRAWN BY: E.M.S DATE: 02/09/2016
CHECKED BY: DATE:
APPROVED BY: DATE:
TITLE/DESCRIPTION
Link
PART NO. 7 - 3
SCALE: 1:1
REVISION: X
SHEET: 37 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
9.50
Ø0.42
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DRAWN
BY: EJM.G DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
INCHES
MILLIMETERS
TITLE/DESCRIPTION
Wheel Axle
PART NO.
7 - 4
SCALE: 1:1
REVISION: X
SHEET: 38 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
1.90
Ø1.00
Ø0.44
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Spacer
PART NO.
7 - 5
SCALE: 2:1
REVISION: X
SHEET 39 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
1.00
0.52
1.66
0.13
2.69
0.67
2.00
0.14
0.15
0.25
1.67
Ø0.90
Ø1.00
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
MATERIAL:
PROCESS:
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
TITLE/DESCRIPTION
Rear Arm Rest Holder
DRAWN
BY: E.M.S DATE: 02/09/2016
CHECKED
APPROVED
PART NO.
8 - 1
SCALE: 1:1
REVISION: X
SHEET: 40 OF 57



SYM
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DATE
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Ø1.00
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0.80
Ø0.25 THRU
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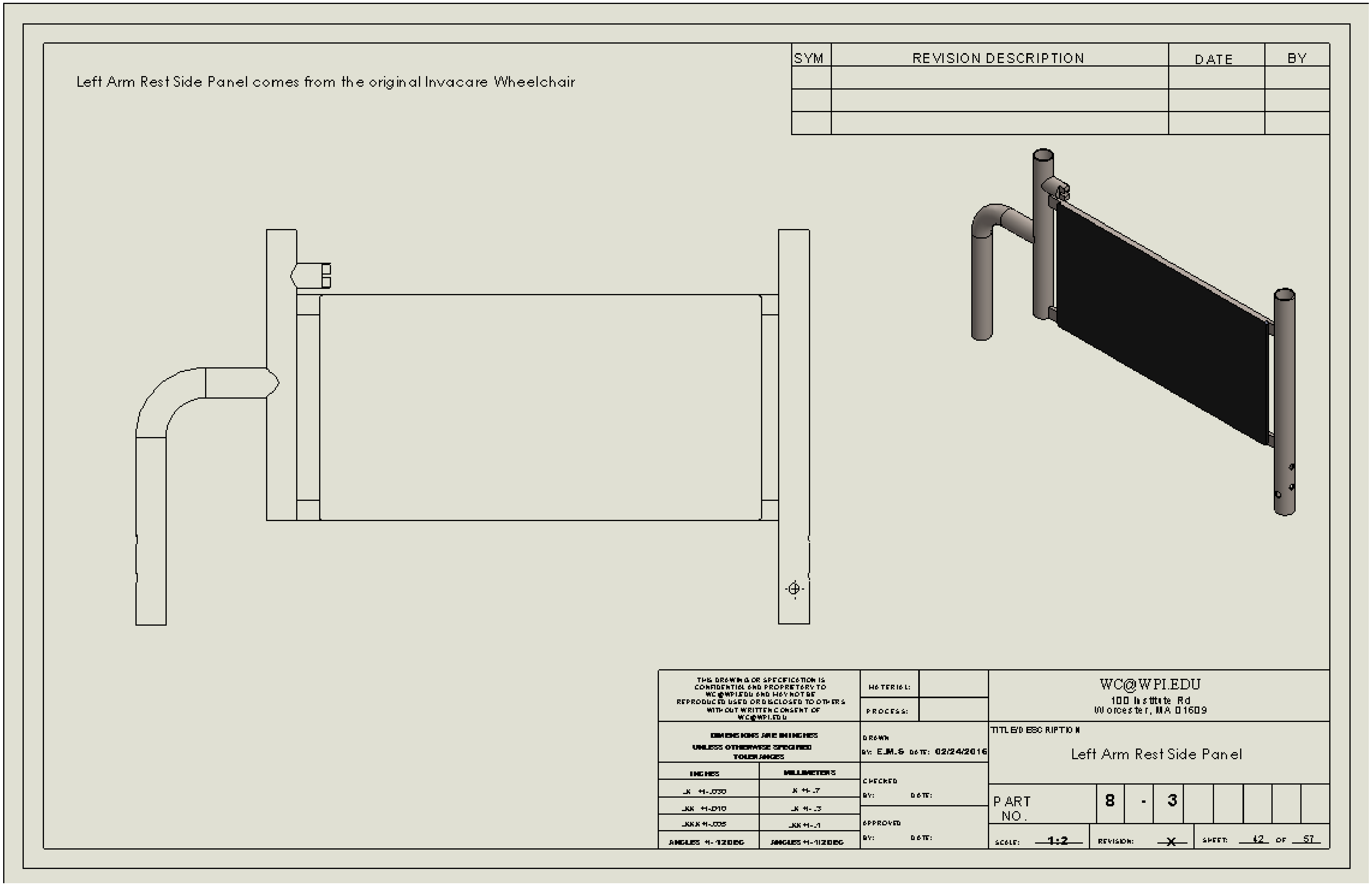
0.23
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DRAWN
BY: E.M.S DATE: 02/09/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
ANGLES +/-.1 DEG
TITLE/DESCRIPTION
Front Arm Rest Holder
PART NO.
8 - 2
SCALE: 1:1
REVISION: X
SHEET: 41 OF 57



Left Arm Rest Side Panel comes from the original Invacare Wheelchair
SYM
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100 Institute Rd
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
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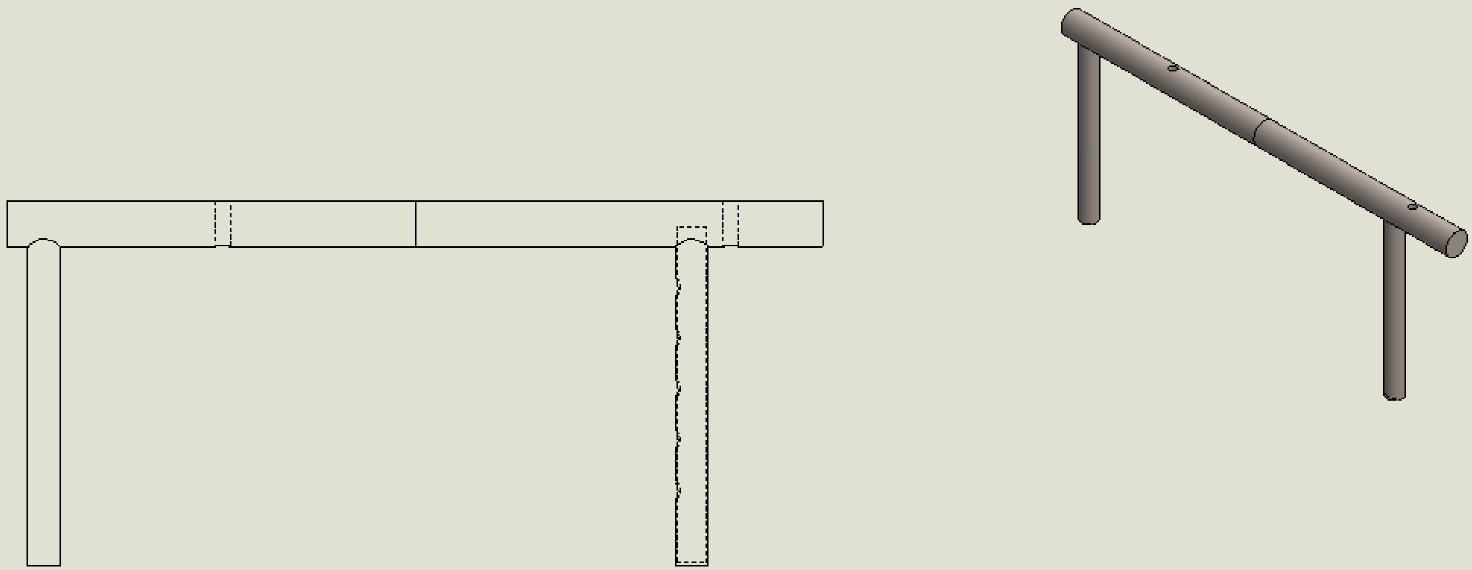
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Left Arm Rest Side Panel
PART NO.
8 - 3
SCALE: 1:2
REVISION: X
SHEET: 42 OF 57

