Collision Mitigation System:
Pedestrian Test Target
Final Design Report

Sponsored by Daimler Trucks North America
Advised by Nikola Noxon and Charles Birdsong

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STATEMENT OF DISCLAIMER

A special thank you to Daimler AG and Nikola Noxon for working with Cal Poly to sponsor our senior project and Dr. Charles Birdsong for advising us throughout the year long process.

EXECUTIVE SUMMARY

Daimler Trucks North America is creating an advanced emergency braking system which uses radar sensors that detect pedestrians and automatically applies the brakes to bring the vehicle to a stop. To improve and validate their technology, they need a mechanical pedestrian target that can mimic a human walking across the street. However, the assisted braking may not work properly during every test and the pedestrian target must be able to survive impact with a vehicle at low speeds. Four senior Mechanical Engineering students from California Polytechnic State University San Luis Obispo decided to take on the challenge.

The main features of the test dummy are as follows:

1. The dummy's shoulders, elbows, and hips articulate under active servo control to imitate human gait.
2. The soft limbs can be crushed without permanent damage.
3. The mannequin rests on a platform that is translated by a pulley system.
4. The speed of translation and frequency of gait vary with separate analog controllers.
5. The mannequin falls off the platform away from the truck upon impact.
6. The dummy survives an impact without serious damage and continues to function.

This report details how this team of students was able to design, build, and test a prototype pedestrian test target shown below by Spring of 2017.

Figure 1. Mannequin and Platform

Figure 2. Walking Mannequin

LIST OF NOMENCLATURE

ARTICULATION - Movement of the limbs in a walking motion

DRIVER - the controller for the large motor

ELECTRONICS - The electrical components that control the ARTICULATION

MANNEQUIN - The crash test dummy, including torso, head, limbs, and pole

TEST TARGET - See MANNEQUIN

TRANSLATION - The motorized system that moves the mannequin between pulleys across the test track

DRIVER - Electronic component that supplies power to the motor and controls the motor speed.

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1. INTRODUCTION

In order to increase pedestrian safety and save lives, Daimler Trucks is developing a collision mitigation system that automatically stops the vehicle when it senses an imminent impact. Validating the technology requires a pedestrian test target, but existing products either do not simulate human motion or are expensive due to excessive features. Daimler requires a target that their detection system recognizes as human and that their trucks can repeatedly impact without permanent damage or extensive refurbishment. While this product is meant specifically for Daimler, other automobile companies may also use it for testing. Team Crosswalker, comprised of Tim Lee, Melanie Lim, Tiffany Prather, and Chris Welch, is a team of Cal Poly senior Mechanical Engineering students who are tackling the challenge of creating a translating, articulating pedestrian test target for Daimler engineers to use to improve the safety of drivers and pedestrians.

The pedestrian test target will mimic a human walking in front of a moving vehicle so the collision mitigation system can undergo proper testing and evaluation. To accomplish this human representation, the mannequin will have motor-driven shoulders and hips that will cause passive movement at the knees and elbows. Reflective materials will attach to the body to test the sensors. The target will travel laterally (perpendicularly to the motion of the vehicle) on a portable track system with variable speeds. The mannequin will be designed to sustain thousands of low speed impacts from vehicles that weigh up to 35 tons.

Our chosen design consists of a metal skeleton covered in padding for the mannequin. Motors directly actuate the shoulders and hips, and wire acts as a tendon to move the forearms. Spring-damper systems control the motion of the lower legs. The mannequin attaches to a platform, which moves on a belt-pulley system. The platform uses multidirectional rollers and detaches from the track when impacted from a specific direction to roll with the impact.

2. BACKGROUND

Creating an articulating, anthropomorphic test device [ATD] that can move laterally in front of a moving vehicle and withstand many impacts is a complicated problem with many different challenges to overcome. In order to increase our knowledge and find the best solutions to these challenges, we have conducted extensive background research. Because the field of assisted braking is still new, there are few existing commercial products to support its development. While crash test dummies have been around for a long time, most of them are inanimate and do not produce the correct radar signature for Daimler's detection system. The few assisted braking pedestrian targets are expensive and have little data available. For that reason, our background research expanded to products with similar functions such as walking robots and non-articulating dummies.

2.1 HUMAN WALKING MOTION

Creating a mannequin that mimics human motion requires understanding the human body. The movements of the hips and shoulders while walking are the most relevant to this project. Although both are ball-and-socket joints, the hip is both more constrained and more stable than the shoulder due to it sitting deeper in the socket. Only three muscles control the hip, while four control the shoulder (Westerheide). In one cycle of walking, the typical angles of the knee cycle through reaching the values of -20 degrees, -2 degrees, -70 degrees, and back to -2 degrees; where 0 degrees is parallel to the thigh and outward from the torso. Furthermore, the angles that the hips go through in one cycle of walking are 35 degrees, -10 degrees, and back to 35 degrees; where 0 degrees is in the vertical direction pointing downward. Figure 1 shows the angles of the joints in the leg for a gait cycle. Figure 2 describes the timing of the angles for the hips and knees. (Yi "Mannequin Development for Pedestrian Pre-Collision System Evaluation"). The cycle that the ankle joint undergoes is described as: heel strike, early flatfoot, late flatfoot, and toe off. The heel strike phase is where the heel initially makes contact with the ground. The early flatfoot is where the foot is flat and the ankle angle is approximately 90 degrees. Late flatfoot is the phase where the ankle angle is declining from 90 degrees before reaching the toe off phase. The toe off phase is the last motion where the heel is no longer in contact with the ground and the toes starts to roll and push off ("Biomechanics of Walking"). To change the walking speed, the step size increases marginally while the majority of the change is due to greater step frequency. Experimental data has produced a parabolic correlation within the walking speed range of 0.5 m/s to 2.0 m/s (Chien, Figure 2). The angles and frequency of gait are the data most relevant to this project, and the rest of the motion information may be used to improve the realism of the ATD.

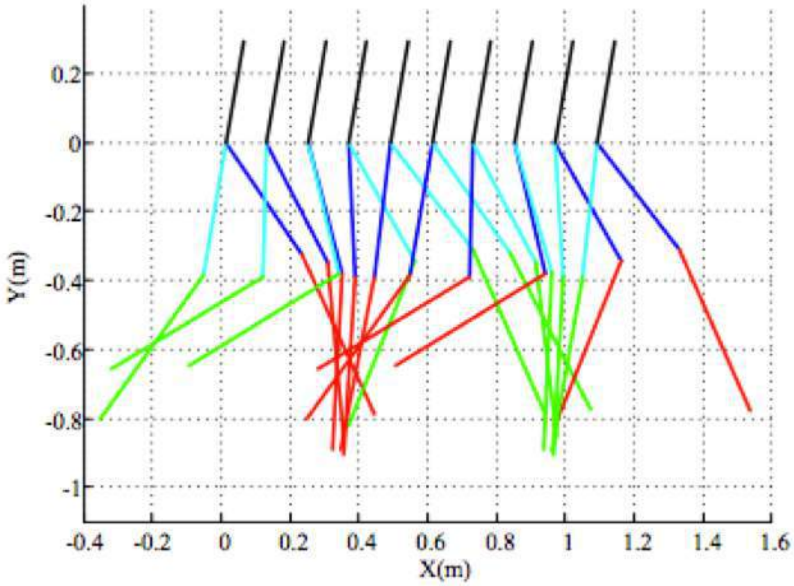


Figure 2.1.1 Stick frame of leg angle, one complete cycle .

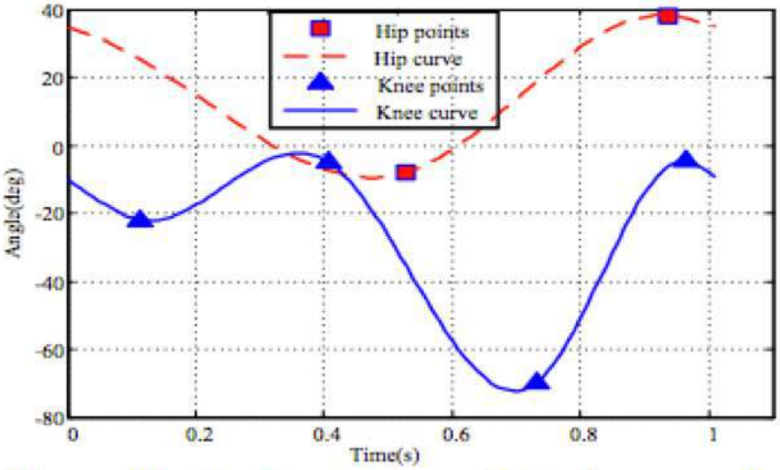


Figure 2.1.2. Pivot points and fitted curve of one gait cycle.

2.2 EVALUATION OF WALKING ROBOTS

We examined walking robots to better understand how human motion is currently simulated.

Boston Dynamics Atlas

Boston Dynamics created Atlas, a humanoid robot with high mobility and the ability to navigate rough terrain. Atlas controls its own motion and balance using Lidar sensors to adjust to variations in terrain. Atlas has near-human anthropometry and walks bipedally with the ability to lift, carry, and manipulate the surrounding environment with its upper body. Atlas has articulated, sensate hands that allow it to use human tools as well as 28 hydraulically-actuated degrees of freedom ("Atlas – The Agile Anthropomorphic Robot"). The legs are 3D printed which allows the actuators and hydraulic lines to be embedded within the legs (Guizzo). Atlas has an on-board real time control computer, electrically powered with a network tether. It has limited crash protection and is able to stand up in a humanlike motion when it is pushed over. Atlas is 150kg with a height of 1.88m and a shoulder width of .76 m. ("Atlas Anthropomorphic Robot"). A design possibility for our mannequin will be to have hydraulic actuators.

Figure 2.2.1. Atlas mid-stride

Georgia Tech DURUS

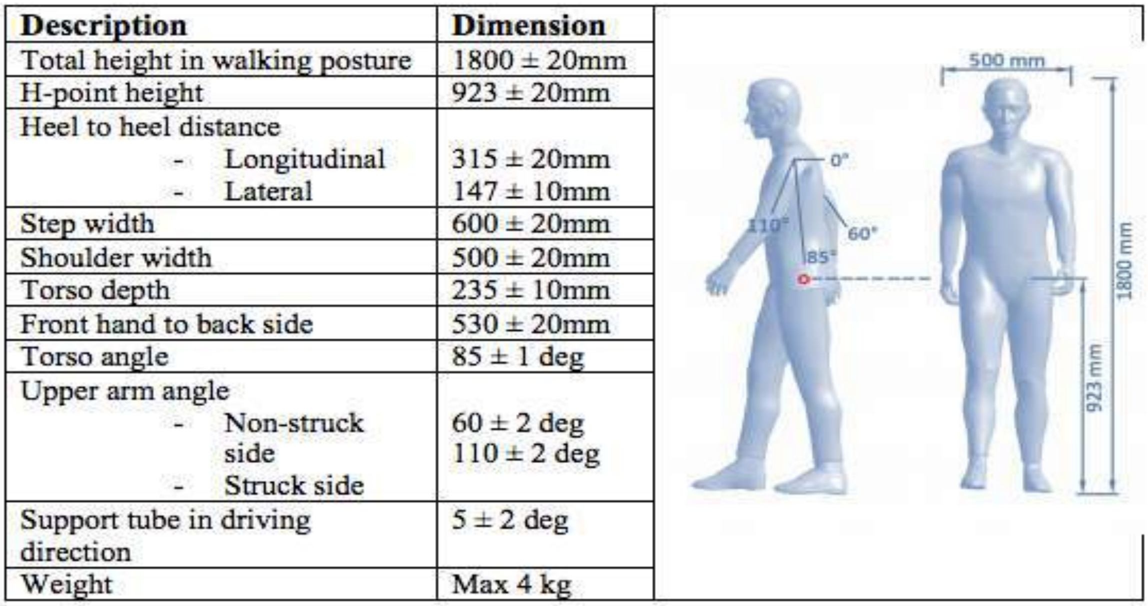
Another humanoid robot is DURUS, which was developed by Georgia Tech's Advanced Mechanical Bipedal Experimental Robots Lab. This robot imitates the walking motion of humans and is capable of crossing uneven terrain. This two-legged robot is able to copy the heel-toe motion of humans, which allows for more mobility than robots that walk flat-footed (Maderer). When the robot takes a step, the heel first makes contact with the ground before rolling and pushing off the front of its feet. This robot utilizes advanced algorithms to keep it balanced despite momentum shifts or when only parts of its feet are on the ground. We will consider the heel to toe motion that DURUS has when designing the walking mechanism for our mannequin.

Figure 2.2.3. Comparison of foot motion of DURUS to that of a human

2.3 TEST TARGETS

There are specifications for pedestrian test targets that companies in the automobile industry may use by to qualify for a safety rating by certain third parties. The European New Car Assessment Programme [Euro NCAP] is one of those third parties; they originated in the UK and have created a voluntary vehicle safety rating system that details the requirements and testing procedure for pedestrian detection using Autonomous Emergency Braking Systems (AEBS). Although the customer has explicitly stated that our product is not required to adhere to their code, we will still use it as a guideline to understand the testing procedure and as a reference for creating engineering specifications. Their specifications state that pedestrian models should be one of the following: a 6-year-old, a 5th percentile female, a 50th percentile male, or a 95th percentile male. The adult pedestrian target should be 1.8m tall with a shoulder width of 0.6m. The child pedestrian target should be 1.15m tall with a shoulder width of 0.3m. (Pedestrian Protection).

The Euro NCAP defines the testing environment for the test track, weather, and surroundings. The testing protocol states that the test must be performed on a dry, uniform track on either level ground or a constant slope of 1% ("Test Protocol - AEB VRU Systems."). In addition, the testing environment must be during dry weather conditions with ambient temperatures between 5°C-40°C and with wind speeds below 10 m/s. These environmental conditions help in predicting the temperature and wind speeds that our pedestrian target and lateral translation device must withstand. Furthermore, the Euro NCAP testing protocol requires that there will be no obstructions or protrusions above the test surface that would cause abnormal radar sensor measurements within a lateral distance of 6 m from the driver side and 4 m on the passenger side of the Vehicle Under Test (VUT). This requirement informs us that our design for the pedestrian target and lateral translation device must have a minimal profile with no protrusions in order for the radar sensor to only detect the pedestrian mannequin. Protrusions or obstructions other than the mannequin itself would cause abnormal radar signatures and possibly compromise the validity of testing data. The dimensions and angles of the Euro NCAP Pedestrian Target (EPT) are also tabulated in Figure 2.3.1 below. These dimensions and angles will be useful in defining our mannequin's size and angles for joint articulation.



Description	Dimension
Total height in walking posture	1800 ± 20mm
H-point height	923 ± 20mm
Heel to heel distance - Longitudinal - Lateral	 315 ± 20mm 147 ± 10mm
Step width	600 ± 20mm
Shoulder width	500 ± 20mm
Torso depth	235 ± 10mm
Front hand to back side	530 ± 20mm
Torso angle	85 ± 1 deg
Upper arm angle - Non-struck side - Struck side	 60 ± 2 deg 110 ± 2 deg
Support tube in driving direction	5 ± 2 deg
Weight	Max 4 kg

Figure 2.3.1. Dimensions and angles of the Euro NCAP Adult Pedestrian Target defined in the Euro NCAP testing protocol

The Euro NCAP has 4 main test scenarios, and the set-up similar to our test case is the Car-to-VRU Farside Adult (CVFA). The Euro NCAP states that this specific test scenario is defined as "A collision in which a vehicle travels forwards towards an adult pedestrian crossing its path running from the far side and the frontal structure of the vehicle strikes the pedestrian at 50% of the vehicle's width when no braking action is applied." ("Test Protocol - AEB VRU Systems."). The CVFA test setup, EPT test path, and important path locations can be found in Figure 2.3.2. This figure helps in determining the necessary acceleration and lateral translation length required for our translation device as well as understanding the testing procedure.

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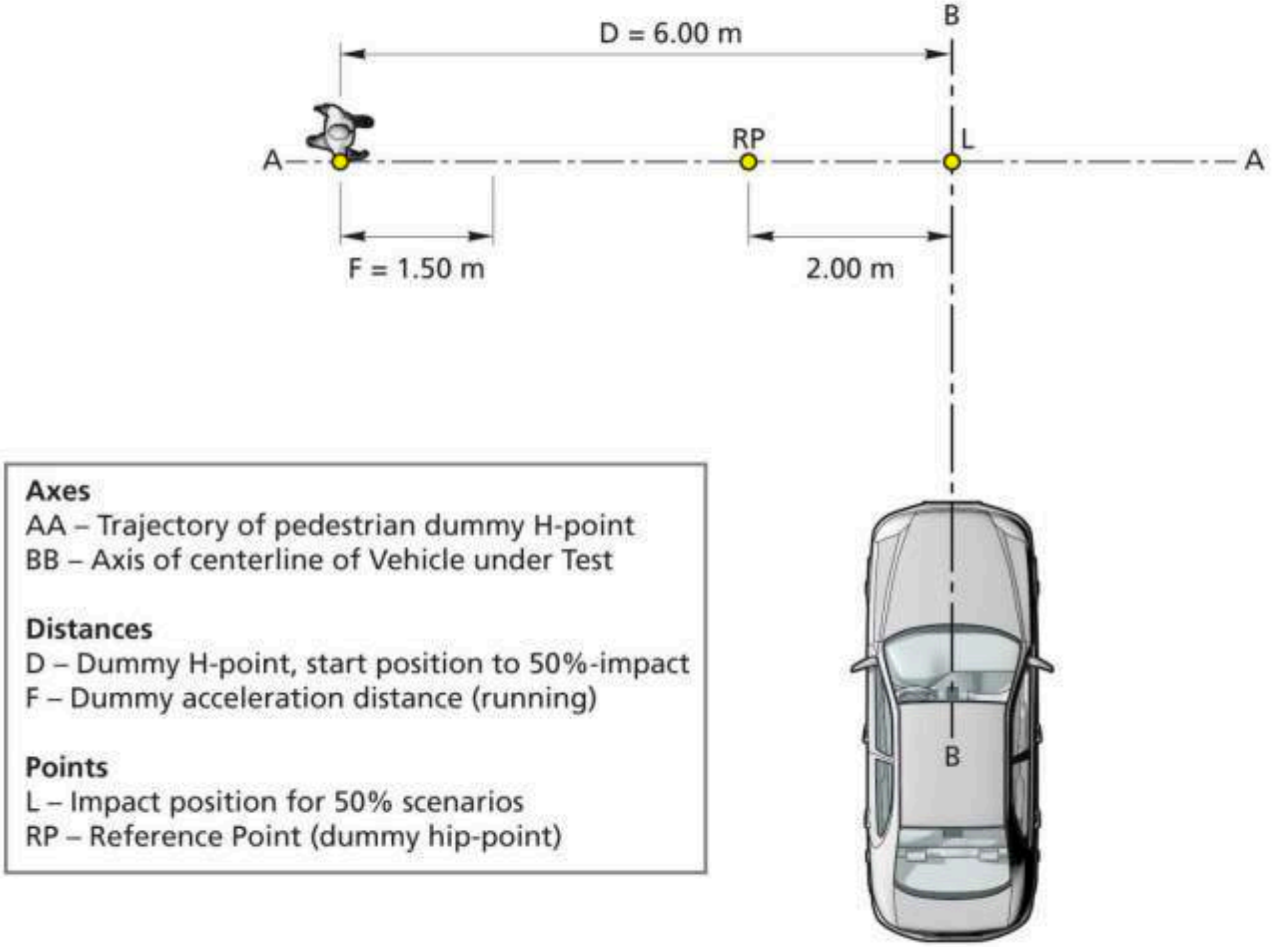


Figure 2.3.2. Test scenario and path for the Euro NCAP Pedestrian Target Car-to-VRU Farside Adult test

The Euro NCAP includes important parameters for the EPT during test execution. One parameter is that the EPT must reach its steady state velocity at 4.5 m from the vehicle centerline. The steady state velocity of the pedestrian target for this testing protocol is 8 kph. However, we will be designing our system to variable steady state speeds ranging from 0.5 m/s - 2.5 m/s. The test is considered finished when any of the following occur: the vehicle reaches 0 kph, there is contact between the pedestrian target and vehicle, or the pedestrian has left the path of the vehicle.

2.4 PROPULSION AND MATERIALS

In order to dissipate the kinetic energy of an impact and avoid significant damage to the vehicle and dummy, Euro NCAP specifies an air, spring, or hydraulic gun to separate the limbs from the torso and propel the body parts. Many groups avoid significant damage to the dummy or vehicle in other ways. The Transportation Active Safety Institute [TASI], for instance, developed mannequins which rely on magnetic couplers to detach the limbs from the body upon impact (Yi. "Mannequin Development for Pedestrian Pre-Collision System Evaluation"). Anthony Best Dynamics, on the other hand, sidesteps the issue entirely by rapidly moving their ATD out of the way when the approaching vehicle breaks a light beam ("Soft Pedestrian Target"). Even with systems to mitigate the effects of an impact, ATDs also need to be tough. Materials such as steel and aluminum make up skeletons, foam or rubber pad the body, and aluminum or plastic house joints and other sensitive components.

2.5 EVALUATION OF EXISTING PEDESTRIAN TARGET SYSTEMS

We studied existing products to explore possible solutions for meeting customer requirements and to ensure that what we create exceeds our competition in the areas deemed most important to our customer. Because collision mitigation systems are a new and developing field, information is very limited on the products most similar to what the customer desires. However, this also means that we have the freedom to generate new and innovative solutions. The products we studied are covered in the following section from most to least relevant.

TASI (Purdue University)

TASI at Purdue University has a system to test Pre-Collision Systems in high-end passenger cars with support from Toyota. Their system includes a mannequin and a 1D gantry crane system to simulate a pedestrian walking in front of a moving car. The mannequin is humanlike with moving joints; the hips, knees, and shoulders are actively driven by motors and the elbows are passive. They use three target sizes for their tests: a child, a fit adult, and an obese adult. To obtain the correct radar cross section for the mannequin for their 77 GHz automotive radar, they developed a multilayer metal fabric skin that mimics the same electrical properties of human skin in the presence of their radar. TASI designed their mannequin to be able to withstand the impact of a vehicle by constructing it as follows:

> To ensure that the mannequin will not be damaged during collision, the frame of arms and legs are made of lightweight polycarbonate which is 250 time stronger than glass but flexible. To protect motors, each motion joints [sic] are assembled inside an aluminum housing. To reduce the potential damage of the vehicle during test, mannequin is completely sheathed with polyethylene foam padding, which has a density of 1.7 lb/ft^3. To protect joint motors, magnetic couplers were developed and used in each shoulder and hip joints. The coupler enables the limbs to detach from

the body at crash and hence protect the driving linkage from overload damage. (Yi "Mannequin Development for Pedestrian Pre-Collision System Evaluation")

TASI also uses gait data and joint trajectory planner software to select the gait of the target by using the joint points and cubic spline fitting method. The input of the software is the four pivot points of a motion cycle and walking speed. The mannequin is battery operated and wirelessly controlled.

To simulate the motion of the mannequin across the road they considered and rejected several systems: a self-driven robot, a jib crane, a 2D bridge crane, and a sled driven by ropes. However, the self-driven robot would have too tall of a base and cause false activation of the pre-collision system. The jib crane and the 2D bridge crane would require permanent installation and the rope driven sled could tangle in car wheels.

Their ultimate solution, a 1D gantry system, consists of a suspension I-beam hung on multiple gantry cranes. This can be seen in Figure 2.5.1. The benefits of this design are the suspension I-beam's versatility, low overall weight, and easy assembly and disassembly by 3-4 people (Yi "Development of Equipment to Evaluate Pre-Collision Systems of Pedestrians"). The cranes across the road, shown as (1) in the figure, can either support the central beam (2) when the target moves along the road or hold it directly for travel laterally across the road. The downsides are the possibility of the equipment affecting radar detection systems and the size necessary for Daimler's large vehicles to clear the gantry cranes.

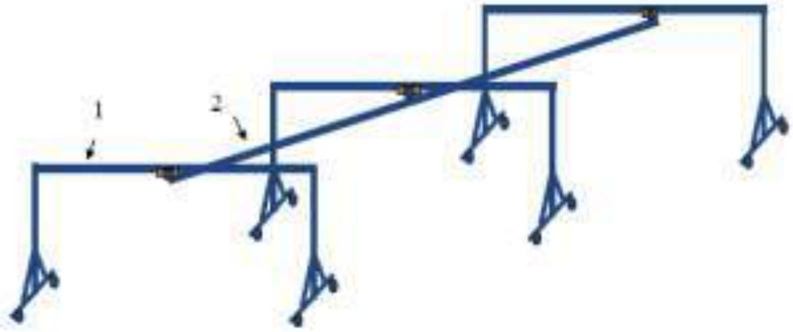


Figure 2.5.1. TASI 1D gantry system
1. Gantry cranes perpendicular to road
2. Central I-beam along road

<u>4Active Systems</u>

4Active Systems currently sells a product that achieves the desired lateral movement without the large gantry crane setup employed by other designs. Their product allows a battery-powered mannequin to be placed on a plastic pole that magnetically attaches to a moving platform. The platform is 25 mm thick with an angled edge to allow wheels to easily travel over it and moves on a flat belt pulley, which is shown in Figure 2.5.2. The motor driving the pulley is housed in a case that sits outside the vehicle lane. This system is much more discreet and less likely to interfere with detection systems, but being driven over presents its own issues. During testing, the platform translating the mannequin stops immediately before impact occurs using a series of motion detection devices placed a specified distance before the conveyer system. The motion sensing triggers via light barriers, GPS, or inertial measurement unit and captures the speed of the vehicle and relays the information to the conveyer system, which calculates the appropriate time to stop the platform. Unfortunately, while this product maintains a low profile to keep the radar from detecting objects other than the mannequin, it is very expensive due to additional features that are not necessary for our project. These features include a wireless local area, bicyclist/motor cyclist mannequin models, and touch screen interface ("4activePA Pedestrian Articulated").

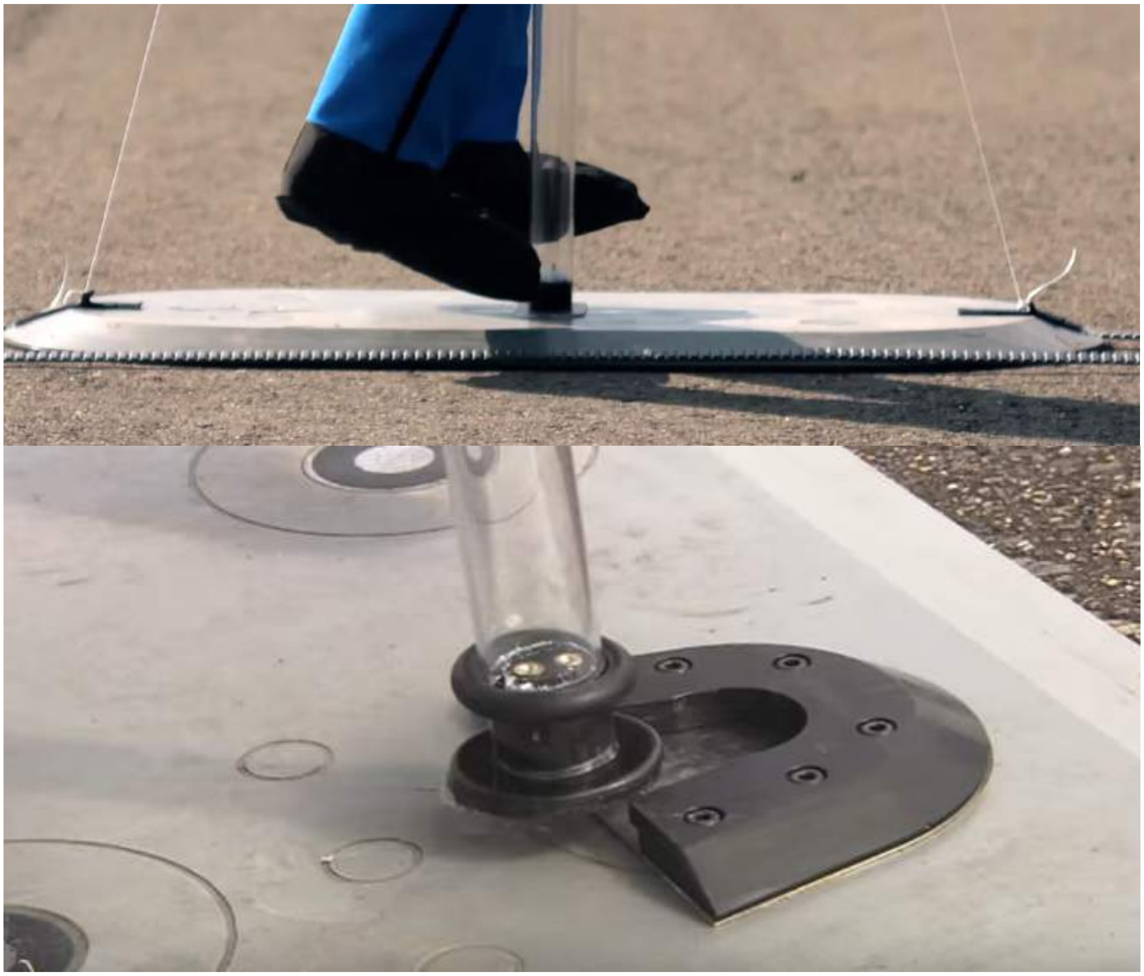


Figure 2.5.2. Top: 4Active Systems platform and flat belt pulley with a magnetic attachment between platform and dummy rod. Bottom: 4Active Systems platform with alternative notch attachment between platform and dummy rod.

Anthony Best Dynamics Test Target

The company Anthony Best Dynamics developed an advanced, soft pedestrian test target for use in testing emergency braking systems specifically for Euro NCAP. The soft pedestrian target uses a standard steering robot motor and controller as a drive unit as seen in Figure 2.5.3. The system allows for easy installation, removal, and replacement of the steering robot. A flat belt propulsion system moves the target with a maximum weight of 15 kg across the path of the vehicle at up to 20kph. This track is designed so that a vehicle can drive over the platform and the belt. The product incorporates features such as synchronizing the pedestrian test target with a test vehicle to the precision of 2 cm ("Soft Pedestrian Target"). Once the test vehicle crosses a light beam, the pedestrian test target's movement is triggered. The mannequin's speed profile can also be predetermined in accordance with the user's test requirements. The synchronization system uses GPS data from the test vehicle to account for any error in the test vehicle's trajectory and consequently adjusts the mannequin's speed and position to ensure the test scenario takes place. The mannequin detaches from the platform on impact, and wheels in the feet allow it to roll with the vehicle. While this a portable system that can be quickly installed on any test track, this product does not have the articulating limbs that are one of the most important requirements of this project.

Figure 2.5.3. Anthony Best Dynamics Track

Toyota "Steve" Target

Toyota also has a pedestrian test target called Steve, who is able to walk at different speeds and angles to allow for more realistic testing ("Meet Steve. The dummy"). Steve hangs from a frame that is sufficiently high to allow vehicles to pass underneath. Steve and the hanging frame are shown in Figure 2.5.4. Steve is suspended under this track using four wires attached to his head. The linear track stops upon impact, but Steve does not detach from the track like other products. Steve only has motors driving his hips and shoulders, while his elbows and knees are free-swinging. This simplification reduces the fidelity of his human mimicry, especially because those joints are not properly constrained and hyperextend at some points.

Figure 2.5.4. Steve and hanging frame

2.6 EVALUATION OF CRASH TEST DUMMIES

Because information on these advanced targets is limited, we also examined crash test dummies to better understand how to create a robust product. Insight gained from examining these products will assist with choosing materials to make our target impact resistant.

Humanetics Innovative Solutions

Humanetics Innovative Solutions produces one of the most commonly used crash test dummies, the Hybrid III Fiftieth Percentile Male. Its skeleton is primarily steel with some aluminum and bronze joints. Butyl rubber and urethane foam make up most of the body. The dimensions conform to those of a 50th percentile adult male and the total weight is 172.3 lb ("Hybrid III 50th Percentile Male"). Because this product is designed for frontal crash and safety restraint testing, it contains several unnecessary features for our application, such as simulation of human force deflection and support for 56 instruments to provide crash data. This project, however, is only interested with whether an impact occurs, not how it happens or the effects thereof.

Humanetics Innovative Solutions also created a side impact dummy that was specifically designed to assess the injury a human would experience in side vehicle collisions. ("SID-IIs Small Side Impact Dummy"). This dummy accurately mimic how a human would be injured in a lateral collision because it uses biomechanics and steel bands with polymer damping to simulate the human shoulders, ribs and abdomen.

The Flexible Pedestrian Legform Impactor GT, also by Humanetics Innovative Solutions, simulates a human leg to assess the effects of an impact with a vehicle. The knee is comprised of springs and stainless steel wires. The wires represent ligaments, which give a greater degree of realism to the movement and reaction. The bones are segments of high strength plastic separated by rubber buffers, and further steel wires limit the bone bending. Neoprene foam and rubber make up the flesh (“Flex-PLI-GTR”).

Polar Pedestrian Dummy

Another example is a pedestrian dummy named Polar, developed by GESAC, HONDA Research and Development, and the Japan Automobile Research Institute. Their main focus was to ensure that kinematics of Polar aligned with those of a pedestrian so that they could assess the effect of vehicle shape on pedestrian injuries, so this dummy was designed to react and take impacts as a human would in a lateral accident. The dummy is durable enough to withstand impacts from a vehicle going 50 km/h. Polar is supported by a single, central steel cable suspended from the roof until 100ms before impact, at which point the cable is released and Polar is freestanding for the collision. Polar is instrumented with load cells and sensors for data collection. The basic structure of the dummy is based on the Advanced Frontal Dummy, Thor, developed by Humanetics for the National Highway Traffic Safety Administration, which is in turn similar to the Hybrid III 50th percentile male crash test dummy (Akiyama). The support system of using a single steel cable suspended from above is a possible component of our lateral translation mechanism.

2.7 MULTI-DIRECTIONAL ROLLERS

Several of our designs include moving the mannequin with the vehicle after a collision to reduce impact loads. This idea was inspired by caster wheels, but the tracking of the wheels prevents them from changing direction quickly and their relatively large height is likely to interfere with the radar detection system. We performed further research to discover suitable alternatives.

Ball transfer units are spheres mounted in some restraining fixture which rotate freely through the use of smaller ball bearings. They offer the range of motion we desired, but are used usually used ball-up for conveyance and are less suited to be used as wheels due to load and surface limitations. Most are made of stainless steel, and even the more robust plastic options are designed to minimize damage to conveyed items (*Omnitrack*).

Figure 2.7.1. Ball Transfer Unit

While ball transfer units are primarily used as conveyors, other products serve as actual wheels. Mecanum wheels are sets of rollers mounted on some angle, usually 45°, to a wheel. They are often used in robotics, where sets of perpendicular rollers allow movement in any direction in the 2D plane. However, they tend to be expensive. Omniwheels, on the other hand, place their rollers so that they rotate on axes perpendicular to the rotational axis of the main wheel. Omniwheels are harder to design machinery for, but this is irrelevant for our purpose. Omniwheels also tend to be cheaper and smaller (*Rotacaster*).

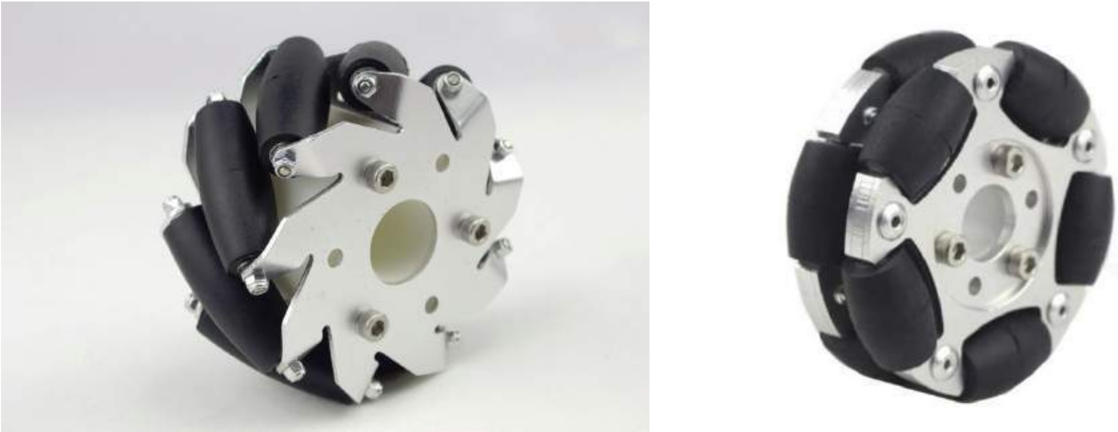


Figure 2.7.2 Left: Mecanum Wheel. Right: Omniwheel

3. OBJECTIVES

Meeting the customer's specifications will allow Daimler Trucks to adequately test their collision mitigation system to be able to improve and implement them into their vehicles and thus save the lives of pedestrians across the world. Successful achievement of our primary specifications will ensure that the product we create for Daimler adequately mimics human motion, moves laterally in front of the vehicle at various speeds, is sufficiently durable to withstand impacts, minimize refurbishment, and is within budget. Meeting the other specifications, will make it easier for Daimler to use our product and allow for function in various testing environments. Table 3.1 lists the engineering specifications we have derived from background research and customer requirements (Smith and Noxon) for the low-cost, functional test target we will create.

In order to have a radar signature resembling that of an adult pedestrian, our test target will have adult human dimensions, which are compiled in "Anthropometric Data" from the University of Rhode Island in Appendix A. The overall human height, H, is specification 6 and the size of each body part in specifications 7-10 are functions of H. In addition, the mannequin will be covered in a reflective material provided by Daimler Trucks, as per specification 20.

Specification 5 states that the target will move laterally across the path of the vehicle for at least 10 meters. The trucks' detection system will have 6 m to recognize and react to the dummy as specified by the customer, the width of the trucks themselves are around 2.5 m, and 1.5 m are reserved for clearance between the vehicle and the ends of the translation apparatus.

To ensure that their collision mitigation system works in a variety of situations, Daimler requested that the mannequin will have linear speeds from 0.5 m/s to 2.5 m/s. This requirement was converted directly into velocity specification 16. In addition, for the radar detection system of their vehicles to function as intended, the limbs of the mannequin must move in a humanlike manner. We obtained data for the hip angles (spec 11), knee angles (spec 12), and step frequency (spec 15) from a study on limb motion for active safety vehicle tests (Chien). The hip and knee angles limit our mannequin's range of motion so that its limbs only reach the angles an ordinary pedestrian achieves rather than swinging around wildly or barely moving at all. The step frequency equation, which determines the frequency at which our dummy moves its limbs in relation to its translational speed, is only valid for walking speeds between 0.5 m/s and 2.0 m/s, as above 2.0 m/s humans begin to run and obey a different step frequency equation. Because of the difficulties associated with tuning an entirely separate velocity profile, either through programming or through physical part change, the mannequin will use only a walking limb profile and not both walking and running ones. Extrapolating the profile to a translation speed of 2.5 m/s yielded a step frequency of 8 Hz, so we have decided to simply cap the step frequency at that of 2.0 m/s translation. The dummy will still translate at speeds up to 2.5 m/s, but above 2.0 m/s the step frequency will not change. The shoulder angles, specification 13, come from the Journal of Experimental Biology (Pontzer) and the elbow angle, specification 14, is from The Royal Society Publishing (Collins).

In order for the mannequin to be usable by Daimler, it needs to withstand the impact of a 35 ton truck traveling at 5 mph. The truck has a maximum speed of 10 mph for the planned tests, and the driver will brake even if the collision mitigation system fails. Collisions in prior tests conducted by Daimler have been at velocities below 2 mph, and we included a large factor of safety because of the imprecision of speed when testing a braking system. This critical specification is number 3 in the table below.

The apparatus will be transported in a semi-truck, which has maximum dimension of 576” x 102” x 162” in the U.S. (“Federal Size Regulations for Commercial Vehicles”). Therefore, specification 18 limits the stored size of the apparatus.

If the apparatus will be run over by the vehicle, it must retain functionality. Specifically, translation mechanisms such as tracks or pulleys are likely to be driven over, but the mannequin itself is not expected to be underneath the vehicle’s wheels at any point. Specification 4 requires that any sections of the product, which may be driven over, be able to hold the weight of the truck and maintain functionality.

We obtained the rest of our specifications directly from the customer requirements and personal interviews. Specification 2 limits the reset time to ensure that a sufficient number of tests can be conducted within Daimler’s limited amount of testing days. Specification 19, the trigger input, will allow the customer to activate the device from a safe distance away from potential crashes. Specifications 21 and 22 establish environmental conditions the product will function in. All of these specifications are detailed in Table 3.1.

The boundary sketch in Appendix B limits our scope by excluding power generation and radar detection. Although parts of our apparatus may use battery power, generators will always be available. The product will be covered in the radar-reflective material provided by the customer and will move in a humanlike manner in an attempt to mimic a pedestrian’s radar signature, but actually verifying that the signature is similar is outside of our scope.

We created a Quality Function Deployment (QFD) document, attached in Appendix C, in order to compare customer requirements with existing products and our engineering specifications. The majority of our specifications are taken directly from well-defined customer requirements. Nonetheless, we listed correlations between their requirements and our specifications to ensure that every requirement is covered by at least one specification and that no superfluous specifications were created. One specification was removed by this process. The relative weight, which combines our ranking of the importance of each specification with the rating of competitors’ products in each category, is the most relevant result of our implementation of QFD. It shows that cost is the factor to focus on and improve the most, with impact resistance and continued functionality being the next most important. Unfortunately, the robustness specifications have negative correlations with the cost.

Table 3.1. Engineering Specifications

Spec #	Parameter	Requirement	Tolerance	Risk	Compliance
1	Production Cost	$3,500	Max	M	A
2	Reset time	10 mins	Max	M	A, T
3	Impact	35 tons @ 5 mph	Max	H	A, T, S
4	Supports Weight (track/no track)	35 tons / N/A	Max	H	A, T
5	Travel length	10 m	Min	M	T, I
6	Pedestrian Height, H	1.69 m	± 0.18 m	L	A, I
7	Shoulder to Elbow Length	0.19H	± 5%	L	A, I
8	Elbow to Fingertip Length	0.27H	± 5%	L	A, I
9	Hip to Knee Length	0.25H	± 5%	L	A, I
10	Knee to foot Length	0.29H	± 5%	L	A, I
11	Hip Angles	-35° to +35°	Min/Max	L	A, I
12	Knee Angles	0° to 75°	Min/Max	L	A, I
13	Shoulder Angles	-10° to +10°	Min/Max	L	A, I
14	Elbow Angles	0° to +60°	Min/Max	L	A, I
15	Step Frequency	$f=-.44v^2+2.06v+0.13$ f [Hz], v[m/s]	± 5%	M	A, I
16	Velocity	0.5-2.5 m/s	Min/Max	M	A, T, I
17	Kill Switch	Shuts Down Power	Y/N	L	A, T, I
18	Stored Size	576” x 102” x162”	Max	L	A, I
19	Trigger Input	Initiates the System	Y/N	L	A, T, I
20	Withstand Wind	7 m/s	1 m/s	M	A, T
21	Withstand Temperature	5-40 °C	Min/Max	M	A, T, I

4. DESIGN DEVELOPMENT

4.1 IDEATION

We began ideation by identifying the main functions and subsystems within our overall design challenge. These main functions were identified through a functional decomposition activity where we distinguished the basic functions from secondary functions. Basic functions are the principal tasks that the overall design must be able to perform, whereas secondary functions are any functions that assist in achieving basic functions or anything resulting from doing the basic function. The basic functions of our design are walking like a human to recreate human radar signatures, moving laterally at controlled speeds, withstanding impact, and having a reset time less than 10 minutes. The secondary functions are leg and arm articulation, variable lateral speeds, dissipating energy, minimal profiles in auxiliary equipment, and allowing for attachment of reflective materials. From this, we divided our system into the main subsystems of arm articulation, leg articulation, lateral translation, and impact resistance.

To come up with as many possible solutions, we conducted various ideation sessions. The first ideation session incorporated the technique of brainsketching as a team for the lateral translation function. Brainsketching is a method where each team member sketches a possible solution for a specified function in 3-5 minutes. Once the time is up, every team member passes their sketch to the team member to their left and tries to build off of the previous member's sketch for another 3-5 minutes. This rotation continues until each member receives his or her original sketch. The benefits of brainsketching are that various concepts are created without any risk of criticism that could hinder creative idea generation. The second ideation session was based around brainstorming as many concepts as possible for articulation, moving laterally, and surviving impacts. As a team, we sketched and wrote down all of the ideas that we could come up for each subsystem. The objectives in brainstorming were to defer judgment, build off each other's ideas, and come up with as many concepts as possible without focusing on minor details. After brainstorming, we had a list of concepts for each subsystem to build upon, enhance, or combine ideas together.

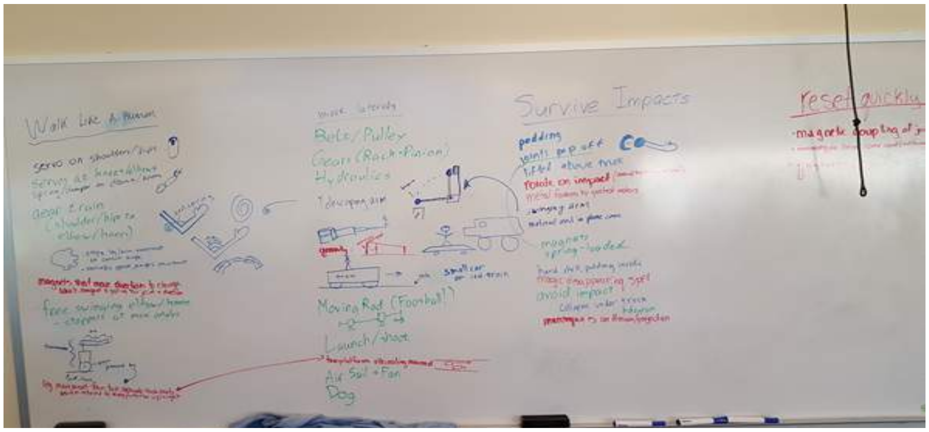


Figure 4.1.1. Brainstorming in the second ideation session

We also created a morphological table where we came up with ideas for how to power the system, arm articulation, leg articulation, lateral translation, and taking impacts. To create the table, we put all of our ideas down on post-its and placed them in the corresponding category. With all of our ideas organized, we were able to form full system solutions by combining a concept from each category based on the compatibility of solutions from each category.

Another method used for ideation was the SCAMPER method. SCAMPER is an acronym that sequentially describes the steps to generate ideas by modifying an existing idea. SCAMPER stands for Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse. We utilized this method to generate various solutions to achieve arm articulation based on the existing idea of having and DC motor drive the shoulder and a free swinging elbow hinge. The ideas that we obtained included a coupling rod in the arms, spring and damper system, and a mechanical tendon.

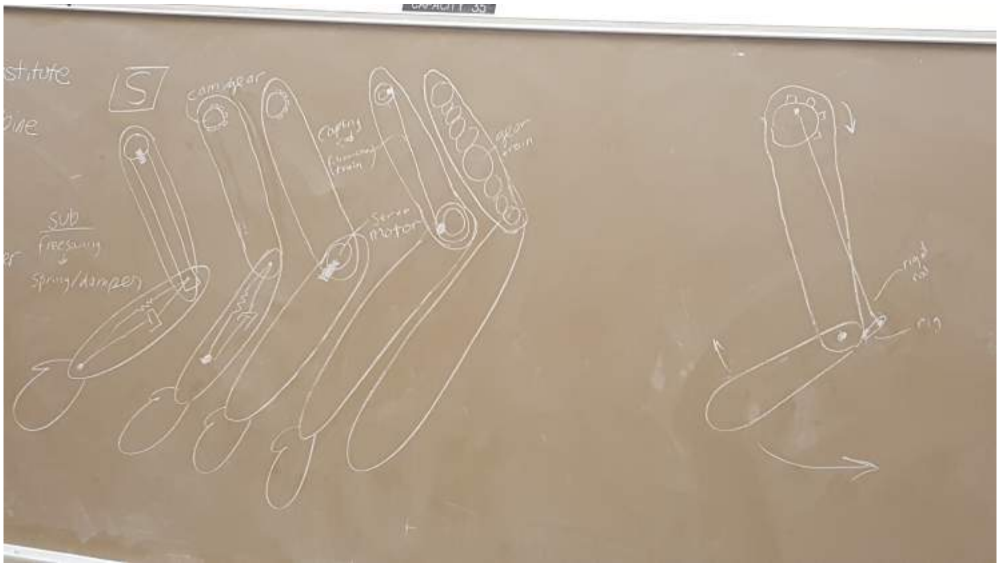


Figure 4.2 The concepts obtained from the Substitute portion of SCAMPER

To tackle the challenge of taking impact loads, we brainstormed and sketched various ideas on how to dissipate energy and prevent damage to the mannequin. In addition to padding, we proposed many different methods to move the dummy away from the vehicle and lessen impact loads. Other ideas included the disassembly used by existing ADTs and the use of bumpers to prevent direct impact.

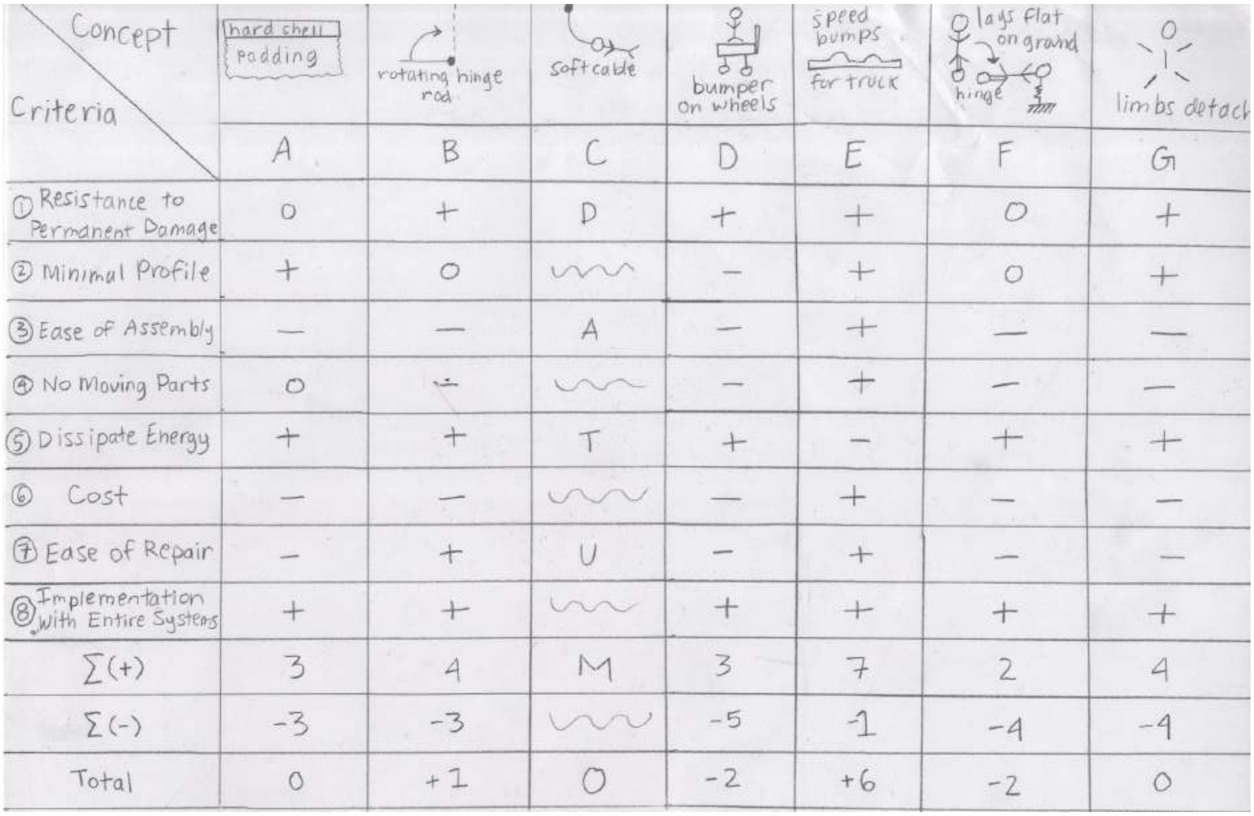
After the ideation sessions, we created physical models of selected concepts such as the arm articulation, leg articulation, and impact resistance. These prototypes provided a proof of concept as well as better insight in the accuracy and precision in each concept for mimicking joint articulation. The physical prototypes can found in Appendix D. The first model illustrated the power of thinking outside the box as the hip driven articulation both simulated hand movement decently well and reduced the number of motors necessary. However, it was deemed mechanically complex and fragile for our application. The second model was used to check the viability of having free-swinging lower limbs or only using basic springs for those sections. The results were acceptable, and the simplicity to make and the robustness make either a strong option even though the motion simulation is not the best. The rod-pulled hand in Figure D.3 was already suspected to be a poor idea, but the physical model also showed that purely horizontal hand motion does not reflect the rotational swinging of a real arm well. The coupling rod idea had many of the same strengths and weaknesses as the hip-driven hand, but had the cost of additional motors. The final picture, caster wheels, were our most interesting concept. As we were prototyping we realized that the chairs in which we sat could roll freely and change directions well after an impact, so we decided to pursue them as a possible method of reducing impact loads and stresses.

4.2 PUGH MATRICES

After generating many realistic and unrealistic solutions to all four functions of our project, namely impact, lateral translation, leg articulation, and arm articulation, we began to consider the validity of each solution. We first eliminated ideas that were completely unfeasible, such as using teleportation to keep the mannequin from being impacted. We then eliminated ideas that clearly violated any of the specifications. We took the remaining ideas and created four Pugh Matrices, one for each function. For each matrix we first listed related specifications on the left and then drew each possible solution along the top. We then selected a datum solution and for each specification, we compared each solution to the datum and placed a +, -, or s (for same) in the corresponding box and summed the total for each concept. This method worked well as a preliminary means of comparing ideas and provided a better understanding of the strengths and weaknesses of each solution.

4.2A IMPACT

Through the idea generation sessions, we were able to come up with unique methods for taking impact loads and protecting the mannequin from permanent damage. The possible impact resistance methods can be seen in Figure 4.2.1 below as concepts A-G.



Concept / Criteria	hard shell padding	rotating hinge rod	soft cable	bumper on wheels	speed bumps for truck	lays flat on ground hinge	limbs detac
	A	B	C	D	E	F	G
① Resistance to Permanent Damage	0	+	D	+	+	0	+
② Minimal Profile	+	0	∿	–	+	0	+
③ Ease of Assembly	–	–	A	–	+	–	–
④ No Moving Parts	0	–	∿	–	+	–	–
⑤ Dissipate Energy	+	+	T	+	–	+	+
⑥ Cost	–	–	∿	–	+	–	–
⑦ Ease of Repair	–	+	U	–	+	–	–
⑧ Implementation with Entire Systems	+	+	∿	+	+	+	+
Σ(+)	3	4	M	3	7	2	4
Σ(-)	-3	-3	∿	-5	-1	-4	-4
Total	0	+1	0	-2	+6	-2	0

Figure 4.2.1. Pugh matrix for impact resistance

For each possible concept, the following criteria were used to assess the viability of the solutions as a method of impact resistance. Criteria 1 judges each concept based on its ability to prevent damage to its components, which is critical for a system which is likely to take impacts from 35 ton trucks. Criteria 2, minimal profile, helps the radar sensors detect only the mannequin and not our auxiliary systems. Criteria 3 considers ease of assembly both for us and for testers who need to reset the system in 10 minutes. Criteria 4 gauges the amount of moving parts in each concept because moving parts are more susceptible to damage during impacts. Criteria 5 is the main function of this subsystem; by effectively dissipating energy, our design will be able to endure larger impacts without damage to the system. Criteria 6, cost, is important to consider in every subsystem to ensure that we remain within budget. Criteria 7 is how easy it is to repair the impact resistance solution in the possible case that it gets damaged. These criteria consider how the concepts are assembled, possibilities of damage, and how those possible damages could be repaired. In the event that a test run causes damage to the impact resistance system, stock parts and having a system that is easy to repair allows for a longer lifetime of the pedestrian target. Criteria 8 judges the compatibility of each concept with the rest of the system. Most of the concepts can be easily implemented with other the other subsystems, but concept C is more restrictive due to the requirement of having a gantry system to be able to attach the cable above the mannequin. Although the Pugh matrix concludes that speed bumps for the truck would be the best option, this idea was ultimately discarded as being ineffective in protecting the mannequin. The remaining impact resistance concepts are integrated in full system designs that are rated using the weighted decision matrix in Appendix E.

4.2B TRANSLATION

We found five strong methods of translating the pedestrian test target after sifting through several ideas generated during the ideation sessions. Sketches of the five ideas are located in the translation Pugh matrix, shown in Figure 4.2.2.

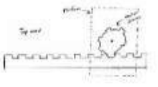
Concept					
Criteria	Datum	2	3	4	5
Simplicity	s	s	-	-	-
Production Cost	s	-	-	-	-
Radar Invisibility	s	s	-	-	s
Portability	s	-	-	-	s
Reset Time	s	s	s	s	s
Control	s	s	s	-	-
∑+	0	0	0	0	0
∑-	0	2	4	5	3
∑s	6	4	2	1	3
Total	0	-2	-4	-5	-3

Figure 4.2.2. Pugh matrix for lateral translation

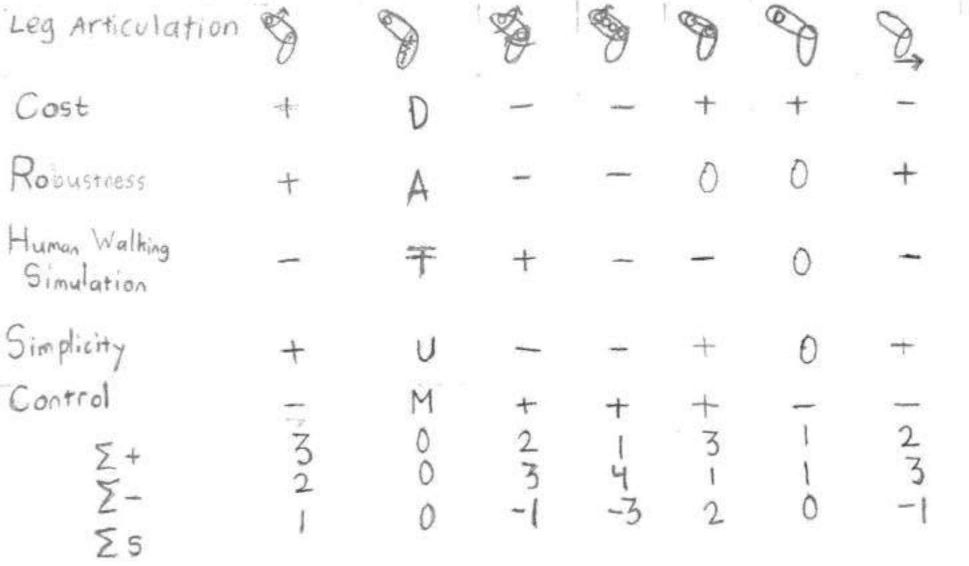
A simple design is favorable because it reduces the overall production cost, allows for replaceable parts that are more readily available, and reduces the time needed to reset the pedestrian test target. The datum concept and the second concept both scored the highest in this criteria. The concept datum requires a motor and belt to achieve translation, which can be built using off the shelf parts. The second concept requires a long rack that can easily be manufactured. The pinion driven by the motor can be assembled using off the shelf parts. The remaining three concepts require more complex equipment for the same translation.

A low cost translation device will allow us to allocate money for other expenses or reduce the overall cost of the pedestrian test target. The datum concept scored the highest in this category because it requires much less material than the second concept and requires less equipment than the remaining concepts. The translation device should not interfere with the radar signal of the pedestrian test target, so concepts which operate low to the ground such as one, two, and five are preferred.

The system will not be permanently located and must be portable. The datum and fifth concept scored the highest in this criteria because belts can easily be condensed and stored. The second concept requires a rack that is rigid and would need to disassemble to fit the space. The third and fourth concept share similar constraints.

When comparing the ability of the concepts to hold a constant speed, the first three allow for precision control of the platform. The fourth concept requires the pedestrian test target to be suspended by a wire or rod, which will swing and create a varying speed as a transient response due to the delay between motion of the top and bottom. The fifth concept requires a substantial amount of tuning to produce a constant speed.

4.2C Leg Articulation

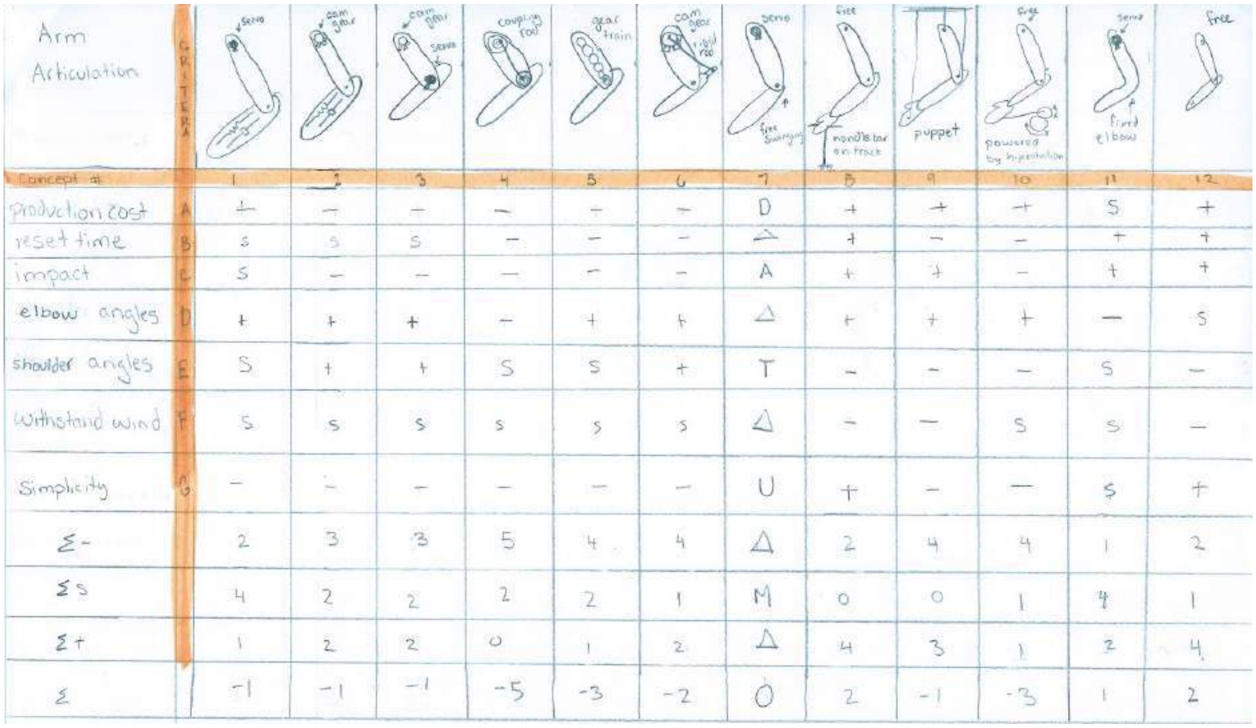


Leg Articulation							
Cost	+	D	−	−	+	+	−
Robustness	+	A	−	−	0	0	+
Human Walking Simulation	−	T	+	−	−	0	−
Simplicity	+	U	−	−	+	0	+
Control	−	M	+	+	+	−	−
Σ+	3	0	2	1	3	1	2
Σ−	2	0	3	4	1	1	3
Σs	1	0	-1	-3	2	0	-1

Figure 4.2.3. Pugh matrix for leg articulation

The majority of our ideas to move the legs used motors at the hip, while the motion below the knee had the options of a free-swinging limb, a spring-damper system, a motorized knee, a gear train, and a coupling rod. The sixth concept utilizes a mechanical cam instead of an encoder to achieve the desired output from the hip motor. We also considered a completely different idea in which the feet drove the motion of the leg, which requires the fifth translation concept described in the prior subsection. As a method to move the legs and imitate human motion, it is poor because it would at best rotate the leg completely about the hip and would more likely lead the motion from the foot. According to the Pugh matrix in Figure 4.2.3 the top three options are the coupling rod, free-swinging leg, and spring-damper system. However, this matrix was unweighted and both the coupling rod and free-swinging limb rated negatively on human walking simulation, which is one of the most important specifications of this project. For these reasons, we decided upon a motor at the hip and a rotational spring/damper system between the upper and lower leg.

4.2D Arm Articulation



Arm Articulation	CRITERIA	servo	cam gear	cam gear servo	coupling rod	gear train	cam gear rigid rod	servo free swinging	free handlebar on track	puppet	free powered by hip rotation	servo fixed elbow	free
Concept #		1	2	3	4	5	6	7	8	9	10	11	12
production cost	A	+	-	-	-	-	-	D	+	+	+	S	+
reset time	B	S	S	S	-	-	-	Δ	+	-	-	+	+
impact	C	S	-	-	-	-	-	A	+	+	-	+	+
elbow angles	D	+	+	+	-	+	+	Δ	+	+	+	-	S
shoulder angles	E	S	+	+	S	S	+	T	-	-	-	S	-
withstand wind	F	S	S	S	S	S	S	Δ	-	-	S	S	-
Simplicity	G	-	-	-	-	-	-	U	+	-	-	S	+
Σ-		2	3	3	5	4	4	Δ	2	4	4	1	2
ΣS		4	2	2	2	2	1	M	0	0	1	4	1
Σ+		1	2	2	0	1	2	Δ	4	3	1	2	4
Σ		-1	-1	-1	-5	-3	-2	0	2	-1	-3	1	2

Figure 4.2.4. Pugh matrix for arm articulation

We explored a number of ideas for the articulation of the shoulder and elbow. All of these ideas can be seen in Figure 4.2.4. Many of these ideas controlled motion at the shoulder with a servo and used other methods to control the motion of the elbow. A notable idea was to have the hand attached to a handlebar running on a track below it. The handlebar would move at different speeds to allow the arm to swing in a more humanlike motion. We also considered having the elbow and shoulder be free swinging and have the motion be generated from the hip. In order to do this, a gear would mesh with a gear that is part of the hip and from this gear a rod would extend to the hand. This rod would move the hand, and therefore the arm, in the opposite direction that the leg is moving.

We compared all the arm articulation methods described above in an un-weighted Pugh matrix. The criteria we ranked them are as follows. Criteria 1 rates each idea on production cost; we considered how much the various components would cost in comparison to the other ideas. Criteria 2 was reset time, where we considered how long it would take to reassemble all of the various parts after impact. Impact was Criteria 3; here we compared how well each idea would hold up when impacted by a large truck. Criteria 4 and 5 were elbow angles and shoulder angles, respectively, and this is where we took into account how well the design would be able to mimic human motion. Criteria 6 rated each design the ability to withstand the wind that the system might see during testing while still retaining function and humanlike motion. Criteria 7 was simplicity; it is important that our designs are easy to make and keep up as well not having a lot of moving parts to better allow it to withstand the needed impacts. The results surprised us because the Pugh matrix suggested that the completely free-swinging arm and the free-swinging arm moved by the handlebar were the best option. We realized that this was due to all the criteria being ranked equally. While it did not score the highest in this matrix, the arm articulation that we thought was the best out of these was the servo at the shoulder and a spring damper at the elbow because it was relatively simple and would not be damaged with repeated impacts like many of the other designs would be.

4.3 TOP CONCEPTS

Once we completed the Pugh matrices, we combined the best solutions for each function to create 6 complete design concepts. A description of each design as well as discussion on its positive and negative elements is below. The ranking for each concept can be found in the Weighted Decision Matrix in Appendix E. Using the weighted decision matrix, we were able to compare the advantages and drawbacks for each system design. With weighted criteria, we were then able to obtain more accurate ratings of the design concepts and correctly decide on the final design.

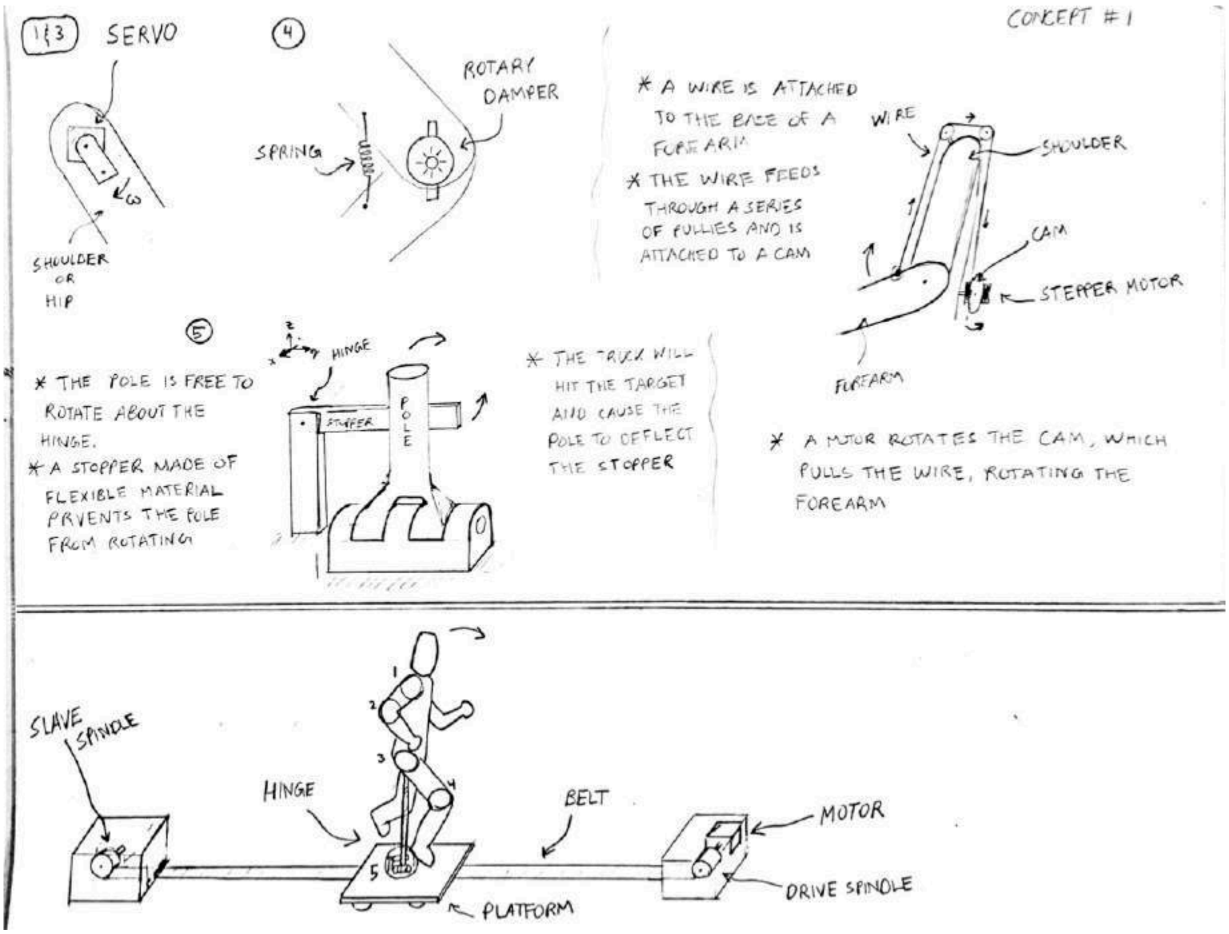


Figure 4.3.1. Concept 1 with a hinge to allow the mannequin to lay flat upon impact

Concept 1 had motors at the hips and shoulders, spring and damper for the knee, a tendon pulley for the elbow, motion along a belt and pulley system, and a hinge to allow the mannequin to fall over when impacted. This concept scored the highest on our decision matrix. This idea met the majority of our specifications well; it was one of the best in adult human dimensions, linear translation, limb articulation, minimal nonhuman profile, and ability to withstand wind and temperature. Concept 1 was not a great choice for meeting the specification of having the track be driven over because while the belt could easily be driven over, the platform and the prone mannequin could not.

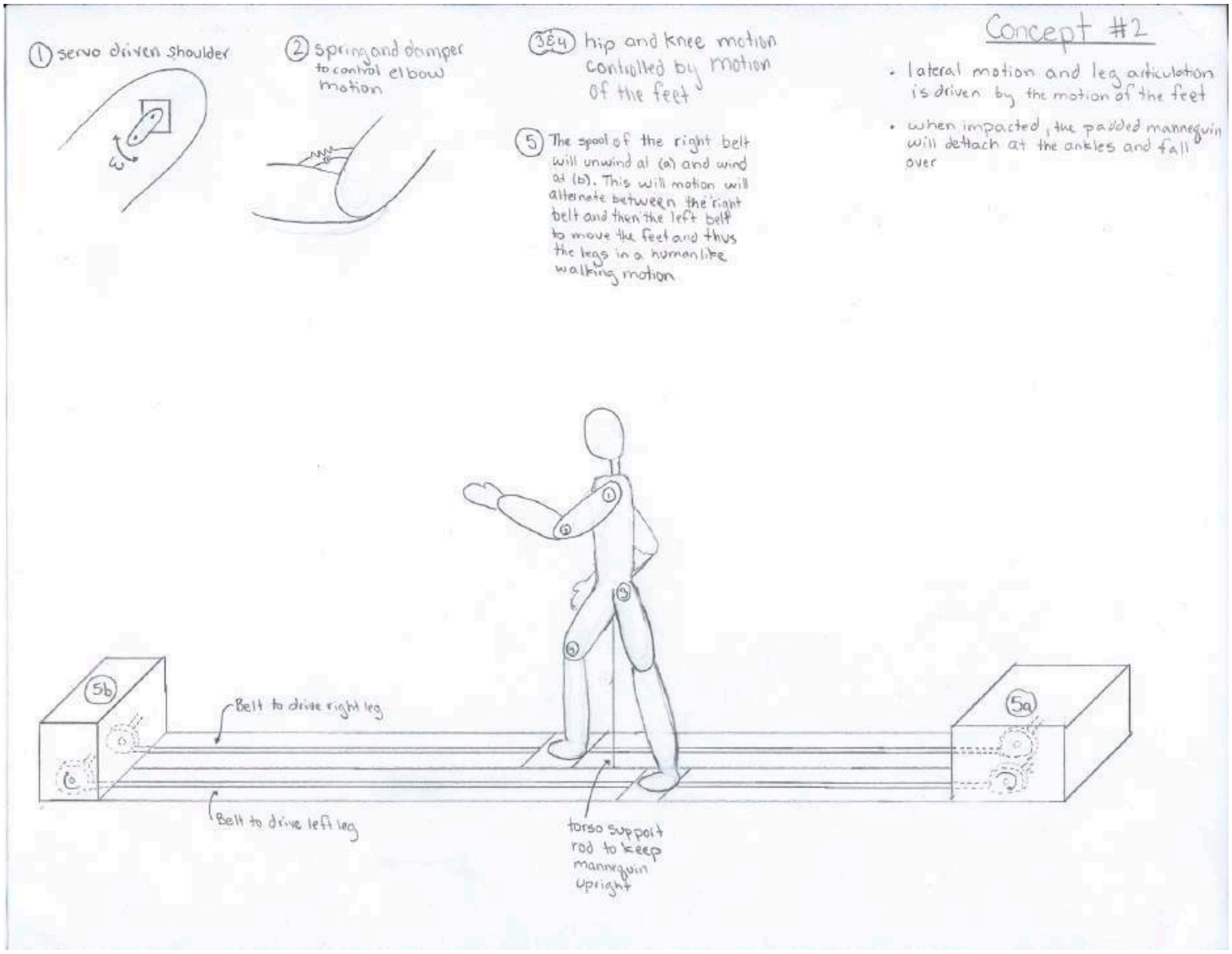


Figure 4.3.2. Concept 2 has a track for each leg to provide leg articulation

Concept 2 had motors at the shoulders, spring and damper at the elbow, motion and leg articulation from two belt and pulley systems that move the feet at different timings, and a rod on a track to support the torso. On impact the rod and ankles would disconnect from the belt and the mannequin would fall to the ground. This concept scored the lowest on our decision matrix. It scored decently in the categories of the track being driven over and minimal nonhuman profile. It was subpar for the specifications adult human dimensions, linear translation precision, and limb articulation because having the feet always in contact with the ground would not properly simulation human walking motion and having two pulleys to program would be difficult to get accurate speeds.

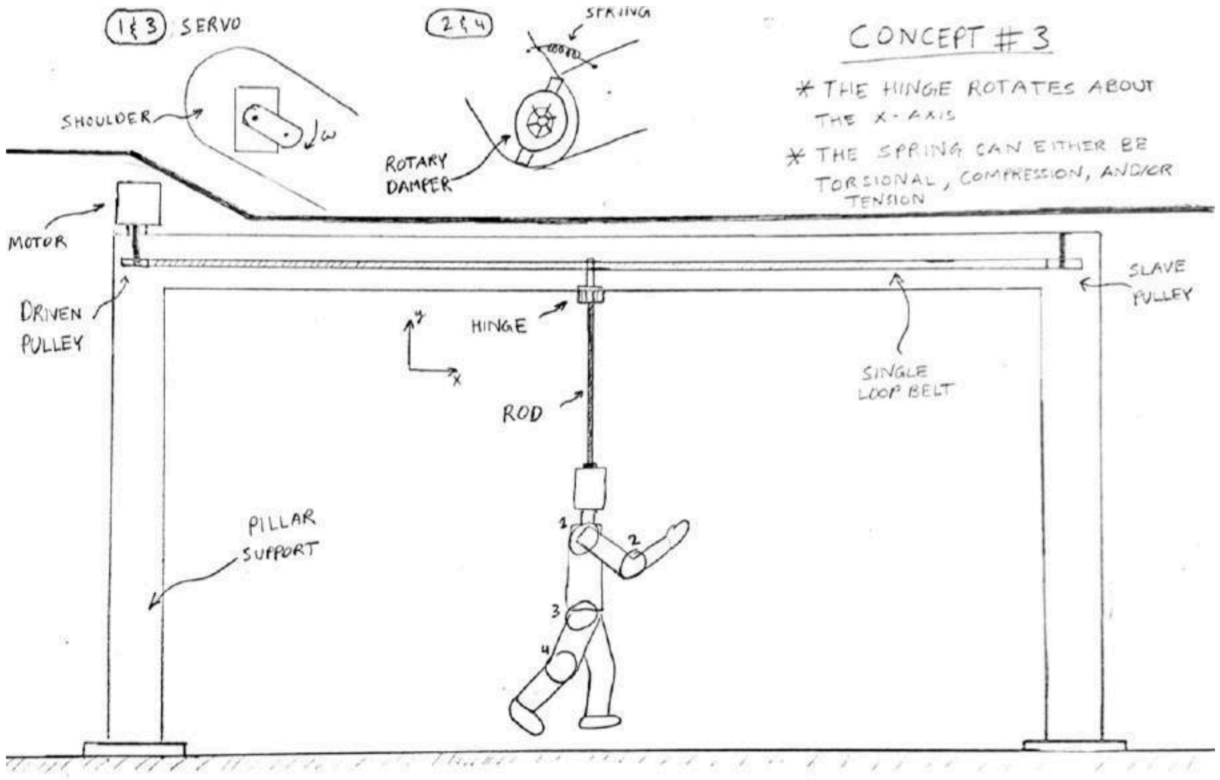


Figure 4.3.3. Concept 3 utilizes a gantry system as the lateral translation mechanism

The primary conceit of Concept 3 is an overhead gantry that had a motor driven hanging rod that would rotate in direction of impact. Limb articulation is the same as in Concept 2. This concept achieved a perfect score for the requirement of being driven over because it avoids the problem entirely. It rated less well in linear translation precision because of the potential of the long hanging rod to swing, especially in high wind conditions. For impact resistance, the idea of the mannequin swinging upward carries the risk of doubling the number of impacts by swinging it back into the truck if the lateral translation does not move it past the truck. The minimal nonhuman profile is worsened by the large structure and the tall rod sticking out of the top of the mannequin's head. The large support structure also hurts the transportability and cost.

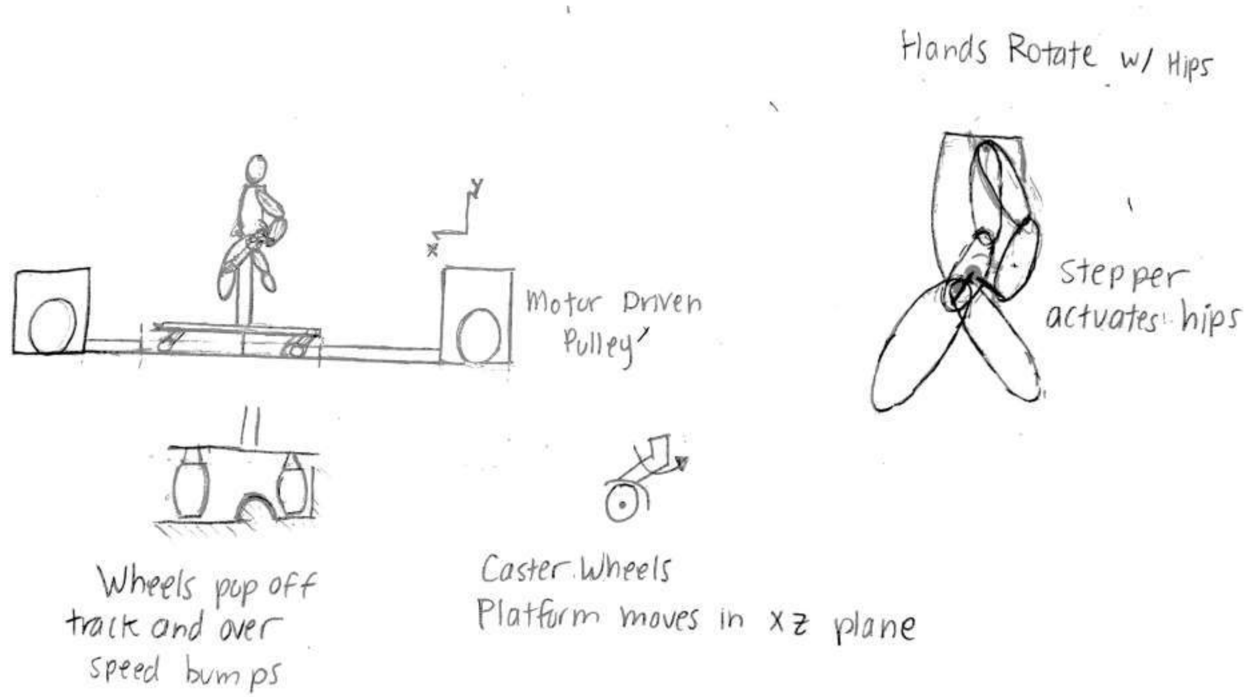


Figure 4.3.4. Concept 4 uses caster wheels for lateral translation as well as impact resistance

Concept 4 was inspired by an Anthony Best Dynamics target which rolled with the vehicle using wheels in the feet. Because our design requires moving legs, we adapted the idea to platform with caster wheels that allow it to move off of the belt pulley system with the truck when impacted. The concept includes a link between the platform and the belt and a bumper that pops up just before impact to help absorb the force. Instead of using motors at the shoulders, the arms are articulated by a rod attached from a hand to a gear off the hip allowing the arms to move opposite to their respective legs. The specifications that this concept did well in were linear translation precision, impact resistance, ability to be driven over, and reset time. This concept did not score as well in adult human dimensions and limb articulation because getting the correct arm length and articulation with the hip powering the motion would be difficult and might result in compromises between those two specifications. The minimal nonhuman profile is another major concern both because the platform might not be low enough to avoid radar detection with the caster wheels and also because the bumper would affect the radar signature. The amount and complexity of subsystems negatively affect the simplicity and cost. We liked the idea of a platform moving with the vehicle, but the complexity of the hand-hip articulation and it low robustness without a bumper are weaknesses of this concept.