Arm Rest Frame comes from the original Invacare Wheelchair

SYM	REVISION DESCRIPTION	DATE	BY



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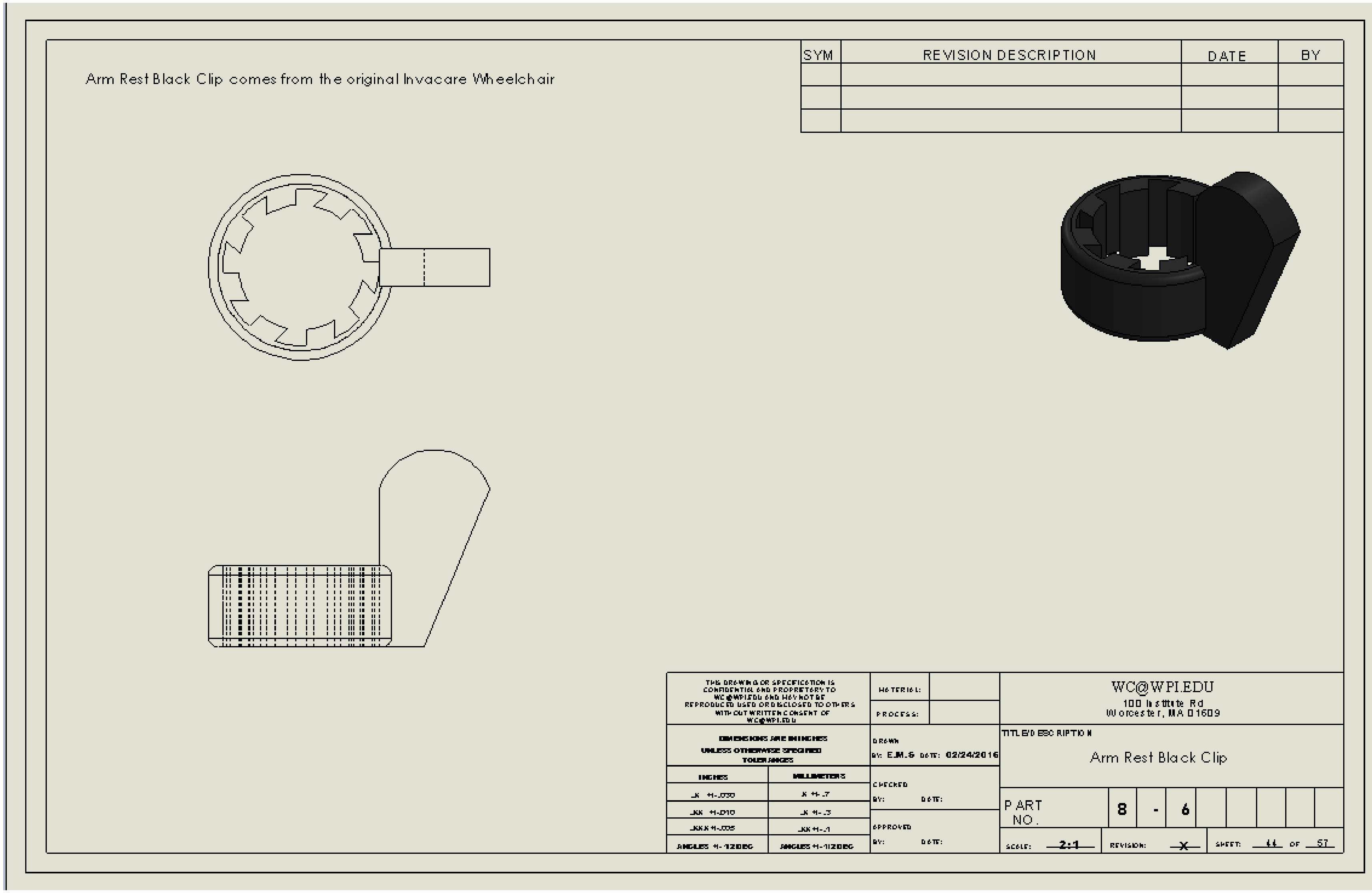
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES		DRAWN BY: EJM.G DATE: 02/24/2016		TITLE/DESCRIPTION Arm Rest Frame
INCHES	MILLIMETERS	CHECKED BY: DATE:		PART NO. 8 - 4
.X +/-.030	.X +/-.7			
.XX +/-.010	.X +/-.3	APPROVED BY: DATE:		
.XXX +/-.005	.XX +/-.1			
ANGLES +/- .12DEG	ANGLES +/- .12DEG			SCALE: 1:2 REVISION: X SHEET: 43 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
Arm Rest Black Clip comes from the original Invacare Wheelchair
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UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
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.X +/-.7
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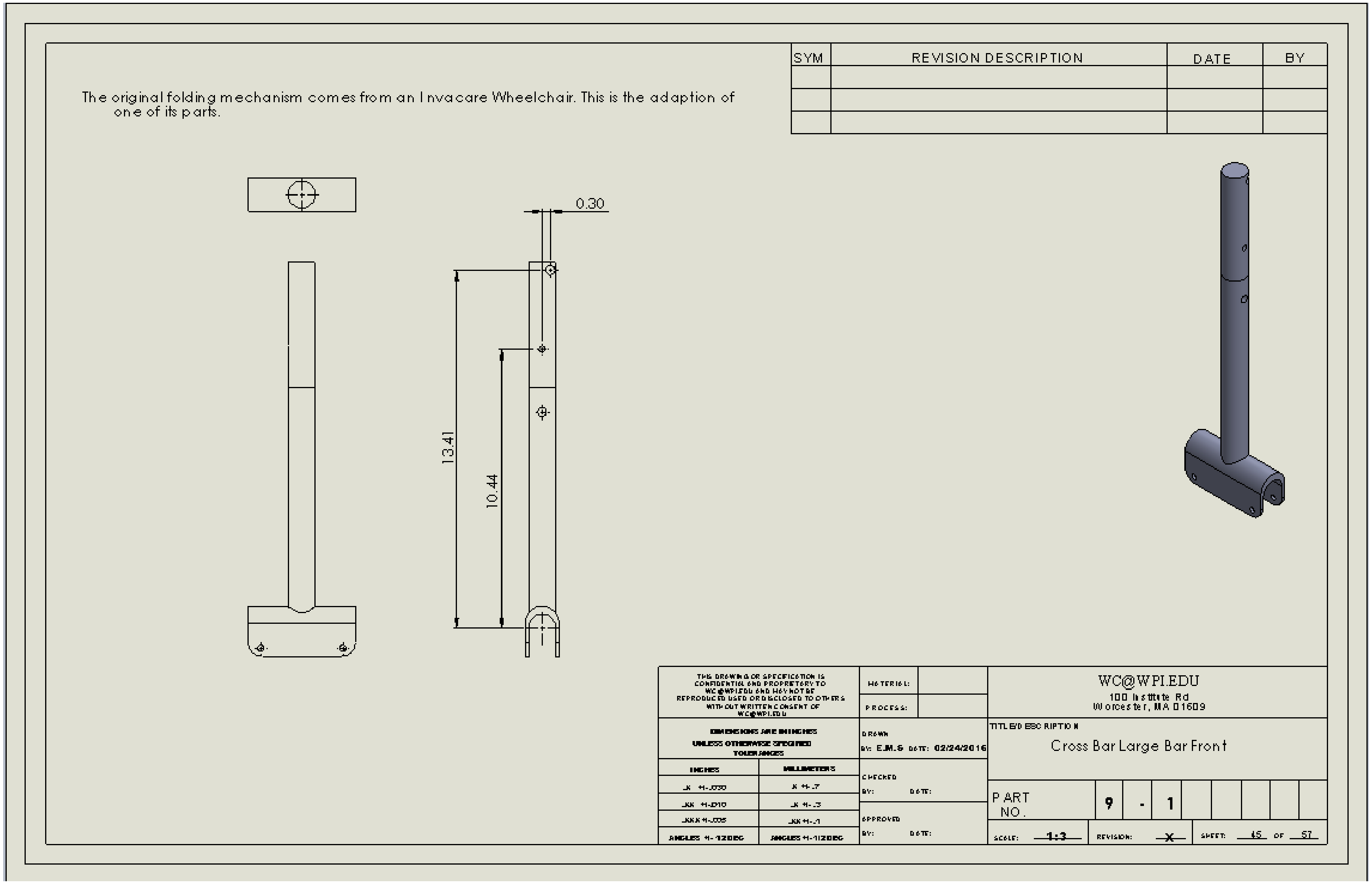
.X +/-.3
.XXX +/-.005
.XX +/-.1
ANGLES +/-1/2DEG
ANGLES +/-1/2DEG
MATERIAL:
PROCESS:
DRAWN
BY: E.J.M.S DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Arm Rest Black Clip
PART NO.
8 - 6
SCALE: 2:1
REVISION: X
SHEET: 44 OF 57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REVISION DESCRIPTION
DATE
BY
The original folding mechanism comes from an Invacare Wheelchair. This is the adaption of one of its parts.
0.30
13.41
10.44
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PROCESS:
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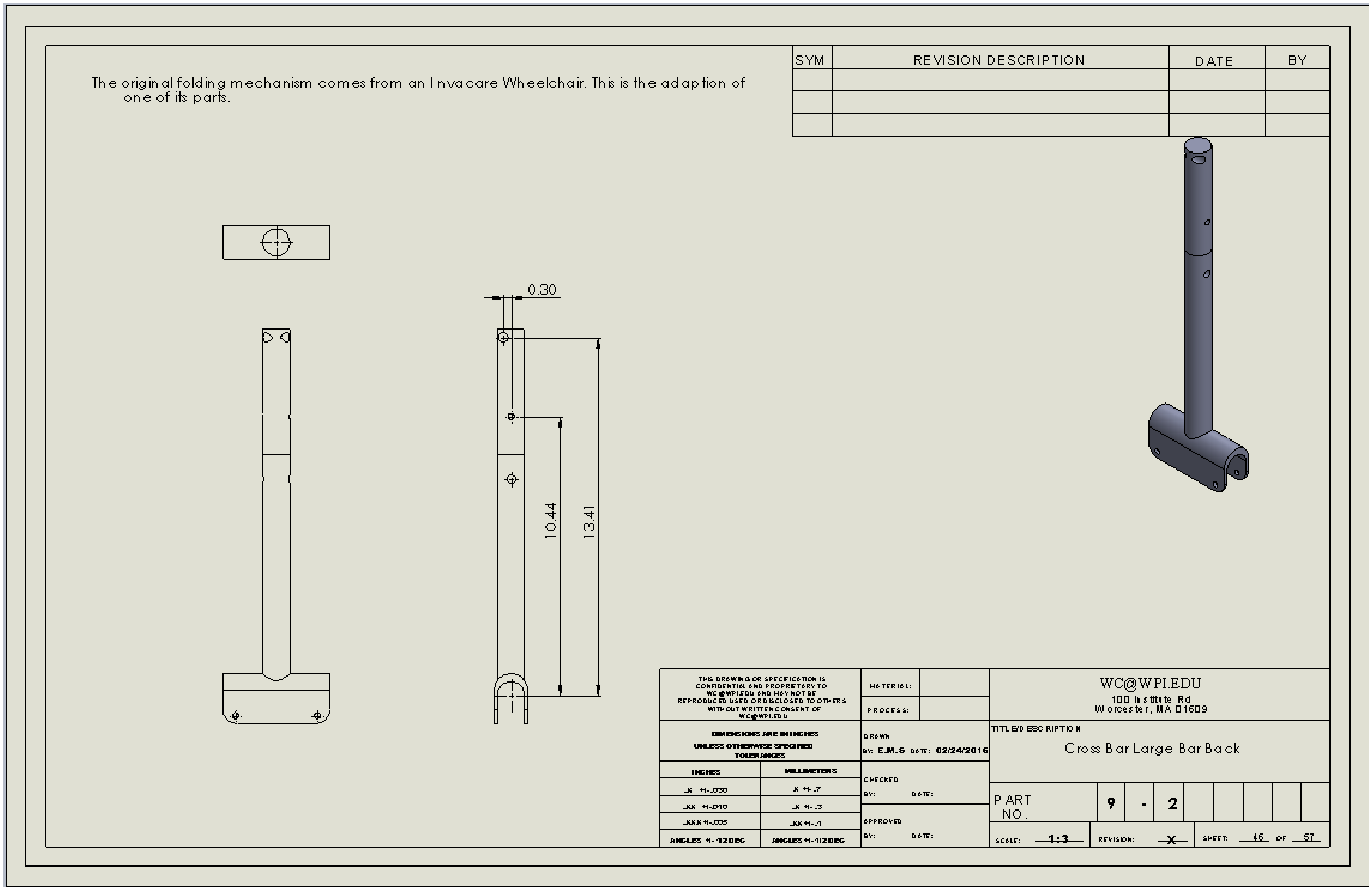
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
.X +/-.030
.X +/-.7
.XX +/-.010
.X +/-.3
.XXX +/-.005
.XX +/-.1
ANGLES +/-.1 2DEG
ANGLES +/-1/2DEG
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Cross Bar Large Bar Front
PART NO.
9 - 1
SCALE: 1:3
REVISION: X
SHEET: 45 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
The original folding mechanism comes from an Invacare Wheelchair. This is the adaption of one of its parts.
0.30
10.44
13.41
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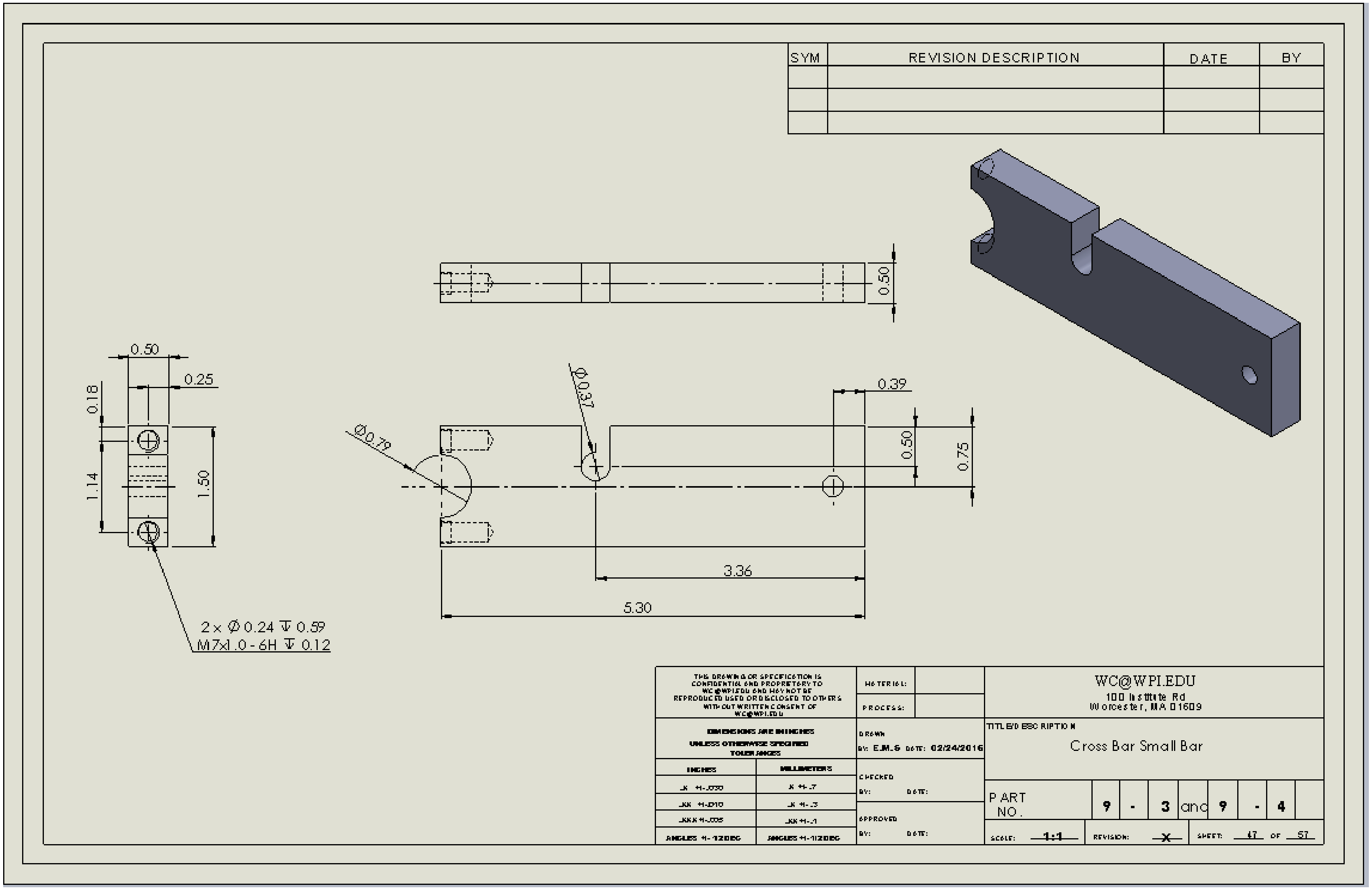
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
.X +/-.030
.X +/-.7
.XX +/-.010
.X +/-.3
.XXX +/-.005
.XX +/-.1
ANGLES +/-.1/2DEG
ANGLES +/-1/2DEG
MATERIAL:
PROCESS:
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Cross Bar Large Bar Back
PART NO.
9 - 2
SCALE: 1:3
REVISION: X
SHEET: 46 OF 57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REVISION DESCRIPTION
DATE
BY
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0.25
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1.50
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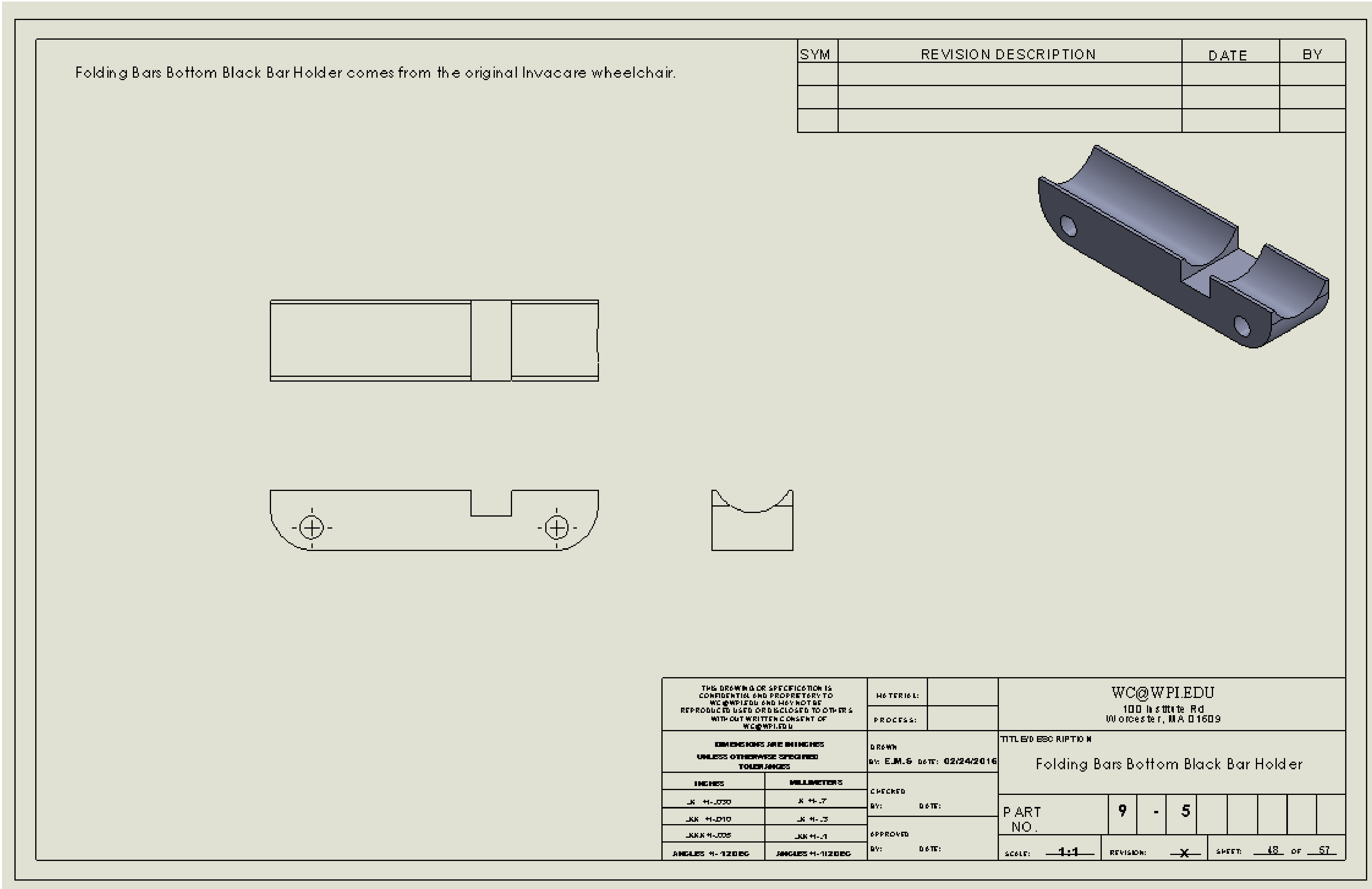
M7x1.0-6H ↧ 0.12
Ø0.79
Ø0.37
0.39
0.50
0.75
3.36
5.30
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Cross Bar Small Bar
PART NO.
9 - 3 and 9 - 4
DRAWN BY: E.M.S DATE: 02/24/2016
SCALE: 1:1
REVISION: X
SHEET 47 OF 57
MATERIAL:
PROCESS:
CHECKED BY: DATE:
APPROVED BY: DATE:
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS