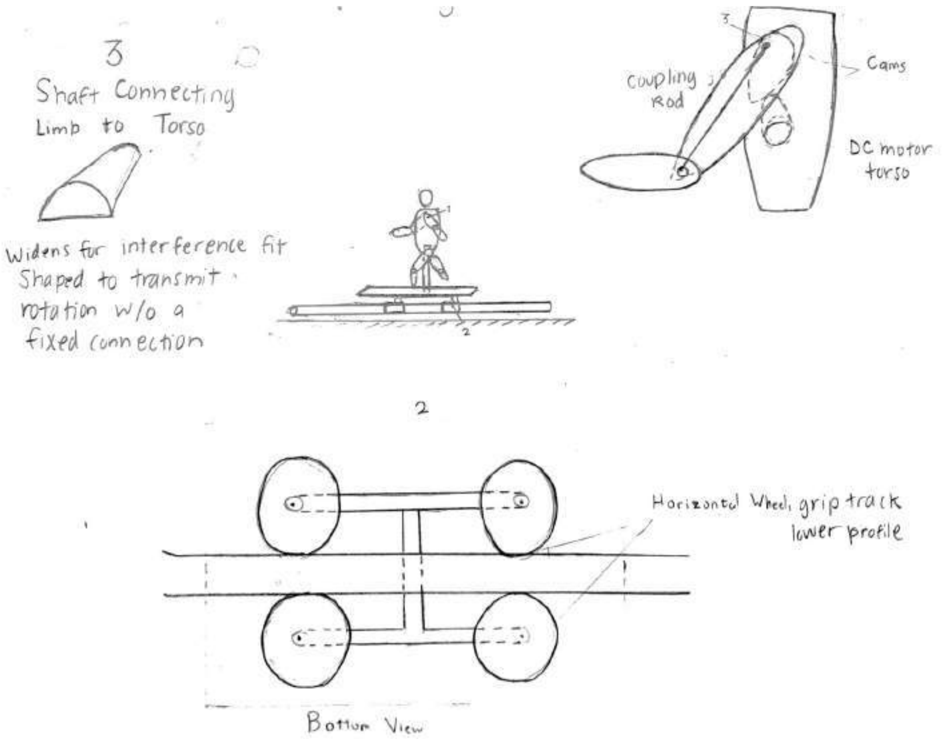


Figure 4.3.5. Concept 5 uses a track system similar to ones used in a rollercoaster

Concept 5 would be moved by a system that has wheels rotating in plane parallel to the plane of the ground on either side of a low track, a mannequin-supporting rod which easily separates from the platform, limbs that detach upon impact, motors with cams at the hips and shoulders, and coupling rods from the hip and shoulder to the knee and elbow respectively. The horizontal wheels were imagined to reduce the height and radar signature of the platform, but this idea is counterbalanced by the necessity of mounting a motor on the platform itself. This translation mechanism does score well in linear translation precision and transportability, but is more complex than many of the other ideas. The limb articulation of the coupling rods is acceptable for the arms, whose sections move in synch, but is less desirable for the legs. The separation of the mannequin parts is a concept proven by 4Active Systems, but raises potential issues for driving hazards and reset time. In addition, because the detached limbs fall to the ground, the system undergoes additional impacts.

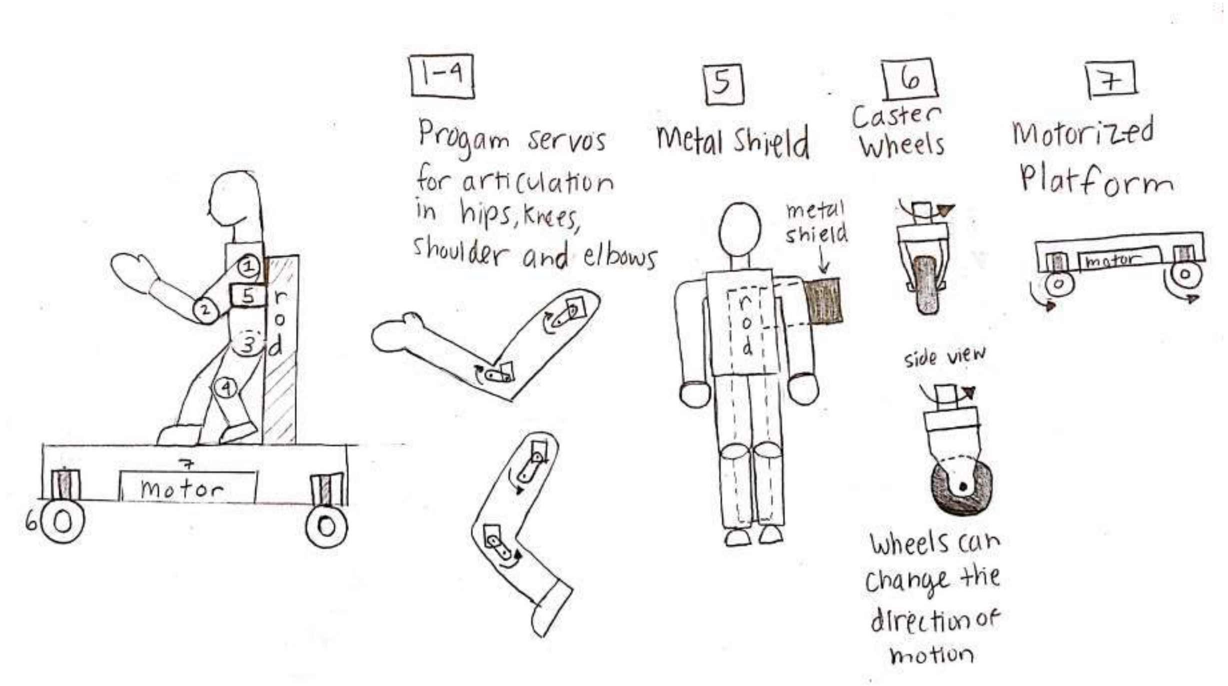


Figure 4.3.6. Concept 6 incorporates a motorized platform and caster wheels

Concept 6 is comprised of a short motorized platform with caster, motors at all main joints, and a metal shield with a spring in line with the arm to absorb some of the impact. This concept scored second highest in our decision matrix. This concept was the best of our concepts for limb articulation, reset time, and transportability. This concept also rated well in adult human dimensions, linear translation precision, ability to be driven over, and low cost. It received a low score in impact resistance primarily because the shield can only prevent direct impacts to the mannequin and must transmit the energy to the platform itself and secondly due to the possibility of tipping. The profile is a concern because the platform would have to be thick in order to house the motor and the caster wheels and the shield might also be detected.

4.4 PRELIMINARY DESIGN

Concept 1 had the best limb articulation design, but basic analysis determined that the hinge would not be able to withstand repeated impact. This analysis was conducted using the known mass of the vehicle, proprietary velocity profile data from previous tests, estimates of our mannequin's mass from existing products, and hinge strength specifications from vendors. Most of the ideas from this concept were recycled into Concept 7, where we changed the impact resistance from Concept 1's falling over with the release of the hinge to Concept 4's releasing the platform from the track so that it rolls in the direction of the truck.

This is accomplished by putting a nub on the bottom of the platform that notches into a slot on the belt, as shown in Figure 4.4.1. This slot constrains the platform in the direction of the belt but does not hinder its motion in the direction of the truck.

Figure 4.4.1. Platform Hook to connect belt and platform

Changing Concept 1 to Concept 7 also replaced the single axis wheels with rollers that are able to roll both perpendicular to and parallel with the truck. The caster wheels in our initial concept were relatively tall, so we replaced them with omniwheels, shown in Figure 4.4.2, which can be inset. In addition, the arrangement of rollers on a main wheel allow omniwheels to change direction quicker than caster wheels, which track.

Figure 4.2.2. Omniwheels that can roll in two axes.

These changes, seen in Figure 4.2.3, allow the platform to detach from the belt, have the rollers move perpendicularly to the truck, and continue rolling with the truck upon impact. The axis primary axis of the omniwheels is in line with the platform base rather than below it to lower the height and profile of the platform. The square hole on top holds the rod supporting the mannequin and the notch on the bottom connects to the belt. Concept 7 received an even higher score than Concept 1 because this it improved the impact resistance specification and the minimal nonhuman profile specification.

Figure 4.2.3. Top view (top) and bottom view (bottom) of the platform.

The final choice of Concept 7, shown in Figure 4.2.4, incorporates motors in the hips and shoulders, spring and damper in the knees, tendon pulley for the elbows, a belt pulley system for the track, and a rolling platform as a technique to dissipate energy.

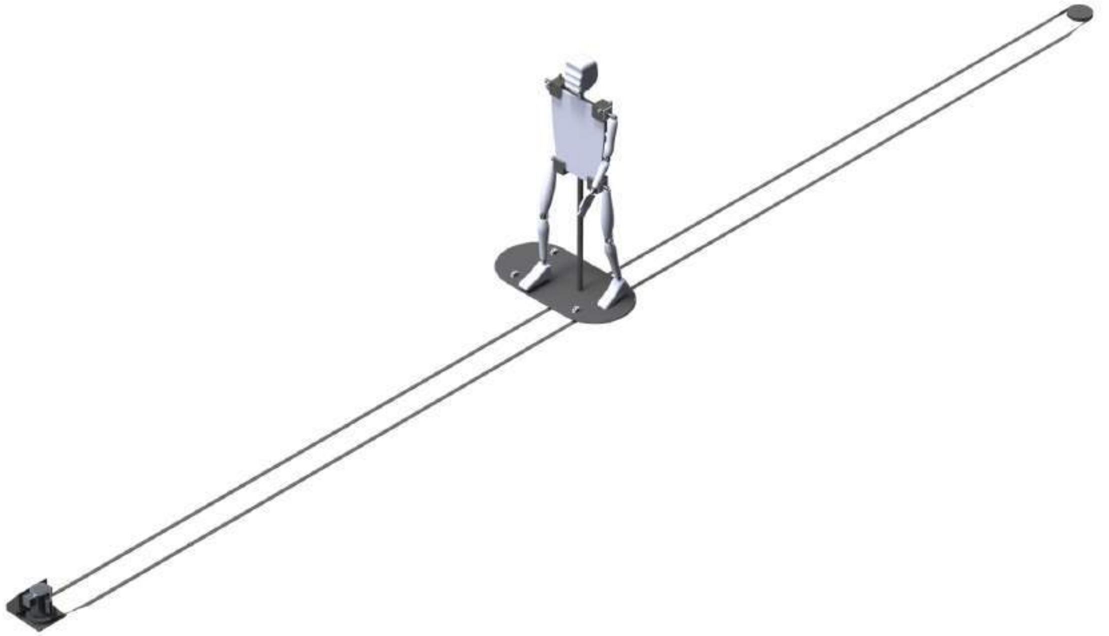


Figure 4.2.4. The entire system for Concept 7

The lateral translation device will be a belt and pulley system that has a platform attached to it that the mannequin will be positioned on. This system will incorporate a flat belt that the truck can drive over without causing any damage, which is currently planned to be twisted by the pulley housing. Furthermore, the belt and pulley system will have speed control based on the discrete voltage inputs to the motor driving the system. The belt will be sized so the platform will travel at least 10 m, which may require the use of tensioners.

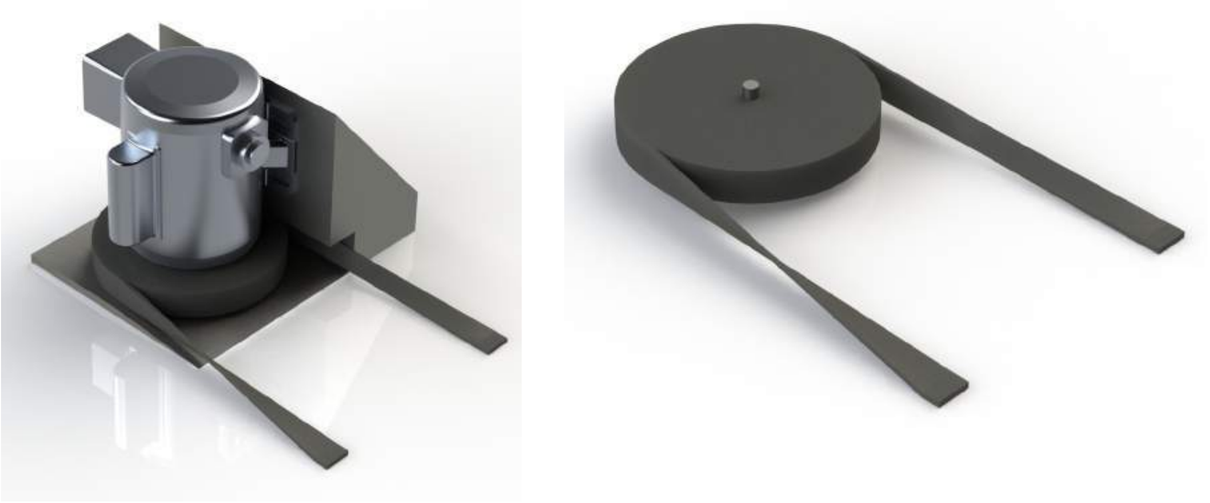


Figure 4.2.5. Belt and pulley system to drive lateral translation

With motors in the shoulders and hips, we will precisely control the angles and frequencies that drive the hip and shoulder movements. The mechanical tendon, a wire attached just below the elbow on the inner forearm that goes around the shoulder to a motor, will also achieve correct elbow articulation based on placement on the forearm and attachment to the upper arm. In addition, the similar trajectories of the arm sections can be easily synchronized. Ideally, the tendon will attach to the same motor that drives the shoulder, but it may attach to a separate motor on the back.

Figure 4.2.6. Side view of the mannequin showing mechanical tendon assembly.

Unlike the arm, the upper and lower sections of the leg do not move in synch while walking, so we will incorporate and springs and dampers that articulate the knee to ensure it reproduces the walking motion. Using only motors in the hips and shoulders and not in the elbow and knee improves the overall cost of the project by reducing the number of motors that need to be purchased.

Figure 4.2.7. Compression spring and rotary damper at the knee

To provide more impact resistance as well as an interface to attach the given reflective materials, there will be padding that will cover most of the mannequin's surface area. We also plan on designing a kill switch that will immediately stop the motor and belt pulley system at any time and would stop the articulation in the mannequin as well. Due to the risks associated with a vehicle driving over a moving belt, the kill switch should activate when the platform is released from the belt. Automatic sensing and stopping is desirable, but because the scope of this project is already large, we may simply instruct operators to manually activate the switch when the vehicle approaches the belt. To engage the system, the user will input the desired lateral speed and push the start button. To stay within the 10-minute reset time, the only steps required in resetting the system are retrieving the mannequin, placing it on the beginning of the track, and moving the belt compression device on the track behind the mannequin. In addition, the entire system will be transportable by allowing the system to break down into its main components. The mannequin and platform will be able to detach from the lateral translation system and the belt will be able to detach from the motor. With these detachments, the entire system can be easily transported in a vehicle. To protect the system from weather conditions, we will include temperature considerations when making material selections and designing the system. To ensure the mannequin does not fall over from wind loads alone, we will design the platform and how it inserts into the belt such that it will not detach until the forces are much larger than wind loads and in the range of the impact loadings, which should be simple as they are expected to differ by at least an order of magnitude.

4.5 JUSTIFICATION OF CHOICE

To check the feasibility of this design, we performed some basic calculations in Appendix F. We assumed steel and foam for materials to obtain a mannequin mass of 105 kg and a platform mass of 20 kg. These values are in the expected ranges based off of existing products, such as the Hybrid III being 172.3 lb (78.2 kg) without actuators. We used these masses in a simplified impact problem in which we assumed the mannequin's mass was insignificant to that of the truck in a perfectly plastic collision, so the mannequin would achieve the same .9 m/s velocity as the truck at impact. In addition, data from the Montana Department of Transportation suggested a vehicle collision time of 0.1 seconds, so we obtained an average force of approximately 1 kN ("There are Three Collisions in a Crash"). We believe this estimate to be high, but cannot perform an accurate analysis with the data we currently possess. These estimated values formed the basis of the preliminary calculations performed in Appendix F: beam dimensions, likelihood of tipping, and motor torques. To get a rough estimate on the required platform dimensions, we utilized static analysis to find that the minimum platform width is 0.5 m to prevent tipping. If the entire mannequin body was the size of the support rod and made of steel, it would be 5 cm x 5 cm. Maintaining a constant speed with the omniwheel rolling resistance of 0.8 suggested by Andy Baker at Chief Delphi (Baker) and a pulley diameter of 10 cm requires a motor torque of 50 Nm. The surface area of the flat face of the torso and the design wind speeds produced a wind load of less than 10 N, well below those of the force to translate the platform and the force of impact. None of these values are final, but provide baseline values to design for. Our conservative estimates provided reasonable values for the sizing of parts and motors.

5. PRELIMINARY PLANS

5.1 PRELIMINARY ANALYSIS PLAN

We will begin our analysis by determining the weight of our mannequin and platform. Determining the weight will be an iterative process based on how material selections can affect our design, primarily in impact and stress, and secondarily in weight and cost. The Materials Engineering Consulting Club will assist in choosing a material which fulfills our requirements. This will allow us to size motors that we can then order early in the build phase as these will be long lead parts. Analysis of the track system will include determining the loads on the track system in order to design and select a belt and pulleys that are capable of withstand the loadings. Our belt will be vertical as it goes around the pulleys and twist to ensure that the belt is parallel to the ground along the length of the track. We plan on designing either the housing of the pulley or a fixture that ensures the belt twists are the correct location to prevent any dragging of the belt. Due to the required length of the track, tensioners will likely need to be added to the belt.

Analysis will also include calculating the angles and frequencies of the articulation in the shoulders, hips, knees, and elbows. The articulation in the knee requires designing the spring and damper system such that the equation of motion represents the desired articulation motion. The articulation in the elbow requires less analysis and more tuning and calibrating the attachment location and wire length such that the elbow motion is operating at the calculated angles and frequencies as well and being in sync with the shoulder frequency.

In order to have quality insight on the loadings upon impact, we will find the stresses imposed on our mannequin and platform through finite element analysis using computer software. Performing this simulation will allow us determine the impact loads and pinpoint critical areas to design for impact resistance as well as ensuring our system functions properly over the life of 1,000 cycles. The impact loads found from performing finite element analysis will drive our material selection process.

5.3 PRELIMINARY TEST PLAN

We will undergo extensive testing throughout the analysis and build phase to ensure the pedestrian test target will mimic the human walking motion. We will purchase motors and drivers shortly after finishing the detailed analysis. Once we have these electronics, we will calibrate them, attach the limbs, and tune the system. We currently have gait data that we can use to create a simulation. One method to tune the model would be to take video of the limb's side profile and compare it to the gait data simulation. We would then tune the model until it adequately mimics the simulation.

To validate the travel length of the mannequin, we will measure how far the mannequin travels on the lateral translation device. To test that the flat belt in the lateral translation device can support the weight of a vehicle, we will set-up and drive over the belt to make sure no there is no damage to the belt or pulley system. We will be able to measure and verify the angles and frequencies of the shoulders, hips, elbows, and knees to ensure it articulates at the specified parameters. The velocities of the mannequin will be verified by measuring how much time it takes for the mannequin the travel a set distance. The velocity testing will be done for each discrete velocity input over the entire range of 0.5 m/s - 2.5 m/s. The system's impact survival will be tested using a Cal Poly van at an off-campus testing facility. Testing the 10-minute reset time will be done by measuring how much time it takes for two people to completely reset the system for another cycle. We will test our pedestrian test target using the Cal Poly wind tunnel to ensure our system can handle winds up to 7m/s. Since the test section of the wind tunnel is too small to fit the pedestrian test target, we will place the target behind the wind tunnel exhaust section and increase the airflow until it reaches 7m/s. The wind resistance of the mannequin is a tertiary concern, so precise testing is not necessary. We will also be able to investigate and confirm that the kill switch turns off all power going into the system.

One day will be allotted for all Daimler Truck senior project groups to test their systems at a local track. We will test our system's durability against a passenger van with cattle guard moving at low speed. All subsystems will be monitored to verify proper function during the test trials. We will also measure the time it takes to reset the pedestrian test target.

In addition, we have a completed a design hazard safety checklist in which can be seen below. The design hazard and safety checklist highlights the possible dangers in our system and the plan for corrective actions. The hazards that we identified are pinch points from motors, high accelerations during impact, large moving masses, falling over upon impact, batteries in the mannequin, and it may be exposed to wind and various temperatures.

5.4 PRELIMINARY DESIGN HAZARD CHECKLIST

We initially determined the potential hazards of our design for our Preliminary Design Review which can be seen here along with our solution for those problems. An updated version of these documents for our Critical Design Review can be found in Appendix J.

Team: Crosswalker Advisor: Dr. Birdsong

Y N
☒ ☐ 1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☒ ☐ 2. Can any part of the design undergo high accelerations/decelerations?
☒ ☐ 3. Will the system have any large moving masses or large forces?
☐ ☒ 4. Will the system produce a projectile?
☒ ☐ 5. Would it be possible for the system to fall under gravity creating injury?
☐ ☒ 6. Will a user be exposed to overhanging weights as part of the design?
☐ ☒ 7. Will the system have any sharp edges?
☐ ☒ 8. Will any part of the electrical systems not be grounded?
☐ ☒ 9. Will there be any large batteries or electrical voltage in the system above 40 V?
☒ ☐ 10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐ ☒ 11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐ ☒ 12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐ ☒ 13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐ ☒ 14. Can the system generate high levels of noise?
☒ ☐ 15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☐ ☒ 16. Is it possible for the system to be used in an unsafe manner?
☐ ☒ 17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses a complete description, a list of corrective actions to be taken, and date to be completed can be found on the following page.

#	Description of Hazard	Planned Corrective Action	Planned Date of Completion
1	Motors in mannequin and those powering the pulley and belt system can cause pinch points.	Keep all motors contained and ensure that no one is in the pathway of the mannequin when it is turned on. A safe observation distance will be specified in the operator's manual.	2/15
2	High accelerations during impact.	Ensure that no one will be near the mannequin during test runs. This will be specified in the operator's manual.	3/9
3	The mannequin will weigh a few hundred pounds and will be moving up to 2.5 m/s before impact and possibly more after impact.	Required that no one is near the testing location during testing. A safe observation distance will be specified in the operator's manual.	3/9
5	Mannequin can tip over during impact with the truck.	We will design impact resistance such that the mannequin should not tip over.	1/15
10	Batteries might be the power source for some of the articulation.	All batteries will be contained to protect electrical elements from contact.	2/15
15	System could be exposed of winds up to 8 m/s and temperatures ranging from 5-40°C	We will design with wind and temperature ranges in mind and will ensure that holes are placed in parts of the mannequin that might act like a large sail. Out system should not be operated outside of the wind and temperature range that will be specified in our operator's manual.	1/15

5.2 PRELIMINARY CONSTRUCTION PLANS

The preliminary build plan that follows is subject to change as we perform more detailed design and analysis. Our preliminary plans for construction include how we will assemble the system and what parts will need to be manufactured by our team or purchased as a stock item. We will purchase the motors, pulleys, rollers, belt, wires, springs, and dampers as stock items. The skeleton will not have complex geometries so its parts should require little or no machining to shape. The motor and pulleys of the track system will be safely enclosed in boxes with removable lids that can unbolt from the box to allow for disassembly. The belt will have a platform hook into which a nub on the rod will slot. This slotting will cause the belt to pull the platform in one direction and also allow the platform to detach and roll in another direction when impacted.

The platform for the dummy will be machined to shape, with cutouts for the rollers and rod. The rollers will be directly bolted to the platform. The rod will have a flange attached so that it will bolt and unbolt from the platform for disassembly and transport. This rod will be permanently fixed to the mannequin. The mannequin itself will be composed of a metal skeleton with padding to form the overall human shape and protect it from impact. The test target skeleton will be machined using metal bar stock. The impact resistant material will be placed on the bar stock of the arms and legs. The head, hands and feet will be made of the same impact resistant material and attach to their respective locations. Motor mounts will affix to the skeleton. The motors and pulleys used to drive the hips and shoulders will be enclosed in a metal box and attach to their respective motor mounts. The output shaft of the motor will then be press fit into the arms and legs. A back plate on the spine will house electronic components such as the drivers, controllers, and battery. The arm's humerus and forearm and the leg's femur and tibia will be metal bars that are joined by a pin connection. The elbows and knees will be made of a free swinging hinge with attachments to provide articulation. A compression spring and rotary damper will connect the upper and lower leg. A small hollow ring above and below the knee will allow springs and dampers to attach for the articulation of the lower leg. The mechanical tendon wire will attach at one end to a point on the forearm and at the other end to an actuator. A series of pulleys will attach to the arms, shoulders and spine to feed a wire from the base of the forearm to the motors on the spine. The padding will be bonded to the skeleton.

6. MANAGEMENT PLAN

The success of this project requires that the team be organized and prepared. Team members bear responsibility for both tasks directly related to the engineering and creation of the product and also tasks necessary to facilitate work and communication.

Secretary duties and responsibilities have been divided and are to be carried out for the remainder of the project. Melanie maintains and organizes the information repository. Tiffany arranges team meetings, arranges the time, and reserving a location for team meetings. Chris and Tiffany will work together on being the team treasurer, maintaining and updating the budget for purchasing materials. Tim is the main point of contact for communication between team Crosswalker and the sponsor or outside resources.

Due to the large scope of this project, team members focused their design efforts in the following areas: Chris on FEA, SolidWorks modeling, and structure design; Melanie on platform design and stress analysis; Tim on circuit design and sizing servo motors for articulation; Tiffany on translation and limb design. All analysis can be seen in Appendix H.

The responsibilities of overseeing the development and construction of our prototype will be divided among our team. Melanie will oversee the manufacturing considerations, ensuring that our design is manufactural. Chris will lead fabrication by establishing responsibility for part fabrication either among the team or through resources such as the Cal Poly machine shop. Tim will ensure that we test and validate every engineering specification. Tiffany will be in charge of code to be written and tested for the Arduino.

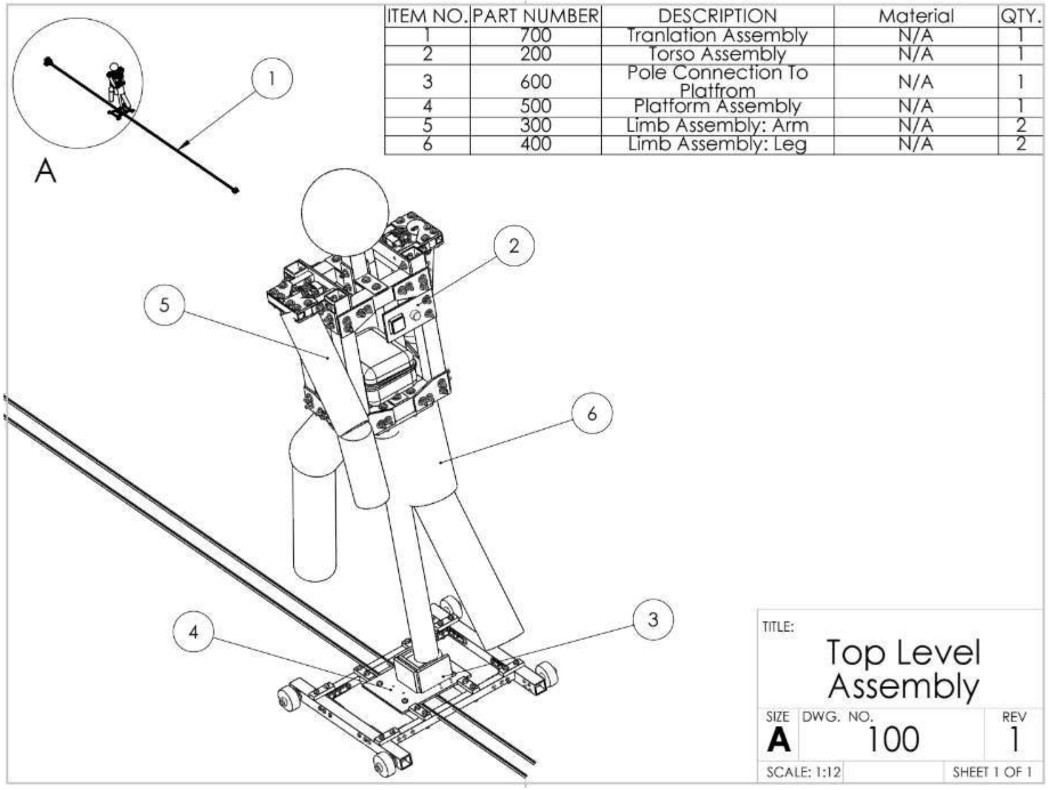
The milestones for this project are listed in Table 6.1.

Table 6.1. Timeline of Milestones

February 13	Begin Ordering Parts
February 15	CDR Presentation
February 20	Begin Building
March 9	Operators' Manual to be Completed
March 16	Project Update Report, Manufacture and Test Review
May 2	Begin Testing
June 2	FDR, Project Expo, Hardware Handoff, Final Report

7. FUNCTION DESCRIPTION

In our design, the 4 main subassemblies are the torso structure, limbs, platform, and lateral translation. These subassemblies interface and cooperate to create a pedestrian target that mimics the walking motion of a human crossing the street. The top level assembly displaying how the subassemblies are connected can be seen in Figure 7.1 below.



ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	700	Tranlation Assembly	N/A	1
2	200	Torso Assembly	N/A	1
3	600	Pole Connection To Platfrom	N/A	1
4	500	Platform Assembly	N/A	1
5	300	Limb Assembly: Arm	N/A	2
6	400	Limb Assembly: Leg	N/A	2

Figure 7.1. Top Level Assembly Drawing of the Pedestrian Target (Original design, prior to changing the direction of the platform and moving the control panel)

The mannequin torso structure creates the main upper-body skeleton of the pedestrian target, houses the electronics to articulate the limbs, and provides impact resistance from a 40 ton truck traveling at 5 mph. This torso structure is assembly 200 in the top level assembly drawing found in Appendix M. The platform, assembly 500 shown in Appendix M, is the transportation method that allows the mannequin to travel laterally in front of the truck. The pole connection assembly is the interface between the pole supporting the mannequin upright and the lateral translation system, which is assembly 600 in Appendix M. The platform is on wheels which allows the pedestrian to move smoothly at various discrete velocities. What controls the walking speed of the target is the lateral translation system and is assembly 700 in the top level assembly drawing . This system consists of a motor that is stepped down by a gearhead and controlled by a driver. The motor for the translation system drives a pulley which moves the platform and mannequin.

The torso assembly is able to distribute the impact loads across the structure and is primarily composed of 2 inch square tubing with a ⅛ inch thickness and steel plates that are ½ and ¼ inch thick.The entire torso assembly, shown in Figure 7.2, is the structure that houses the electronics, motors, and is the main source of impact resistance for our design. It is covered with fabric to give it a better human shape and prevent other fabric or wires from rubbing against sharp edges.

Figure 7.2. Torso Assembly (Original design, control was moved to the top of the torso to protect it from impact in a fall)

Steel is the material choice because it is readily available, rigid enough to keep the shape of a human, and provides the yield strength necessary to survive repeated impacts from a vehicle. Square tubing is the chosen cross sectional geometry because the cost and weight is less than bar stock. As shown in Figure 7,2, the individual parts of the structure are joined using bolts. This design is chosen over welding because allows the users to easily remove and replace damaged parts as needed.

For the torso structure assembly, it is further divided into the following subassemblies: shoulder, torso frame, neck, electronics housing, pole, control panel, and servo. The shoulder is the first point of contact upon impact and it's responsible for protecting the servo motor from damage. An image of the shoulder can be seen in Figure 7.3.

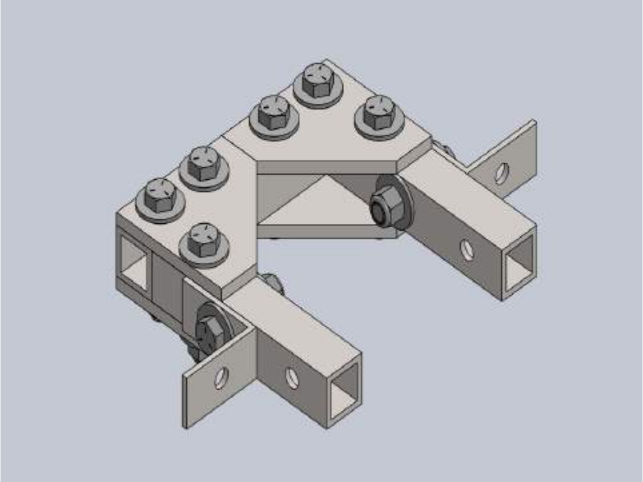


Figure 7.3. Shoulder Subassembly in the Torso Assembly

The shoulder is mounted to the top of the torso frame on left and right side of the target. Inside of the shoulder assembly is where the arm limb assembly will be placed. The arms are articulated by high torque servo motors mounted at the top of the torso frame shown in Figure 7.4. The frame allows us to safely mount the various components in the torso assembly.

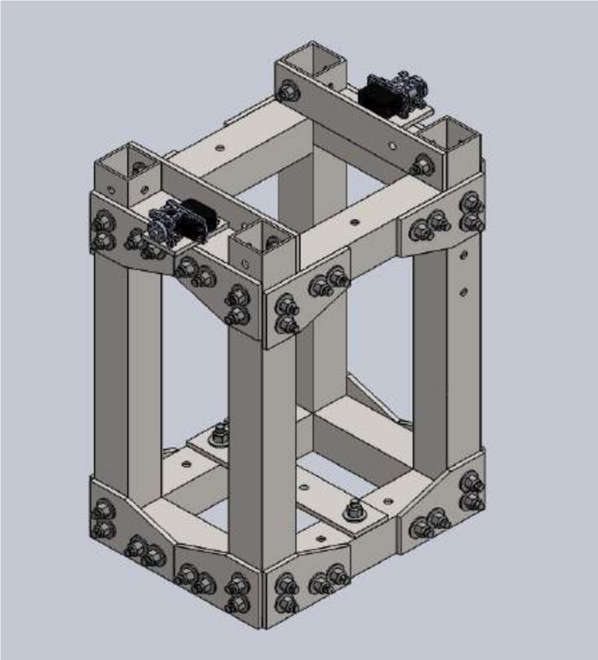


Figure 7.4. Torso Frame Subassembly

On top of the torso frame, a plate is bolted as a mounting point for the head. At the base of the frame, an electronic housing case secures the electronics and further protect them from damage upon impact. The electronic housing contains the batteries, Arduino, and circuitry controlling the limb articulation. A model of the electronic housing is shown in Figure 7.5 with the components placed inside. The electronic housing is attached to a cross plate at the base of the torso frame. This cross plate is shown in Figure 7.6. A control panel is mounted on top of the torso. The control panel has a knob that controls the step frequency of the servo motors articulating the limbs, and a switch to turn articulation on and off.

Figure 7.5. Electronics and Housing

A base plate is bolted inside the torso frame to provide the mounting point for the servo motors articulating the hips. The base plate is located inside of the torso and will be bolted to the tubings that create the lower rectangular shape of the frame. Surrounding the base plate are steel plates to protect and shield the lower servo motors. To connect the supporting polypropylene rod to the mannequin, a flange will be attached underneath the torso frame. This support rod is attached by being bolted to the base plate. The support rod attachment and the base plate are shown in Figure 7.6.

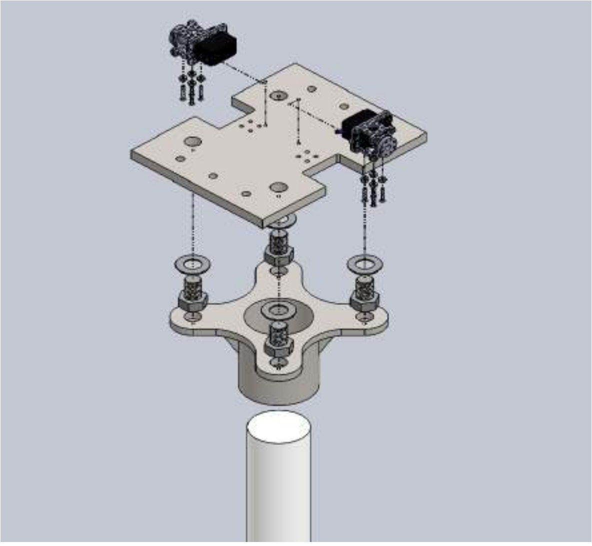


Figure 7.6. Base Plate and Rod Attachment of the Torso Assembly

An Arduino Uno, further protected in a housing box alongside the batteries, reads these inputs and sends pulse-width-modulation signals to 5 servos. Four of these motors follow a set path to mimic the motion of a human swinging his limbs as he walks and only vary in their frequency. The fifth servo pulls on wires attached to the lower limbs to The wiring diagram is shown in Drawing 800 in Appendix M. The servo shafts connect to the shoulders and hips of the mannequin to articulate the limbs and the legs have shaft couplers to ensure that the legs are far enough away from the body.

Each hip and shoulder has its own servo motor dedicated for articulation. A 90^o shaft clamp connects the motor shaft to the core of each limb. The leg, assembly 400, is relatively simple and has additional batting to give the legs shape. The knee is free-swinging because analysis found that with our dimensions the original idea of a spring connection only minimally improves the realism of the movement. Due to concerns about twisting the fabric and batting of a limb rather than smoothly rotating it, the motor torque is distributed along the length of the upper limb through the core of each limb, polyethylene tubing for the arms and hollow aluminum tubing for the leg. The aluminum is needed for stiffness in the legs since they have more inertia and tend to bend at higher speeds. The arms do not need the extra rigidity aluminum tubing, but instead benefit more from the ability of the polyethylene tubing to compress and deform because they are crushed during impacts.

In contrast to the rigid steel of the main torso, the limbs are made of padding to help absorb the impact stresses. The chosen batting, shown in Figure 7.7, is rigid enough to keep the shape of a limb, but compresses and deforms under sufficient force. It was selected because it holds its shape, compresses to dampen forces well, is cheap, and is easily replaceable.\


Figure 7.7. Batting for Prototype Limb

The elbow articulation in both arms is controlled by a separate servo in the center of the torso. Wire attaches to a grommet on the forearm, through the eye bolt on the shoulder, and tied to servo motor. When the servo rotates, the distance from the center of rotation to the elbow is sinusoidal and causes it to extend and contract the forearm. Figure 7.8 shows the eye bolt at the top of the shoulder that the wire loops around, and the 90° shaft clamp, which connects the motor shaft to the hollow rod inside the limbs.

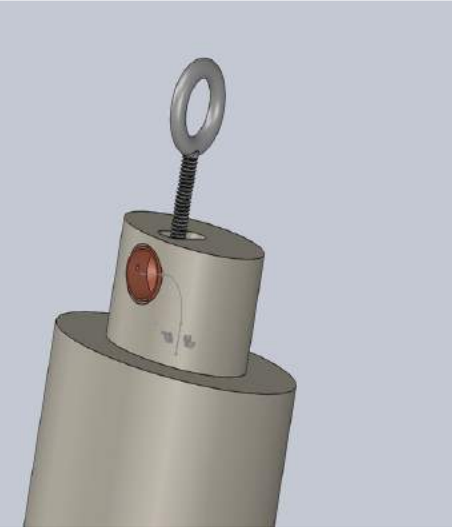


Figure 7.8. Shoulder with pipe connector and eye bolt (Original design, current uses a 90° shaft clamp instead of the pipe connection)

The connection between the support rod and the platform is one of the crucial design sections, as the two actually disconnect to allow the mannequin to move with the vehicle so the force of the impact does not ground itself in the mannequin or pull and damage the motor. The rod is held by 2 U-bolt clamps to a free-standing steel plate. That plate remains secure against a backing plate welded to the platform through the use of neodymium magnets. These magnets hold the rod upright and stable normally, but with sufficient force the mannequin will be released to fall. In addition, 2 other plates around the pole holder prevent it from sliding or tipping in all directions except for the direction of impact. A partial top plate restrains the mannequin from falling toward the truck. Upon impact, the pole and mannequin will be free to tip away from the vehicle and come out of the enclosure. The assembly can be seen in Figure 7.9 and is further detailed in assembly 600. The magnets can be seen sitting between two plates in the gap caused by the U-bolts. That bolt space will be covered by a nut in the actual product; the manufacturer's provided CAD models treated the entire U-bolt as a single piece and did not allow repositioning of the nuts. The side walls extend past the U-bolts when the system is stable so as to limit its horizontal movement to one direction. The magnets were chosen to be the same thickness as the nuts clamping the U-bolts to the holding plate for a snug fit. In addition to solving the issue of gap space between the plates, the manufacturer notes that the strongest force is applied when between 2 metal plates, so with this setup the magnetic force should be close to their rated load.

Figure 7.9 Pole Holder in Containment, with the pole attached.

The platform's function is to provide a smooth transport for the mannequin to travel laterally as if a pedestrian is crossing the street. The platform is composed of square tubing that are bolted to each other to create the overall structure. The platform is mounted onto a set of wheels with a durometer of 82a so that the platform will allow the mannequin to travel smoothly and be easily able to roll over cracks and pebbles. The assembly of the platform can be found in Figure 7.10.