Folding Bars Bottom Black Bar Holder comes from the original Invacare wheelchair.
SYM
REVISION DESCRIPTION
DATE
BY
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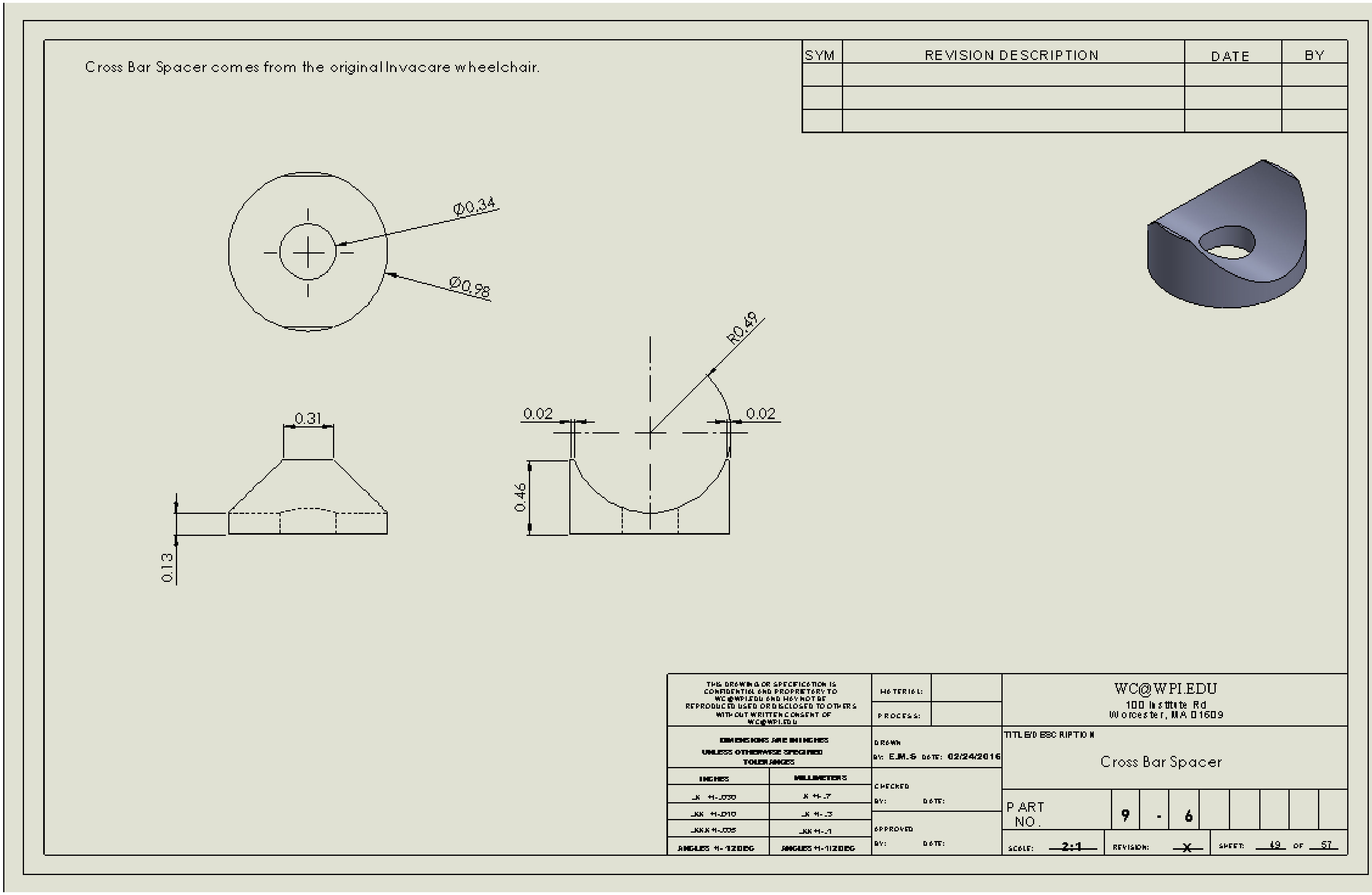
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: E.M.S DATE: 02/24/2016
TITLE/DESCRIPTION
Folding Bars Bottom Black Bar Holder
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
9 - 5
SCALE: 1:1
REVISION: X
SHEET: 48 OF 57



Cross Bar Spacer comes from the original Invacare wheelchair.
SYM
REVISION DESCRIPTION
DATE
BY
Ø0.34
Ø0.98
R0.49
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0.13
0.02
0.02
0.46
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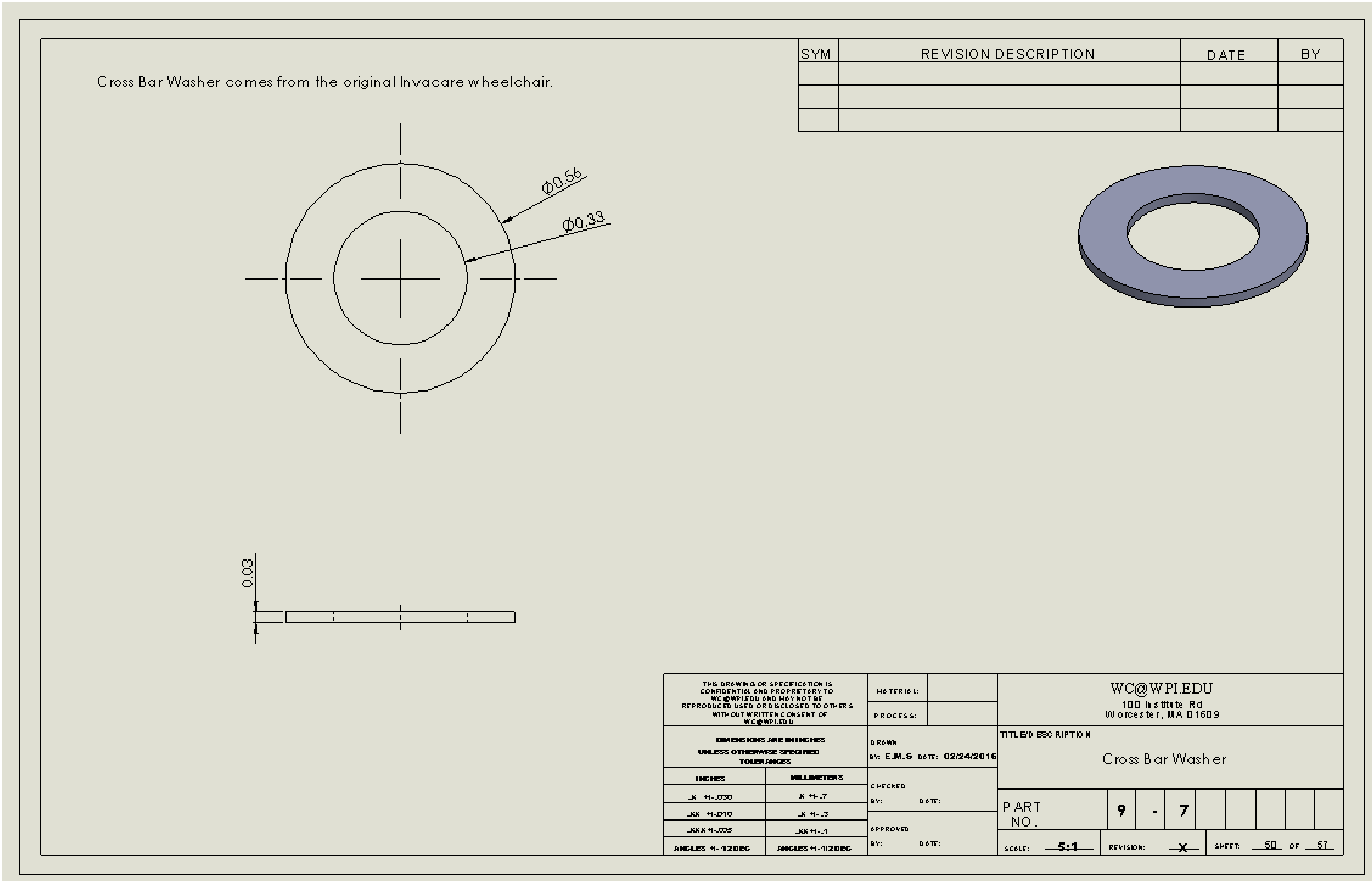
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2DEG
DRAWN
BY: EJM.G DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Cross Bar Spacer
PART NO.
9 - 6
SCALE: 2:1
REVISION: X
SHEET: 49 OF 57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REVISION DESCRIPTION
DATE
BY
Cross Bar Washer comes from the original Invacare wheelchair.
Ø0.56
Ø0.33
0.03
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PROCESS:
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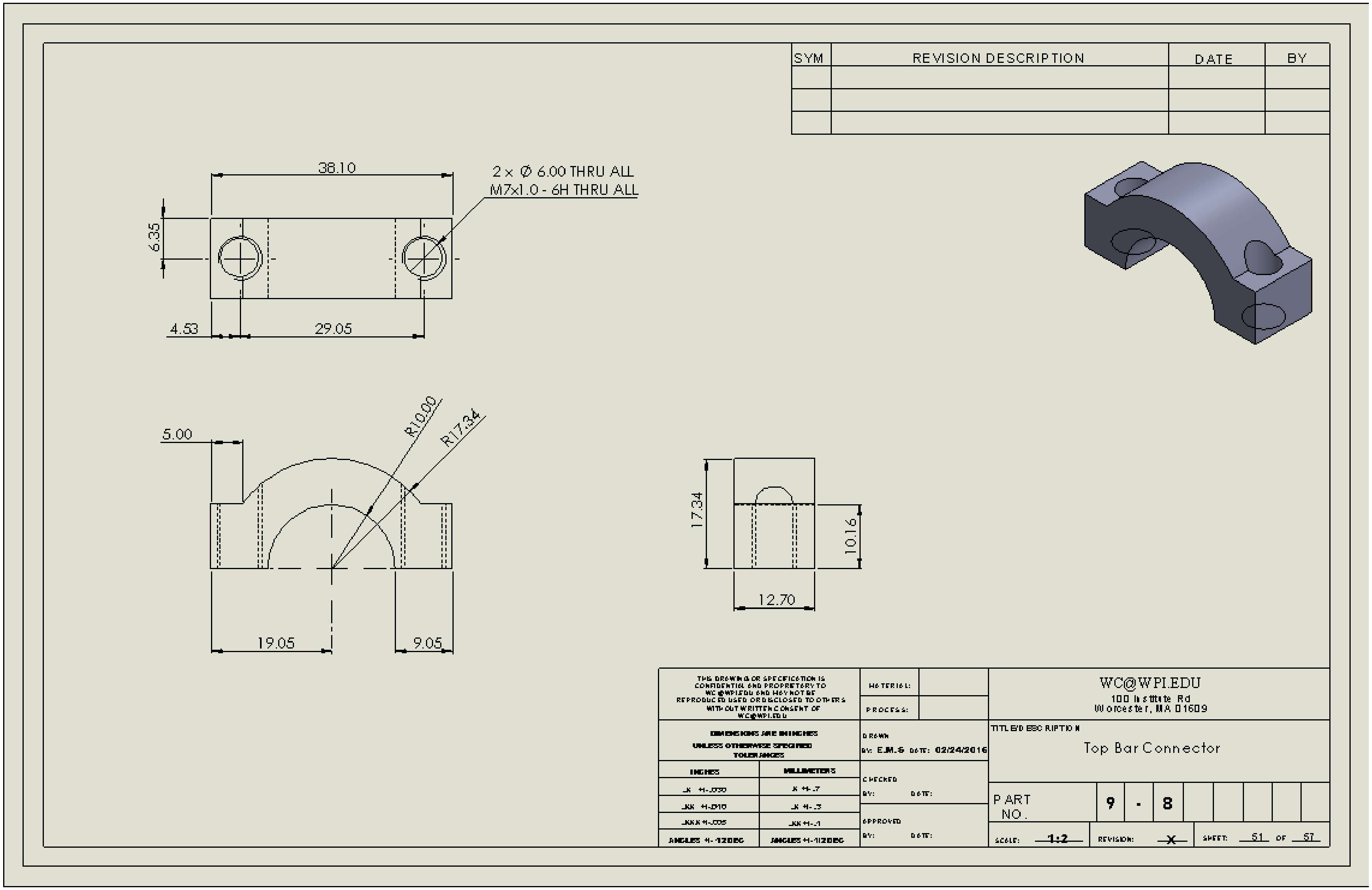
Worcester, MA 01609
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: EJM.S DATE: 02/24/2016
TITLE/DESCRIPTION
Cross Bar Washer
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
9 - 7
SCALE: 5:1
REVISION: X
SHEET: 50 OF 57