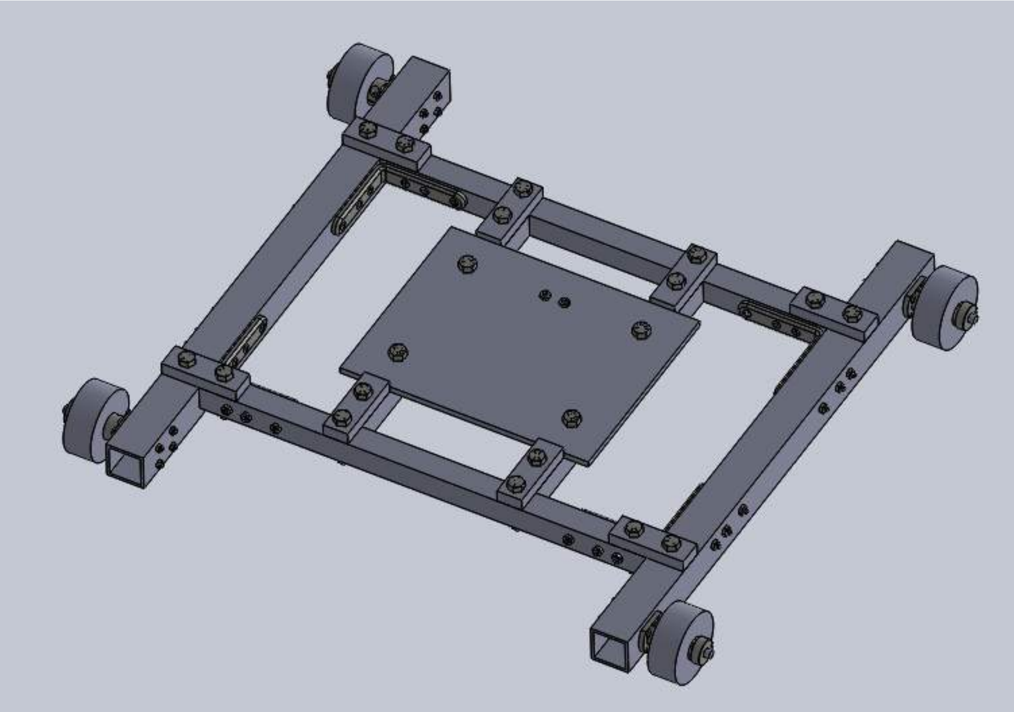


Figure 7.10. Isometric View of the Platform Assembly

The top plate of the platform allows for the attachment of the mannequin through an attachment for the support rod. The platform allows the mannequin to roll easily as the wheels have a set of ball bearings that fit the inner diameter of the wheels and diameter of the shaft. These ball bearings are spaced by a bushing on the inner diameter of the wheels. The shaft is fixed and mounted through a flanged shaft mount. The shaft mount, shown in Figure 7.11, is bolted to the platform and will force the shaft to be fixed through a clamp-on method.

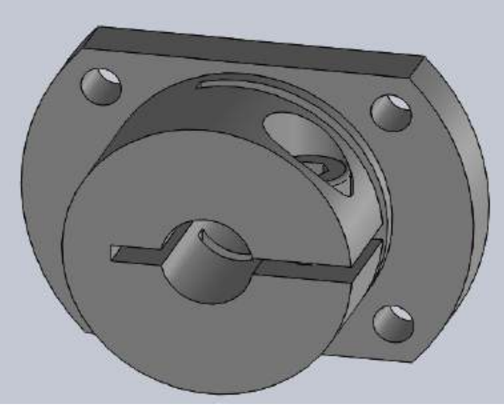


Figure 7.11 Flanged Shaft Mount

To keep the wheels and bearings from shifting axially along the shaft, a shaft collar is placed at the end of the shaft. A thrust bearing is placed in between the shaft collar and the wheels to further reduce friction when the wheels are rolling and the mannequin is in motion. An exploded view of the wheels and shaft can be seen in Figure 7.12 below. From left the right, the components shown in Figure 7.12 are shaft collar, thrust bearings, wheel, ball bearing, bushing, ball bearing, shaft, and flanged shaft mount.

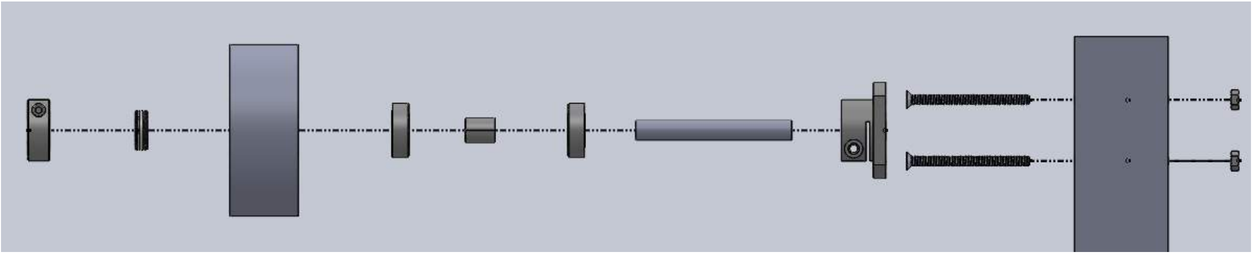


Figure 7.12. Exploded View of the Wheel Assembly

Underneath the platform a hook, shown in Figure 7.13, is bolted so that the translation system will be able to pull the platform on a straight, directed path. Approximately 3 feet of rope and a rope clamp are used to create a small loop that is 2 inches in diameter. This rope loop slips into the snap-hook underneath the platform, shown in Figure 7.13. The metal snap-hook is able to open and close so that the rope loop can easily be detached and reattached from the platform. Both free ends of the loop are fastened to the one side of the translation system rope. Two rope clamps fasten one end of the loop in front of the platform and two rope clamps will fasten the other end of the loop behind the platform. This allows the system to be driven both forwards and backwards by the translation system. These rope clamps should be positioned such as in Figure 7.14 where the curved side of the U-bolt is facing the ground.

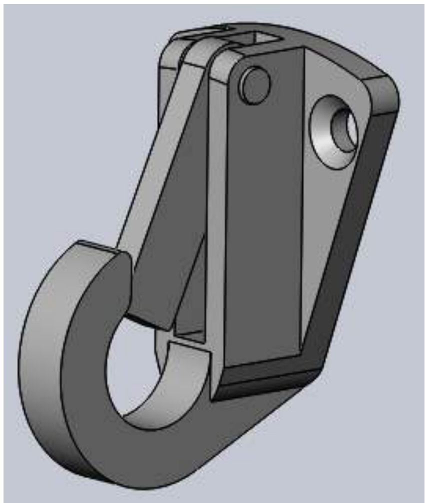


Figure 7.13. Snap-Hook Bolted Underneath the Platform

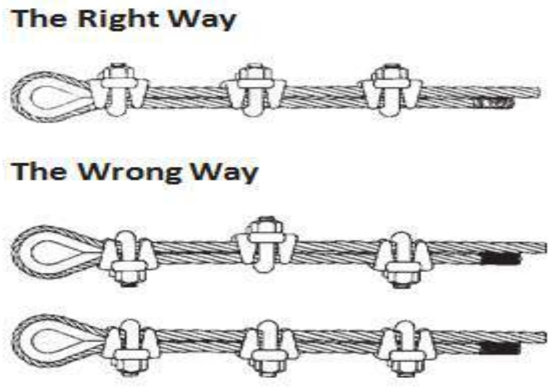


Figure 7.14a. Loop Made from Manilla Rope, Ropes using Rope Clamps, and a Thimble

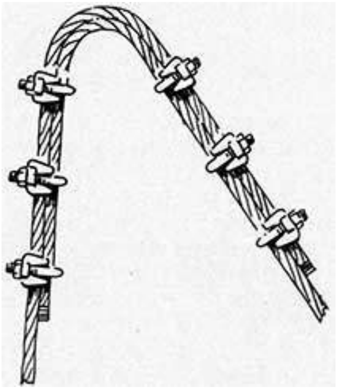


Figure 7.14b. Joining Two ropes clamps

The platform has an overall dimension of 21 by 22 inches and places the mannequin a little over 2.5 inches above the ground. The tubing sizes used to create the platform is 1"x1" square tubing with a thickness of ⅛" and 1.5"x1.5" square tubing with a thickness of 0.12 inch. The material choice for the tubing is steel as it provides a higher yield strength. Steel is chosen because it has higher material properties than aluminum, weight of the platform is not crucial, and to help with impact resistance as the impact loads can be unpredictable.

The lateral translation subsystem is divided into four subassemblies. The entire subsystem is seen in Figure 7.15 and description of all subassemblies follows.

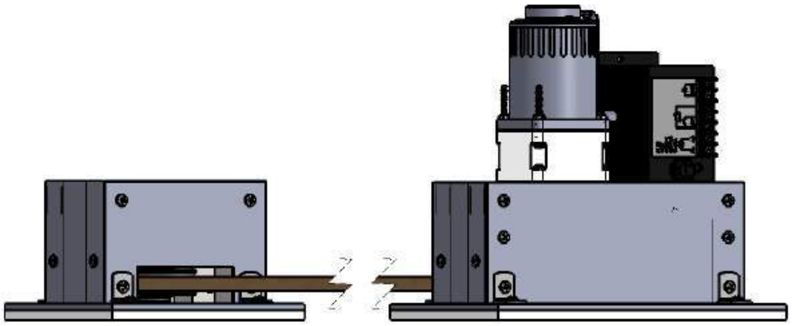


Figure 7.15 Motor Housing for the Lateral Translation System (Original design, current has a slightly different motor and the base plates are longer to leave room for cinder blocks to add weight).

The first subassembly for the lateral translation is the motor housing subassembly as seen in Figure 7.16 and in assembly 710 in Appendix M. It is a base of two 12" by 12" plates, the bottom plate is .25” thick rubber to increase the friction between the housing and the road to ensure that the housing does not move. This bottom plate will be adhered to the upper plate using contact cement. The upper plate is a .1875 in thick steel plate. The bottom plate has holes to allow the end of the bolts attaching the corner brackets to the top plate to sit. The top plate has a .08 deep hole to seat the bearing on the motor shaft. Attached to these plates are four 3.5 in tall vertical supports that are made of 1 inch square tubing that is .125 in thick. Resting on top of the vertical supports are two, 6.2 in long, horizontal cross supports of the same square tubing used for the vertical supports. The supports are encased by a sheet metal cover made of four pieces of .024 in thick steel sheet. All of these pieces are bolted together with M4 bolts and corner brackets to secure the supports to the base. The front of housing is left open for easy access to the pulley.

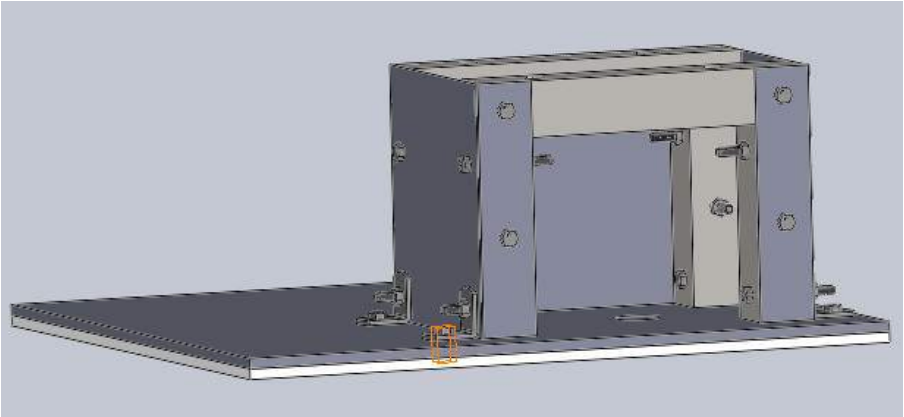


Figure 7.16 Housing for the Motor, Pulley, Driver, and Gearbox

The second subassembly is the slave pulley housing subassembly. This is very similar to the motor housing subassembly. One of the differences are that there is only one cross support in the back that has holes to support a bearing for the top of the shaft through the pulley. Another difference is that the two front vertical supports are as tall as the back vertical supports with the cross support on top of it. The covering has a door on the top for better access to the pulley. The other difference is that this housing has a base of 6” by 12” with a thin plate on top to extend the plate to be 14” long to give room to place cinder blocks. This subassembly can be seen in Figure 7.17 and in assembly 720 in Appendix M.

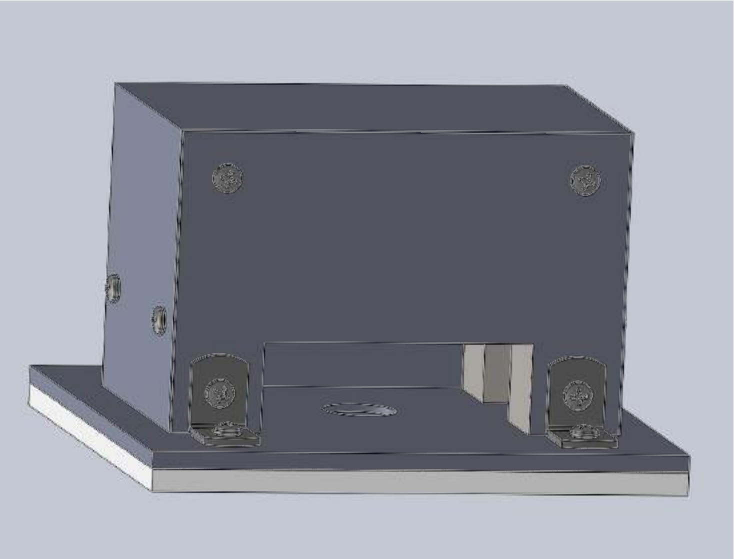


Figure 7.17 Slave Pulley Housing (Original design, current has no front panel, a door on the top, and a larger base plate to allow room for cinder blocks).

The next subassembly is the motor and pulley subassembly which can be seen in Figure 7.18 and assembly 730 in Appendix M. The driver is the white box on the left; this will control the speed that the motor will run. The driver is powered by 110 VAC input. The selected motor is a 200W single phase variable speed motor. The motor is connected to the driver as well as to a gearhead to increase the motor torque to the 25 lb-in we need to move the mannequin. These three parts are ordered from the same company and are designed to work well together. The pulley has a 2.25” outer diameter and has a groove designed for a ⅜” diameter rope. This was selected to work with a strong but small strength size of manila rope which has more friction than other ropes of similar strength; this will help ensure that there is little to no slip between the pulley and the rope. The shaft coming out of the gearhead is ⅞ mm and we need to connect to a pulley for a shaft of ⅜” diameter. This coupling is accomplished with a slotted-disc shaft coupling made of the three parts, two hubs and a disc center. This coupling is attached to a ⅜” diameter 2” long shaft through the pulley. On the end of this shaft is a thrust ball bearing that will be seated in the base of the housing.

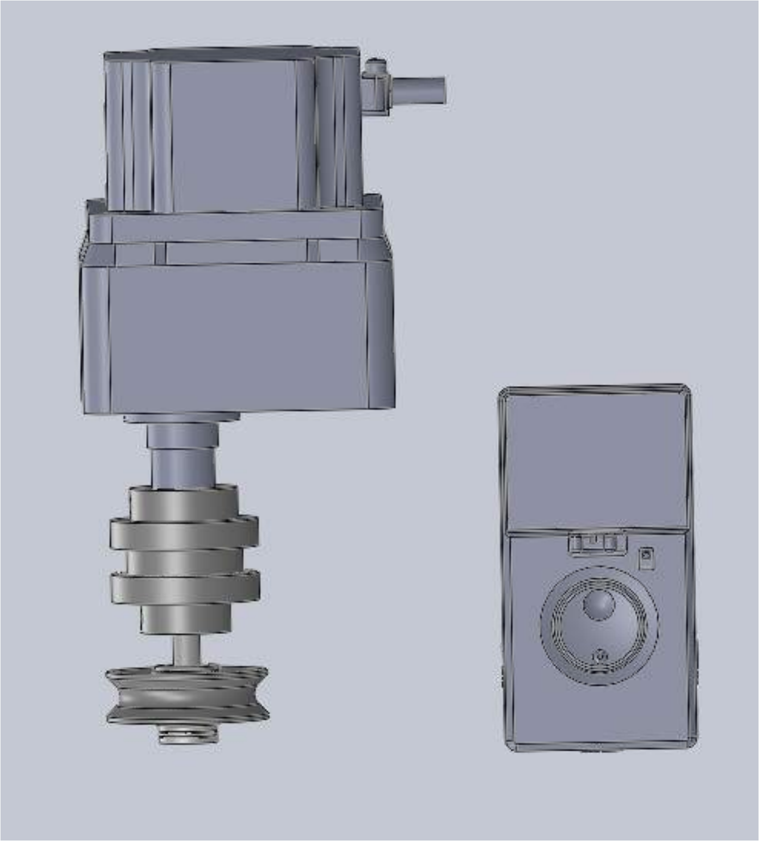


Figure 7.18 Motor and Pulley Subassembly

The final subassembly for the lateral translation is the slave pulley subassembly which can be seen in Figure 7.19 and assembly 740 in Appendix M. This subassembly is composed of only five parts: the thrust ball bearing, ⅜" shaft, pulley, manila rope, and a mounted ball bearing. The first four parts are the same as those used in the motor and pulley subassembly except that the shaft will be 3.25" long. The mounted thrust ball bearing will support the top of the shaft and is designed to mate with a ⅜" diameter shaft. The completed assembly of both sides of the lateral translation system can be seen in Figure 7.20.

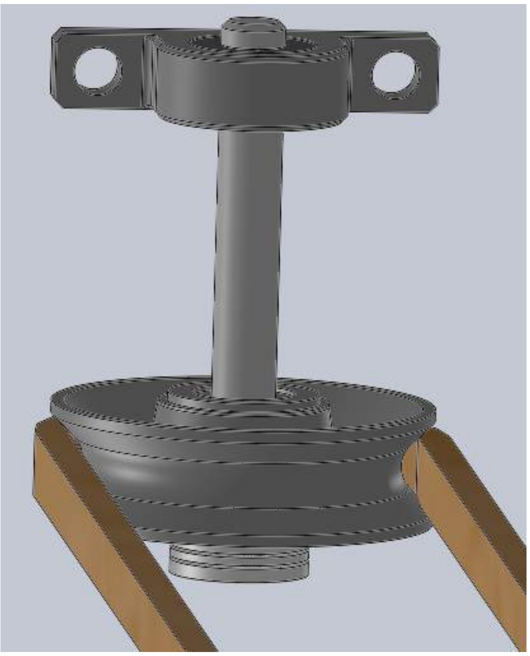


Figure 7.19

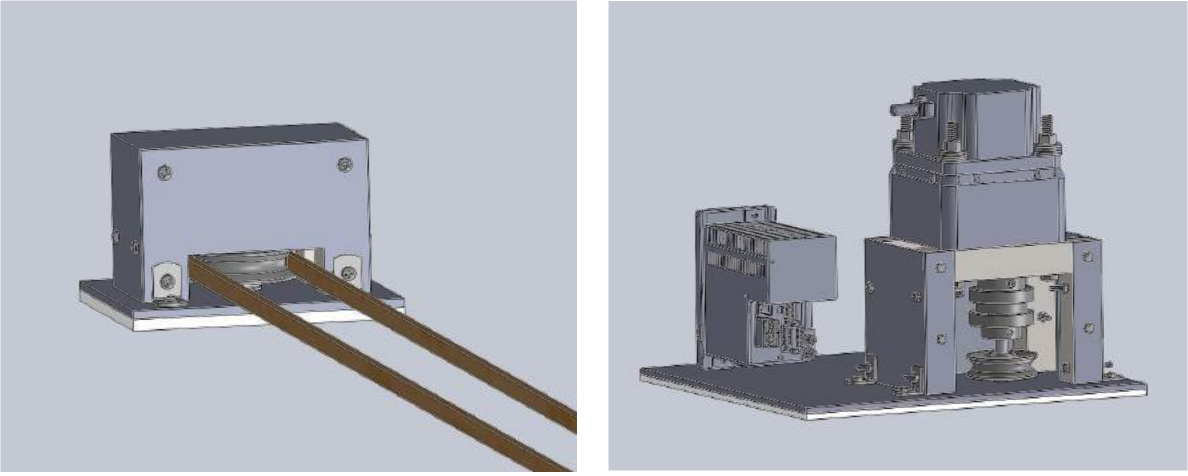


Figure 7.20 Isometric Views of the Lateral Translation Assembly Showing the Slave Side (Left) and Driver Side (Right).

8. PLANNED FABRICATION AND ASSEMBLY

The next step in our Senior project will be to order parts and then begin building our design. Careful consideration has been put into the best and easiest ways for the construction. The steps we will take to make each subassembly are seen below.

8.1 TORSO STRUCTURE

The stock materials used in the torso structure will be steel plates and square tubing. The tubing will be cut roughly larger than the specified size using a band saw; a milling cutter will be used to cut the tubes to size. To ensure alignment between mating parts, we will then use the end mill to cut holes into the square tubes. The triangles used in the body and shoulders will be made of steel plates. We will use the band saw to cut the stock to the relative size. An end mill will be used cut the triangle shape and cut the holes into the parts. The main torso structure will be assembled using various bolts, all ⅜ inch diameter in order to standardize the process The base plate will be shaped using an end mill and several holes will be drilled. The holes that connect the bottom torso plate with the pole flange will be threaded using a ¾ inch hand tap. Once all the parts are cut, the torso structure will be assembled using bolts. Expanded polyester foam will be attached to the torso structure. The process to do this will involve roughing the surface of the metal will 400 grit sandpaper, cleaning the surface and applying spray adhesive to the rough surface. The adhesive will be left to dry until the surface of the metal feels sticky. The foam will then be applied to the metal. The foam head will be attached to the neck tube using the same method. The servos will be bolted to the torso structure.

8.2 DETACHMENT

The updated detachment method is relatively simple and relies on magnets to hold and release the rod. Because magnetic materials such as steel were discarded for the rod itself due to their high radar visibility, the rod will instead be held by a relatively unobtrusive amount of steel at the base. Because this has a much smaller profile than a multiple-foot long rod, covering it with anechoic foam to hide its radar signature is feasible. The actual device will be built by drilling 4 holes in a steel plate to allow 2 U-bolts to hold the pole tightly. The plate will have nuts on its back preventing it from sitting flush against another plate; as such, we have selected magnets with the same thickness as the nuts to allow them to sit directly between the 2 plates. The 3 plates keeping the apparatus in place will be welded to the platform. This is due to the concern that the original design, which bolted the plates to the platform with brackets, ran the risk of having the rod holder catch on a bolt when attempting to slide free. The small modular nature of the magnets allows us to add or subtract some as we experimentally test our product. However, their small size runs the risk of getting lost if they move with the grip plate and rod rather than remain with the platform during an impact, or even being lost in between testing sessions. For this reason, we will provide extra magnets to the customer. The welding can be easily accomplished separately from the rest of construction because the top plate. The top plate which the plates will weld to is separate from the rest of the platform and can bolt on after the rest of the structure is complete. Because we are welding relatively thin steel without the need for extremely precise welds, MIG is the option of choice.

8.3 LIMBS

To assemble the limbs, batting will be cut to the correct length for each segment of each limb. The batting will then be rolled tightly around the core tubing until the correct diameter is reached and the batting will be cut to size. The fabric covering will be sewn inside out to the correct limb sizes and shapes based on our human anthropometric data; one total covering for an entire limb. The covering will then be turned right-side-out and sewn across at the elbow or knee many times in a zigzag pattern to create the joint. Holes will be cut near the top of the limb for the 90 degree elbow attachment to the servo shaft and grommets will be installed just below the mannequin's elbow to connect to the fishing line. The elbow will have a hole drilled through it for the eye bolt, which be placed at the correct height by use of two nuts. The elbow will then be inserted on the core and tightened with the set screw. The core will be tacked (with thread) to the covering at the base of each segment to ensure that it does not move. Once all components are inside the limb, the top and bottom will be sewn shut. The 90 degree elbow will then be attached to the servo shaft with the set screws. The fishing line will be connected using strong knots between each eye bolt and the grommet. If it is determined to be necessary, hands and feet will be sewn and stuffed to be attached at the correct locations. The intention of the batting is that the limbs deform and suffer no permanent damage, but if any maintenance is needed adding more stuffing is a simple fix. For damage to the fabric covering, a patch can cover for small rips but larger tears may require creating entirely new covering. Doing so is neither expensive nor difficult, but it is a nuisance for the customer we aim to minimize by using durable upholstery as the cover. If the fishing line is to snap, a taut length should be tied between the eye bolt and the grommet when the arm is the neutral position (not bent).

8.4 PLATFORM

For the components used to create the platform, most are stock part with only a handful of fabrication required. By incorporating almost all stock parts, the maintenance and repair can be easily completed. If a component is broken, the operators will be able to purchase the stock part and use the detailed drawings to make simple and minor modifications such as cutting parts to size and drilling holes in their correct locations. In addition, the platform is assembled by bolts so if the platform were to need repair, it would be easy to disassemble the platform to replace a component and reassemble it again. One component that will require cutting stock part to length is the top plate as it must be cut down to the 8"x10" dimensions. In addition, the 6 tubings, 4 shafts, and 8 connector plates must be cut down to the correct length. The rest of the manufacturing will be drilling or tapping holes as the physical assembly of the platform is achieved through bolting the members together. The correct dimensions, hole type and location can be found in the drawings for the platform assembly starting at drawing 500 in Appendix M. For the wheel assembly, the flanged shaft mount will be bolted to the outermost, 22 inch long tubing. Then the shaft will be mounted by the clamp-on mechanism found in the shaft mount using a hex socket head cap screw. Going first onto the shaft is a single ball bearing and what follows is the bushing, the second ball bearing. The wheel will then be placed onto the two ball bearings, possibly requiring added force as the inner diameter of the wheel is the same size as the outer diameter of the ball bearings. The thrust bearing will then be added onto the shaft after the wheel. To keep all of the components from sliding axially along the shaft, a shaft collar will be added as the last component on the shaft.

8.5 ELECTRONICS

The electronic assembly aims to be as simple as possible because it is not the main focus of this project. Once components arrive, we will create the circuit shown in Drawing 800 in Appendix M on a breadboard to verify that everything functions correctly. A 9V battery will power the Arduino board, which will in turn power the input sensors. The servos will connect to their own separate power sources for longevity; the arms and legs each have their own battery because connecting batteries in parallel poses a risk if care is not taken to ensure that they are at the same charge state. The 9V battery will mostly likely need to be replaced before each testing day, as tests are general months apart. The 7.4V cells should likewise be charged before each use. When we are confident the wiring and electronics work as intended and have finished building and testing the mannequin structure, the components will be set in their final positions and connections will be soldered. The Arduino controller and the batteries will have as much protection as possible, being encased in a hard shell housing in addition to being surrounded by padding in the center of the torso. Wires will run out from the casing to the servos and sensors, which must be partially exposed. They will all mount onto the frame with bolts. The primary electronics are expected to last the lifetime of the product, and the cheaper parts such as the button are easily replaceable. The only issue is desoldering the connections, which can be accomplished with a desoldering pump if the need for replacement is not urgent. The users will have access to the internal systems by opening a flap on the torso padding secured by Velcro, so they can adjust the electronics if necessary.

8.6 LATERAL TRANSLATION

Construction of the motor and pulley housings should be relatively simple. All tubing and plate should be cut to the correct size and holes should be drilled into all pieces according to the drawings in assembly 700 in Appendix M. Once this has occurred, the rubber plates should be attached to their respective steel plates using the contact cement. This should be allowed to set for the time specified on the container. After this, all the pieces can be placed bolted together. The motor shaft should be attached to the gearhead and bolted together. The shaft out of the gearhead will be attached to the shaft coupling and then that will be attached to the ⅜" shaft. This should then be press fit into the pulley far enough onto the shaft so that there is just enough space for the thrust ball bearing. A similar process should be followed for the slave side shaft, pulley, and bearings. The next step will be to bolt the front or back covering onto the vertical and cross support to hold them together. Once the back and front are assembled, the motor to bearing assembly and the driver should be bolted to the cross pieces (for the slave pulley housing, instead bolt the mounted bearing in place using the M5 bolts). The side coverings can then be bolted on (for the slave pulley housing, the side and top cover will be bolted on at this step). Next these components will be bolted to their respective base plates using the short M4 bolts and the corner brackets. The rope with be tied together, around both pulleys. When this is ready for testing, the platform can then be attached to the rope. If the rope is to break during testing, extra lengths will be available and manila rope is easy and cheap to purchase. If any of the steel supports or coverings become damaged, the housing is easy to unbolt and replace a piece, if made to the specifications in our drawings; all pieces are just cut to length with a few holes drilled into it.

9. SAFETY CONSIDERATIONS

As is the nature of a collision with a 40 ton truck, safety is a large priority. To ensure that everyone involved will be safe, we designed our pedestrian target to mitigate possible hazards. There is a concern that there may be flying parts upon impact or that the 135 lb mannequin might hit someone during impact. Our solution to ensuring no parts will come flying off of the mannequin when struck is to cover the entire torso assembly with padding. This will make sure that any internal parts that could come loose will remain inside of the padding instead of being a projectile object. In addition, the padding will cover any sharp corners on the mannequin. This will help protect those handling the mannequin in the case that they drop it. However, in the operator's manual, we will specify that at all times a minimum of three operators must cooperate in handling, lifting, or transporting the mannequin at any time. In addition, every operator must wear safety glasses and hardhats at all times when working with the mannequin. We will provide clear and concise instructions on the set-up procedure. Furthermore, no small children shall be running around when the mannequin is in transport and during testing, operators must be safely outside the path of the truck and mannequin.

Another concern is that the tension on the rope may be too high and that it could break and possibly whip and strike someone. To prevent this danger from happening, we selected an extremely strong rope that has a break strength of 1,200 lbs, which is much larger than the tension that will be applied to the rope from the translation system. With the lateral translation system, there is also the concern with the truck driving and pulling the rope and consequently the entire lateral translation system with it. To mitigate this issue, we designed the translation system such that the rope and pulley are about an inch off the ground so that the truck will be able to drive over the rope without any components being trapped or pulley by the wheels. In addition, the power source available during testing will be 110VAC. To protect those involved with testing, the motor allows for this input voltage without any adjustments and can be directly plugged into the generator providing this high voltage. The motor housing will also contain the moving parts such at the pulley and the output shaft of the gearbox. This will prevent moving parts from being projectiles as the housing will be able to contain them.

The expected usage of this product involves contact with vehicles traveling less than 3 mph and braking at a rate of 3 m/s^2 (10 ft/s^2) due to either assisted braking technology or a manual driver. Under these conditions, the risk of the mannequin as a whole becoming a projectile is very low. The greater concern is material failure, which could cause a piece to break off and become a projectile. These concerns are addressed in the detailed analysis that can be found in Appendix H. The detailed analysis is used to verify that there is an acceptable factor of safety to prevent any yielding or failure of all components.

The weight of the mannequin is itself a safety concern, especially with the intentional detachment of the mannequin and platform. To mitigate this, we have enclosed the rod on 3 sides such that it will only fall in one direction so it is less likely to fall on a person. In addition, the mass can be an ergonomic hazard as it will be lifted up from the ground. At least 3 people should lift it together and split the weight to less than 50 lb each.

The motors are not safety concerns in and of themselves. Both the translation motor and the articulation servos will be enclosed in housings to prevent pinch points. The motion of the limbs is not dangerous as they have little mass and move at low speeds. The overall motion of the large masses of the platform and mannequin is a safety hazard inherent to this product, which we can only mitigate by instructing operators to remain a safe distance away from the system while in motion. Considering the fact that it is intended to operate in concert with a large moving vehicle, this instruction should be redundant.

The electronics are another safety hazard. The motor driving the pulley will connect to a 110 V power source. However, that assembly will be entirely stock and trust in the reliability of a commercial motor manufacturer. For our purposes, the only concern there is the power cable coming loose, which could occur if the pulley housings do not remain stationary. Because sliding motors would cause a multitude of issues, the housings are designed with rubber bottoms to increase friction with the ground and shall have sufficient weight to prevent sliding under the loads required to move the platform. Analysis for this is shown in Appendix H. Greater loads could occur if the rope is caught under the truck tires, but the customer has stated that the space between the bumper and tires is sufficiently large that a braking truck will not run over the rope or platform.

The electrical components in the mannequin itself are especially hazardous because of the potential impacts they will experience. Although the entire mannequin will be padded, the most sensitive electronics (the Arduino microcontroller and the batteries) will be further protected inside a hard shell case with foam. Some components have to be exposed, such as the user inputs, but their wires at least will be soldered into place to prevent loose connections. We will ensure that all hazardous components will be protected inside a locked, hard shell case and the only exposed components will be those required for a user interface such as a switch or potentiometer.

10. ANALYSIS FOR DESIGN

We did analysis to verify that our chosen design will function how we anticipate. Our hand calculations and computer simulations can be seen in Appendix H.

10.1 TORSO STRUCTURE

We began the analysis of the torso structure by investigating the force that would be applied to the torso during the impact. Early in our investigation, we found a SAE paper [SAE 751165, 1975] which produced a graph of the impact force felt by a leg based on the speed of the vehicle, shown in Figure 10.1. In this simulation the leg of the mannequin was made of padding wrapped around a steel skeleton. A body force measuring trolley hit the mannequin and measured the impact force. The trolley had a bumper that could adjust to various angles and heights. These heights and angles labeled for each curve in Figure 10.1.

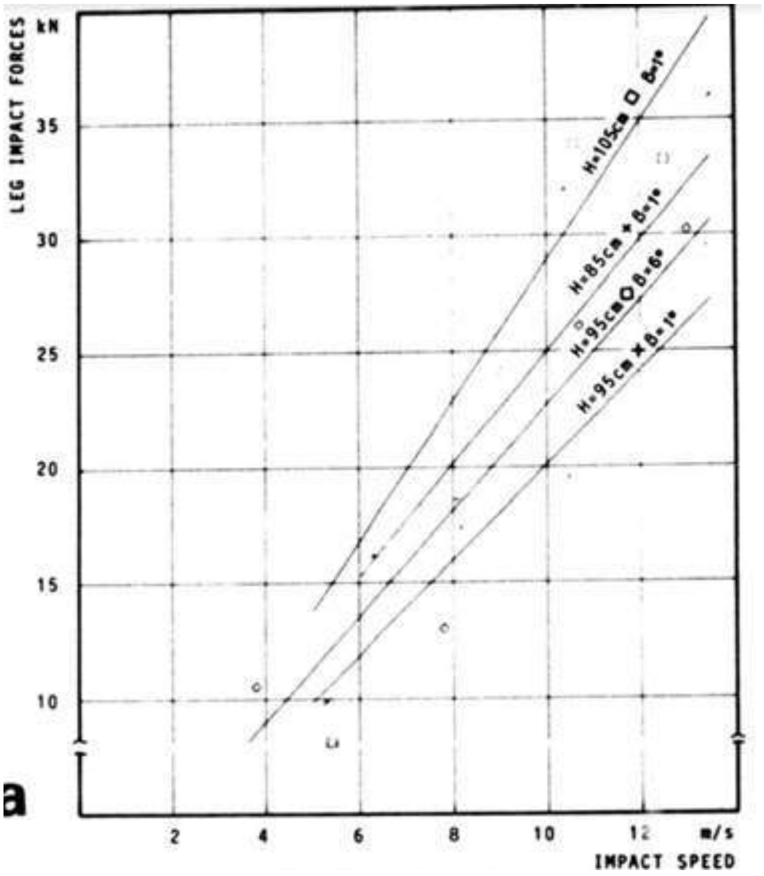


Figure 10.1. Leg impact forces at various speeds for a pedestrian vehicle accident simulation.

We chose to interpolate the curve corresponding to a bumper height of 105cm and angle of 1° because the large height and small angle best represented the bumper of a semi-truck. The interpolated force for a 5 mph impact was approximately 700 lbf.

We understood this force was not completely representative of the impact force our test target would feel. In this simulation, the steel skeleton was wrapped in foam, which deformed and absorbed energy in the system. Additionally, the impact was of a leg not the torso of the mannequin. With these limitations considered, we chose to use this force to only initially size the square tubing for the torso structure. We would later use a dynamic finite element model to refine our design.

We began the first iteration of our design by determining the cross-sectional dimensions of the square tubing. We analyzed a simple static loading case shown in Figure 10.2. In this case a L shaped square tube is fixed to a wall like a cantilever beam. A force is applied at the tip of the beam to produce a moment, shear force, and torsion near the base of the beam. A detailed description of the analysis is shown in Appendix H.

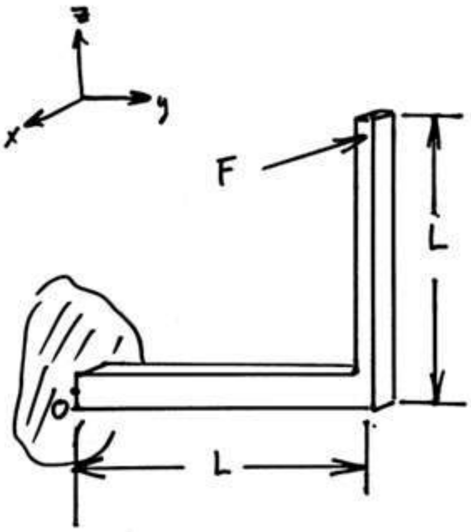


Figure 10.2. A force acting on a cantilever beam made of square tubing.

The length of the largest member in the torso, 20 inches in length, was used in this analysis. We used steel as our material and placed a design factor of 2 on the yield stress of the part. In addition, we considered buckling with end conditions that are completely fixed, since all the parts would be rigidly attached to each other. The input criteria are shown in Table 10.1. A figure of the dimensions of the cross section are shown in Figure 10.3.

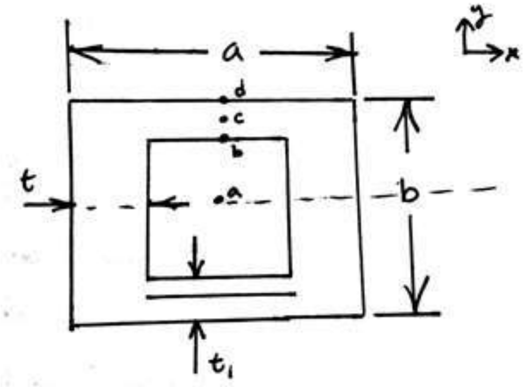


Figure 10.3. Cross-sectional dimensions of the square tubing.

Table 10.1. Input criteria of the 20-inch square tube.

Inputs	
Material	Steel
G [lbf/in^2]	11500000
E [lbf/in^2]	30000000
S_y [lbf/in^2]	46000
Density [lbf/in^3]	0.282
a [in]	2
b [in]	2
t [in]	0.12
t_1 [in]	0.12
Area [in^2]	0.902
n_d	2
S_y' [lbf/in^2]	23000
C	4
l [in]	20

We found a 2x2 inch square tube with a thickness of 1/8 inch produced stresses that were acceptable. As shown in Table 10.2, bending stress was the highest stress and was only slightly larger than the design yield stress of 23000 psi. The axial stress was small and buckling was not an issue since the buckling stress was larger than the yield stress. All the tube members, except for the shoulder, had this type of cross-section.

Table 10.2. Stress values for a 20-inch-long 2x2 inch square tube with a thickness of 1/8 inch.

Max Bending Stress	
$\sigma_{x,b,max}$ [lbf/in^2]	26230
$\sigma_{y,b,max}$ [lbf/in^2]	26230
Bend % Diff	14
Max Transverse Shear Stress	
$\tau_{x,s,max}$ [lbf/in^2]	1740
$\tau_{y,s,max}$ [lbf/in^2]	1740
Shear % Diff	-92.4
Avg Torsional Shear Stress	
$\tau_{x,t}$ [lbf/in^2]	16504
$\tau_{y,t}$ [lbf/in^2]	16504
Torsion % Diff	-28
Max Axial Stress	
$\sigma_{a,max}$ [lbf/in^2]	775
Axial % Diff	-96
Buckling Stress	
$\sigma_{x,buck}$ [lbf/in^2]	45697

The stresses on the shoulder were found using the same method used in the previous square tube. The length of the tubes was set to 5 inches because it will be the largest length of the shoulder. As before, the inputs are shown in Table 10.3.

Table 10.3. Input criteria of the 5-inch square tube.

Inputs	
Material	Steel
G [lbf/in^2]	11500000
E [lbf/in^2]	30000000
S_y [lbf/in^2]	46000
Density [lbf/in^3]	0.282
a [in]	1
b [in]	1
t [in]	0.12
t_1 [in]	0.12
Area [in^2]	0.422
n_d	2
S_y' [lbf/in^2]	23000
C	4
l [in]	20

Again, assuming a 700 lbf would hit the shoulder tube. We found a 1x1 inch square tube with a thickness of 1/8 inch would be sufficient for our application. The stresses are shown in Table 10.4. We see again, bending stress is the highest stress. It is noticeably higher than the design yield stress, but lower than the actual yield stress. We decided to move forward with this selection.

Table 10.4. Stress values for a 5-inch-long 1x1 inch square tube with a thickness of 1/8 inch.

Max Bending Stress	
$\sigma_{x,b,max}$ [lbf/in^2]	31513
$\sigma_{y,b,max}$ [lbf/in^2]	31513
Bend % Diff	37
Max Transverse Shear Stress	
$\tau_{x,s,max}$ [lbf/in^2]	3683
$\tau_{y,s,max}$ [lbf/in^2]	3683
Shear % Diff	-84
Avg Torsional Shear Stress	
$\tau_{x,t}$ [lbf/in^2]	18831
$\tau_{y,t}$ [lbf/in^2]	18831
Torsion % Diff	-18
Max Axial Stress	
$\sigma_{a,max}$ [lbf/in^2]	1657
Axial % Diff	-92
Buckling Stress	
$\sigma_{x,buck}$ [lbf/in^2]	44641

We then checked the stresses of the bolts joints in each tube to ensure they would not fail under the 700 lbf load. We began by checking the tensile stresses in the connection of the torso bottom plate and the pole flange. A drawing of this loading case is shown in Figure 10.4 and the details of the calculation can be seen in Appendix H.

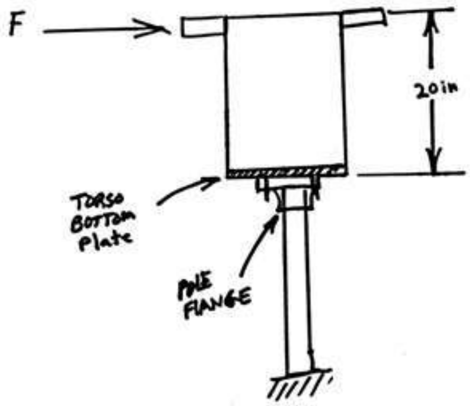


Figure 10.4. Force acting on shoulder of test target causing a moment at the pole connection.