SYM
REVISION DESCRIPTION
DATE
BY
38.10
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M7x1.0 - 6H THRU ALL
6.35
4.53
29.05
5.00
R10.00
R17.34
19.05
9.05
17.34
10.16
12.70
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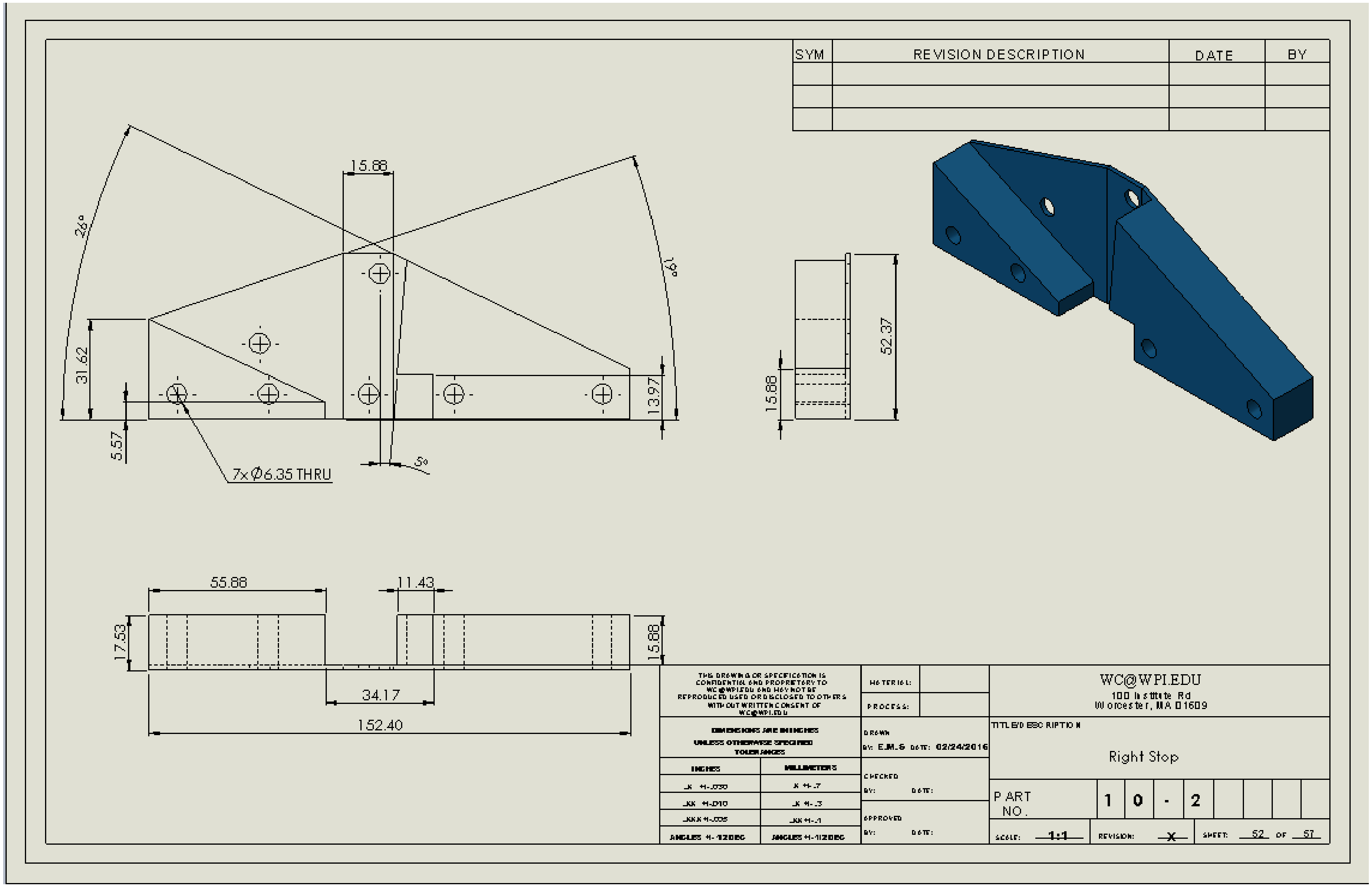
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
MATERIAL:
PROCESS:
DRAWN
BY: EJM.6 DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Top Bar Connector
PART NO.
9 - 8
SCALE: 1:2
REVISION: X
SHEET: 51 OF 57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REVISION DESCRIPTION
DATE
BY
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26°
19°
31.62
5.57
13.97
7x Ø6.35 THRU
5°
15.88
52.37
55.88
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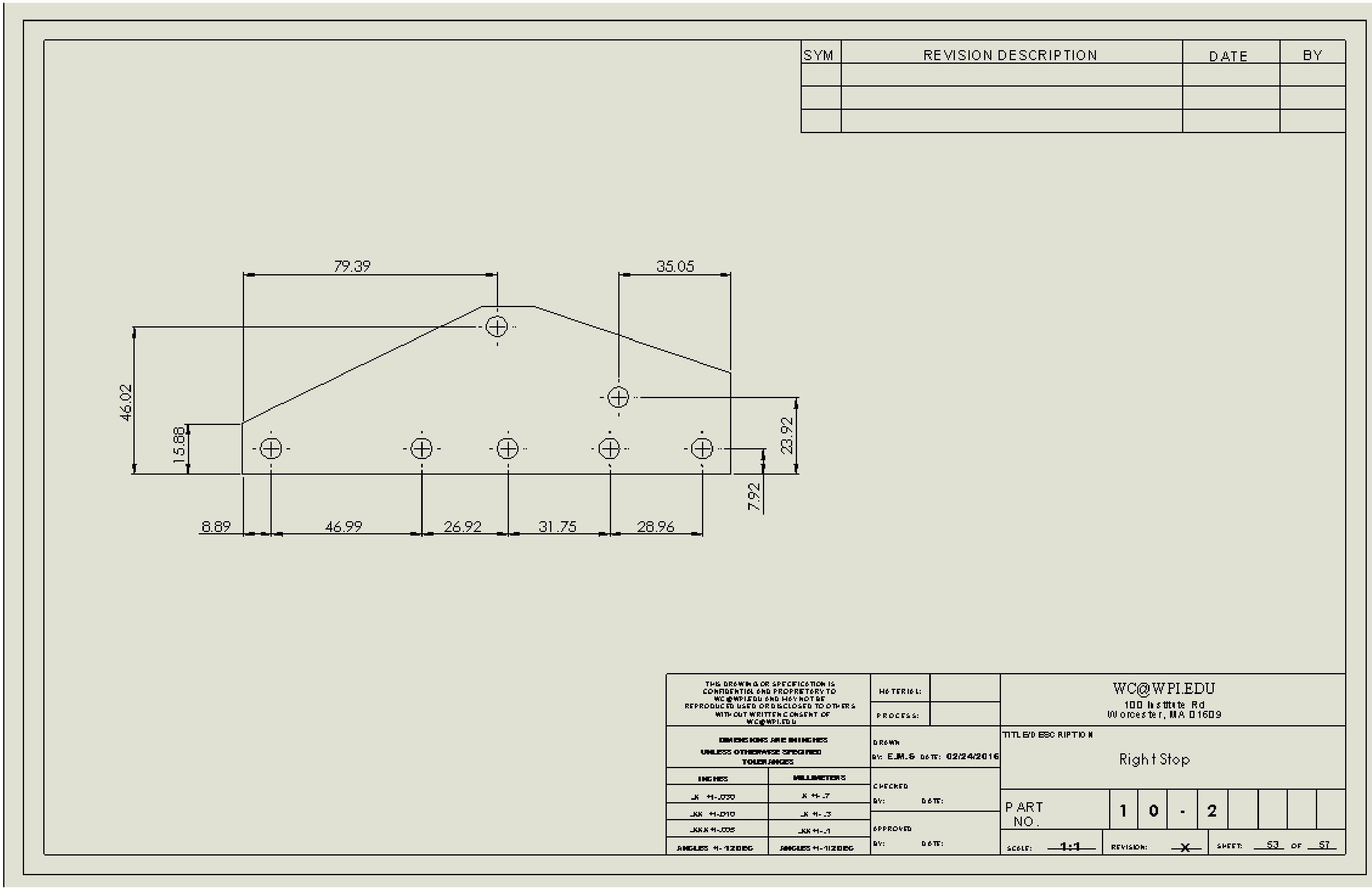
17.53
15.88
34.17
152.40
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Right Stop
PART NO.
1 0 - 2
DRAWN
BY: E.M.S DATE: 02/24/2016
SCALE: 1:1
REVISION: X
SHEET: 52 OF 57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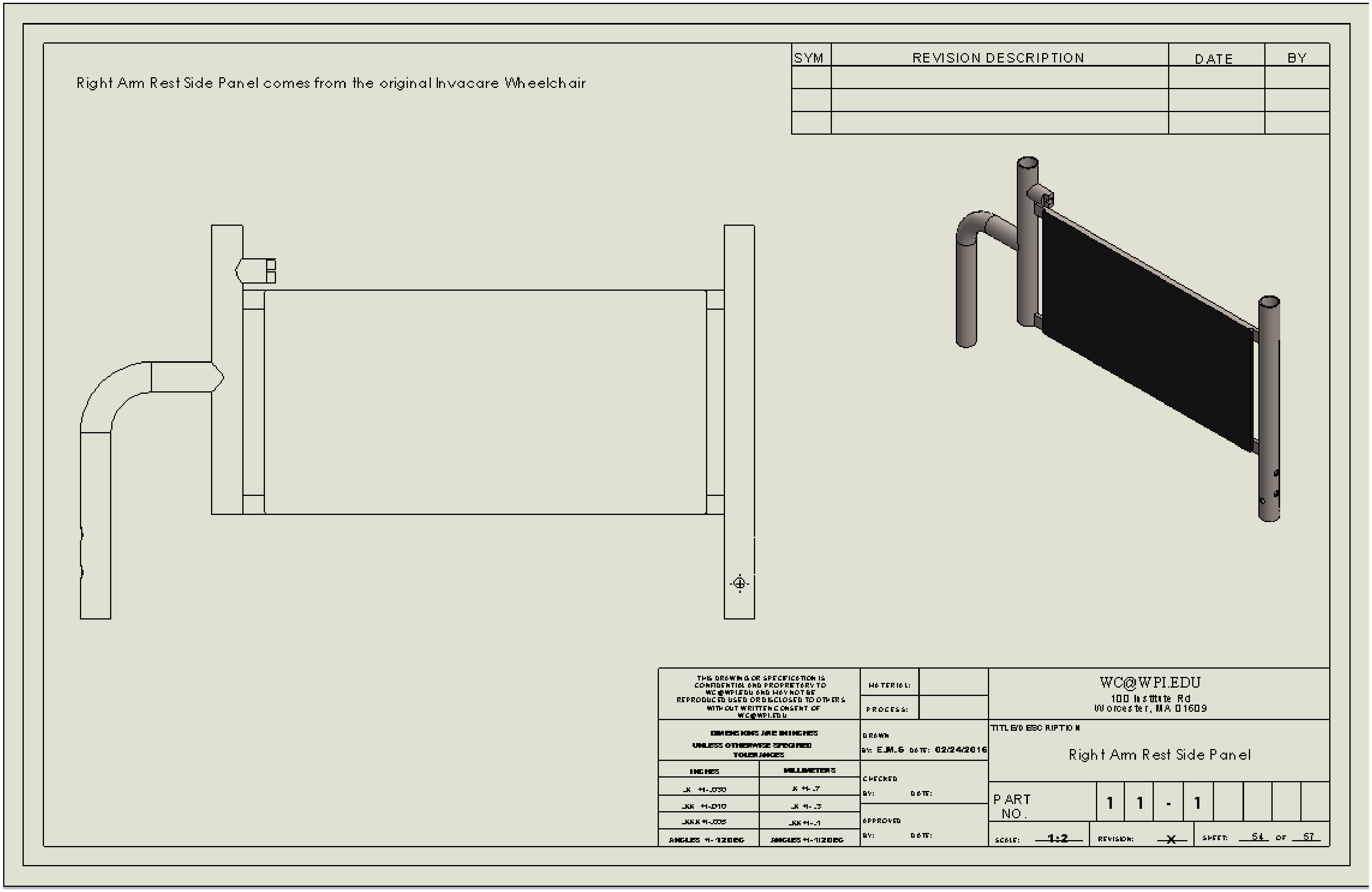
46.99
26.92
31.75
28.96
MATERIAL:
PROCESS:
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
DRAWN
BY: EJM.S DATE: 02/24/2016
TITLE/DESCRIPTION
Right Stop
CHECKED
BY: DATE:
APPROVED
BY: DATE:
PART NO.
1 0 - 2
SCALE: 1:1
REVISION: X
SHEET: 53 OF 57



SYM
REVISION DESCRIPTION
DATE
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TOLERANCES
INCHES
MILLIMETERS
.X +/-.030
.X +/- .7
.XX +/-.010
.X +/- .3
.XXX +/-.005
.XX +/- .1
ANGLES +/- 1/2 DEG
ANGLES +/- 1/2 DEG
DRAWN
BY: EJM.G DATE: 02/24/2016
CHECKED
BY: DATE:
APPROVED
BY: DATE:
TITLE/DESCRIPTION
Right Arm Rest Side Panel
PART NO.
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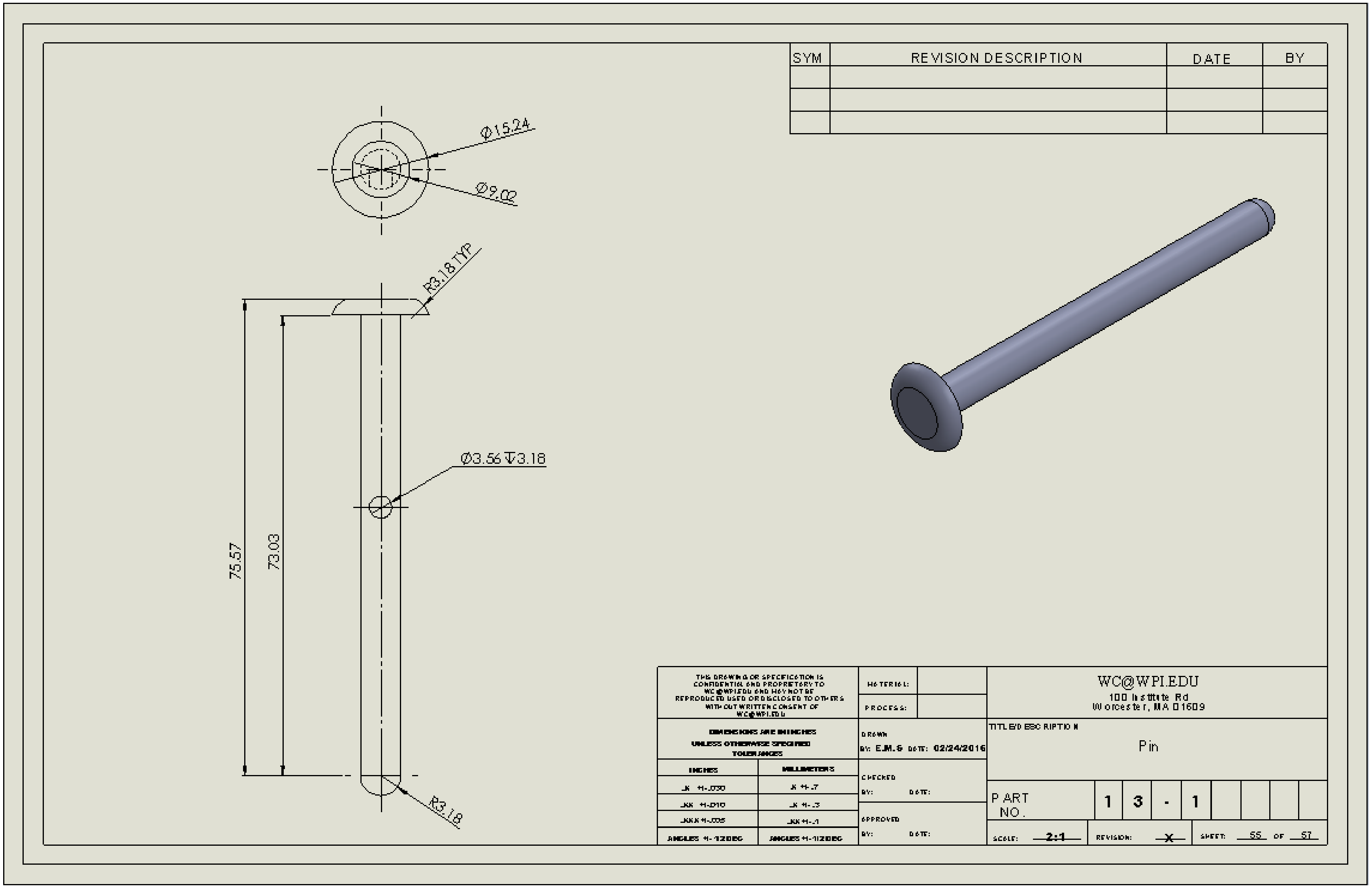
SCALE: 1:2
REVISION: X
SHEET: 54 OF 57


SYM
REVISION DESCRIPTION
DATE
BY
Ø15.24
Ø9.02
R3.18 TYP
Ø3.56 ↧3.18
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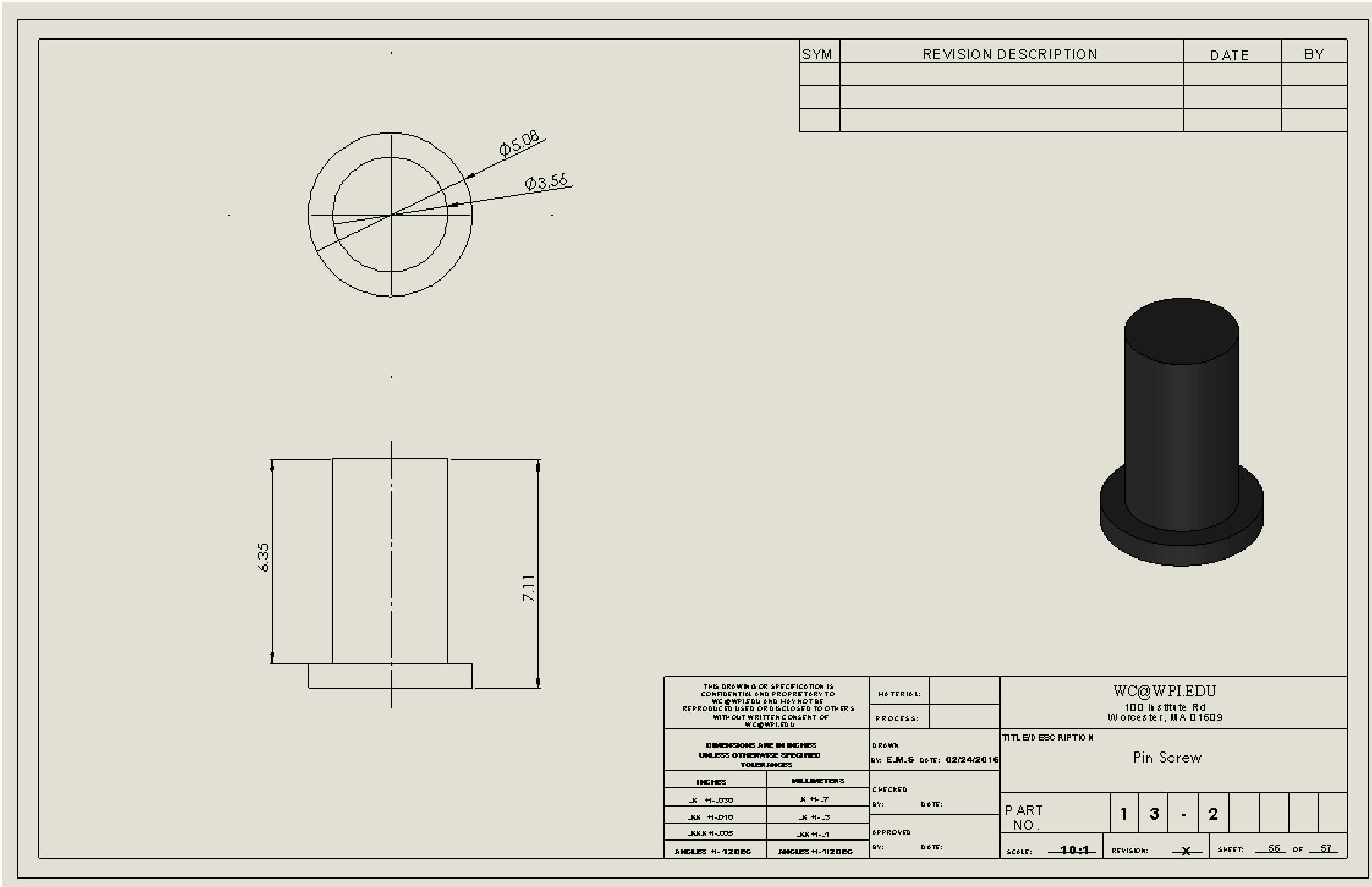
73.03
R3.18
WC@WPI.EDU
100 Institute Rd
Worcester, MA 01609
MATERIAL:
PROCESS:
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED
TOLERANCES
INCHES
MILLIMETERS
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
APPROVED
TITLE/DESCRIPTION
Pin
PART NO.
1 3 - 1
SCALE: 2:1
REVISION: X
SHEET 55 OF 57