The force acting at the shoulder of the test target would produce a moment at the connection between the torso bottom plate and pole flange. This moment would transform into a force couple acting on the bolts that connect the plate and flange. The magnitude of this force couple is shown in Table 10.5. Figure 10.5 can be used as a reference to understand the variables shown in Table 10.5.

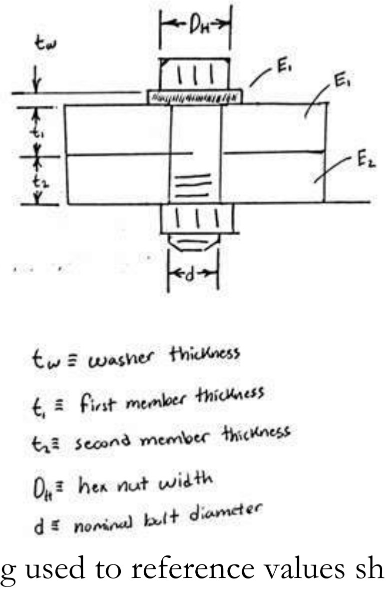


Figure 10.5. Drawing used to reference values shown in Table 10.5.

Table 10.5. Input variables for tensile loading of the bottom plate and flange bolt joints.

Inputs	
t_w [in]	0.104
t_1 [in]	0.375
t_2 [in]	0.5
D_H [in]	1.5
d [in]	0.75
E_1 [lbf/in^2]	30000000
E_2 [lbf/in^2]	14500000
E_b [lbf/in^2]	30000000
H (hex nut) [in]	1
P [lbf]	1000
F_i [lbf]	0
n_d	2
S_p [lbf/in^2]	33000
S_y' [lbf/in^2]	16500

Where H is the diameter of the hex nut, P is the tensile load, and F_i is the initial pretension. For this case the pretension was set to zero since the bolts will be tightened using a wrench. The tensile stress acting at the pole and bottom plate connection is shown in Table 10.6. The stresses occurring in this region are minimal

Table 10.6. Bottom plate and pole flange stress due to and bending moment.

Tensile Stress	
σ [lbf-in]	607
% Diff	-96

Shear loading is a significant issue in bolts. In this analysis, the square tube was modeled as a plate bolted to another plate with a force pulling along each plate as shown in Figure 10.6.

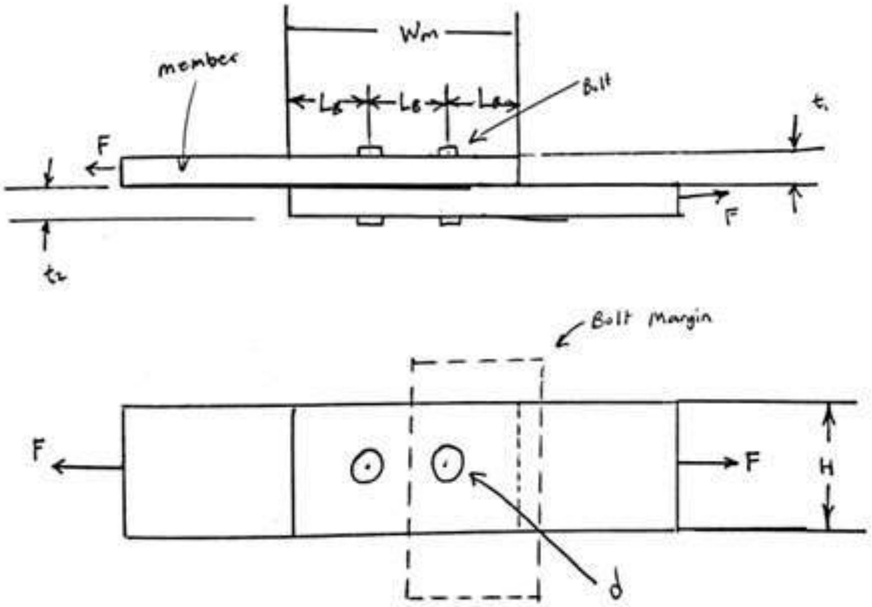


Figure 10.6. Bolts under shear loading.

There are several modes of failure that must be investigated for shear loading. The bearing stress in the bolt is due to the pressing of the bolt against the channel web, the member also experiences stress due to this interaction. There is shear stress on the bolts and a possibility that there would be shear tear out if the bolt diameter is too large. Detailed calculations are shown in Appendix H. Edge shear at the margin of the bolt and tensile yielding can also occur. All these stresses were calculated for a 1x1 inch tube as well as a 2x2 inch tube. The input calculations are shown in Table 10.7 for a 1x1 inch tube. A force of 700 lbf was used in this case.

Table 10.7. Shoulder 1x1 inch square tubing bolt shear inputs

Inputs	
L_B [in]	1
t_1 [in]	0.12
t_2 [in]	0.12
H [in]	1
d [in]	0.375
a [in]	0.813
F [lbf]	700
n_d	2
d/H	0.375
k_t	2.4
S_y [lbf/in^2]	46000
$(S_y)_{memb}$ [lbf/in^2]	46000
S_y' [lbf/in^2]	23000
S_{ys}' [lbf/in^2]	13271
$(S_y')_{memb}$ [lbf/in^2]	23000

The resulting stresses are shown below, in Table 10.8. Using a 3/8-inch bolt diameter, we see all the stresses are well below the yield stress, even with a design factor of 2. Although, there still is a possibility of shear tear out.

Table 10.8. Shoulder 1x1 inch square tubing bolt shear stresses

Bolt Bearing Stress	
σ [lbf-in]	15556
% Diff	-32
Member Bearing Stress	
σ [lbf-in]	15556
% Diff	-32
Bolt Shear Stress	
τ [lbf-in]	6338
% Diff	-52
Shear/Tensile Tear-out	
d<H/4 % Diff	50
d<L_b/4 % Diff	50
Edge Shear @ Bolt Margin	
τ [lbf-in]	7179
% Diff	-46
Tensile Yielding	
σ [lbf-in]	22400
% Diff	-3

Not all shear loads occur with two plates being pulled apart. There are several cases where the shear stress is caused by an eccentric load. A drawing of the load condition is shown in Figure 10.7. In this figure, the upper portion of the drawing shows the cross sectional dimensions. The middle drawing includes the load acting at the center of the bar. Under this type of loading stress can occur from shear, bearing stress on the bolt and member, as well as a critical bending stress on the bolt closest to the eccentric load. A force of 350 lbf was used since each pair of bolts share the load equally. A detailed analysis of this loading case is in Appendix H. The inputs for a 1x1 inch and 2x2 inch tube are shown in Table 10.9 and Table 10.10, respectively.

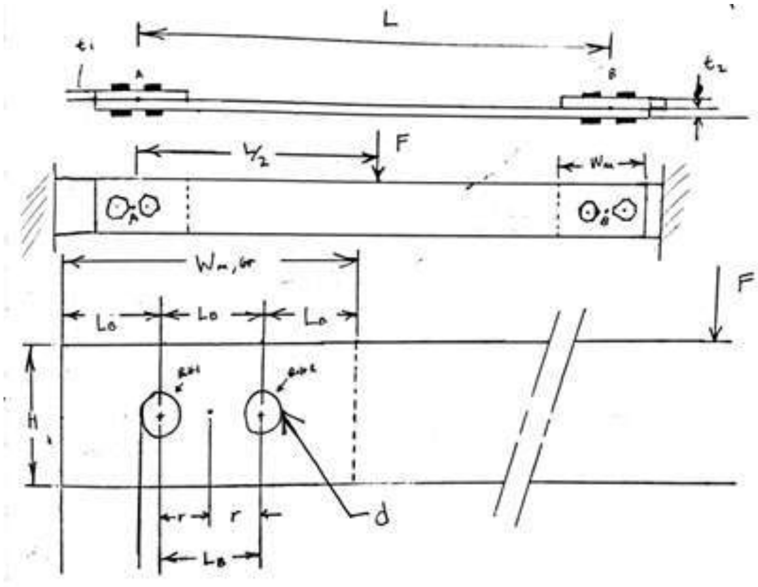


Figure 10.7. Drawing of an eccentric loading acting on two bolted ends.

Table 10.9. Inputs for shear Joint with eccentric loading on shoulder front.

Inputs	
L [in]	3
L_B [in]	1
t_1 [in]	0.125
t_2 [in]	0.125
H [in]	1
d [in]	0.375
F [lbf]	350
n_d	2
S_y [lbf/in^2]	46000
S_y' [lbf/in^2]	23000
S_{ys}' [lbf/in^2]	13271

Table 10.10. Inputs for shear joint with eccentric loading on the middle of a vertical 2x2in column

Inputs	
L [in]	10
L_B [in]	1
t_1 [in]	0.125
t_2 [in]	0.125
H [in]	2
d [in]	0.375
F [lbf]	350
n_d	2
S_y [lbf/in^2]	46000
S_y' [lbf/in^2]	23000
S_{ys}' [lbf/in^2]	13271

The stress due to eccentric loading for each tube are below the yield stress, so there is no issue with the bolt diameter nor the tube cross-sectional dimensions.

Table 10.11. 1x1 inch tube stresses caused by eccentric loading

Shear Stress on Bolt	
τ [lbf-in]	1980.6
% Diff	-85.1
Bearing Stress	
σ [lbf-in]	4666.7
% Diff	-79.7
Critical Bending Stress	
σ [lbf-in]	22169.1
% Diff	-3.6

Table 10.12. 2x2 inch tube stresses caused by eccentric loading.

Shear Stress on Bolt	
τ [lbf-in]	4753.4
% Diff	-64.2
Bearing Stress	
σ [lbf-in]	11200.0
% Diff	-51.3
Critical Bending Stress	
σ [lbf-in]	20082.4
% Diff	-12.7

A finite element model was used to simulate a semi-truck impacting a torso structure. This model is shown in Figure 10.8. Shell elements were used for each part of the test target structure since they require less computational time with little loss in accuracy. Solid elements could have been used, but the thin features of the tube structure could cause difficulties in meshing the assembly. There were no boundary conditions on the test target because we assumed the pole would easily detach from the platform. The large wall shown in the figure simulates the truck grill impacting the test target. The wall was modeled as analytically rigid, weighed 40 ton, and traveled at 5 mph. The wall could not rotate and was only allowed to travel in the Z direction.

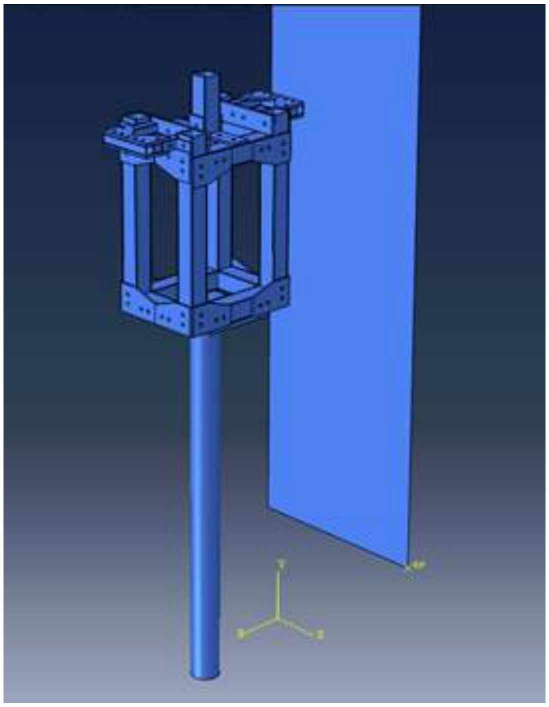


Figure 10.8. Finite element model of a truck impacting the test target structure.

The main body of the structure had material properties of ASTM 513 steel for the square tubing and 1018 CD steel for the plates. Partitions were made at the bolt hole locations and were tied their respective part to create the bolted joint. The pole has material properties of polypropylene. The edge of the pole was directly attached to the bottom plate of the torso body. Higher stresses may occur in this area because the pole flange was not modeled.

A convergence study was produced for this model. The test target was completely fixed at the end of the pole and a pressure load of 20 psi was applied to the one side of the test target. Figure 10.9 shows the results of the convergence studies. As we can see, the model begins to converge at an element size of 0.5 inches. An element size of 0.25 inches was used for a more refined mesh along the bolt hole locations.

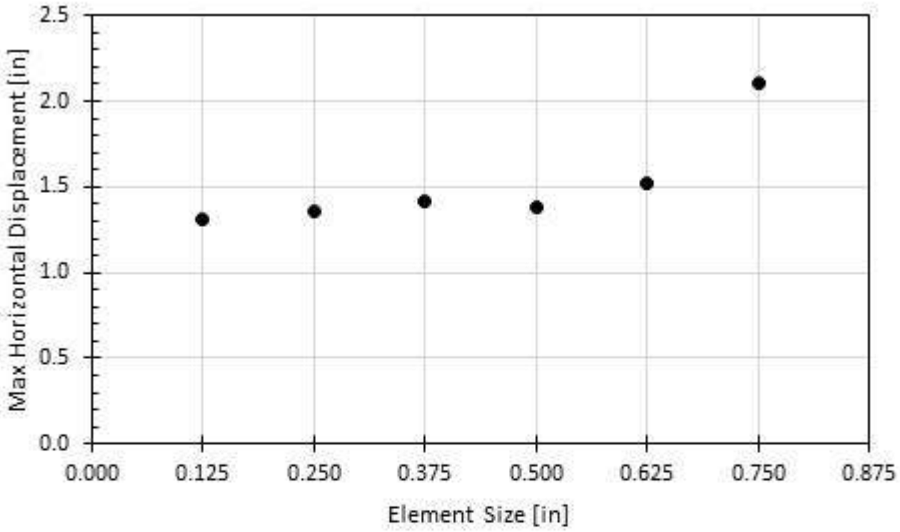


Figure 10.9. Convergence study for the test target structure.

The next step was to test the target under its self-weight. This was a standard analysis using a gravity field to simulate earth's gravitational acceleration acting on the torso structure. The results are shown in Figure 10.10. In this figure we see that the peak stresses under the self-weight occur at the lower bolt locations. The peak stress in this case was 2339 psi.

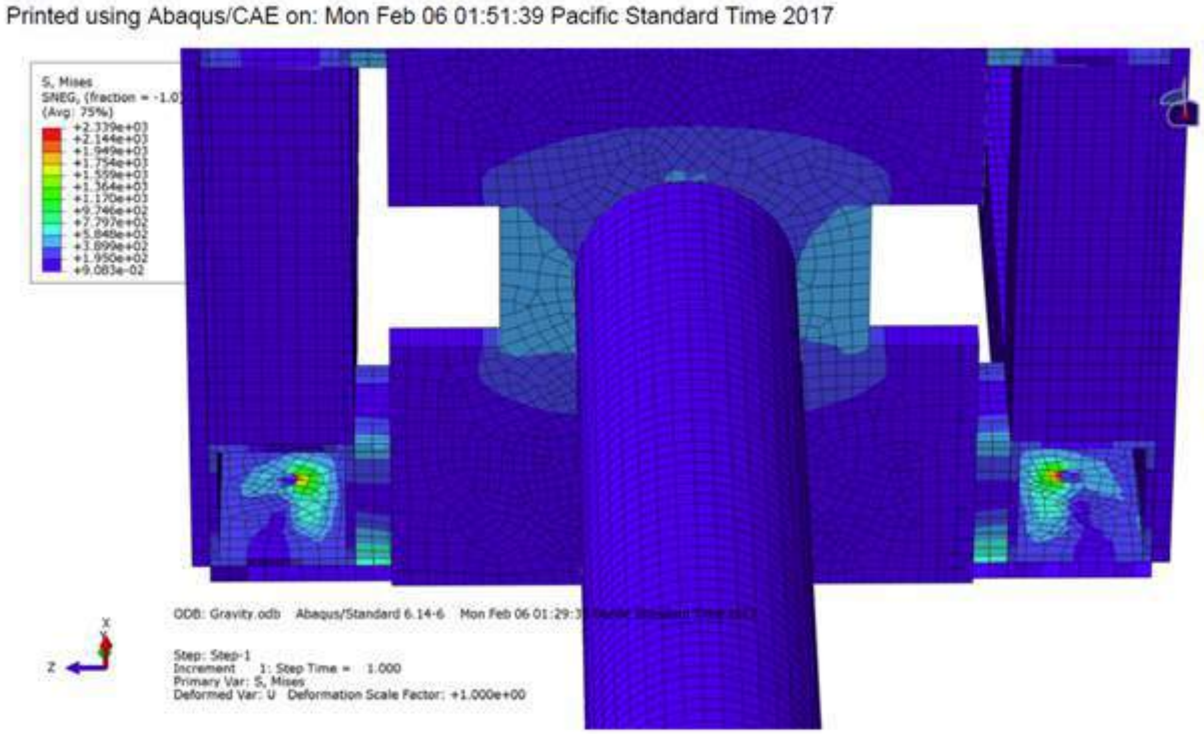


Figure 10.10. Location of peak stresses due to self-weight.

The model was then tested against the "semi-truck". The simulation was dynamic explicit with a total duration of 50 milliseconds. The truck traveled 4.4 inches in this time period. The following set of figures showcase the first 15 milliseconds of the impact.

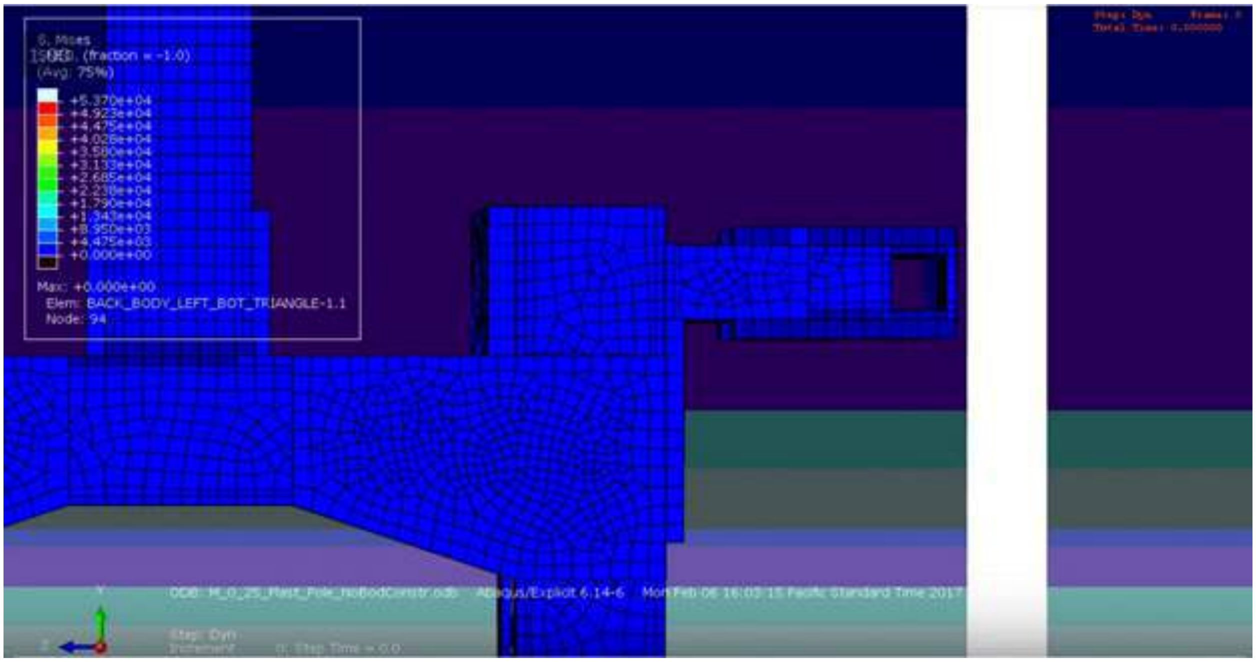


Figure 10.11. The start of the simulation.

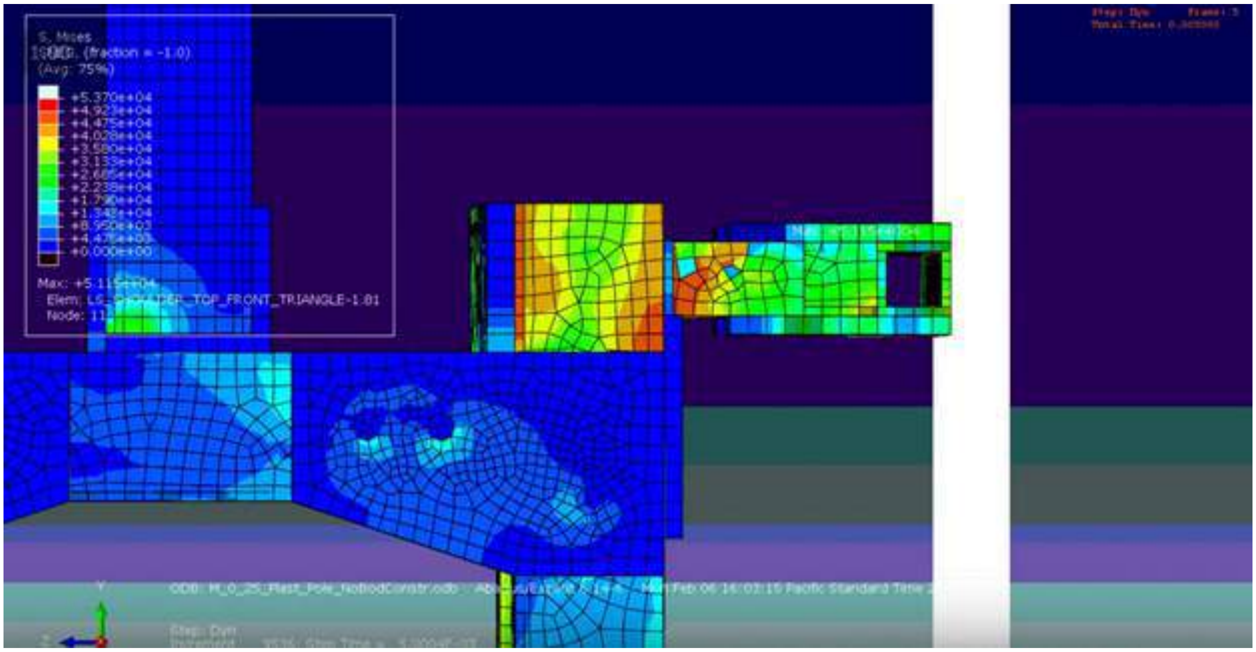


Figure 10.12. The initial impact.

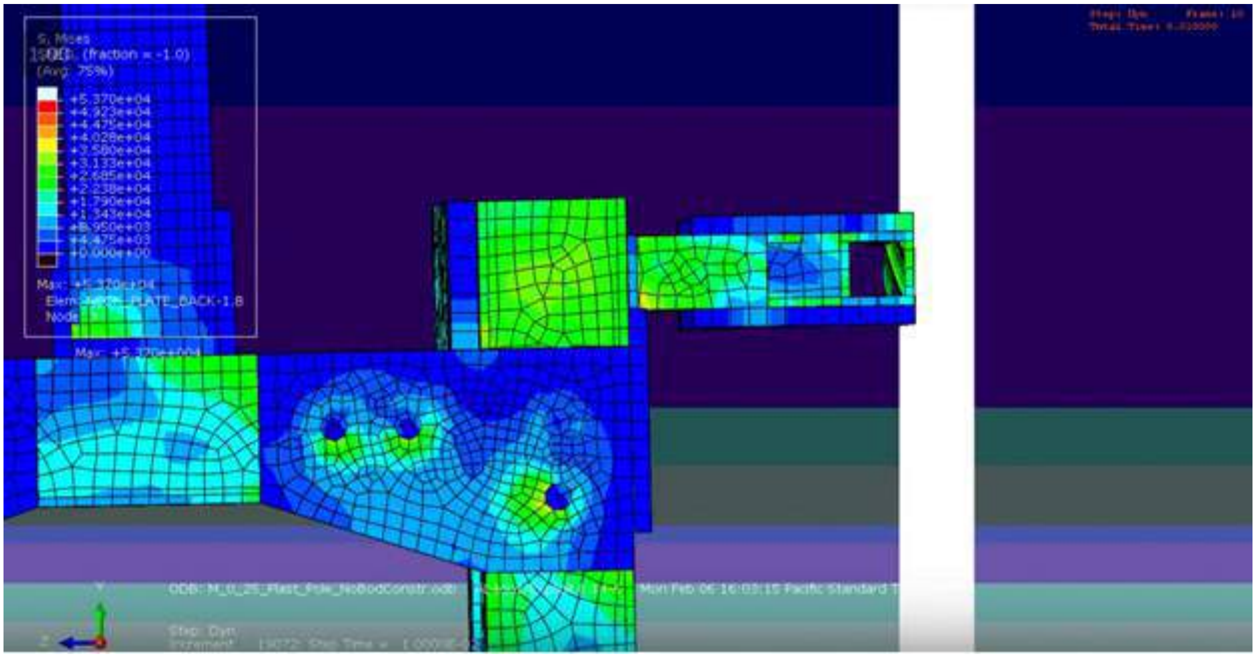


Figure 10.13. Five milliseconds after the impact.

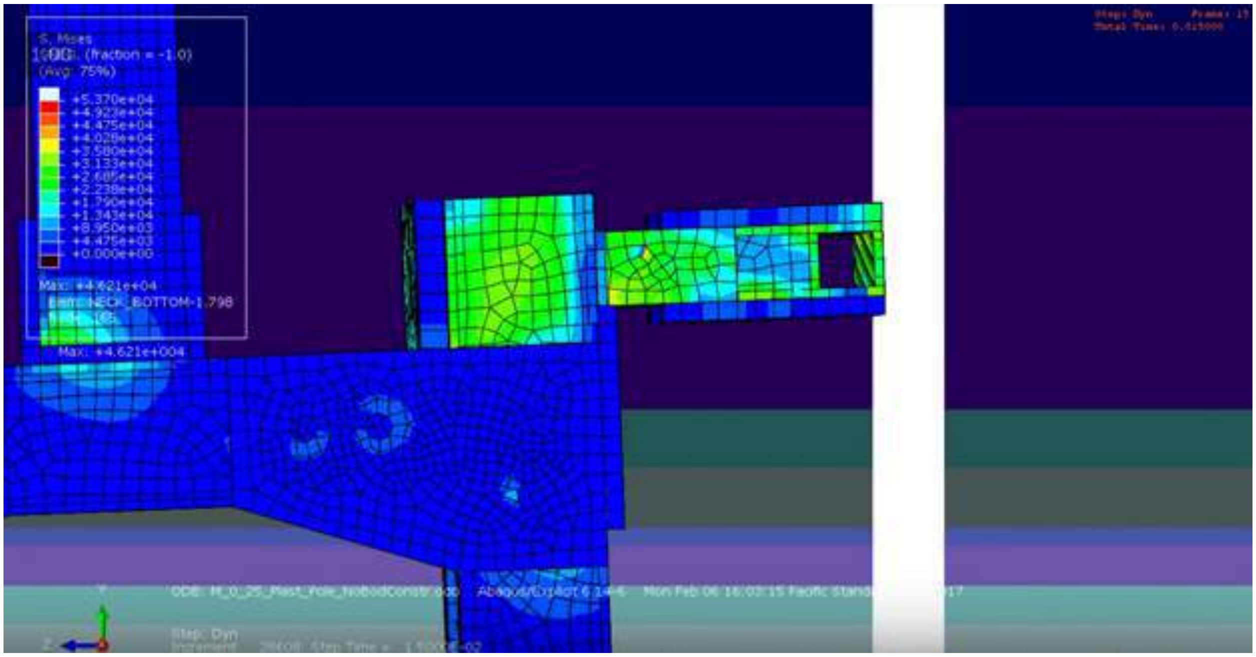


Figure 10.14. Ten milliseconds after the impact.

As shown in Figure 10.12, during the impact there are stresses that exceed the yield stress of the material in the square tubing. The stresses propagate through the material and the bolt joints, as shown in Figure 10.13. Finally, a steady state condition occurs ten milliseconds after the initial impact, shown in Figure 10.14.

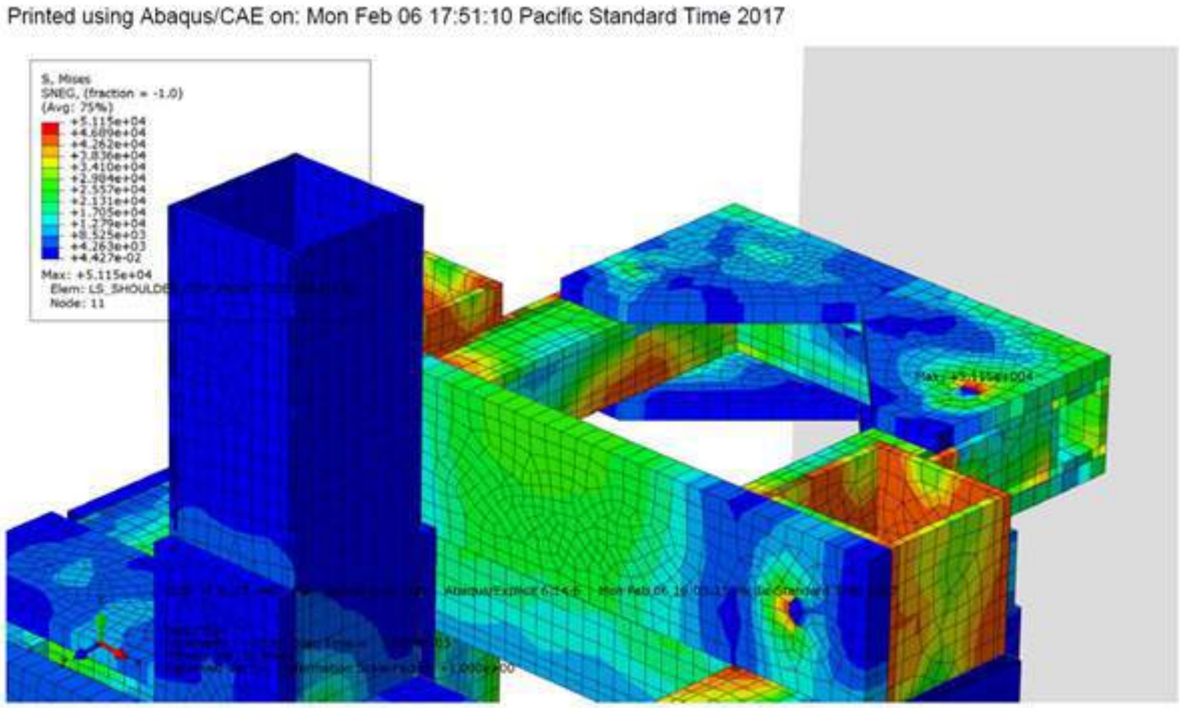


Figure 10.15. Isometric view of the shoulder as the impact occurs.

Figure 10.16. Stresses propagating through bolt holes one millisecond after impact.

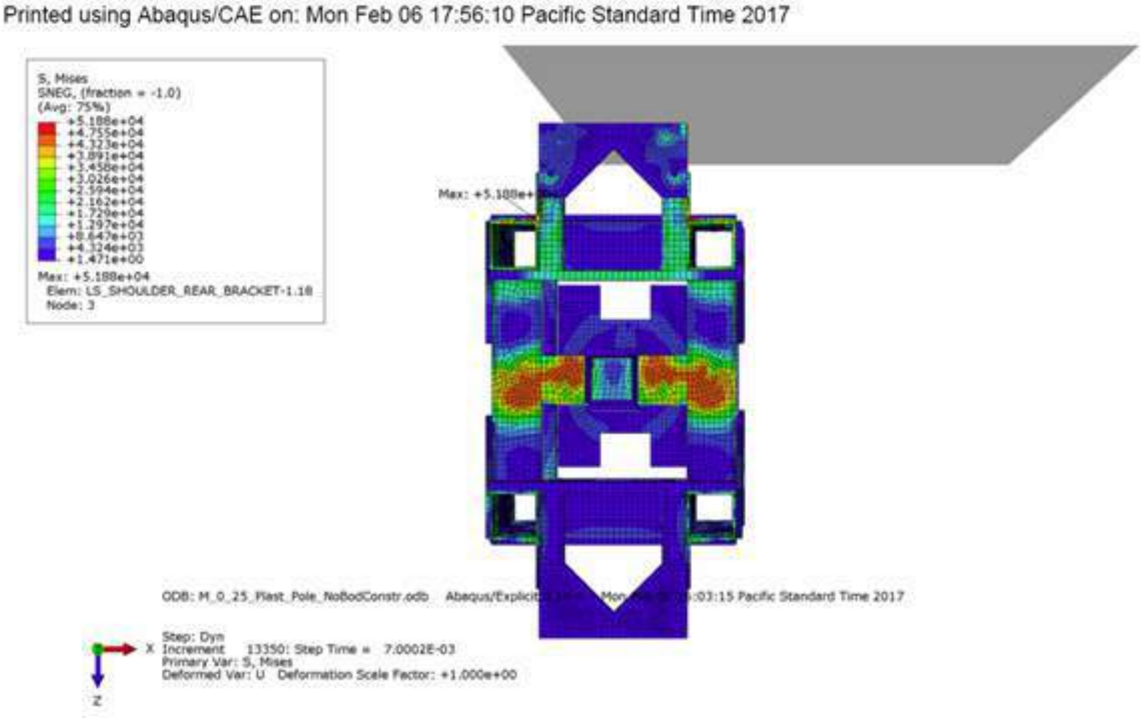


Figure 10.17. The stresses propagating through the square tubing and through the neck. (2 milliseconds after impact)

There are peaks stresses that can be seen throughout the torso structure immediately after impact. These high stresses are due to the completely rigid wall impacting the steel torso structure. The stresses are likely to be lower in the real world since the truck will actually deform as it hits the target. A layer of expanded polyester foam, the same foam used on bicycle helmets, and batting will cover the torso structure to protect the truck as well as the test target. Further modeling can be done to see the effects of foam in reducing the peak stress throughout the structure.

10.2 DETACHMENT

One of the aspects of this design is that the mannequin moves with the truck if impacted to reduce the loads and stresses. Our original design called for omniwheels to allow the entire platform to roll with the truck, but updated calculations with better force estimates and our lowered mannequin weight determined that such idea was infeasible without a prohibitively large platform to prevent tipping upon impact. As such, we moved to decoupling the pole from the platform. This presented some new challenges such as ensuring that the dummy both detach at the desired load so as not to damage the translation system and not detach at lower loads, which could ruin tests or severely injure people. We decided to use grip clamps for this, which designed to snap around pipe but be elastic enough to deform and snap off with sufficient force. However, we were not able to find grip clamps of sufficient size for our rod diameter, and discovered why when we calculated how to make our own. As shown in Appendix H, using Castigliano's Theorem to find the setup required to have the opening be larger than the rod diameter gave an unfeasibly small number. The holding tube would deflect less than 1/16" before freeing the rod, which is actually below the tolerances of the rod and tube. For that reason, we have settled on the final magnetic attachment design. The chosen magnets give can up to 40 lbf combined, but the manufacturer warns that their load rating tests are performed under ideal conditions and that actual force is almost always less. Because of that uncertainty and the fact that magnets of these small sizes come in bulk, we have selected the smallest load size that meets our physical specifications. We expect to use 12 2-lb magnets to achieve our design load of 24 lbf, but can easily add or remove more as necessary as we experimentally refine our values. The chosen design load is low so as to have a large factor of safety for the detachment system activating. It also has the benefit of significantly reducing stress and load calculations for any piece below the detachment point.

10.3 PLATFORM

To analyze the stresses throughout the platform, the detachment load upon impact with the truck at the shoulder is assumed to be 25 lbf at 60 inches above the platform. In addition, the total weight of the mannequin is found to be 135 lbf and the weight of the platform is 35 lbf. The loads were tracked and analyzed to determine the stresses through each component of the platform assembly. The stresses found from this analysis are shown to be very low with the detailed values and hand calculations shown in Appendix H. The loads were first found in the top plate which originate from the weight of the mannequin and the load at detachment. Then, the loads were traced through to the tubing holding the top plate as well as the bolts that connect the tubing to the rest of the platform frame. The platform was also analyzed as an entire structure to find the reaction forces at the wheels. This was followed with tracing the stresses and loads from the wheels to the tubing that the wheels are mounted to. After those loads were found, the stresses could then be backtracked towards the inner tubing of the platform frame. With these load assumptions, the stresses are merely a fraction of the yielding strength of the various components such as the tubing, bolts, and shaft. With a relatively small load onto the wheels of the platform, the bearing choice was chosen so that the bearing would directly fit on the shaft and inside of the wheels. The loads on each wheel came out to be about 70 lbf and that ensured that the bearings would be able to handle the load due to load capacity for the ball bearing being well above that at 300 lbf. In the end, the platform design is meant to be structurally robust to take unpredictable loads that can induce high peak stresses without yielding or fracturing any of the components.

10.4 SERVO MOTORS

The servo motors were selected based on their rated loads and the expected torques. To calculate the torques we performed a kinematics analysis on a 2-body system, with the two sections connected by a pin. The free body diagrams and algebraic calculations are in Appendix H. Knowing the physical properties such as mass and length, we derived equations for the forces and torques based on the linear and angular accelerations of the centers of mass. From there we took motion capture data of the legs and processed it to find the accelerations of the centers of mass for every instant captured by the data. The Matlab script used to solve the systems of equations for all inputs is also in Appendix H. Based on the data and knowing that the leg loads would be higher than the arm loads, we found a maximum torque of 90 oz-in. The average torque was much lower, around 20 oz-in. In addition, this method calculated the torques necessary to move the lower limbs like those of a human. While we knew that we would not be able to fully replicate this, we were surprised to find that the error of a free-swinging leg was comparable to that of one with a simple linear spring. A brief summary of the 325 data points is below. Note that these are magnitudes and can be applying in either direction.

Table 10.13. Highlights of Solving Kinematics Equations of Motion with Motion-Capture Data

	Hip Torque [oz-in]	Knee Torque [oz-in]
Max	104.82	102.32
Min	0.06	0.02
Avg	23.67119	23.04935

10.5 BATTERY CAPACITY

The servos were given a separate power supply for a variety of reasons, including concerns about their power drain. To determine how long this system would last, we took the current drains at no-load and at stall from the manufacturer's data sheet in Appendix H and linearly interpolated to estimate the current drain for any given load. Based on our average torque of 90 oz-in, we found that a 6500 mAh LiPo battery could run 2 servos for approximately 5.4 hours. In addition, we checked the maximum discharge rate of the batteries and the 40C cells have a maximum discharge well above even the stall current of the servos.

10.6 MECHANICAL TENDON

The articulation of the lower arm depends on the correct functioning of the mechanical tendon. This is a length of fishing line that is attached between an eye bolt above the shoulder to a grommet just below the elbow on the lower arm. The mechanical tendon works by the location of the eyebolt rotating in a different arc than the center of the servo shaft that rotates the arm. The connection of the fishing line to the center servo, through the eyebolt, and connection to the forearm is shown in Figure 10.18. This rotation pulls the fishing line and shortens the length of line from the rotation point to the attachment point just below the elbow. This causes the lower arm to rotate to a larger angle than the upper arm. In order to create the correct angles for the upper arm and the lower arm, the location of eye bolt and the grommet must be calculated. This can be seen in Appendix H. The results from this calculation was that in order to minimize the height of the eye bolt while having the tension in the fishing line not exceed the rating, the grommet should be placed 0.42 inches below the elbow on the lower arm and the attachment point on the eyebolt needs to be 2.5 inches above the center of the servo shaft. This will allow for the correct angles to be met while having the max tension in the fishing line be about 60% of the rated strength, giving us a factor of safety of 1.6.

Figure 10.18.1. Connection to Center Servo

Figure 10.18.2. Mechanical Tendon Through Eye-bolt

Figure 10.18.3 Connection to Forearm

10.7 LATERAL TRANSLATION

To move the mannequin across the track in front of the truck, we choose a rope and pulley system. In order to power this system, we needed a motor. We first sized the pulley to mate with selected size of manila rope that had the small diameter but still had the strength we desired. We choose manila rope because it had a high coefficient of friction which would help reduce slip between the rope and pulley. The pulley we selected was designed to work with ⅜” rope we chose. We found a relationship between torque and pulley diameter by using the initial tension in the rope, caused by trying to start the motion of the mannequin and platform, and the hoop tension. Using equations found in our Shigley’s Mechanical Engineering Design textbook we were able to use these tensions to find the force in the tight side of the rope and the force in the loose side of the rope. We then plugged those forces and the diameter of the selected pulley into a relation between torque, diameter, and those two forces and were able to find that the torque the motor needs to be able to output would be about 5 in-lbf. We also needed to find the range of speeds that the motor would need to rotate out. We we able to do this using the range of velocities for the mannequin and the diameter of the pulley. These calculations required that our motor have the range of 167 - 835 rpm.

After selecting a motor that needed a shaft coupling to mate with the pulley due to different unit systems, we decided to perform fatigue analysis on the shaft since it had three different diameters. We anticipated the revolutions of the shaft over a 5-year life to be about $3(10^5)$ revolutions. Our fatigue analysis showed that the lifetime of the shaft would be 10^{10} times greater than what we hoped it would be.

11. DESIGN VERIFICATION PLAN

To test and measure our pedestrian target and how it compares to our objectives and engineering specifications, we created a Design Verification Plan. The Design Verification Plan is a table that details our test plan to test each of the engineering specifications previously listed in Objectives, section 3 of the report. Depending on the parameters and requirements, the tests will verify that our final product has met the objective either by pass/fail or specifying the acceptable range of the criteria. This verification plan lists the requirement to be met, the test description, acceptable criteria range, as well as the sample test quantity. The Design Verification Plan can be found in Appendix K showing the full details on what tests we plan on performing for a corresponding engineering specification.

The requirements that have a pass/fail type testing are ones such as having a 10-minute reset time, staying within the $3,500 budget, 10 meter minimum travel length, incorporating a kill switch and trigger inputs, allowing for attachment of reflective material, and being able to handle max wind speeds of 7 m/s and a temperature range of 5-40 ^{o}C. For these design parameters, multiple tests will be conducted to validate that the mannequin has met these requirements. In addition, a test to check that our mannequin has adult human dimensions can simply be done by measuring the dimensions of each body part and comparing them to anthropometric data.

Many of our engineering specifications require a more in depth test to experimentally measure whether or not our pedestrian target has met these specifications. Requirements such as ensuring the articulation of the arms and legs are at the correct angles and frequencies will be tested by videotaping the articulation and determining the maximum and minimum angles of the hips, knees, shoulders, and elbows. To measure the step frequency of our mannequin, we plan on experimentally timing how much time it takes for 25 steps to occur. To validate that our lateral translation velocity covers the range of 0.5 to 2.5 m/s, we will measure the time it takes for the mannequin to travel 10 meters for each motor speed that is set by the driver. The step frequency and lateral translation velocity tests will be performed multiple times to help mitigate human errors such as time keeping. To simulate the impact and test the impact resistance of our prototype, we will be performing low speed impacts on the mannequin. This test will be conducted with the other Daimler groups for one day at a test track and for a limited amount of time. We will be using the Mechanical Engineering Department van with a small ram attached at a similar height as the rams used on Daimler trucks. While we will share our testing time with the other groups, we hope to complete 10 trials of the department van travelling at a speed of 3-5 mph to impact with the mannequin as it is travelling laterally. By having a test plan for each objective, we will be able to determine how well our designs and analyses represented the actual loads, as well as verifying the quality of the final product. The purpose of the Design Verification Plan is to show what objectives our final design and product has achieved, what specifications were not met, and how the product could be improved to meet all the design goals.

12. COST ANALYSIS

Our project is under budget after spending a total of $3,200 of the allotted $3,500. Most of the budget is being spent on the structure; the tubing, brackets, bolts, and nuts are used in nearly every aspect of this project and the amount quickly adds up. The other major contributor is the motors, with 4 high-torque servos and shafts costing $260 and the large DC motor for translation costing $520 with the motor and driver. The general breakdown of our costs are shown in Table 12.1. A detailed cost breakdown can be found in Appendix L.

Table 12.1 Summary of cost breakdown.

Component	Cost
Torso Structure	$760
Articulation	$275
Lateral Translation System	$1315
Platform	$625
Electronics	$520

13. MANUFACTURING

13.1 TORSO

The torso structure was made entirely of stock metal. One and two inch square tubing were cut slightly above their specified length using a cut off saw. The alignment of the vice clamp was checked before proceeding with any operation on the milling machine. The pieces were then faced using an endmill and deburred using a grinding wheel. The corner of the vice clamp was set as a datum. The square tubing was placed on the vice and a parallel was used to align the tubing surface to the vice clamp surface. A drill chuck was inserted into a collet and placed in the spindle of the milling machine. Pilot holes were drilled in the specified locations using a center drill bit before larger holes were drilled. Coolant was used as a cutting fluid. The tubing was removed from the vice clamp and the holes were deburred. The edges of the square tubing were polished using a wire wheel.

The steel plates holding the square tubing followed a similar process to the square tubing. The pieces were cut with a cold saw, faced with an end mill, and holes were drilled using the milling machine. The angled cuts of the steel plates were made by clamping the plate in a vice and making several passes using a cut off wheel. The steel plates were deburred using a grinding wheel and polished with a wire wheel. All the pieces were assembled using nuts, bolts, and washers. Two wrenches of the same size were used to tighten the nuts and bolts. The polypropylene rod was cut to size using a vertical band saw.

13.2 PLATFORM

The 1 inch square tubing, 1.5 inch square tubing, and 0.5 inch thick by 1 inch wide steel bars were cut to length using a chop saw. The top plate of the platform was cut to length using a vertical band saw. The sides and edges were then faced using a mill, deburred using a grinder, and edges smoothed with a wire wheel. Holes were drilled using a drill press by first using a center drill to create pilot holes, and completed using a drill bit slightly larger than the nominal hole dimension to create a clearance fit between the bolt and drilled hole. All hole locations and nominal sizes can be found in drawings for the platform assembly. The holes were finished off by deburring them using a grinder wheel. Steel plates were welded to the top plate of the platform to create the pole enclosure. Assembling of the platform was done entirely by bolting the tubing and top plate together, connecting them with the rectangular steel bars and corner brackets. The flanged shaft mount was first bolted to the outer side of the 1.5 inch tubing. The shaft was inserted to sit flush against the tubing and tightened with a set screw located in the shaft mount. The following components were then placed on the shaft: ball bearings, bushing, rubber wheel, and a thrust bearing. A shaft clamp was tightened against the thrust bearing to ensure the components are unable to slide along the shaft.

13.3 TRANSLATION

To create the housing for translation, we first cut the 1 in steel tubing to length using a chop saw and then deburred the edges using a bench grinder. Holes were then drilled in the tubing using the drill press and deburred using a deburring tool. The stainless steel base plates were cut to size using a vertical band saw and the edges were smoothed using a bench grinder. Holes were then drilled using a drill press. Coolant was used as a cutting fluid. The sheet metal covering was cut into the specified rectangular size using a sheet metal brake. These pieces were then cut the correct shape by using metal snips. The holes for the sheet metal were made using a metal hand punch. These holes had to be slightly bigger than previous holes because the punch only had a small number of sizes to choose from (used 3/16" punch instead of 5/32" drill bit). The pulley shafts were cut to length using a chop saw and then smoothed using a bench grinder. The shaft conversion from the motor to the pulley shaft needed additional clearance to fit in the housing, so the key-shaft was extended using a mini-mill. The rubber bases were cut to size using an xacto knife. Square holes were cut on the rubber base at bolt locations. This allowed the rubber to adhere to steel base plate without any interference from the bolts. Everything was bolted as according to the drawings. The hinges and rubber base plates were attached using contact adhesive.

13.4 ELECTRONICS

The electrical components were prototyped using an Arduino Uno, a breadboard, and jumper wires. Once these parts proved themselves workable, they were placed into more permanent positions on the mannequin. The servos are in mounting blocks so they can be screwed into the steel torso frame. The power switch and potentiometer are screwed into the mounting panel and held in place with the provided nuts. The breadboard was replaced with a protoboard and placed inside an electronics control box with the Arduino and batteries. The electronics housing is filled with foam with sections cut out for the components to rest in and has two holes drilled into the lid to allow wires to travel in and out. Some terminals are soldered directly to wires, while the power switch has screw terminals. All wire leads are secured: the potentiometer and the protoboard are soldered, the power switch has a screw terminal holding spades crimped onto wires, and the servos and Arduino have hot glue holding jumper wires.

The circuit is wired such that the power switch is a hard cutoff for both the Arduino and the servos. The 9V battery clip was cut and spliced with other wires running through one set of terminals on the switch. The 7.4 LiPo battery's positive lead runs directly to the switch and then down into the protoboard in the electronics housing. All 5 servos have their power wire connected to this lead. The ground lead of the LiPo batteries, the ground wires for all the servos, and the ground terminal of the Arduino all connect on the protoboard.

13.5 LIMBS

To create the limbs, canvas fabric was cut in a rectangular shape that would yield upper and lower limbs of the correct dimensions as can be seen in Figure 13.1. This was then sewn into a cylinder for the legs and a cylinder with reducing diameter for the arms.

Figure 13.1. Cutting the fabric to size.

For the elbows and knees, some pleats were added to give the joints shape and help them bend in only one direction. On the arms, grommets were added just below the elbow for attachment of the mechanical tendon wire. Batting was the then rolled around the core to the correct diameter for the upper limbs which can be seen in Figure 13.2. The polyethylene tubing was chosen for the upper arm core because of its low weight and its malleability.

Figure 13.2. Rolling the batting around polyethylene tubing.

The arms are crushed during impact. Therefore a soft material was preferred because no rigid material has a low enough density to be moved by the servos and enough durability to survive the crushing it would undergo. The leg core is hollow aluminum tubing because the plastic tubing is too flexible for the higher mass of the legs and caused the limbs to flex rather than swing. A more rigid material is acceptable for the legs because they do not extend as far from the body as the arms and do not take as much direct damage. Batting without a center core was rolled for the lower limbs; leaving out the core for the lower limbs reduced the overall weight of the limbs. The rolled batting was then shoved into sewn covering (the cylinders) to give the canvas limbs their shape. A small ball of batting was placed between the upper and lower limbs inside the covering to function as the elbow or the knee. The top of the limbs were gathered to close it around the tubing that was sticking out. Two grommets on either side of the limb were added just below the gathering. Mating holes sized for M4 bolts were drilled through the core. A M4 bolt was then bolted on through the grommets and the hole in the core to securely attach the limbs. The bottom of the arms were closed off by sewing a glove filled with batting to the end as can be seen in Figure 13.3.

Figure 13.3. Attaching the hands.

The tubing that forms each limb core extends past the end of the padding to reach a 90° clamping mount. The mount consists of 2 clamps that hold their respective shafts with set screws. The clamping mounts connect the limb core to the servo shafts. For the legs to maintain sufficient distance from the body, the leg servo shafts are extended with straight shaft couplers and aluminum tubing.

The forearms move with a tendon connected to a servo within the main body. Fishing wire ties to grommets just below the elbow on each arm. This wire runs up the arm to an eye bolt screwed into the hollow plastic limb core, which forces the wire to turn at a specific point to properly pull the forearm instead of taking the most direct path. The wire continues through the eye bolt to tie into a servo horn that pulls the tendon to raise the lower arm. This setup is mirrored on the opposite side so that when the servo pulls one arm up it is releasing the other.

14. TESTING

14.1 TORSO

Although the test target experiences stress during the initial low speed impact of a truck, a large amount of stress is produced by the test target hitting the ground. Our goal was to measure the stress that occurs during the impact between the test target and the ground. The stress data would later be compared to a finite element model under similar conditions. The test began with the application of a strain gauge on the inner side of the right shoulder, shown in Figure 14.1. The inner portion of the shoulder was chosen because it allowed the strain gauge to take measurements near the impact area without receiving any damage. The strain gauge was oriented parallel to the longer portion of the box beam to measure any type of stress on the outer surface along that path.

Figure 14.1. Foil strain gauge applied to the right shoulder of the test target.

The strain gauge was configured in a half bridge circuit and the signal was sent to a Focus ll signal analyzer. The data was captured and saved using computer software. The test target was allowed to fall from a standing position with the help of a slight nudge, shown in Figure 14.2.

Figure 14.2. Test target falling on its side while testing with the strain gauge.

After small adjustments, strain data of the impact was taken. Subsequent calculations were made to convert the strain into stress. The maximum stress measured was approximately 28 ksi, which was smaller than the 46 ksi yield stress of the steel. A sample of the data set that includes the peak stress is shown in Figure 14.3.

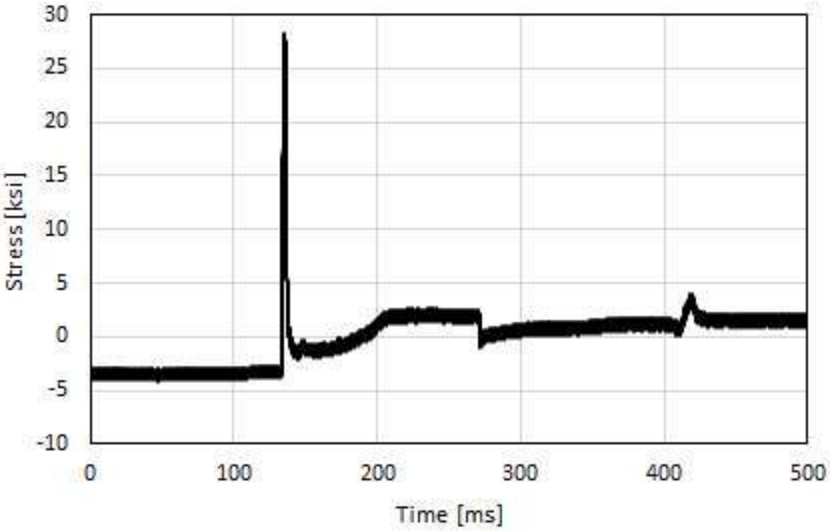


Figure 14.3. Stress data take throughout the impact between the test target and ground.

As mentioned before, the measured stress data was compared to the finite element model. The speed right before impact with the ground was necessary to carry out the FEA. To accomplish this, the team used geometry and video evidence to approximate the speed immediately before impact. The speed was found to be approximately 10 mph. An analysis was carried out on the finite element model. A comparison of the two data sets are shown in Figure 14.4.

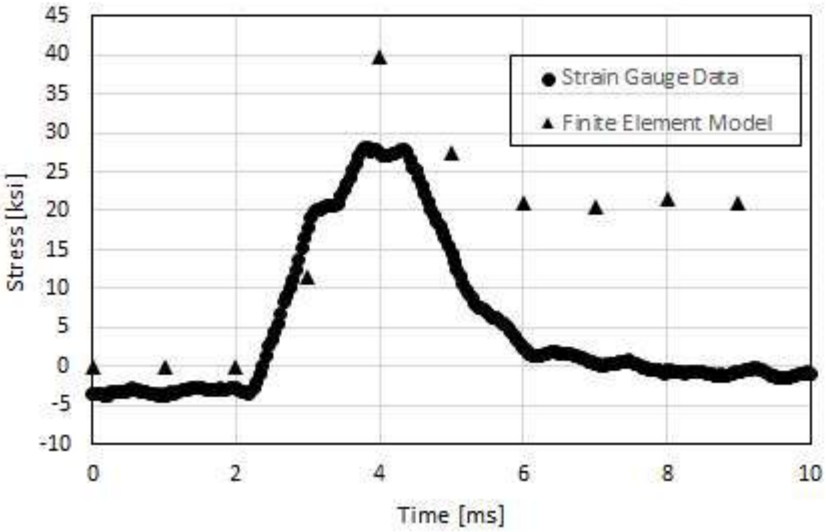


Figure 14.4. Stress through time for the strain gauge measurement and finite element model of the test target falling on the ground.

The peak stress produced by the finite element model was approximately 39.7 ksi, which was 34% different than the value measured by the strain gauge. The significant difference between the values may come from the absolute rigidity imposed on the wall in the finite element model. A surface that is infinitely stiff, such as the rigid wall, will not absorb any energy and cause the stresses to increase. Additionally, a foam piece was attached to front of the test target shoulder. The addition of the foam piece would absorb some energy and reduce the peak stress. Moving past the peak stresses, the finite element model continues to produce a stress of 20 ksi, while the strain gauge measurement approaches zero, but later rises to 2 ksi as shown in Figure 14.3. The additional bump in the FEA stress may be due to the continued motion of the rigid wall after the initial impact was made.

From a qualitative standpoint, the shoulder received minor damage from the drop test. Figure 14.5 shows the small dent in the shoulder from the single test performed without any padding to dampen the impact. Even without any soft protection, the mannequin survived the test and continued to function. The tests with the padding added back on did not noticeably damage the metal. This product will accumulate damage over its lifetime, but with the additional padding on the impact points of the shoulders it will last multiple rounds of usage before requiring repair or replacement.

Figure 14.5. Shoulder after Impact

After we performed the analysis of the shoulder, we moved onto a larger test: hitting the mannequin with a van. We used a school van to impact the articulating mannequin placed on the stationary platform. We were able to see how the pole detaches from the platform and visually inspect the mannequin for damages after the impact. A metal ram with an added plywood board was attached to the front of the van to model the ram on Daimler's freight trucks. This can be seen in Figure 14.6 as the van is just about to impact the mannequin. Three impact tests were performed at various speeds with the van stopping immediately as it hit the mannequin. The van speeds were approximately 3 mph, 6 mph, and 10 mph. We found that these impacts, mainly from the mannequin hitting the ground, caused some minor damages. In the test performed without any shoulder padding, the shoulder was scratched and minorly dented, but this did not occur in any of the tests with shoulder padding. For all tests, the torso structure shifted around the bolt locations slightly causing the torso to no longer be square. Relatedly, the bolts that attached the neck to the body allowed the neck and head to move quite a bit, which bent our control panel as can be seen in Figure 14.7. The structure can be fixed by loosening the bolts, straightening the structure, and re-tightening the bolts. In the short term these damages do not impede the mannequin's functionality, unless the torso becomes so misaligned that the limbs rub against the main structure or the center of gravity becomes too offset. In the long term fatigue can build up and cause failure, but fatigue is considered outside the scope of this project as immediate failure from high impact is considered a larger concern. Also in this testing, one of the arms fell off (they were only sewn on at this point in time), which led to us using bolts to more securely attach them. We found that we were able to reset the mannequin very quickly between tests which gave us a reset time well below our specification of 10 minutes.

Figure 14.6. Impact Testing

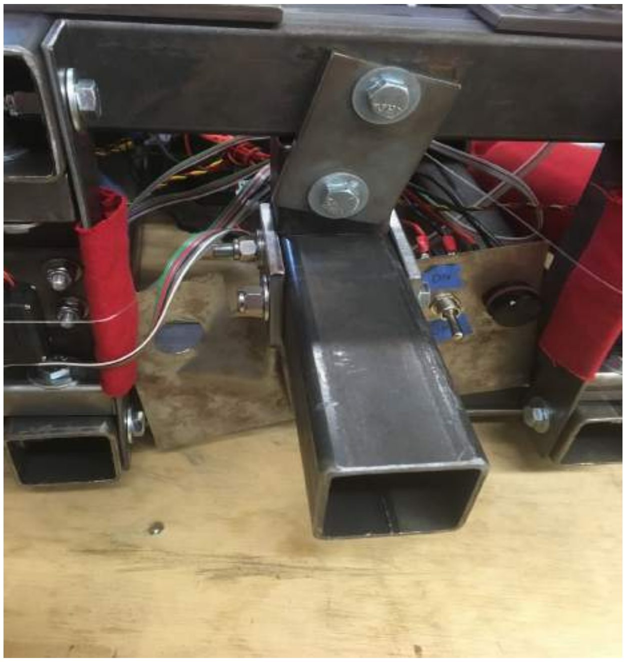


Figure 14.7. Neck and Control Panel after impact testing

14.2 PLATFORM

Weight was added on top of the platform to verify that it can securely hold slightly more than the weight of the mannequin. The pedestrian target was then placed on top of the platform to show that it was able to hold the entire weight of the pedestrian target and was stable. The mannequin and platform were then gently rolled forward to test that the platform was able to roll smoothly while supporting the mannequin. The platform was used during impact testing and showed that there was no permanent damage from any of the impact tests.

14.3 TRANSLATION

To test translation, we first tested the system with just the platform. We found that the system was able to move the platform, but the tension required caused the the slave side pulley towards the motor housing before moving the platform. This requires holding the pulleys in place with additional weight after they are pulled apart to properly tension the system.. We remedied this problem by increasing the plate size of the slave side base and placing cinder blocks on top of the plates. We found that two cinder blocks held the housings well enough, but still required retensioning every few runs if the platform did not travel directly between the two pulleys and pulled the rope off to the side.

We placed the mannequin on the platform with C-clamps to prevent the mannequin from accidentally tipping, and wrapped it in padding to prevent any damage. When we increased the translation speed with the default deceleration time, we found that the motor stopped too abruptly and caused the mannequin to tip over. The mannequin tipping over and falling is shown in Figure 14.8. We increased the deceleration time to find the setting that was long enough to stop the mannequin without tipping over, and a short enough deceleration time to prevent the platform and mannequin from hitting the motor housings. We found that for the entire speed range of the motor, the deceleration setting on the driver should be set in between the 5th and 6th tick mark, where the first tick starts at 0. This corresponds to taking 2.5 seconds to ramp up/down for the rated speed of 3000 rpm.

Figure 14.8. Fallen Mannequin after Abrupt Deceleration

We verified the translational speeds of the system with the mannequin clamped to the platform to prevent accidental falls. We ran the entire system at different motor speeds and measured the time it took for the mannequin to travel 5 meters. That data yielded the chart seen in Figure 14.9. This meant that the range of translation velocities our system can obtain are less than our specification: our specification was 0.5 - 2.5 m/s and our actual system can only do 0.2 - 1.6 m/s. After testing the speed range of the motor, we removed the clamps from the mannequin and ran the test with the mannequin simultaneously articulating and translating. We found that the mannequin and platform was stable enough to not tip over actual operating circumstances.

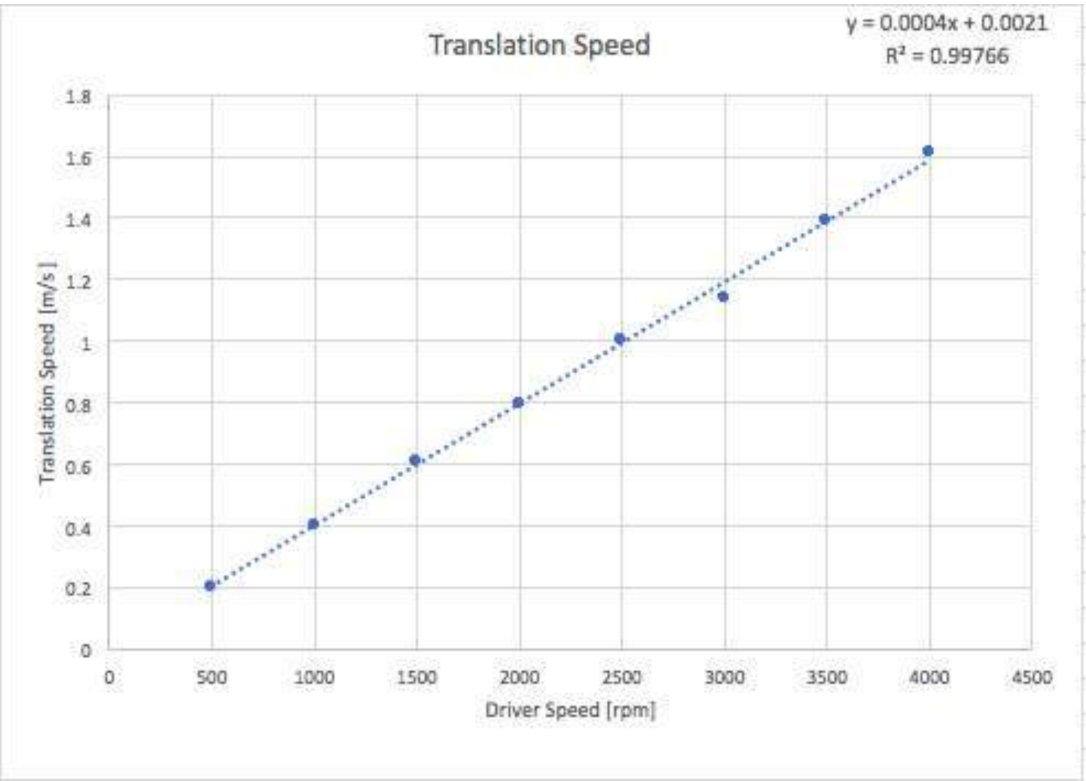


Figure 14.9. Conversion Between Motor Angular Velocity and Platform Linear Velocity

14.4 ELECTRONICS

The electronics were prototyped on a breadboard to ensure that all components and the overall program function correctly. This included verifying that turning the potentiometer altered the speed of the servos and that the servos reached the correct angles and frequencies before being loaded with the limbs. We also tested that all of our kill switches disabled articulation. We performed some rewiring as some switches initially cut power to the Arduino and not the servos, which caused the servos to seize and hold position rather than go slack as we initially expected.

These tests were all repeated after the electronics were properly mounted on the body structure and before being permanently set. Unfortunately, we discovered that the reed switch attached at the base of the pole and the platform does not work as intended and seems to be stuck open after being near the magnets holding the mannequin to the platform. However, even though the articulation does not automatically cease when the dummy is toppled, later testing shows that the servos do not seem damaged from attempting to function while the mannequin is prone. Overall, the mannequin electronics work as intended, with the power switch and potentiometer knob on the control panel controlling the system properly.

14.5 LIMBS

To test articulation, we first eye-balled the articulation to fix egregious errors. From there we performed more rigorous testing and videotaped the motion of the limbs and used a software called Tracker to measure the angles of the limbs at the peaks of their arcs and to time their frequency. We placed brightly colored pieces of tape on the critical points (shoulder, elbow, and hand for the arm and hip, knee, and ankle for the leg) to allow the software to better track these points. We then took video of the limbs with several gait cycles at their slowest speed, their fastest speed without significant twisting, and the fastest speed the leg servos could handle. To measure the joint angles, we paused the videos when the limbs were at their peak and used Tracker's built-in protractor tool with the points we had marked earlier. The shoulders angles are close to what we intended, with some bias due to the limb core not being perfectly straight. The elbow angles are smaller than desired due to the limitations of the servo horn pulling the tendon: a longer servo arm, or better yet a pulley wheel or linear actuator would be able to pull the wire further. The hips do not reach the maximum angles desired, and the free-swinging knee angles depend significantly on the speed and inertia of the limb.

The range of frequencies for the gait is smaller than intended. The lowest frequency was given a floor of 1.34 Hz because we found that the motion was too choppy below that point. However, due to the nature of the articulation code, this motion could be smoothed out and the frequency could be lowered to the specification of 1.05 Hz by adding more data point for the servos to follow. The maximum frequencies are lower than the specifications primarily due to the limitations of the purchased servos. The servos were sized and purchased before modifications were made to the legs, so they cannot rotate the higher mass at the top speeds intended. More powerful servos would rectify this problem. However, the frequency is also limited because of the tendency of the legs to twist at higher speeds. The servos can move the legs up to 1.82 Hz, but significant twisting begins to occur around 1.6 Hz. We are unsure of whether this twisting matters for Daimler's purposes and have chosen to place the cap at 1.8 Hz, so that if twisting is undesirable the frequency control knob will simply not use its full range.

To verify the adult human dimensions, we measured the dimensions of each body part and compared them to the dimensions found from anthropometric data. A summary of the tests performed, criteria, and result can be found in Table 14.1.

Table 14.1. Testing Requirements and Results

Spec #	**Parameter**	**Requirement**	**Tolerance**	**Result**
1	Production Cost	\$3,500	Max	\$3174.53
2	Reset time	10 mins	Max	5 minutes
3	Impact	35 tons @ 5 mph	Max	Survived
4	Track Supports Weight	35 tons	Max	Passed
5	Travel length	10 m	Min	> 10 m
6	Pedestrian Height, H	1.75 m	± 0.025 m	1.753 m
7	Shoulder to Elbow Length	0.19H	± 5%	0.23H
8	Elbow to Fingertip Length	0.27H	± 5%	0.25H
9	Hip to Knee Length	0.25H	± 5%	0.27H
10	Knee to foot Length	0.29H	± 5%	0.22H
11	Hip Angles	-35^{o} to $+35^{o}$	Min/Max	-25.5^{o} to $+24.5^{o}$
12	Knee Angles	0^{o} to 75^{o}	Min/Max	1.5^{o} to 12.0^{o}
13	Shoulder Angles	-10^{o} to $+10^{o}$	Min/Max	-11.5^{o} to $+9.0^{o}$
14	Elbow Angles	0^{o} to $+60^{o}$	Min/Max	4.5^{o} to 30.0^{o}
15	Step Frequency	$f = -.44v^2+2.06v+0.13$ 1.05 - 2.53 Hz	± 5%	1.34 - 1.62 Hz
16	Velocity	0.5-2.5 m/s	Min/Max	0.2 - 1.6 m/s
17	Kill Switch	Shuts Down Power	Y/N	Yes
18	Stored Size	576” x 102” x 162”	Max	24” x 67” x 30”
19	Trigger Input	Initiates the System	Y/N	Yes
20	Withstand Wind	7 m/s	1 m/s	Passed
21	Withstand Temperature	5-40 ˚C	Min/Max	Passed

15. PEDESTRIAN TEST TARGET

OPERATOR'S MANUAL

SAFETY GUIDELINES

1. Hard hats and safety goggles should be worn at all times when using this system.
2. The mannequin falls easily when pushing the left shoulder if correctly placed in the platform. Be mindful of this and take care to keep the mannequin from tipping in this direction.
3. At least 3 people should work together to move or lift the mannequin.
4. The platform should never be ridden or sat on by a human or animal.
5. The translation system should be disconnected or set on STANDBY whenever anyone is within 10 feet of the system.

SETUP

The setup for the pedestrian target consists of setting up the lateral translation and attaching the platform and mannequin to the lateral translation system.

1. Place the two housings on the ground on either side of the track.
2. Open the top of the slave side housing.
3. If the rope is not already attached, thread a loose end of the rope around both pulleys and tie the rope together using a square knot as seen in Figure 15.1. The square knot will be made twice should be closer to one end. The knot will be positioned underneath the platform to prevent the loops from going into the motor housings.

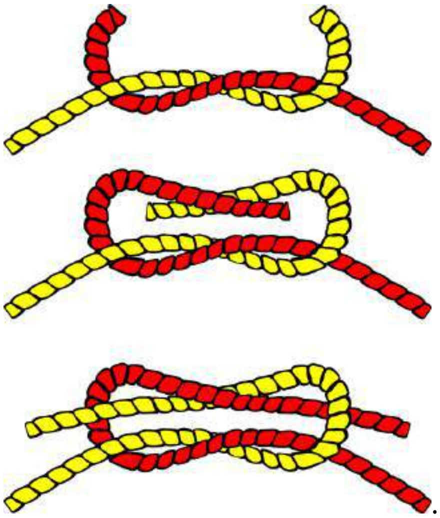


Figure 15.1. Square Knot Steps

4. Once the motor housing is placed correctly, place at least two cinder blocks on the base to hold it in place.
5. Tension the rope
   a. One person pushes the slave side housing as far back from the other housing as it will go.
   b. Another person places at least 2 cinder blocks directly flush against the back of the slave side housing to hold it in place and to prevent the housing from breaking.
6. Check to ensure that the pulley shaft in the slave side housing is still through both bearings and that the pulley is at the bottom of the housing.
7. Connect the driver to the motor and then connect the driver to 110 volt AC power source
8. Next move the platform to the start point. This should be close to one end and on top of the knot that connects the two ends of the pulley. The forward direction for the platform should be setup as seen in Figure 15.2.

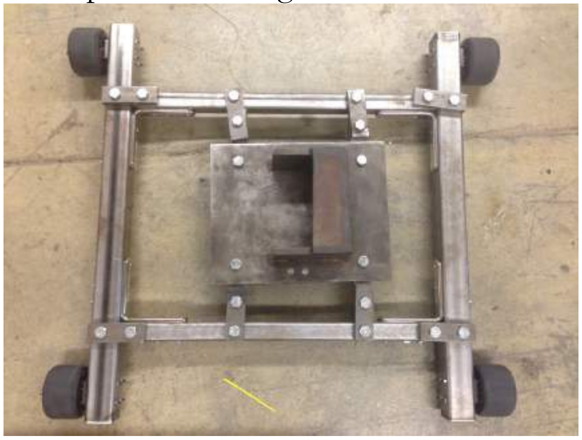


Figure 15.2. Platform Forward Direction is Upward

9. Connect the platform to the translation system.
    a. Using a separate piece of rope, create a small loop using one rope clamp.
    b. Place the loop in the snap-hook located underneath the platform, seen in Figure 15.3. The metal snap-hook is able to open and close so that the rope loop can easily be detached and reattached from the platform.

Figure 15.3. Snap-hook on Platform for Mate of Rope Loop

    c. Both free ends of the loop will be fastened to the one side of the translation system rope. Two rope clamps will fasten one free end of the loop in front of the platform and two rope clamps will fasten the other free end of the loop behind the platform. This will allow the system to be driven both forwards and backwards by the translation system. These rope clamps should be positioned such as in Figure 15.4 where the curved side of the U-bolt is facing the ground.

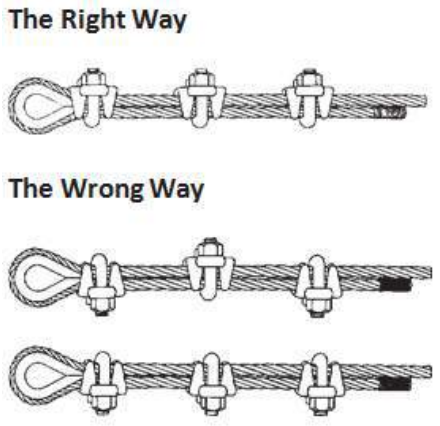


Figure 15.4. Correct Way to Create a Rope Loop

10. Place the power cells inside the mannequin if not already done.
    a. The 9V battery should be new, and the 7.4 LiPo battery should be fully charged
    b. Access the electronics control box by removing the removing the velcro cloth covering around the mannequin
    c. Unlatch and open the control box (latches are on the dummy's LEFT side)
        i. The protoboard will want to move up with the lid; this is fine

d. Clip the 9V battery into place
e. Place the LiPo battery in its slot and plug the wires in if not already done
f. Feed the male deans connector through the hole in the lid and connect to the female end

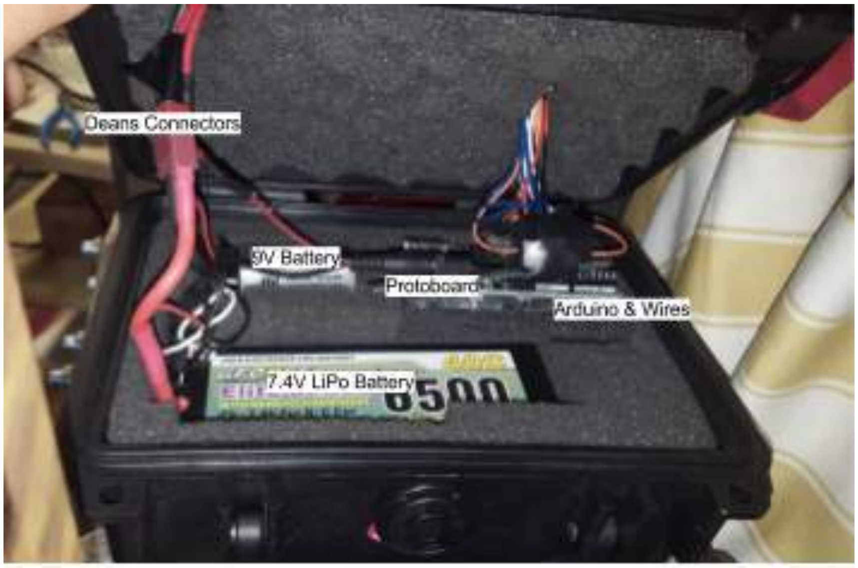


Figure 15.5. Electronics Housing

11. Ensure the support pole is securely fastened inside the U-bolts of the pole attachment as seen in Figure 15.6. Tighten the nuts on the back of the pole attachment as necessary.

Figure 15.6. Pole Attachment

12. Place the pole attachment in its enclosure on top of the platform, shown in Figure 15.7. At least 3 people should lift the mannequin, while a fourth person guides the pole attachment into the enclosure. The vertical wall of the pole attachment should be flush against magnets inside the enclosure, and the curved side of the U-bolts facing outwards Check that it is held tight by the magnets.

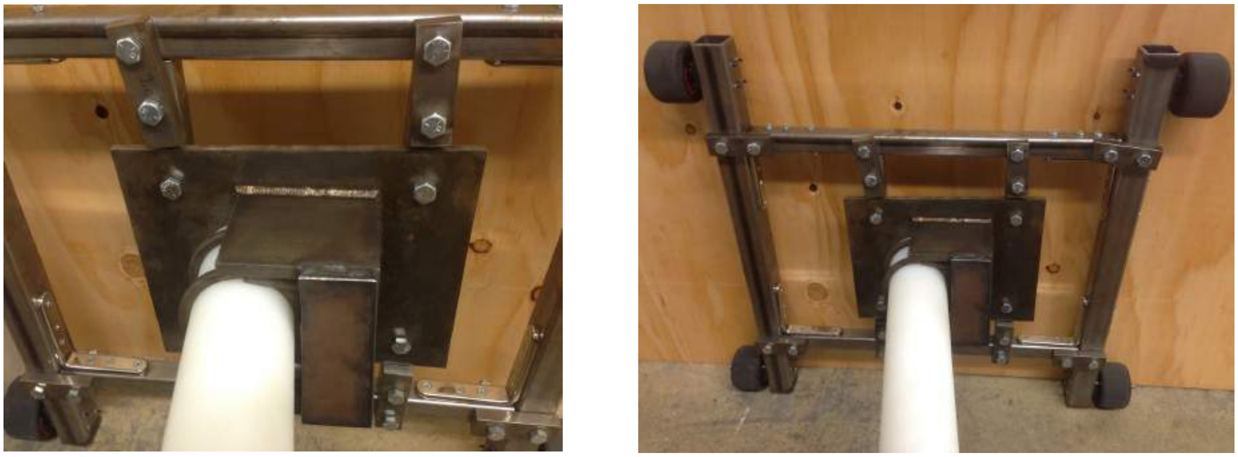


Figure 15.7. Pole Attachment In Enclosure on Platform

RUNNING THE SYSTEM

CAUTION: In an emergency, turn off translation by setting the motor driver to STANDBY, which safely slows the mannequin to a stop. Shutting off power will cause the mannequin to tip over from the abrupt stop.

1. Set the step frequency of the limbs using the knob on the control panel on top of the mannequin.
2. Turn the mannequin on by flipping the switch as seen in Figure 15.8.

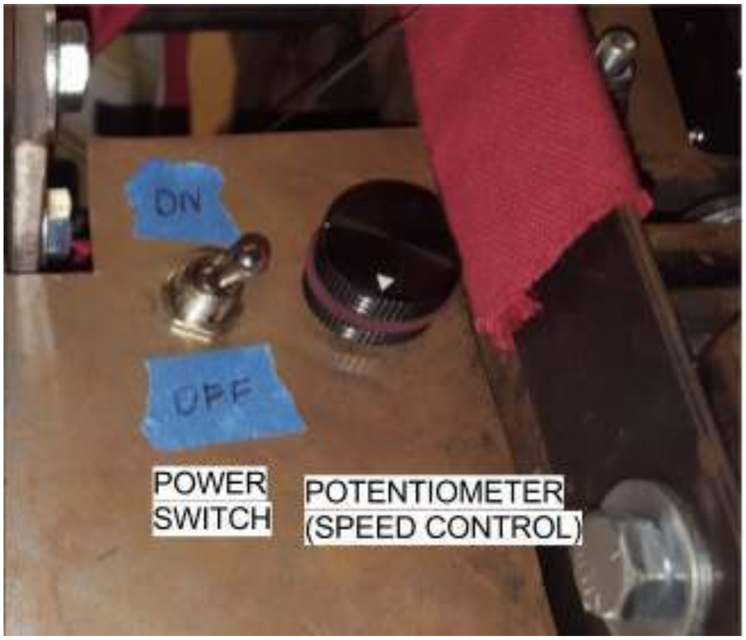


Figure 15.8. Control Panel

3. Set the speed of the translation motor using the driver.
    a. Consult the provided chart in Figure 15.9 to convert desired linear speed in m/s to RPM.

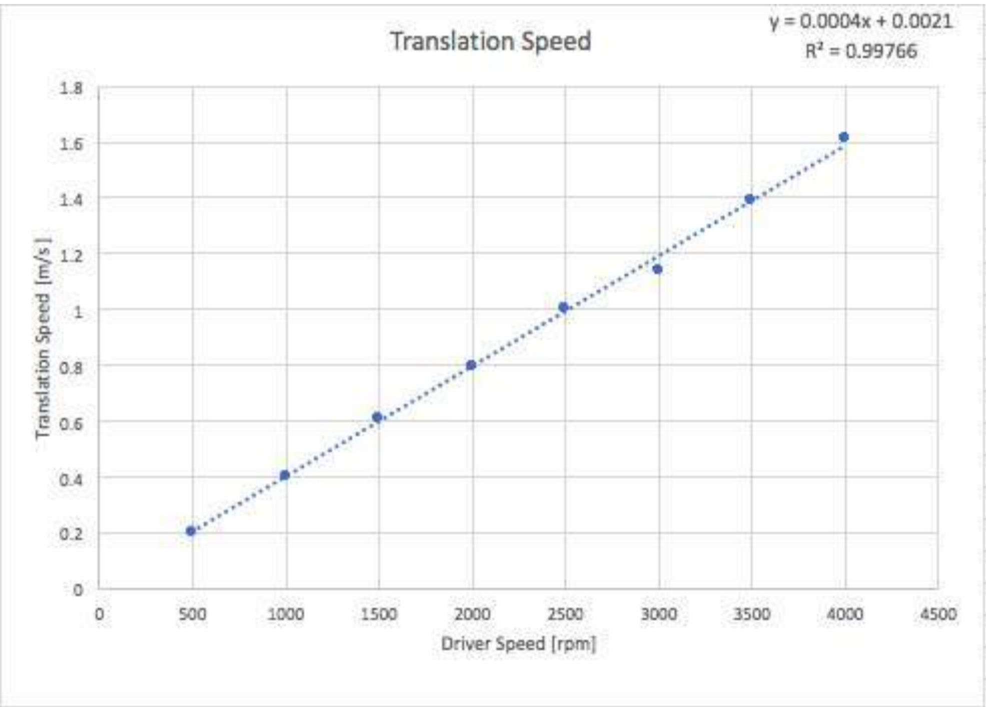


Figure 15.9. Conversion Between Motor Angular Velocity and Platform Linear Velocity

4. SAFETY: check that all safety protocols are still being observed.
    1. All personnel wearing safety glasses and hard hats.
    2. No one standing within 10 feet of the system.
5. Begin translation by moving the switch on the motor driver from STANDBY to RUN.
    1. Check direction : FORWARD/REVERSE do not necessarily match
        1. FORWARD moves the rope CCW (counter-clockwise)
    2. The driver automatically accelerates; there is no need to ramp up manually.
        1. Acceleration time can be changed; see Operating Manual for the BMU Series 200W / 400W Brushless Motor and Driver Package
        2. Time of 2.5 s to reach 3000 rpm prevents tipping and is still responsive.
6. Be prepared to return motor to STANDBY to stop the motor and translation.
    1. No automatic stop.
    2. Motor automatically safely decelerates and does not stop instantly.
        1. No e-brake was included because abrupt stops can topple the mannequin.
        2. Stop the system early so the platform and rope clamps do not hit housing.
7. After ensuring that the test area is clear and safe:
    1. Stop mannequin limbs by flipping switch on top to OFF.
    2. Reset the system.