SYM
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DATE
BY
Ø5.08
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TOLERANCES
INCHES
MILLIMETERS
ANGLES +/- 1/2DEG
DRAWN
BY: E.M.S DATE: 02/24/2016
CHECKED
BY: DATE:
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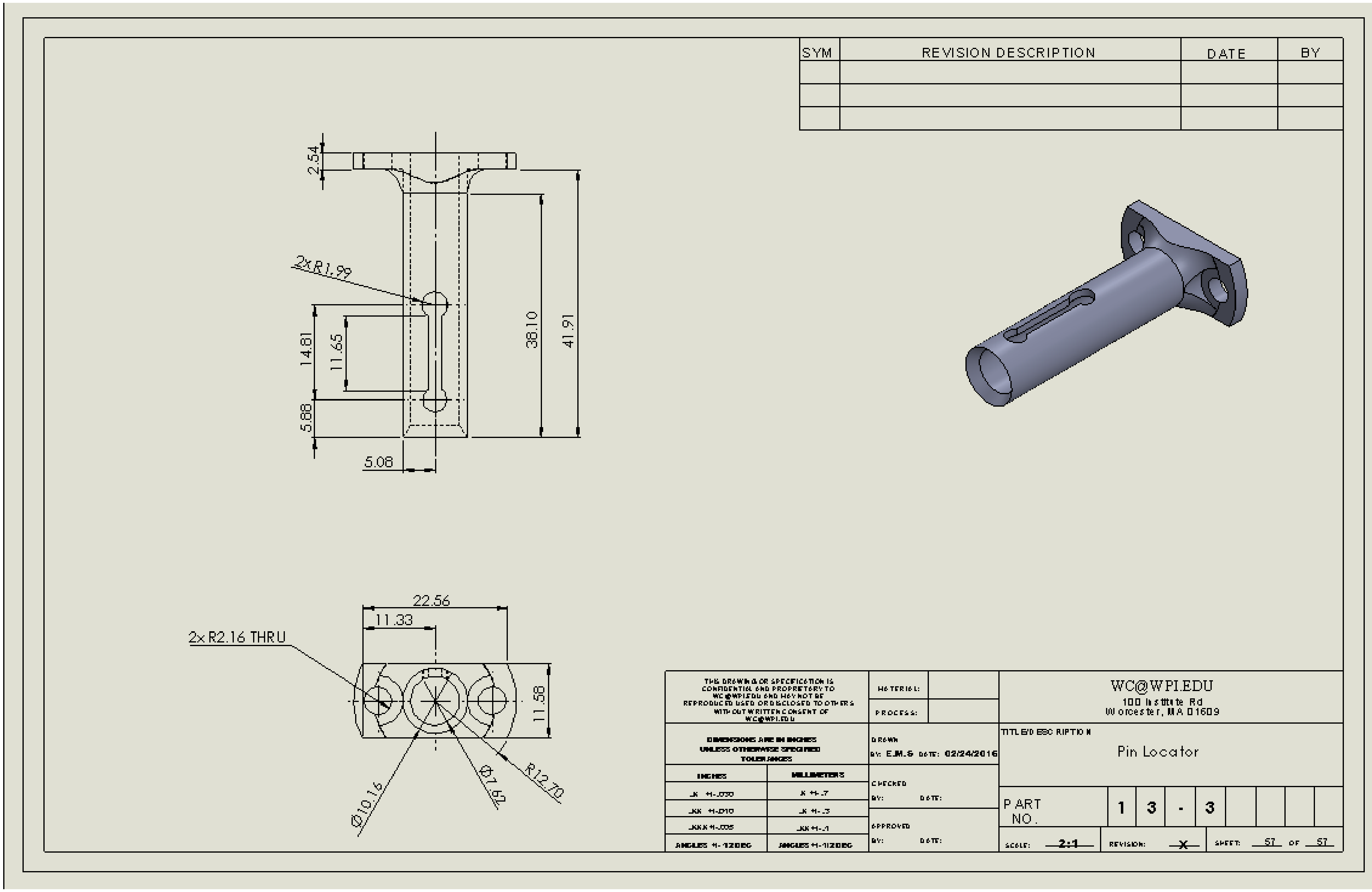
BY: DATE:
TITLE/DESCRIPTION
Pin Screw
PART NO.
1 3 - 2
SCALE: 10:1
REVISION: X
SHEET: 56 OF 57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DATE
BY
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5.88
5.08
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11.33
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Ø10.16
Ø7.62
R12.70
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED
INCHES
MILLIMETERS
MATERIAL:
PROCESS:
DRAWN
BY: E.M.S DATE: 02/24/2016
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APPROVED
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100 Institute Rd
Worcester, MA 01609
TITLE/DESCRIPTION
Pin Locator
PART NO.
1 3 - 3
SCALE: 2:1
REVISION: X
SHEET: 57 OF 57

Part Number	Description of Part
1-0	Shifting Mechanism
1-1	Shifting Mechanism Rod, From Link A to Lock Bolt
1-2	Shifting Mechanism Link A, From Rod to Link B
1-3	Shifting Mechanism Link B, From Link A to Bent Rod
1-4	Shifting Mechanism Bent Rod, From Link B to Ratchet
1-5	Socket Welded to Chain Piece, From Ratchet to Axle
1-6	Ratchet, From Socket to Bent Rod
1-7	4.80 ID Nut
1-8	4.8mm Screw
1-9	7.90 ID Nut
1-10	3.15mm Screw
2-0	Propulsion System
2-1	Bushing, From Drive Lever to Ratchet
2-2	Drive Lever Tubing, To Bushing
2-3	Grip, To Drive Lever Tubing
2-4	Brake Handle, To Drive Lever Tubing
2-5	Bolt Lock, From Drive Lever Tubing to Shifting Mechanism Rod
2-6	Wooden Spacers, From Drive Lever to Lock Bolt
3-0	Wheel System
3-1	Wheel, On Axle
3-2	Disc Brake, From Wheel to Propulsion System
4-0	1-0,2-0,3-0 System

5-0	Caster Assembly
5-1	Caster Frame, From Frame to Caster Wheel
5-2	Caster Wheel, On Caster Frame
5-3	Caster Extension
5-4	Caster Bearing Holder, From Caster Frame to Frame
6-0	Seat Assembly
6-1	Seat Frame Pipe, From Corner Elbow to Seat Clamp
6-2	Corner Elbow, From Seat Frame Pipe to Back Rest Frame Pipe
6-3	Back Rest Frame Pipe, To Corner Elbow
6-4	Seat, To Seat Clamp
6-5	Seat Rods, From Seat to Seat Frame Pipe
6-6	Back Rest, To Seat Frame Pipe
7-0	Left of Wheelchair, 4-0,5-0,6-0,8-0 System
7-1	Left Frame
7-2	Left Stop, From Left Frame to Link
7-3	Link, To Stop
7-4	Wheel Axle, From Frame to 4-0
7-5	Spacer
8-0	Left Arm Rest Assembly
8-1	Rear Arm Rest Holder, From Arm Rest to Frame
8-2	Front Arm Rest Holder, From Arm Rest to Frame
8-3	Left Arm Rest Side Panel, From Holders to Arm Rest Frame
8-4	Arm Rest Frame, From Arm Rest Padding to Arm Rest Side Panel
8-6	Arm Rest Black Clip, To Arm Rest Side Panel

9-0	Folding Mechanism
9-1	Cross Bar Large Bar Front
9-2	Cross Bar Large Bar Back
9-3	Cross Bar Small Bar
9-5	Folding Bars Bottom Black Bar Holder
9-6	Cross Bar Spacer
9-7	Cross Bar Washer
9-8	Top Bar Connector, From Small Cross Bar to Frame
10-0	Right of Wheelchair
10-1	Right Frame
10-2	Right Stop, From Right Frame to Link
11-0	Right Arm Rest Assembly
11-1	Right Arm Rest Side Panel, From Holders to Arm Rest Frame
12-0	Full Assembly
13-0	Pin Assembly
13-1	Pin, To Stop
13-2	Pin Screw
13-3	Pin Locator

Appendix E: Propulsion System Failure Testing Protocols

This test was set up with the same configuration as the propulsion system in the final prototype. This determined feasibility of the design in regards to system failure.

To be tested:

- Potential failure modes of the system
- Maximum torque applied before failure
- Part that fails first (ratchet, lever arm, weld connections, wheel spokes, hub)

Materials:

- Spring Gauge (with tape covering the indicator to give a maximum force reading)
- 10 lb. Weights
- Bucket
- Rope
- Wheel
- Socket
- Ratchet Wrench
- Clamps or Equivalent

Setup:

3. Using self-tapping screws, a steel plate was attached to the wheel hub and then a pass through socket was welded onto the steel plate, Figure 100.

Figure 100: Wheel with Welded Steel Plate and Socket.

This simulated the final prototype, which had a steel piece onto which the steel socket was welded. The wheel that was used for the prototype is shown in Figure 101.

Figure 101: Wheel that was used for Final Prototype.

Although different shapes, the steel piece screwed to the hub is what the socket will be welded to. The similarity between the intended prototype wheel and the tested wheel provides an accurate representation of the wheel hub and this allows for destructive testing on a wheel that will not be needed for the final prototype.

4. The test wheel was secured to a table in a horizontal orientation. Torque was applied so it was fastened in a way to prevent rotation. This was done by clamping the wheel directly to the table edges and creating a perimeter around the other edges to prevent it from lifting up or spinning, Figure 102.

Figure 102: Wheel Clamped to Table.

4. The ratchet was connected to the outside of the lever arm via hose clamps. A metal tube was used as the lever arm. A hole was drilled 36 inches from the center of the ratchet for the spring gauge, which was attached in later steps, Figure 103.

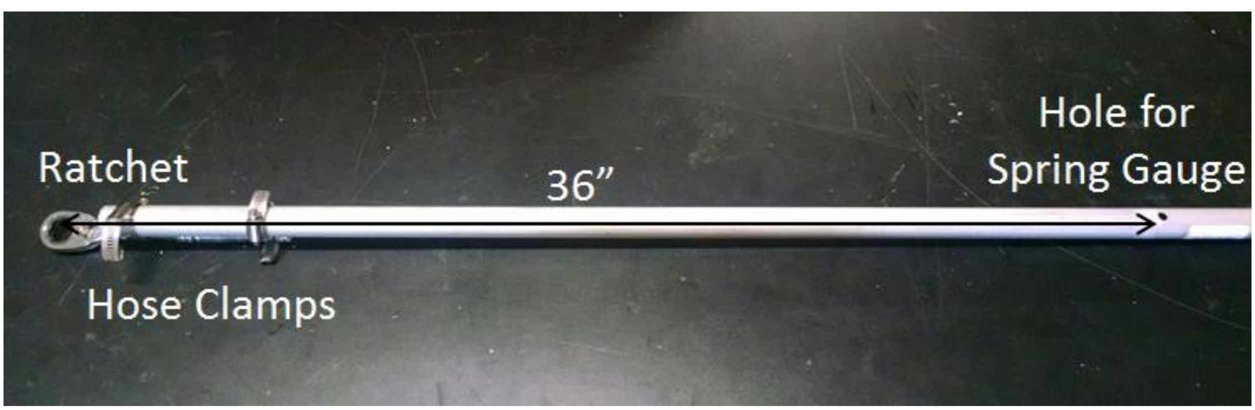

Figure 103: Ratchet attached to Lever Arm.

5. The ratchet was connected to the socket that is mounted to the wheel hub. An additional piece of plywood was added to support the weight of the lever arm due to the orientation of this test. The final prototype will have the wheel in a vertical orientation, so this will not be a factor. Supporting the

lever arm in this way makes it a more realistic test. The spring gauge was connected to the lever at the hole that was drilled earlier, Figure 104.