RESETTING THE SYSTEM

After the test is complete and both the truck and mannequin have come to a complete stop, the system can be reset.

1. If the mannequin has fallen, have three people place it back in the platform.
    1. Two people should hold the torso and one person should hold/guide the pole into the enclosure on the platform.
    2. Ensure that the pole holder is snugly against the back wall of the enclosure, tight against the magnets.
2. Run the motor in the opposite direction no faster than 1500 rpm until the platform is nearly to the starting location. Stop the platform early so that it does not hit the housing and the rope clamps do not contact the pulleys.
3. Switch the motor back to the desired direction to prepare for the next run.

STORING THE SYSTEM

1. Turn off the power for the mannequin using the power switch on the control panel.
2. Unplug the translation system from the 110 volt AC power.
3. Unplug the driver from the motor.
4. Remove the covering around the middle of the mannequin by releasing the velcro.
5. Remove the 2 batteries:
    a. Unclip the 9V battery.
    b. Unplug the Deans connector/T-connector and feed one side back into the casing.
    c. Lift the LiPo battery and attached wires out of the casing.
6. Discharge the LiPo batteries using the provided balance charger.
    a. Use STORAGE mode, not DISCHARGE mode.
7. Remove the mannequin from the platform or off the ground.
    a. At least two people should hold the mannequin torso and one person should hold the pole.
8. Move the mannequin to the transportation or storage location.
9. Unhook the platform from the rope using the snap hook.
10. Move the platform to the transportation or storage location.
11. Unclamp the rope clamps and untie the rope.
12. Carefully remove the rope from the pulleys.
13. Coil the rope for storage.
14. Carefully lift and carry each housing to the transportation or storage location.

CHARGING AND DISCHARGING LIPO BATTERIES

The Imax B6 Balance Charger includes an operator's manual that is somewhat unclear. This simplified guide aims to clearly explain the basic functions needed for this application.

ALWAYS MONITOR BATTERIES AS THEY CHARGE OR DISCHARGE

1. Connect the LiPo cells to the balance charger
    a. Plug leads into charger before connecting battery and charger deans connectors
    b. White balance plug from cells goes into top right socket for 2S (2 cells per pack)
2. Plug the balance charger into an outlet using the provided power adapter
3. Check that the charger is set to LiPo batteries:
    a. The battery select should be the default menu after powering on the charger
    b. To return to this menu, use the Batt. Type / Stop button
    c. Cycle through programs by continuing to hit the Batt. Type button
    d. Once the LiPo battery is highlighted, hit Start / Enter
4. Select mode : Charge or Storage

    a. DO NOT use Discharge mode: it is for discharging before disposal
    b. Use the Status buttons (Dec. and Inc.) to select mode
    c. Hit Start / Enter once the appropriate mode is highlighted
5. Select current (time to charge / discharge):
    a. These 6500 mAh cells can safely handle the maximum current of the charger
    b. 1.0A max storage current, 6.0A max charge current
    c. Hit Start / Enter
6. Set number of cells: 7.4V (2S)
7. Begin charge/discharge:
    a. Hold Start / Enter button for several seconds
    b. Check settings
    c. Confirm and hit Enter

16. CONCLUSION AND RECOMMENDATIONS

The final product meets the customer's requirements to be human-shaped, articulate its limbs like a walking pedestrian, translate across a road, and survive an impact. It does not achieve all of our more stringent engineering specifications and can be further improved, but a functional test dummy is ready to be handed to Daimler Trucks.

During the design phase, we chose to design the product to our modest manufacturing skills. This led to using bolts instead of welding pieces together. After manufacturing we found that for a structure with a large number of components to be assembled, welding would have been the proper choice. This would have saved a lot of time drilling holes, tightening bolts, and some alignment issues. In addition, welding may have allowed stress to be carried better throughout the structure rather than transmitting loads through bolted joints alone. In addition, we selected stainless steel for some uses where it was unnecessary, resulting in increased manufacturing difficulty and time.

An alternative design concept which could have sidestepped the aforementioned manufacturing issues is the lightweight crash test dummy. Our design uses strong materials and a rigid structure to survive an impact, but an early idea we had was to use light materials and a structure which purposely disassembled upon impact. We did not pursue this route because we did not have a good idea of how to combine the separating body parts concept with the necessity of actively controlling the limb motion.

After testing, the pedestrian target has shown to be able to survive impacts without critical damage. Performing drop tests from rest, we found that the steel tubing representing the neck of the mannequin can become misaligned. This was further shown during impact tests with a moving van. Misalignment causes the control panel, made of sheet metal, to easily be deformed. This problem can be solved by loosening the bolts, realigning the tubing, and tightening the bolts. However, this must be fixed after a handful of tests and is a very tedious process. To permanently resolve this problem in the future, there should be more support restraining the movement of the neck tubing by adding crossbars or a brace. Due to a bolted assembly in the platform, there is some misalignment between components that could have been resolved by replacing bolts with welding. In addition, the platform could have had a different wheel choice that allowed turning, or the system could use a track or other method to keep the platform traveling directly between the ends of the pulley. The connection between the platform and translation system could have allowed detachment during impact so that there is no risk for the motors to be dragged alongside the vehicle and pedestrian target.

Further improvements for this project would be to create articulation that is more realistic to human walking motion. Our design does not have articulation in the knees and too small of angles for the articulation in the elbows, and hips. The hip motion would have benefitted from having stronger servo motors, as our initial estimates for the inertia of the legs proved to be too low. To improve the elbow articulation, the servo motor controlling the tendon could be replaced with a linear actuator. The rotation of the servo gives diminishing returns on the projected distance it travels as it rotates, so it is difficult to pull the forearms up past a certain point. In addition, the servo has the issues of requiring a larger moment arm in order to pull the wire tendon more. The knee motion would be improved by active control, most likely with a similar system to that of the elbows. Unfortunately we did not include a method to route the tendon wire for the legs and lacked the time to add one.

Because of the large scope of this project, the electronics and programming are extremely simple. This system would benefit immensely from a remote control and an automatic stop, both of which would allow personnel to remain even further from the impact and still ensure that the system does not continue to run and potentially damage itself. We are not experienced enough to recommend a way to incorporate these components with the industrial motor and driver from Oriental Motors, but the mannequin limbs are controlled by a simple hobby Arduino which can be modified without much issue if desired.

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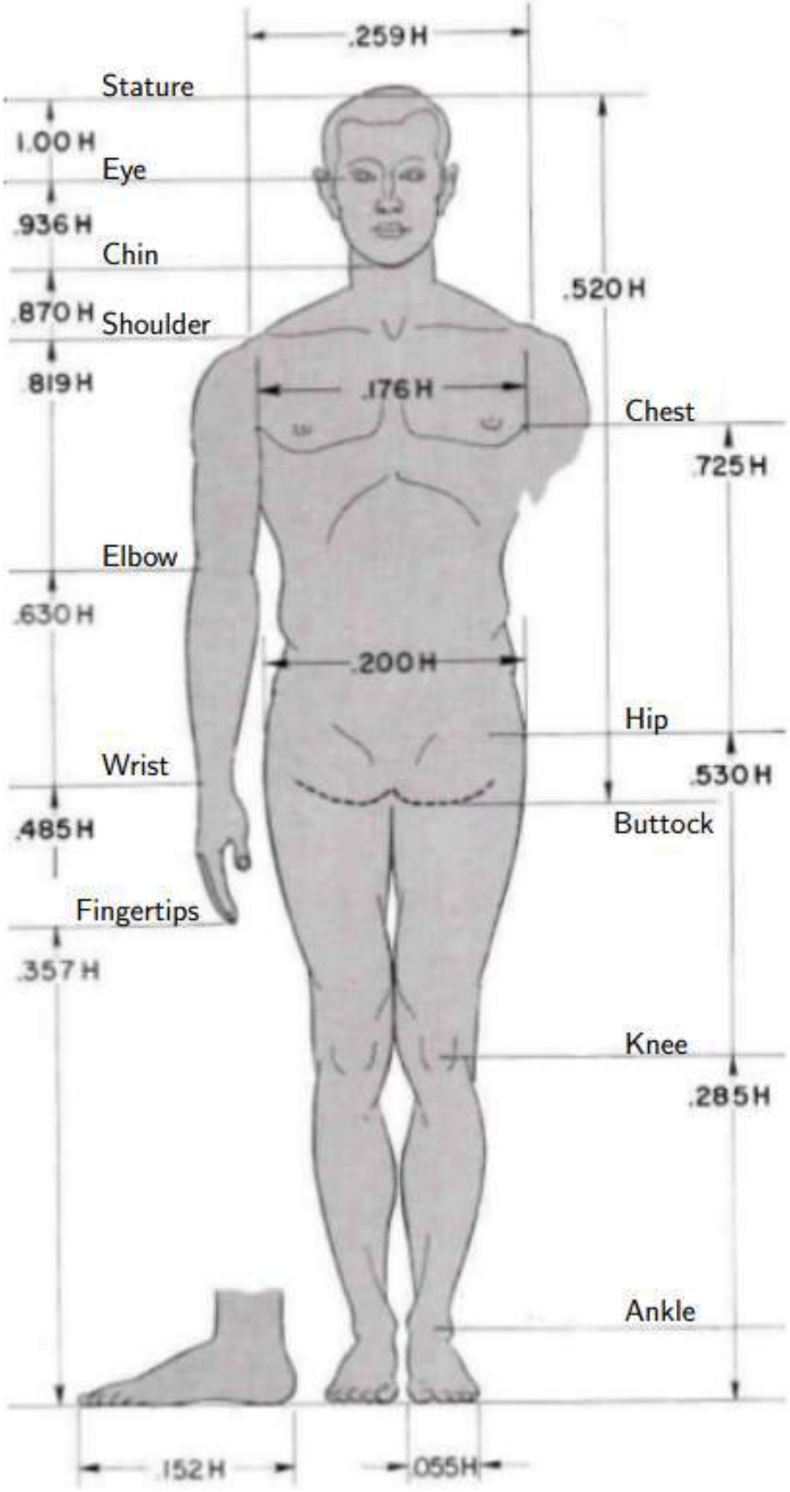
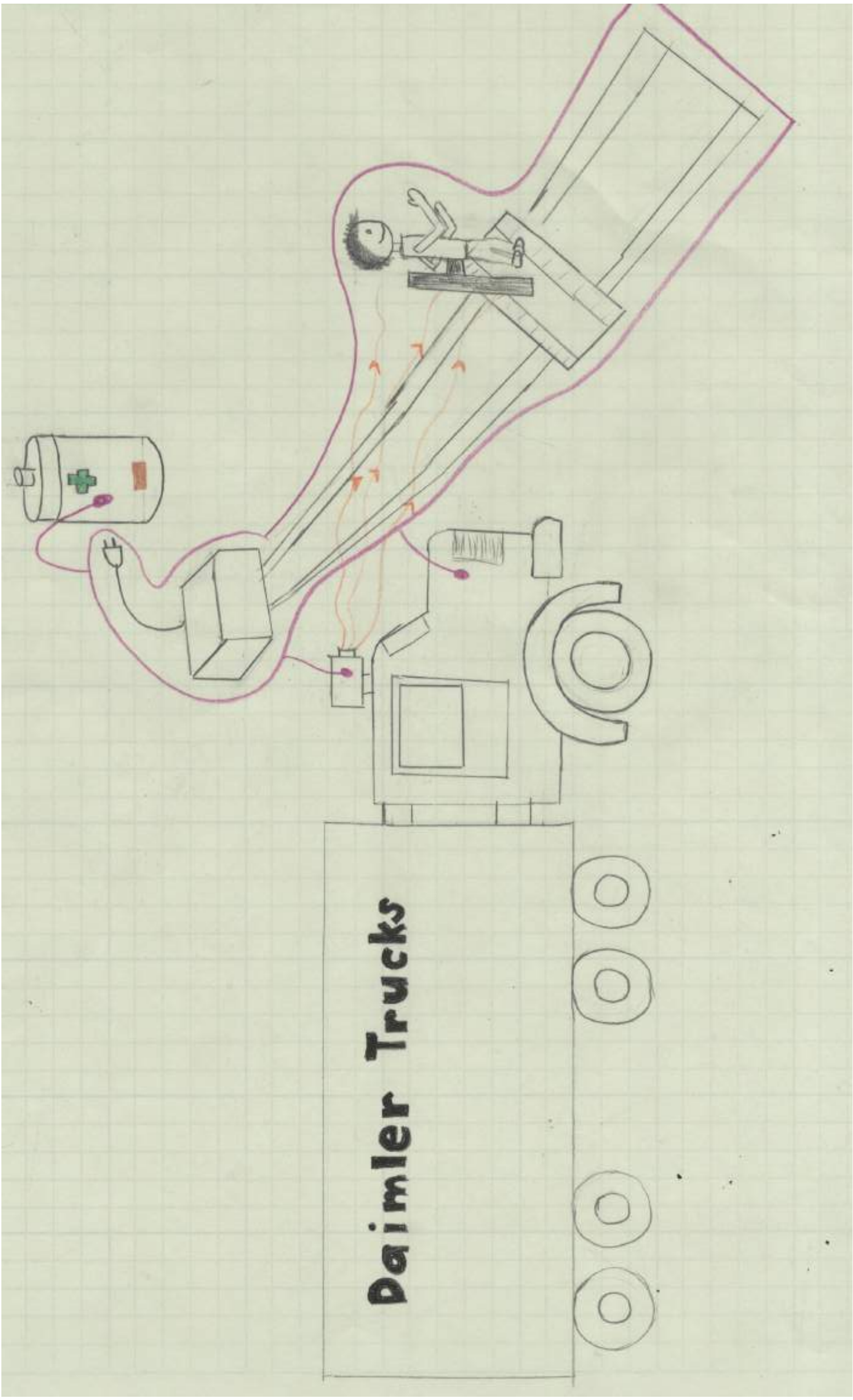
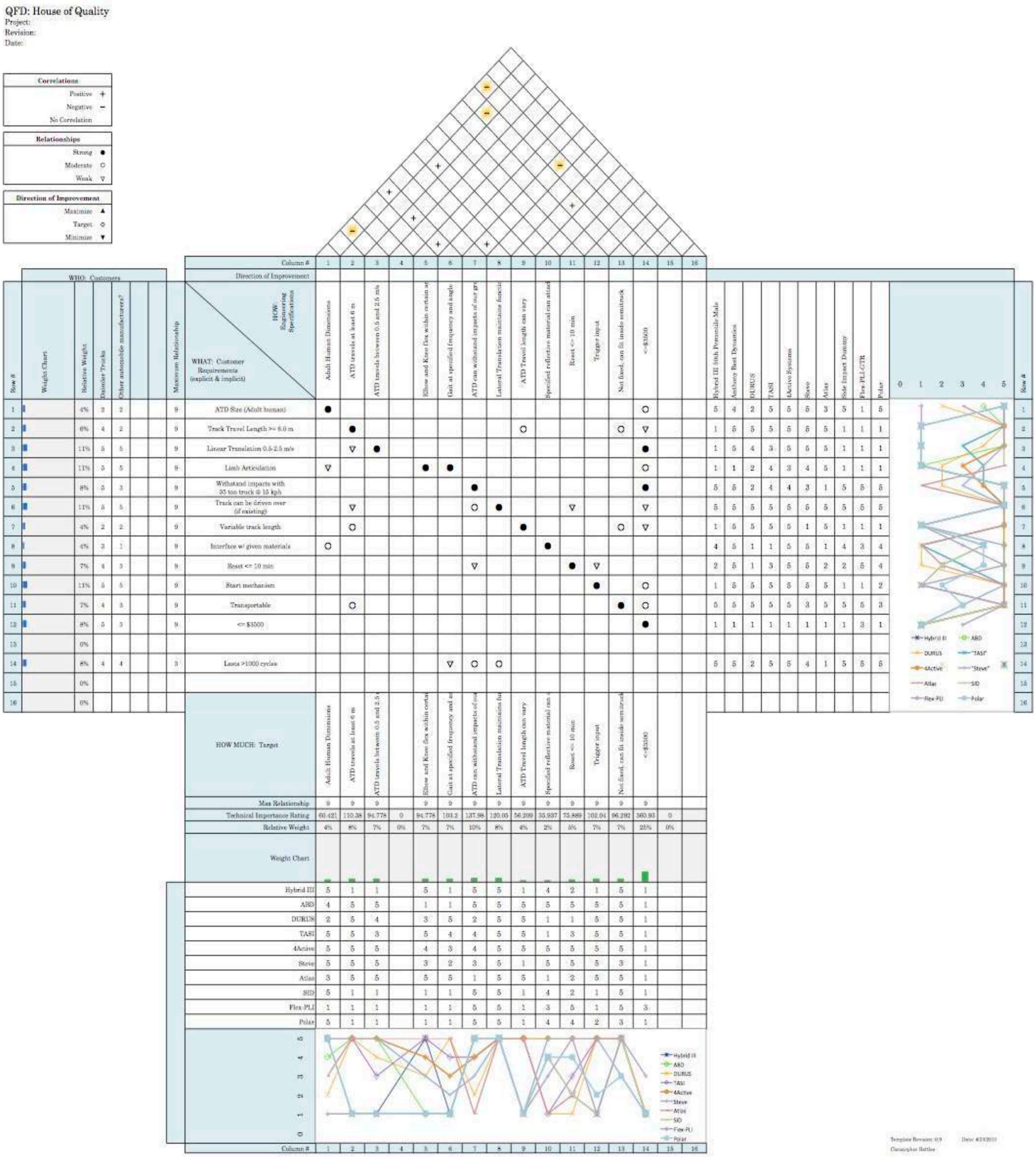
APPENDIX A: ANTHROPOMETRIC DATA



APPENDIX B: BOUNDARY DIAGRAM



APPENDIX C: QUALITY FUNCTION DEPLOYMENT



QFD: House of Quality
Project:
Revision:
Date:

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

Row #	Weight Chart	Relative Weight	Daimler Trucks	Other automobile manufacturers?			Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	1 Adult Human Dimensions	2 ATD travels at least 6 m	3 ATD travels between 0.5 and 2.5 m/s	4	5 Elbow and Knee flex within certain ar	6 Gait at specified frequency and angle	7 ATD can withstand impacts of our gr	8 Lateral Translation maintains funcio	9 ATD Travel length can vary	10 Specified reflective material can attac	11 Reset <= 10 min	12 Trigger input	13 Not fixed, can fit inside semitruck	14 <=$3500	15	16
1		4%	2	2			9	ATD Size (Adult human)	●													○		
2		6%	4	2			9	Track Travel Length >= 6.0 m		●							○				○	▽		
3		11%	5	5			9	Linear Translation 0.5-2.5 m/s		▽	●											●		
4		11%	5	5			9	Limb Articulation	▽				●	●								○		
5		8%	5	3			9	Withstand impacts with 35 ton truck @ 15 kph							●							●		
6		11%	5	5			9	Track can be driven over (if existing)		▽					○	●			▽			▽		
7		4%	2	2			9	Variable track length		○							●				○	▽		
8		4%	3	1			9	Interface w/ given materials	○									●						
9		7%	4	3			9	Reset <= 10 min							▽				●	▽				
10		11%	5	5			9	Start mechanism												●		○		
11		7%	4	3			9	Transportable		○											●	○		
12		8%	5	3			9	<= $3500														●		
13		0%																						
14		8%	4	4			3	Lasts >1000 cycles						▽	○	○								
15		0%																						
16		0%																						

Row #	Hybrid III 50th Percentile Male	Anthony Best Dynamics	DURUS	TASI	4Active Systems	Steve	Atlas	Side Impact Dummy	Flex-PLI-GTR	Polar
1	5	4	2	5	5	5	3	5	1	5
2	1	5	5	5	5	5	5	1	1	1
3	1	5	4	3	5	5	5	1	1	1
4	1	1	2	4	3	4	5	1	1	1
5	5	5	2	4	4	3	1	5	5	5
6	5	5	5	5	5	5	5	5	5	5
7	1	5	5	5	5	1	5	1	1	1
8	4	5	1	1	5	5	1	4	3	4
9	2	5	1	3	5	5	2	2	5	4
10	1	5	5	5	5	5	5	1	1	2
11	5	5	5	5	5	3	5	5	5	3
12	1	1	1	1	1	1	1	1	3	1
13										
14	5	5	2	5	5	4	1	5	5	5
15										
16										

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	Adult Human Dimensions	ATD travels at least 6 m	ATD travels between 0.5 and 2.5		Elbow and Knee flex within certa	Gait at specified frequency and a	ATD can withstand impacts of our	Lateral Translation maintains fu	ATD Travel length can vary	Specified reflective material can	Reset <= 10 min	Trigger input	Not fixed, can fit inside semitruck	<=$3500		
Max Relationship	9	9	9		9	9	9	9	9	9	9	9	9	9		
Technical Importance Rating	60.421	110.38	94.778	0	94.778	103.2	137.98	120.05	56.209	35.937	75.889	102.04	96.292	360.93	0	
Relative Weight	4%	8%	7%	0%	7%	7%	10%	8%	4%	2%	5%	7%	7%	25%	0%	
Weight Chart																
Hybrid III	5	1	1		5	1	5	5	1	4	2	1	5	1		
ABD	4	5	5		1	1	5	5	5	5	5	5	5	1		
DURUS	2	5	4		3	5	2	5	5	1	1	5	5	1		
TASI	5	5	3		5	4	4	5	5	1	3	5	5	1		
4Active	5	5	5		4	3	4	5	5	5	5	5	5	1		
Steve	5	5	5		3	2	3	5	1	5	5	5	3	1		
Atlas	3	5	5		5	5	1	5	5	1	2	5	5	1		
SID	5	1	1		1	1	5	5	1	4	2	1	5	1		
Flex-PLI	1	1	1		1	1	5	5	1	3	5	1	5	3		
Polar	5	1	1		1	1	5	5	1	4	4	2	3	1		

Template Revision: 0.9
Christopher Battles
Date: [illegible]

APPENDIX D: PHYSICAL PROTOTYPES

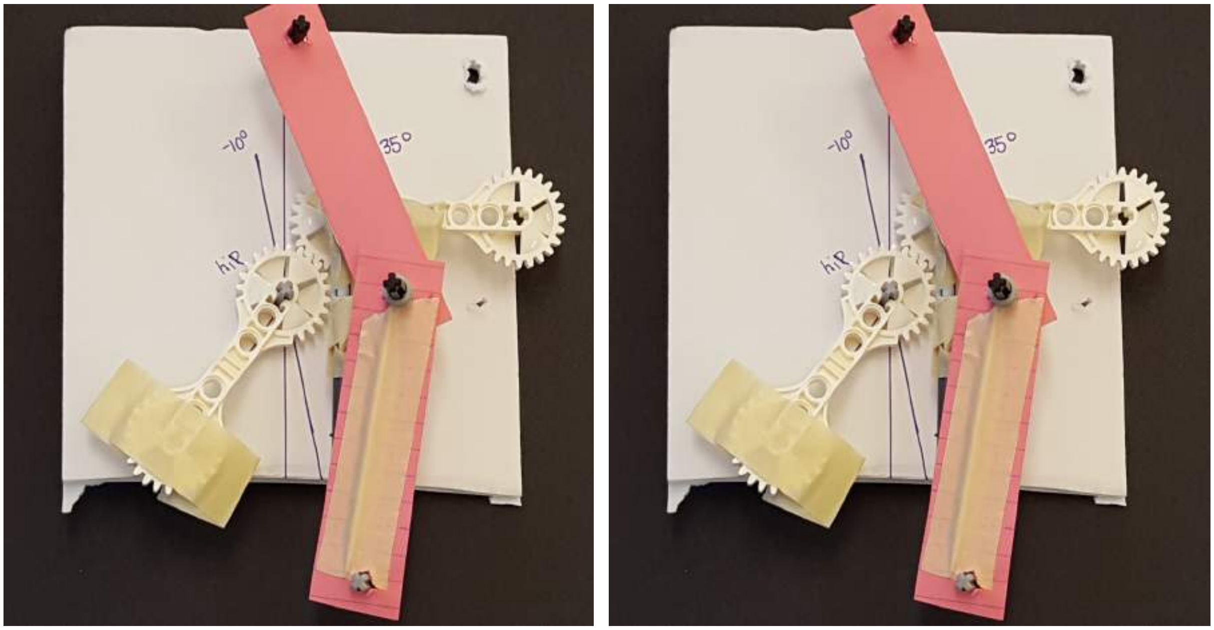


Figure 1. Physical model of hip articulation driving arm articulation by rigid attachment at the hands

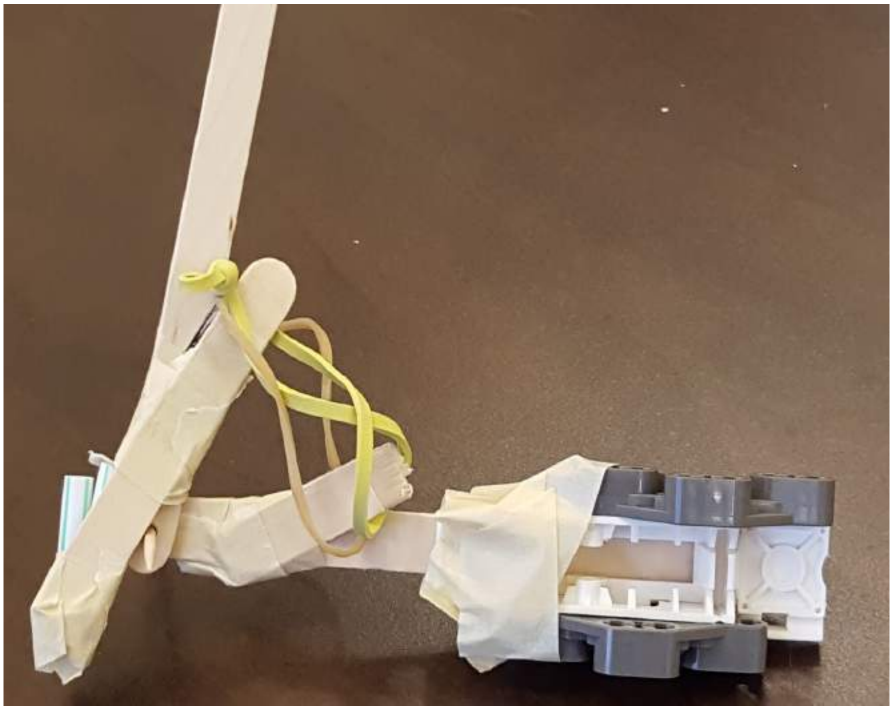


Figure 2. Knee articulation using a counterweight and spring and damper system

Figure 3. Arm Articulation using rigid rod attached to a belt/pulley track system

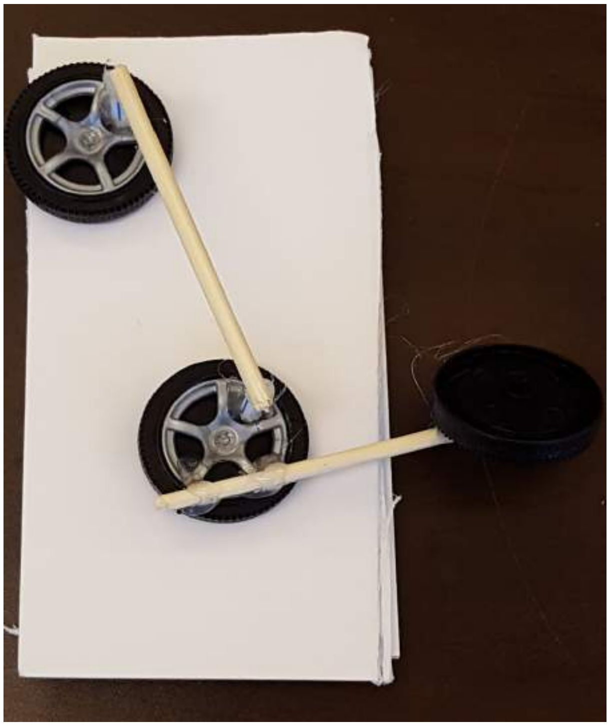


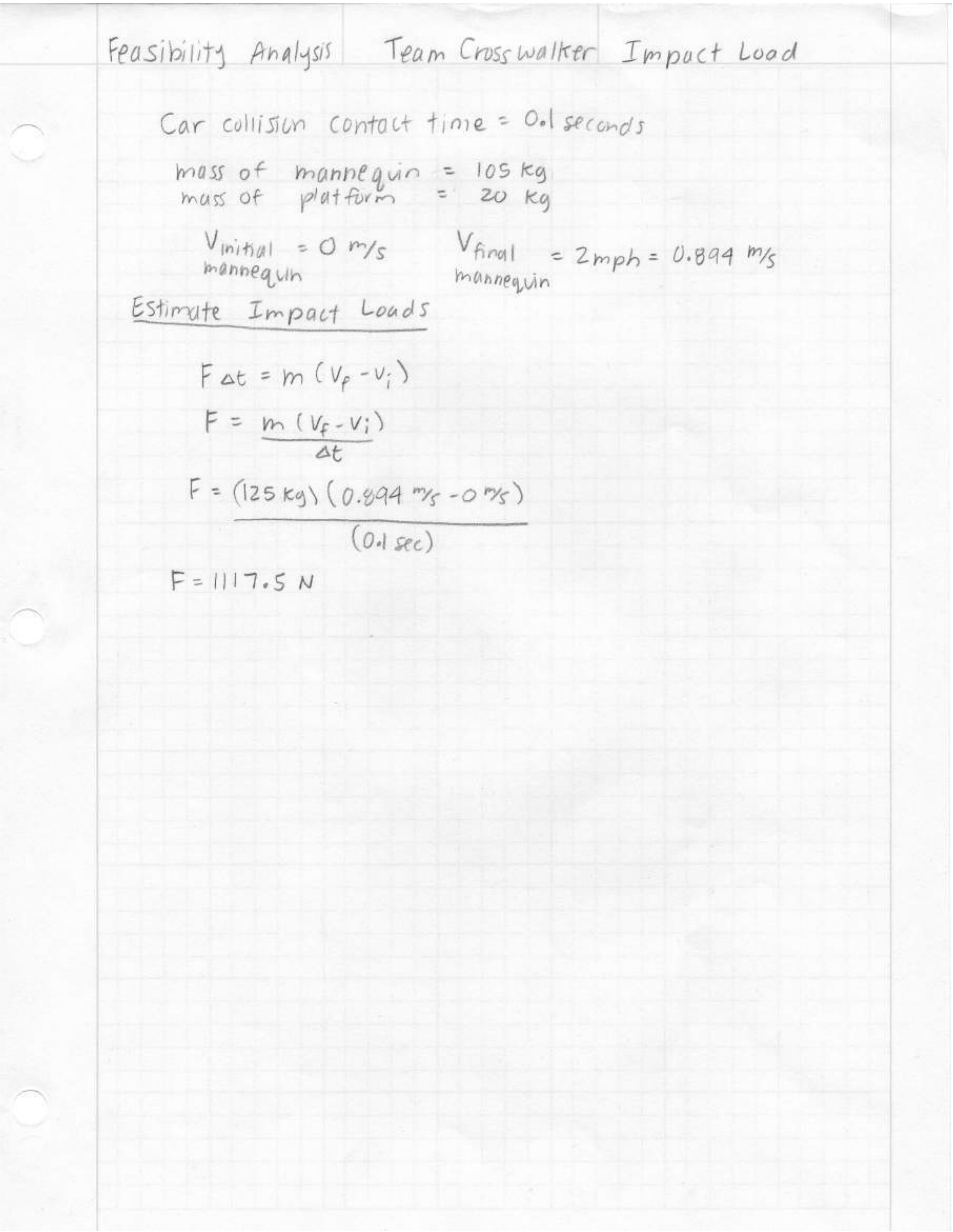
Figure 4. Coupling rod to provide elbow articulation from a driven shoulder

Figure 5. Caster wheels guided by a track low enough to leave with the help of an impact

APPENDIX E: WEIGHTED DECISION MATRIX

		Adult Human Dimensions	Track Travel Length (10 m min)	Linear Translation Precision	Limb Articulation	Impact resistance	Track can be driven over	Variable Track Length	Minimal Nonhuman Profile	Interface w/ given materials	Reset time	Transportable	Low Cost	Simplicity	Withstand Wind/ Temperature	Total	
	Weight	7	8	8.5	10	7	9	0	9	10	6	6	5	9	6	100.5	
	Relative Weight (decimal form)	0.0697	0.0796	0.0846	0.0995	0.0697	0.0896	0.0000	0.0896	0.0995	0.0597	0.0597	0.0498	0.0896	0.06	1.0000	
1	Rating	7	10	8	8	8	7	4	7	8	8	8	7	9	8	107	1
	Wgt Rtg	0.4876	0.7960	0.6766	0.7960	0.5572	0.6269	0.0000	0.6269	0.7960	0.4776	0.4776	0.3483	0.8060	0.4776	**7.9502**	
2	Rating	5	10	5	5	6	8	7	7	8	5	5	5	7	8	91	2
	Wgt Rtg	0.3483	0.7960	0.4229	0.4975	0.4179	0.7164	0.0000	0.6269	0.7960	0.2985	0.2985	0.2488	0.6269	0.4776	**6.5721**	
3	Rating	7	10	6	8	5	10	6	4	8	8.5	5	3	8	6	94.5	3
	Wgt Rtg	0.4876	0.7960	0.5075	0.7960	0.3483	0.8955	0.0000	0.3582	0.7960	0.5075	0.2985	0.1493	0.7164	0.3582	**7.0149**	
4	Rating	5	10	8	6.5	10	8	4	5	7	8	7	4	5	7	94.5	4
	Wgt Rtg	0.3483	0.7960	0.6766	0.6468	0.6965	0.7164	0.0000	0.4478	0.6965	0.4776	0.4179	0.1990	0.4478	0.4179	**6.9851**	
5	Rating	7	10	8	7	6	6	8	6	8	5	8.5	5	5	8	97.5	5
	Wgt Rtg	0.4876	0.7960	0.6766	0.6965	0.4179	0.5373	0.0000	0.5373	0.7960	0.2985	0.5075	0.2488	0.4478	0.4776	**6.9254**	
6	Rating	7	10	8	9	7	9	10	5	8	9	10	6	7	7	112	6
	Wgt Rtg	0.4876	0.7960	0.6766	0.8955	0.4876	0.8060	0.0000	0.4478	0.7960	0.5373	0.5970	0.2985	0.6269	0.4179	**7.8706**	
7	Rating	7	10	8	8	9	7	4	8	8	8	8	7	9	8	109	7
	Wgt Rtg	0.4876	0.7960	0.6766	0.7960	0.6269	0.6269	0.0000	0.7164	0.7960	0.4776	0.4776	0.3483	0.8060	0.4776	**8.1095**	

APPENDIX F: HAND CALCULATIONS



Feasibility Analysis Team Crosswalker Impact Load

Car collision contact time = 0.1 seconds

mass of mannequin = 105 kg
mass of platform = 20 kg

$V_{\text{initial mannequin}} = 0 \text{ m/s}$ $V_{\text{final mannequin}} = 2 \text{mph} = 0.894 \text{ m/s}$

Estimate Impact Loads

$$F \Delta t = m (V_f - v_i)$$

$$F = \frac{m (V_f - V_i)}{\Delta t}$$

$$F = \frac{(125 \text{ kg})(0.894 \text{ m/s} - 0 \text{ m/s})}{(0.1 \text{ sec})}$$

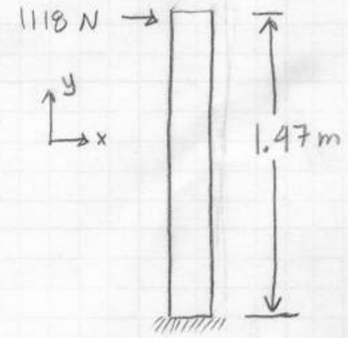
$$F = 1117.5 \text{ N}$$

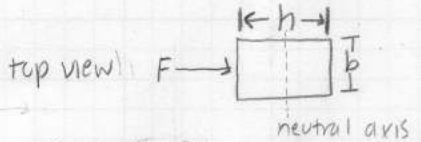
Feasibility Analysis

Bending

Minimum rod cross section to prevent yielding

$$\sigma_{yield,\,steel} = 250\ mPa$$





$$I = \frac{1}{12} b h^3$$

$$b = 5\,cm$$

$$\frac{\sigma_{bend}}{F.S.} = \frac{My}{I} = \frac{M(h/2)}{\frac{1}{12} b h^3} = \frac{(M/2)}{(\frac{1}{12} b h^2)}$$

$$\frac{250\ mPa}{2} = \frac{\left[(1118N)(1.47m)/2\right]}{(\frac{1}{12})(.05m)(h^2)}$$

$$125\ mPa = \frac{821.7\ Nm}{(.00417m)(h^2)}$$

$$h^2 = \frac{(821.7\ Nm)}{(.00417m)(125\ mPa)}$$

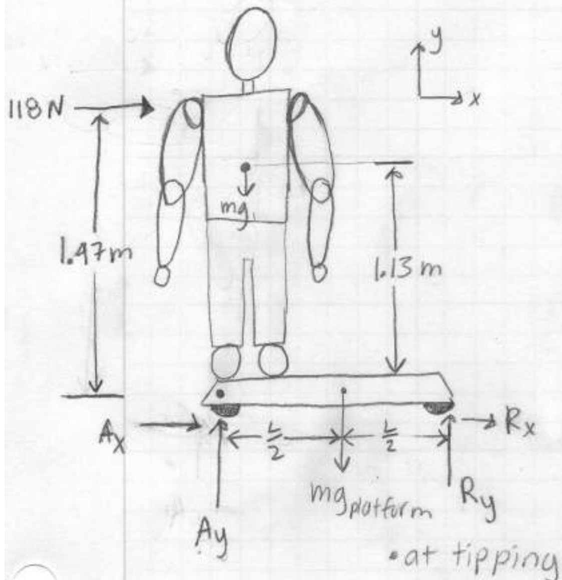
$$h^2 = .00158\ m$$

$$h = .0397\,m \cong 4\,cm$$

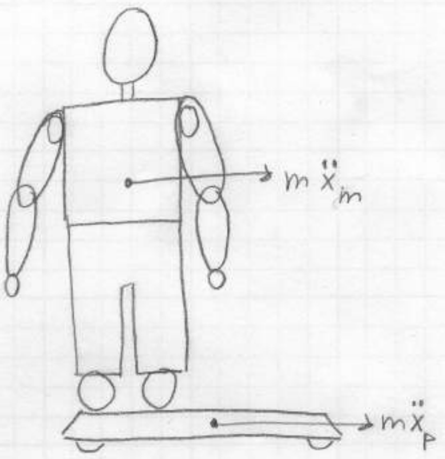
minimum cross section of a 5cm × 4cm rectangle

Find minimum platform length to prevent tipping during impact.