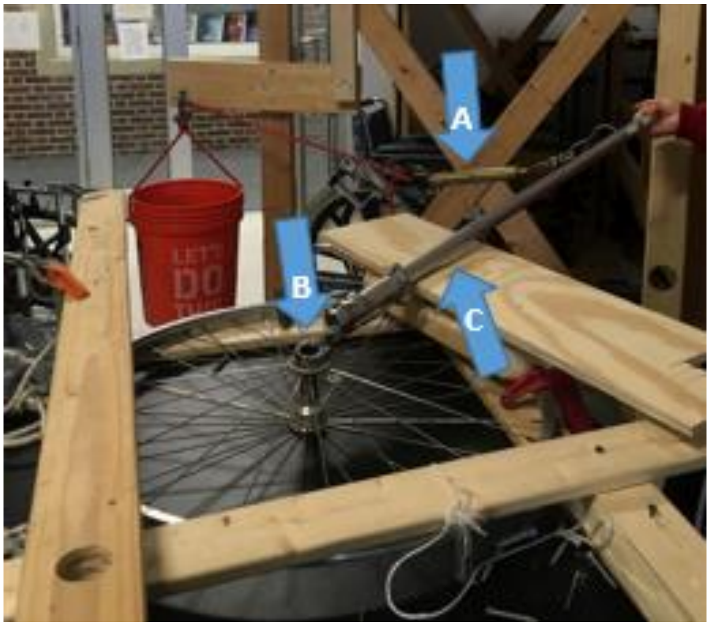

Figure 104: Lever Arm attached to Socket.

A	The Spring Gauge attached to the lever arm
B	Ratchet attached to the socket
C	Wood piece supporting lever arm weight

6. The other side of the spring gauge was attached to a rope that leads to a pulley system with a bucket on the other end that weights can be put in, Figure 105.

Figure 105: Pulley and Weight Bucket Configuration.

A is the pulley. B is the bucket to hold the weights. The metal bar inside of the bucket prevents the rim from collapsing under the weight.

Appendix F: Design Specification Testing

The following table describes each of tests conducted to determine if the prototype pass all of the initial design specifications. Note that P denotes Pass and that F denotes Fail.

Table 46: Design Specification Testing

Design Specification Testing			
Design Specification	**Test Steps**	**Expected Result**	**Pass/Fail**
Indoor Operation Requirements Design Specification Tests The tests in this section should be performed with the device in the indoor position			
1	1. With the drive levers in the down position, measure the horizontal distance between the front most and rear most point of the device.	The device does not exceed 51 inches in length.	
2	2. With the drive levers in the up position, measure the vertical distance between the lowest point and highest point of the device.	The device does not exceed 43 inches in height.	
3	1. Measure the horizontal distance between the left most and right most points of the device as viewed by the user.	The device does not exceed 28 inches in width.	
4	1. Visually verify that wheel locks are present on the device and engage the wheel when activated.	Wheel locks are present and engage the wheel in the locked position.	
5	1. No outside help and no use of the tester's legs are allowed for this test. The user must remain on seat of the device for steps 2 – 7. 2. Move the seat from the indoor position to the outdoor position by using the arm rests to lift and pull the seat forward. 3. Move the seat from the outdoor position to the indoor position by using the arm rests to lift and push on the seat backrest. 4. With the propulsion system in the forward direction, push both drive levers to propel the wheelchair forward at least 3 feet on an ADA approved surface. 5. Put one of the drive levers into reverse and leave the other in forward and use both drive levers to turn the device at least 90°. 6. Reverse the direction of both drive levers and use both drive levers to turn at least 90°in the opposite direction as step 5. 7. Put both drive levers in reverse and	All features of the device can be operated solely by the user including the seat adjustment, propulsion, and folding.	

	use the drive levers to move backward sat least 3 feet on an ADA approved surface. 8. Transfer from the device to another seat or equivalent. 9. Remove the seat from the device and fold the frame. 10. Unfold the frame and replace the seat.		
6	1. Verify that the device can pirouette by using one drive lever in forward and one drive lever in reverse.	The device can pirouette.	
7	1. With the seat in the indoor position, place 250 lbs. onto the seat in any configuration. 2. Repeat Step 1 with the seat in the outdoor position.	The device can support a load of 250 lbs.	
8	1. While in the indoor position, measure the vertical distance from the lowest point of the device to the surface of the seat.	The seat does not exceed 20 inches from the ground.	
9	1. In the indoor position, move the wheelchair by either have another person manually pushing it or use of the drive levers. 2. While moving, activate the brake handle on the drive lever until the device comes to a stop.	The device has a means of slowing down and stopping.	
10	1. While in the indoor position, push or propel the device on an ADA approved surface at least 14 feet per second. 2. Verify the speed by using a video camera with a backdrop displaying distances. Use frames per second to determine the speed traveled just before braking. 3. Activate the brakes and measure the distance traveled from first activating the brakes until coming to a complete stop as verified by the video.	The device is capable of coming to a complete stop within a distance of 10 feet when traveling at a speed of 14 feet per second.	
11	1. Weigh the entire device on a scale.	The device weighs 50 lbs. or less.	
12	1. Remove the seat and fold the frame. 2. Measure the dimensions of the folded frame in a manner in which they would be placed into the back seat of a car.	The device is less than 30 x 29 x 60 inches during transportation.	
13	1. Obtain a wrench set, pliers, screwdrivers and a hammer. These are the only tools allowed for this test. 2. Unscrew the bolts holding on each axle and remove each axle.	The major components of the device are capable of being assembled and disassembled with common household tools.	

	3. Remove the brake handle from each drive lever. 4. Remove each wheel with drive lever attached. 5. Unscrew the screws at the inside of each wheel hub that supports the disc brake and drive levers. 6. Undo the bolt that holds each front caster and remove both casters. 7. Replace all components of the device.		
14	1. Test 13 is indicative of the success of this Test. If Test 13 passes, the same procedure with new parts instead of the old could also be executed, meaning it satisfies this requirement and no further testing is required.	Part replacement can be conducted using only common household tools.	
15	1. Due to the time constraints, this design specification cannot be tested.	N/A	
16	1. Add up the costs of all parts that make the prototype.	The parts required for prototype construction cost less than $640.	
17	1. Attach armrests to the wheelchair. 2. Remove the arm rests from the wheelchair.	The wheelchair has the option to have armrests.	
18	1. Attach wheelie bars to the frame of the wheelchair frame. 2. Remove the wheelie bars from the wheelchair frame.	The wheelchair has the option to have wheelie bars.	
19	1. Visually verify that operation of the device does not require touching the wheel.	The user is protected from dirt and debris that come from direct contact with a wheel.	
20	1. Verify that portions of the wheelchair have the ability to accept paint.	The wheelchair can be produced in a variety of colors.	
21	1. Visually verify that the wheelchair has the option for storage either underneath the seat or at another location.	The wheelchair has storage that is accessible while seated,	
22	1. Verify that a portion of the frame or armrest has the possibility of attaching a cup holder to it.	The user has the option of attaching a cup holder to the side of the wheelchair.	
23	1. Use the handles attached to the seat back to push the wheelchair.	The user has the option to have handles on the back of the wheelchair.	
24	1. Visually verify safety labels are present at any potential dangerous part of the wheelchair.	Safety labels are present and visible.	

25	1. Find a crack or gap at least 30 inches long andbetween1.5and 1.6inches wide. 2. While operating the wheelchair, pass over the crack with a perpendicular approach. 3. Pass over the crack at an approximate45° angle. 4. Pass parallel over the crack so that one wheel of the device is completely covering the width of the crack.	The device is able to navigate at least 1.5 inches wide gaps or cracks from any direction.	
26	1. Find or create a ditch 6 inches deep, 30 inches long, and 13 inches wide. 2. While operating the wheelchair, pass through the ditch from a perpendicular approach.	The device is not impeded by a ditch less than 6 inches deep and less than one radius of the driven wheel wide.	
27	1. While operating the wheelchair, pass through grass at least 4 inches tall.	The device is able to navigate grassy terrains with grass up to 4 inches tall.	
28	1. Verify that no parts of the device are significantly affected by temperatures as low as 0° F.	The device must be operable in cold, winter conditions with temperature as low as 0° F.	
29	1. Propel the wheelchair on a walkway covered with at least 2 inches of snow.	The device can traverse a walkway that has at least 2 inches of snow.	
30	1. Place the device on a piece of plywood and load the seat with 250lbs.of sand bags or equivalent, while attempting to evenly distribute the load. 2. Engage the wheel locks. 3. Using a car jack, slowly lift either the left or right side of the plywood until the chair begins to tip. 4. Measure the maximum angle before tipping with an inclinometer.	The device does not tip when stationary and positioned transversely on a 25° slope.	
31	1. Repeat Test 30 but lift the front of the plywood. 2. Repeat Test 30 but lift the rear of the plywood.	The device does not tip when stationary and positioned longitudinally on a 25° slope.	
32	1. Use a double sided ramp (one with a peak and a down slope on each side), or equivalent, that is a height sufficient to tilt the wheelchair transversely to a 15° angle when one wheel is at the peak and the other is on the ground. 2. Propel the wheelchair to have one of the wheels pass over the ramp and down the other side while the other wheel remains on the ground.	The device is able to navigate bumps or rocks without tipping that lift one wheel up to create a 15° angle.	

33	1. Propel the wheelchair up a slope of at least 15°. 2. Return down the same slope.	The device must be able to climb and descend up to 15° slopes while maintaining stability.	
34	1. Propel the device over at least a ¾ inch gravel or stone walkway.	The device is able to traverse at least ¾ inch gravel or stone walkways.	
35	1. Use the device on a class 1 hiking trail for 1000 feet without getting stuck or tipping.	The device is able to traverse a Class 1 Hiking Trail	
36	1. Propel the wheelchair over a log at least 4 inches in diameter.	The device is able to travel over a log at least 4 inches in diameter.	
37	1. Visually verify that the device has no exposed sharp edges, pinch points, or foot/leg entrapments.	The device has no exposed sharp edges, pinch points, or foot/leg entrapments.	
38	1. During testing, verify that no discomfort or injury is being inflicted to the tester. This demonstrates the safety of the device under correct operation.	The user is not endangered when operating the device correctly.	
39	1. Visually verify the routing of all cables and wires are done to mitigate risk and do not interfere with operations of the chair. 2. Visually verify all moving mechanisms cannot interfere with operations of the chair.	All mechanisms and wires do not interfere with the use of the chair.	
40	1. Verify that all manufacturing was completed on the WPI Campus.	All manufacturing was completed on the WPI campus.	
41	1. Verify the date of completion of the prototype and testing.	The device was constructed and tested before April 21st.	
42	1. Verify the lead-time on any purchased material did not exceed one week and that no individual part cost more than $200.	All materials required for manufacturing were readily available and low-cost.	