FBD



MAD



- at tipping point, $A_y = 0$

$$\ddot{X}_{mannequin} = \frac{.894\,m/s - 0\,m/s}{0.1\,s} = 8.94\,m/s^2$$

$$\left(\sum M_R\right)_{FBD} = \left(\sum M_R\right)_{MAD} \quad \circlearrowleft +$$

$$(1118\,N)(1.47\,m) - (105\,kg)(9.81\,m/s^2)(L) - (25\,kg)(9.81\,m/s^2)\left(\frac{L}{2}\right) = m\ddot{x}_m(1.13\,m)$$

$$1643.5\,Nm - 1030\,L - 245\frac{L}{2} = (105\,kg)(8.94\,m/s^2)(1.13\,m)$$

$$1643.5\,Nm - (1152.5)(L) = 1060.7\,Nm$$

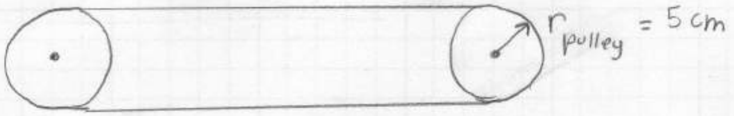
$$582.8\,Nm = (1152.5)L$$

$$L = \frac{582.8\,Nm}{1152.5\,N}$$

$$L_{min} = 0.506\,m$$

Feasibility Analysis

Torque on motor



Mannequin + platform on wheels

rolling resistance = 0.8

$$F_{friction} = (0.8)(125\text{ kg})(9.81\text{ m/s}^2)$$

$$F_{friction} = 981\text{ N}$$

$$Torque_{\text{on motor}} = F_{friction}\, r_{pulley}$$

$$T_m = (981\text{ N})(.05\text{m})$$

$$T_m = 49\text{ Nm}$$

Wind Loads

$$F_{wind} = \frac{1}{2} \varphi v^2 A_s$$

$\varphi = 1.2 \frac{kg}{m^3}$

$V = 7\ m/s$

$A_{s,front} = 0.3\ m^2$

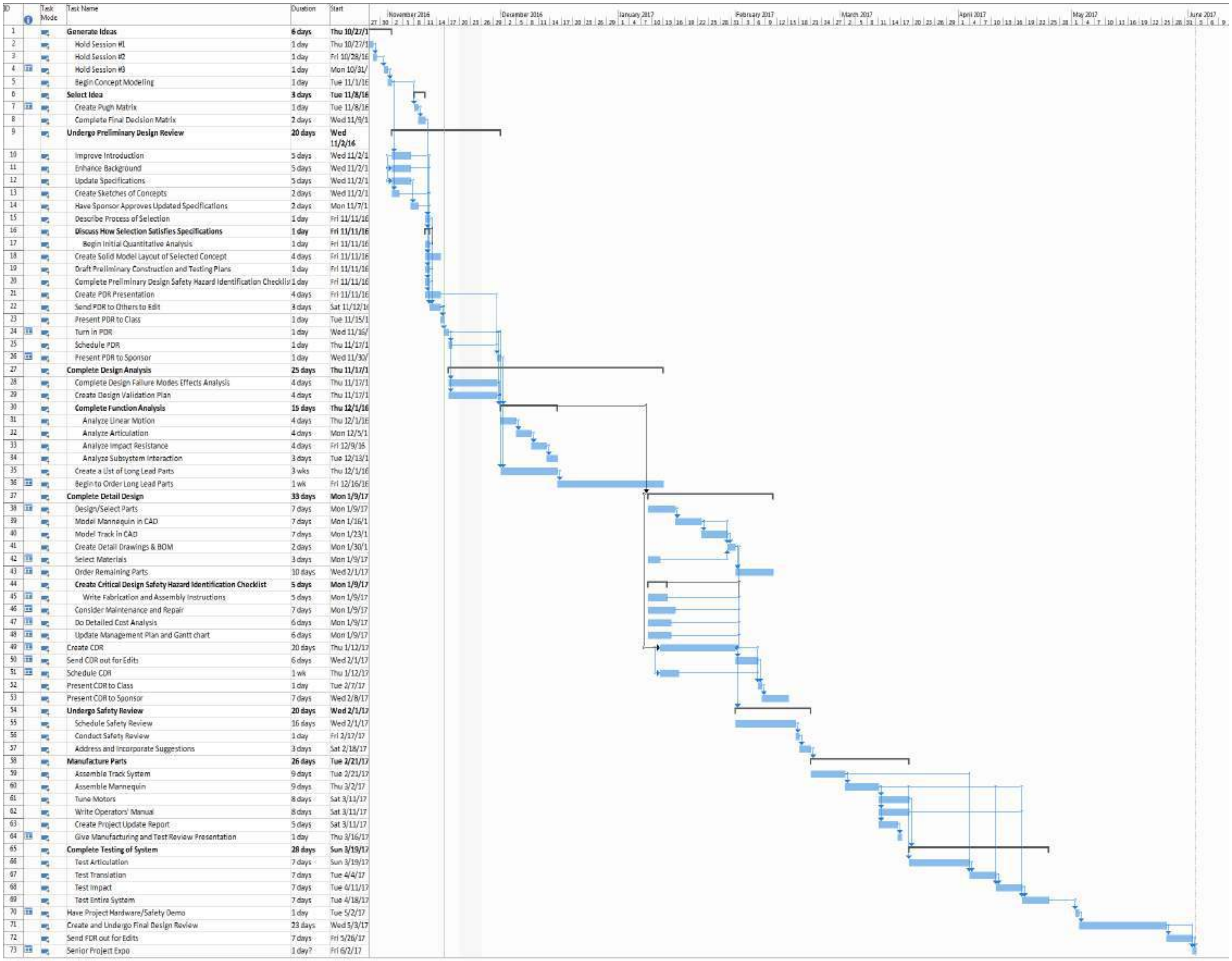
$$F_W = \frac{1}{2}(1.2\ kg/m^3)(7\ m/s)^2(0.3 m^2)$$

$$F_{wind} = 8.82\ N$$

Wind load on front of mannequin

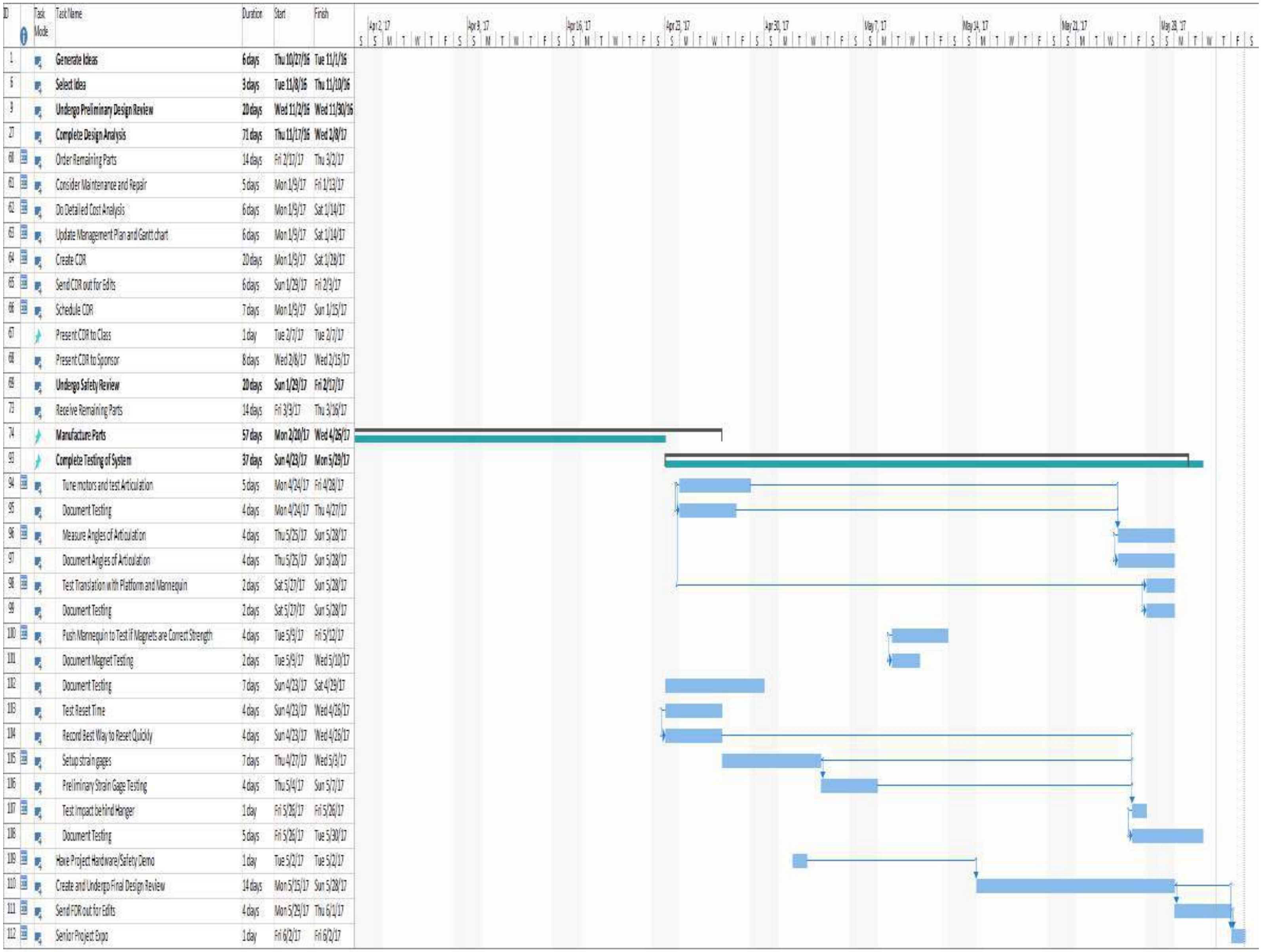
APPENDIX G: GANTT CHART

Planned:



ID	Task Name	Duration	Start
1	**Generate Ideas**	**6 days**	**Thu 10/27/1**
2	Hold Session #1	1 day	Thu 10/27/1
3	Hold Session #2	1 day	Fri 10/28/16
4	Hold Session #3	1 day	Mon 10/31/
5	Begin Concept Modeling	1 day	Tue 11/1/16
6	**Select Idea**	**3 days**	**Tue 11/8/16**
7	Create Pugh Matrix	1 day	Tue 11/8/16
8	Complete Final Decision Matrix	2 days	Wed 11/9/1
9	**Undergo Preliminary Design Review**	**20 days**	**Wed 11/2/16**
10	Improve Introduction	5 days	Wed 11/2/1
11	Enhance Background	5 days	Wed 11/2/1
12	Update Specifications	5 days	Wed 11/2/1
13	Create Sketches of Concepts	2 days	Wed 11/2/1
14	Have Sponsor Approves Updated Specifications	2 days	Mon 11/7/1
15	Describe Process of Selection	1 day	Fri 11/11/16
16	**Discuss How Selection Satisfies Specifications**	**1 day**	**Fri 11/11/16**
17	Begin Initial Quantitative Analysis	1 day	Fri 11/11/16
18	Create Solid Model Layout of Selected Concept	4 days	Fri 11/11/16
19	Draft Preliminary Construction and Testing Plans	1 day	Fri 11/11/16
20	Complete Preliminary Design Safety Hazard Identification Checklis	1 day	Fri 11/11/16
21	Create PDR Presentation	4 days	Fri 11/11/16
22	Send PDR to Others to Edit	3 days	Sat 11/12/1
23	Present PDR to Class	1 day	Tue 11/15/1
24	Turn in PDR	1 day	Wed 11/16/
25	Schedule PDR	1 day	Thu 11/17/1
26	Present PDR to Sponsor	1 day	Wed 11/30/
27	**Complete Design Analysis**	**25 days**	**Thu 11/17/1**
28	Complete Design Failure Modes Effects Analysis	4 days	Thu 11/17/1
29	Create Design Validation Plan	4 days	Thu 11/17/1
30	**Complete Function Analysis**	**15 days**	**Thu 12/1/16**
31	Analyze Linear Motion	4 days	Thu 12/1/16
32	Analyze Articulation	4 days	Mon 12/5/1
33	Analyze Impact Resistance	4 days	Fri 12/9/16
34	Analyze Subsystem Interaction	3 days	Tue 12/13/1
35	Create a List of Long Lead Parts	3 wks	Thu 12/1/16
36	Begin to Order Long Lead Parts	1 wk	Fri 12/16/16
37	**Complete Detail Design**	**33 days**	**Mon 1/9/17**
38	Design/Select Parts	7 days	Mon 1/9/17
39	Model Mannequin in CAD	7 days	Mon 1/16/1
40	Model Track in CAD	7 days	Mon 1/23/1
41	Create Detail Drawings & BOM	2 days	Mon 1/30/1
42	Select Materials	3 days	Mon 1/9/17
43	Order Remaining Parts	10 days	Wed 2/1/17
44	**Create Critical Design Safety Hazard Identification Checklist**	**5 days**	**Mon 1/9/17**
45	Write Fabrication and Assembly Instructions	5 days	Mon 1/9/17
46	Consider Maintenance and Repair	7 days	Mon 1/9/17
47	Do Detailed Cost Analysis	6 days	Mon 1/9/17
48	Update Management Plan and Gantt chart	6 days	Mon 1/9/17
49	Create CDR	20 days	Thu 1/12/17
50	Send CDR out for Edits	6 days	Wed 2/1/17
51	Schedule CDR	1 wk	Thu 1/12/17
52	Present CDR to Class	1 day	Tue 2/7/17
53	Present CDR to Sponsor	7 days	Wed 2/8/17
54	**Undergo Safety Review**	**20 days**	**Wed 2/1/17**
55	Schedule Safety Review	16 days	Wed 2/1/17
56	Conduct Safety Review	1 day	Fri 2/17/17
57	Address and Incorporate Suggestions	3 days	Sat 2/18/17
58	**Manufacture Parts**	**26 days**	**Tue 2/21/17**
59	Assemble Track System	9 days	Tue 2/21/17
60	Assemble Mannequin	9 days	Thu 3/2/17
61	Tune Motors	8 days	Sat 3/11/17
62	Write Operators' Manual	8 days	Sat 3/11/17
63	Create Project Update Report	5 days	Sat 3/11/17
64	Give Manufacturing and Test Review Presentation	1 day	Thu 3/16/17
65	**Complete Testing of System**	**28 days**	**Sun 3/19/17**
66	Test Articulation	7 days	Sun 3/19/17
67	Test Translation	7 days	Tue 4/4/17
68	Test Impact	7 days	Tue 4/11/17
69	Test Entire System	7 days	Tue 4/18/17
70	Have Project Hardware/Safety Demo	1 day	Tue 5/2/17
71	Create and Undergo Final Design Review	23 days	Wed 5/3/17
72	Send FDR out for Edits	7 days	Fri 5/26/17
73	Senior Project Expo	1 day?	Fri 6/2/17

Actual:

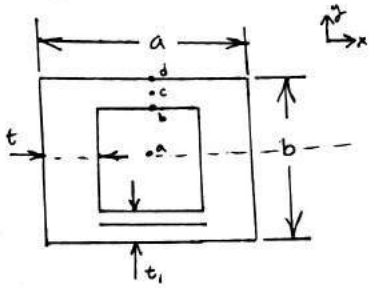


ID	Task Name	Duration	Start	Finish
1	**Generate Ideas**	**6 days**	**Thu 10/27/16**	**Tue 11/1/16**
6	**Select Idea**	**3 days**	**Tue 11/8/16**	**Thu 11/10/16**
9	**Undergo Preliminary Design Review**	**20 days**	**Wed 11/2/16**	**Wed 11/30/16**
27	**Complete Design Analysis**	**71 days**	**Thu 11/17/16**	**Wed 2/8/17**
60	Order Remaining Parts	14 days	Fri 2/17/17	Thu 3/2/17
61	Consider Maintenance and Repair	5 days	Mon 1/9/17	Fri 1/13/17
62	Do Detailed Cost Analysis	6 days	Mon 1/9/17	Sat 1/14/17
63	Update Management Plan and Gantt chart	6 days	Mon 1/9/17	Sat 1/14/17
64	Create CDR	20 days	Mon 1/9/17	Sat 1/28/17
65	Send CDR out for Edits	6 days	Sun 1/29/17	Fri 2/3/17
66	Schedule CDR	7 days	Mon 1/9/17	Sun 1/15/17
67	Present CDR to Class	1 day	Tue 2/7/17	Tue 2/7/17
68	Present CDR to Sponsor	8 days	Wed 2/8/17	Wed 2/15/17
69	**Undergo Safety Review**	**20 days**	**Sun 1/29/17**	**Fri 2/17/17**
73	Receive Remaining Parts	14 days	Fri 3/3/17	Thu 3/16/17
74	**Manufacture Parts**	**57 days**	**Mon 2/20/17**	**Wed 4/26/17**
93	**Complete Testing of System**	**37 days**	**Sun 4/23/17**	**Mon 5/29/17**
94	Tune motors and test Articulation	5 days	Mon 4/24/17	Fri 4/28/17
95	Document Testing	4 days	Mon 4/24/17	Thu 4/27/17
96	Measure Angles of Articulation	4 days	Thu 5/25/17	Sun 5/28/17
97	Document Angles of Articulation	4 days	Thu 5/25/17	Sun 5/28/17
98	Test Translation with Platform and Mannequin	2 days	Sat 5/27/17	Sun 5/28/17
99	Document Testing	2 days	Sat 5/27/17	Sun 5/28/17
100	Push Mannequin to Test if Magnets are Correct Strength	4 days	Tue 5/9/17	Fri 5/12/17
101	Document Magnet Testing	2 days	Tue 5/9/17	Wed 5/10/17
102	Document Testing	7 days	Sun 4/23/17	Sat 4/29/17
103	Test Reset Time	4 days	Sun 4/23/17	Wed 4/26/17
104	Record Best Way to Reset Quickly	4 days	Sun 4/23/17	Wed 4/26/17
105	Setup strain gages	7 days	Thu 4/27/17	Wed 5/3/17
106	Preliminary Strain Gage Testing	4 days	Thu 5/4/17	Sun 5/7/17
107	Test Impact behind Hanger	1 day	Fri 5/26/17	Fri 5/26/17
108	Document Testing	5 days	Fri 5/26/17	Tue 5/30/17
109	Have Project Hardware/Safety Demo	1 day	Tue 5/2/17	Tue 5/2/17
110	Create and Undergo Final Design Review	14 days	Mon 5/15/17	Sun 5/28/17
111	Send FDR out for Edits	4 days	Mon 5/29/17	Thu 6/1/17
112	Senior Project Expo	1 day	Fri 6/2/17	Fri 6/2/17

APPENDIX H: ANALYSIS HAND CALCULATIONS

12/19/16

Cross sectional dimensions and formulas



Bending stress

$$\sigma_x = -\frac{M_x y}{I_x} \qquad \sigma_y = -\frac{M_y x}{I_y}$$

Transverse Shear stress

$$\tau_{x,y} = \frac{V Q_{x,y}}{b_1 I_{x,y}}$$

Torsional shear stress

$$\tau_{avg} = \begin{cases} \dfrac{T}{2t(a-t)(b-t_1)} & \text{short side} \\ \dfrac{T}{2t_1(a-t)(b-t_1)} & \text{long side} \end{cases} \Bigg\} \text{ Roarké Formulas for stress \& strain}$$

Axial

$$\sigma_a = \frac{F}{A}$$

Polar moment of inertia

$$K = \frac{2tt_1(a-t)^2(b-t_1)^2}{at + bt_1 - t^2 - t_1^2} \leftarrow$$

From book called Roark's Formulas for Stress and Strain

when $t = t_1$ and $a = b$

$$K = \frac{t^2(a-t)^4}{at - t^2}$$

Area moment of inertia

$$I_x = \frac{ab^3 - (a-2t)(b-2t_1)^3}{12}$$

$$I_y = \frac{a^3 b - (a-2t)^3(b-2t_1)}{12}$$

when $t = t_1$ and $a = b$

$$I_{x,y} = \frac{a^4 - (a-2t)^4}{12}$$

First moment of area

About x-axis

$$Q_a = \frac{(b-t_1)at_1}{2} + \left(\tfrac{1}{2}b - t_1\right)^2 t \qquad b_a = 2t$$

$$Q_{b,c} = \frac{(b-t_1)at_1}{2} \qquad b_b = \cancel{2a}\ 2t \qquad b_c = a$$

$$Q_d = 0 \qquad b_d = 0$$

About y-axis

$$Q_a = \frac{(a-t)(bt)}{2} + \left(\tfrac{1}{2}a - t\right)^2 t_1 \qquad b_a = 2t_1$$

$$Q_{b,c} = \frac{(a-t)bt}{2} \qquad b_b = 2t_1 \qquad b_c = b$$

$$Q_d = 0 \qquad b_d = b$$

Buckling

slenderness ratio

$$\left(\frac{l}{k}\right)_{x,y} = \frac{l}{\sqrt{\frac{I_{x,y}}{A_c}}}$$

$$\left(\frac{l}{k}\right)_1 = \left(\frac{2\pi^2 CE}{S_y}\right)^{1/2}$$

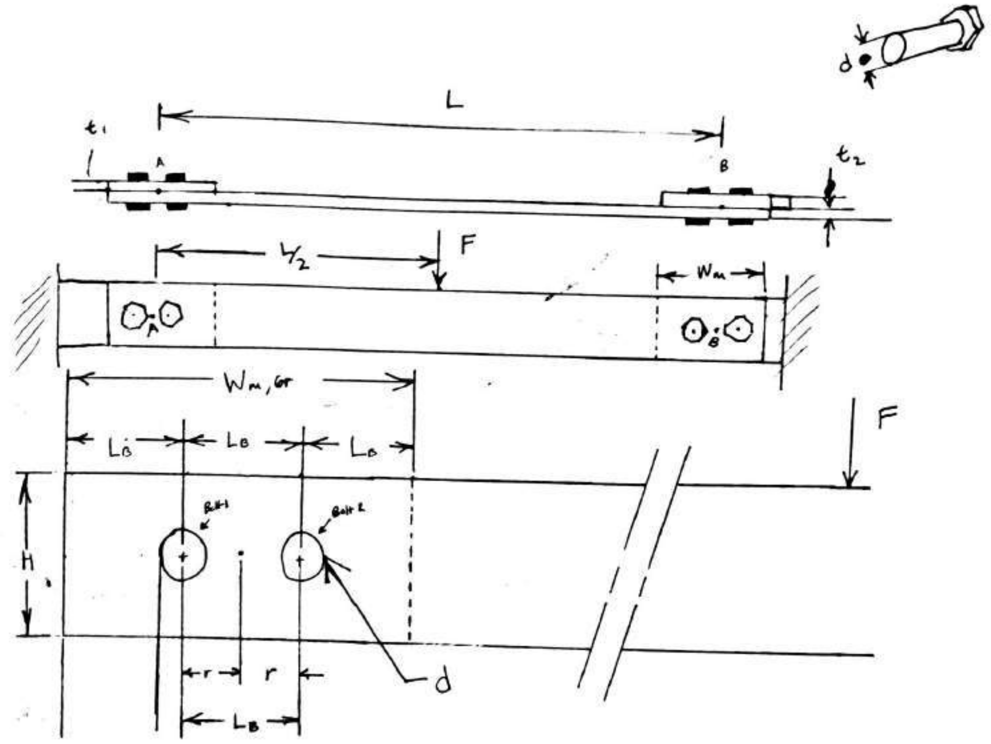
Euler Column Formula

$$\frac{P_{cr}}{A} = \frac{C\pi^2 E}{(l/k)^2} \qquad \left(\frac{l}{k}\right)_{x,y} > \left(\frac{l}{k}\right)_1$$

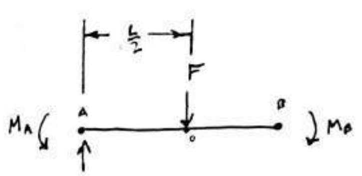
Intermediate length ~~with~~ Column with central loading

$$\frac{P_{cr}}{A} = S_y - \left(\frac{S_y}{2\pi}\left(\frac{l}{k}\right)\right)^2 \left(\frac{1}{CE}\right) \qquad \left(\frac{l}{k}\right)_{x,y} \leq \left(\frac{l}{k}\right)_1$$

Shear Joints with Eccentric Loading 12/26/16



FBD: Bar



$V = R_A = R_B = F/2$

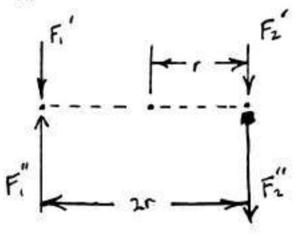
$M_A = M_B = \frac{FL}{8}$

$F' \equiv$ direct load or primary shear

$M_{AJ} = \frac{F}{8}(4x - L)$

$F'' \equiv$ moment load or secondary shear

FBD: Bolt section



$$F_n' = \frac{V}{N} = \frac{(F/2)}{2} = \frac{F}{4}$$

$$F_n'' = \frac{M_A r}{r^2 + r^2} = \frac{M_A}{2r} = \frac{FL}{16r}$$

$$F_2 = F_n'' + F_n' = \frac{FL}{16r} + \frac{F}{4} \Rightarrow \underline{\underline{F_2 = \frac{F}{16}\left[\frac{L}{r} + 4\right]}}$$

12/26/16

T8-1, T8-

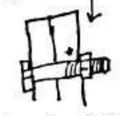
use minor diameter if thread is inside channel

* Check T8-10

$$S_{ys}' = \frac{0.577 S_y}{n_d}$$

Max Shear stress on each bolt

$$\tau = \frac{F_{1,2}}{A} \quad , A = \frac{\pi d^2}{4}$$



Max bearing stress around hole area ≡ due to the pressing of the bolt against the channel web

smallest channel thickness

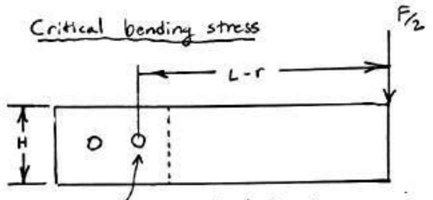
$$\sigma = \frac{-F_{1,2}}{A_b} \quad , \quad A_b = t\,d$$

* Check S_y for bolt

T8-9, 8-10, 8-11

$$S_y' = \frac{S_y}{n_d}$$

Critical bending stress



Taking most of the bending stress

$$M_c = (F/2)(L-r)$$

Second moment through section

$$I = I_{bar} - (I_h)$$
$$= \frac{1}{12}(t_{1,2})(H)^3 - \frac{1}{12}(t_{1,2})(D)^3$$

* Check S_y for bolt

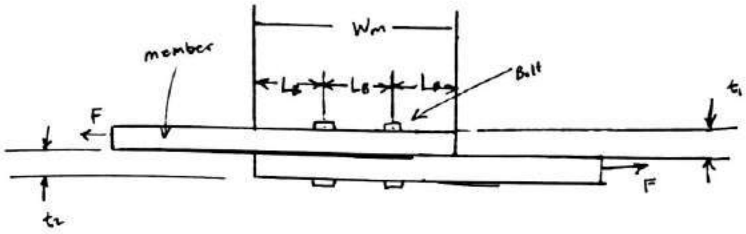
T8-9, 8-10, 8-11

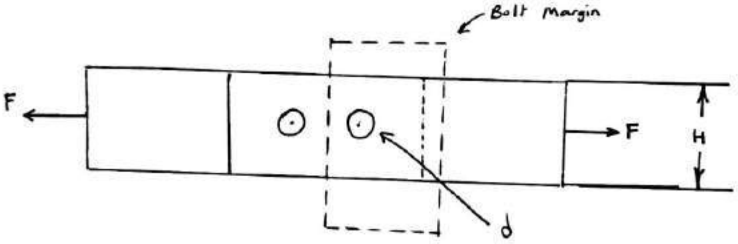
$$S_y' = \frac{S_y}{n_d}$$

$$\sigma = \frac{M_c(H/2)}{I}$$

Shear Joint

12/29/16





Bearing stress in bolt

$\sigma_b = \frac{F}{td}$ ← Diameter of bolt
↑ thickness of thinnest member

of bolt

* Check with $S_y' = \frac{S_y}{n_d}$

Bearing stress in member

$\sigma = \frac{F}{td}$

* Check wth $(S_y')_{mem} = \frac{(S_y)_{mem}}{n_d}$

Shear stress of bolt

$\tau = \frac{F}{N\left(\frac{\pi d^2}{4}\right)}$

↑ number of bolts

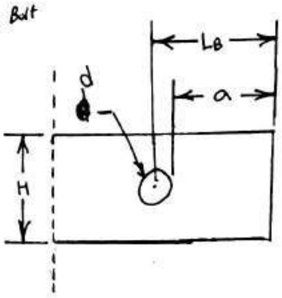
compare
* Check with $S_y' = \frac{0.577\, S_y}{n_d}$

Shear or tensile tear-out

* space bolts at least 1.5d away from edge, so entire width should be 4d long, $w = 4d$, so ~~[illegible]~~ $d \le \frac{w}{4}$

72 Margin Bolt

12/29/16



$a = L_B - \frac{d}{2}$

Edge Shear at margin bolt

$\tau = \frac{F}{Nat}$ ↖ thickness of thinnest plate

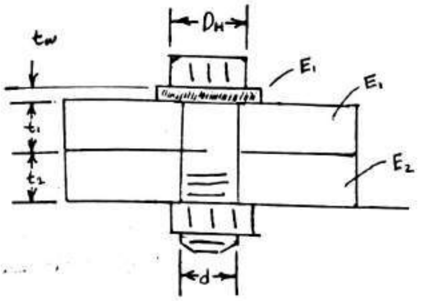
*Check with $S_y' = \cancel{S_y}\ \frac{0.577\, S_y}{n_d}$

Tensile yeilding ↙ TA-15

$\sigma_{max} = \frac{K_t F}{(H-d)t}$

*Check $(S_y')_{mem} = \frac{(S_y)_{mem}}{n_d}$

Tension Joint



$t_w \equiv$ washer thickness

$t_1 \equiv$ first member thickness

$t_2 \equiv$ second member thickness

$D_H \equiv$ hex nut width

$d \equiv$ nominal bolt diameter

Equations

$\ell = t_w + t_1 + t_2$

$\ell_m = \frac{1}{2}(t_w + t_1 + t_2)$

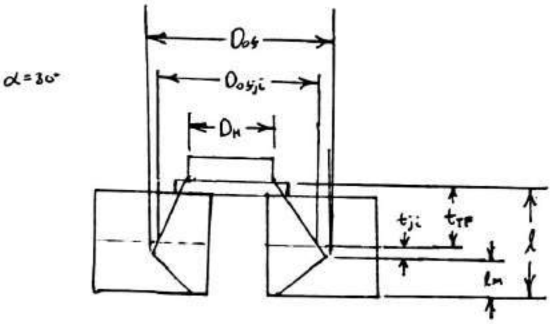
$$t_{ji} = \ell_m - t_1 - t_w$$
$$= \frac{1}{2}(t_2 - t_1 - t_w)$$

$t_{TF} = t_w + t_1$

$$D_{ofji} = D_H + 2(t_{TF})\tan 30^\circ$$
$$= D_H + 2(t_w + t_1)\tan 30^\circ$$

$$D_{of} = D_H + 2(\ell_m)\tan 30^\circ$$
$$= D_H + [t_w + t_1 + t_2]\tan 30^\circ$$

1/3/17



$\ell \equiv$ grip length (frusta thickness)

~~t_{ji}~~

$\ell_m \equiv$ grip midpoint (frusta midpoint)

$t_{ji} \equiv$ Joint interface length

$t_{TF} \equiv$ top member/washer frusta thickness

~~$t_{BF} \equiv$ bottom member frusta thickness~~

$D_{ofji} \equiv$ outer diameter of frusta at joint interface

$D_{of} \equiv$ outer diameter at midpoint of entire joi

1/3/17

Member stiffness

$$K_1 = \frac{0.5774\pi E_1 d}{\ln\left[\frac{(1.155 t_{TF} + D_H - d)(D_H + d)}{(1.155 t_{TF} + D_H + d)(D_H - d)}\right]}$$

$$K_2 = \frac{0.5774\pi E_2 d}{\ln\left[\frac{(1.155 t_{ji} + D_{osji} - d)(D_{osji} + d)}{(1.155 t_{ji} + D_{osji} + d)(D_{osji} - d)}\right]}$$

$$K_3 = \frac{0.5774\pi E_2 d}{\ln\left[\frac{(1.155 l_m + D_H - d)(D_H + d)}{(1.155 l_m + D_H + d)(D_H - d)}\right]}$$

$$K_m = \left[\frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3}\right]^{-1}$$

1/3/17

bolt stiffness

$$K_b = \frac{A_d A_t E_b}{A_d l_t + A_t l_d}$$

$A_t \equiv$ tensile - strength area
T8-1, T8-2

** Look @ T8-7 for pics

$A_d \equiv$ major diameter area of fastener

$l_t \equiv$ length of threaded portion

$l_d \equiv$ length of unthreaded portion of grip

Process (shown in T8-7)

compare
$L > l + H_H$
use TA-17 and round up
e.g.. $L_{comp} = l + H$
$\rightarrow L > L_c$

$$L_T = \begin{cases} 2d + \frac{1}{4} & L \leq 6\text{in} \\ 2d + \frac{1}{2} & L > 6\text{in} \end{cases}$$

$l_d = L - L_T$

$l_t = l - l_d$

$A_d = \frac{\pi d^2}{4}$

$A_T \equiv$ T8-1 or T8-2

Combined stiffness $C = \frac{K_b}{K_b + K_m}$

Stress!!!

external tensile load per bolt

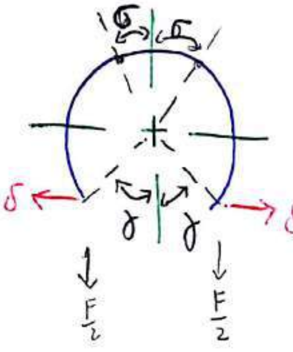
preload $\equiv$ clamping force from tightening nut

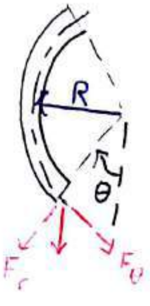
$$\sigma_{T} = \frac{CP + F_i}{A_t}$$

* Check with $S_y' = \frac{S_p}{n_d}$

Proof Strength
T8-9
T8-10
T8-11

Deflection of Beam as Release Mechanism





σ: mounting points
γ: end of tubing

Castigliano's Theorem for Curved Beams in Bending

$$\delta = \underbrace{\int \frac{M}{AeE}\left(\frac{\partial M}{\partial F}\right)d\theta}_{\text{Moment}} + \underbrace{\int \frac{F_\theta R}{AE}\left(\frac{\partial F_\theta}{\partial F}\right)d\theta}_{\text{Axial}} - \underbrace{\int \frac{1}{AE}\frac{\partial(MF_\theta)}{\partial F}d\theta}_{\text{Coupling}} + \underbrace{\int \frac{CF_r R}{AG}\left(\frac{\partial F_r}{\partial F}\right)d\theta}_{\text{Transverse}}$$

$F_\theta = F\sin\theta$ $\qquad \frac{\partial F_\theta}{\partial F} = \sin\theta$

$F_r = F\cos\theta$ $\qquad \frac{\partial F_r}{\partial F} = \cos\theta$

$M = F(R\sin\theta - R\sin\gamma)$ $\qquad \frac{\partial M}{\partial F} = R(\sin\theta - \sin\gamma)$

$MF_\theta = F^2R(\sin^2\theta - \sin\theta\sin\gamma)$ $\qquad \frac{\partial MF_\theta}{F} = 2FR(\sin^2\theta - \sin\theta\sin\gamma)$

$$\delta = \frac{FR^2}{AeE}\int_\gamma^{\pi-\sigma}(\sin^2\theta - 2\sin\theta\sin\gamma + \sin^2\gamma)d\theta + \frac{FR}{AE}\int_\gamma^{\pi-\sigma}\sin^2\theta\, d\theta - \frac{2FR}{AE}\int_\gamma^{\pi-\sigma}(\sin^2\theta - \sin\theta\sin\gamma)d$$
$$+ \frac{CFR}{AG}\int_\gamma^{\pi-\sigma}\cos^2\theta\, d\theta$$

Desire rod free at rated load

$$\text{Rod } \varnothing = 2\left(\frac{ID}{2}\sin\gamma\right) + 2\delta$$

Equation solver used w/ Rod Ø = 2.75" $\qquad e = R - \frac{t}{\ln(r_o/r_i)} = 2.4e^{-4}$

ID = 2.87" $\qquad E = 10.0e^6$ psi

R = 1.4675" $\qquad G = 3.8e^6$ psi

A = 0.145 in² $\qquad C = 1.2$

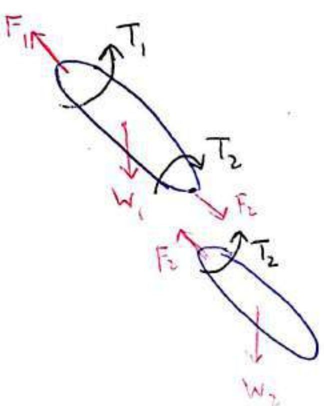
$F = \frac{25}{2}$ (divided among 2 points of contact

$\gamma = 73.038°$

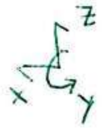
Naturally free at $\gamma = \sin^{-1}\left(\frac{\cancel{R}\text{Rod }\varnothing}{ID}\right) = \sin^{-1}\left(\frac{2.75}{2.87}\right) = 73.370°$

Far too close, could be ruined by tolerances

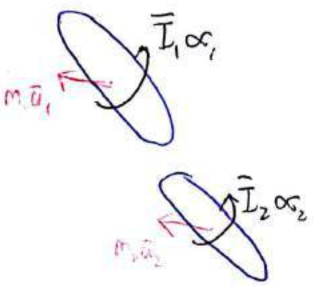
FBD



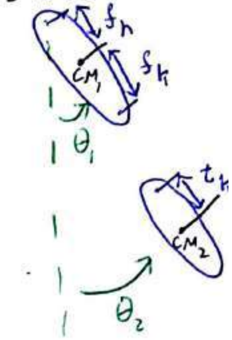
Servo Torque



MAD



Dimensions



All values assumed positive for equation

$$m_1\bar{a}_{1x} = F_{1x} - F_{2x}$$

$$m_2\bar{a}_{2x} = F_{2x}$$

$$m_1\bar{a}_{1z} = -W_1 + F_{1z} - F_{2z}$$

$$m_2\bar{a}_{2z} = -W_2 + F_{2z}$$

$$\bar{I}_1\alpha_1 = T_1 - T_2 - F_{1x}f_{hz} + F_{1z}f_{hx} - F_{2x}f_{kz} + F_{2z}f_{kx}$$

$$\bar{I}_2\alpha_2 = T_2 - F_{2x}t_{kz} + F_{2z}t_{kx}$$

$$\begin{array}{cccccc|c}
F_{1x} & F_{2x} & F_{1z} & F_{2z} & T_1 & T_2 & \\
1 & -1 & 0 & 0 & 0 & 0 & m_1\bar{a}_{1x} \\
0 & 1 & 0 & 0 & 0 & 0 & m_2\bar{a}_2x \\
0 & 0 & 1 & -1 & 0 & 0 & m_1\bar{a}_1z + W_{1z} \\
0 & 0 & 0 & 1 & 0 & 0 & m_2\bar{a}_{2z} + W_2 \\
-f_{hz} & -f_{kz} & f_{hx} & f_{kx} & 1 & -1 & \bar{I}_1\alpha_1 \\
0 & -t_{kz} & 0 & t_{kz} & 0 & 1 & \bar{I}_2\alpha_2
\end{array}$$

m's, W's, I's, f's & t's known

a & α known at any given instant

Contents

```
clear
format compact
```

Import Position data

```
P = xlsread('Full_Gait.xlsx','A7:K332');
prate = 60;

time = P(:,2);
trochanter(:,1) = P(:,3); % position data in mm
trochanter(:,2) = P(:,5);
knee(:,1) = P(:,6);
knee(:,2) = P(:,8);
ankle(:,1) = P(:,9);
ankle(:,2) = P(:,11);

len = length(P(:,1));
```

Scaling and Dimensions

angles defined from vertical

```
theta_f = zeros(len,1); % angle of femur (upper leg)
theta_t = zeros(len,1); % angle of tibia (lower leg)

theta_r = zeros(len,1); % relative angle between leg joints

% Rescales framerate to match desired step frequency and position data for
% size of mannequin
perframe = 0.0132; % seconds / frame
lengthRatio = 0.0328/12; % ft / mm

trochanter = trochanter * lengthRatio;
knee = knee * lengthRatio;
ankle = ankle * lengthRatio;

% Mass
m_f = 2.23 / 32.2; % Femur mass in slugs from 2.23 lbm
m_t = 2.33 / 32.2; % Tibia mass
% Mass moment of inertia of cylinder = 1/12 * m * (3r^2 + h^2)
I_f = 0.1414; % Femur mass moment of inertia [slug * in * ft] (to lbf*in later)
I_t = 0.1895;

for i = 1:len
```

```
    % Angles defined from vertical
    % Some sign manipulation to match function results with our sign convention
    theta_f(i,1) = atan2( (knee(i,1)-trochanter(i,1)) , (knee(i,2)-trochanter(i,2)) );
    theta_f(i,1) = sign(theta_f(i,1)) * (pi-abs(theta_f(i,1)));
    theta_t(i,1) = atan2( (ankle(i,1)-knee(i,1)) , (ankle(i,2)-knee(i,2)) );
    theta_t(i,1) = sign(theta_t(i,1)) * (pi-abs(theta_t(i,1)));

    % Relative angles for spring
    theta_r(i,1) = theta_f(i,1) - theta_t(i,1) + pi;
    time(i) = i * perframe;
end

%{femur = sqrt( TK(i,1)^2 + TK(i,2)^2);%}
clear i lengthRatio
```

Acceleration of Each Point

```
CM_f = (trochanter + knee) / 2;
CM_t = (knee + ankle) / 2;

omega_r = zeros(len,1);
omega_r(:,1) = myDiff(time, theta_r(:,1));

a_f(:,1) = mySecDiff(time, CM_f(:,1));
a_f(:,2) = mySecDiff(time, CM_f(:,2));
a_t(:,1) = mySecDiff(time, CM_t(:,1));
a_t(:,2) = mySecDiff(time, CM_t(:,2));

alpha_f(:,1) = mySecDiff(time, theta_f(:,1));
alpha_t(:,1) = mySecDiff(time, theta_t(:,1));
```

Solving for Forces and Torques

```
syms a1x a1z a2x a2z alpha1 alpha2 fhx fhz fkx fkz tkx tkz
F1 = zeros(len,2);
F2 = zeros(len,2);
T1 = zeros(len,1);
T2 = zeros(len,1);

A = [1 -1 0 0 0 0
    0 1 0 0 0 0
    0 0 1 -1 0 0
    0 0 0 1 0 0
    -fhz -fkz fhx fkx 1 -1
    0 -tkz 0 tkx 0 1];
B = [m_f * a1x/12
    m_t * a2x/12
    m_f*a1z/12 + m_f*32.2
    m_t*a2z/12 + m_t*32.2
    I_f * alpha1
    I_t * alpha2];

for i = 1:len
    a1x = a_f(i,1);
```

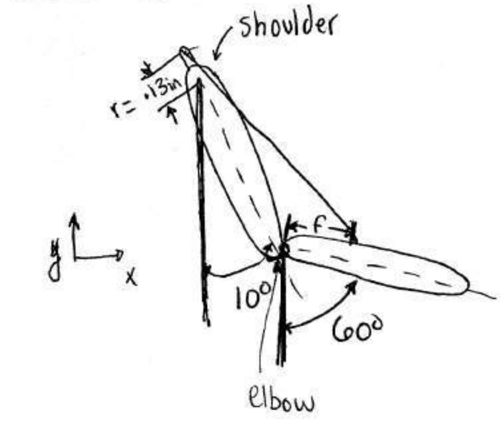
```
    a1z = a_f(i,2);
    a2x = a_t(i,1);
    a2z = a_t(i,2);
    alpha1 = alpha_f(i);
    alpha2 = alpha_t(i);
    fhx = CM_f(i,1) - trochanter(i,1);
    fhz = CM_f(i,2) - trochanter(i,2);
    fkx = CM_f(i,1) - knee(i,1);
    fkz = CM_f(i,2) - knee(i,2);
    tkx= CM_t(i,1) - knee(i,1);
    tkz = CM_t(i,2) - knee(i,2);

    C = double(subs(A));
    D = double(subs(B));

    X = linsolve(C,D);
    F1(i,1) = X(1); % lbf
    F2(i,1) = X(2);
    F1(i,2) = X(3);
    F2(i,2) = X(4);
    T1(i) = X(5) * 16; % oz-in
    T2(i) = X(6) * 16;
end
```

Published with MATLAB® R2016a

Schematic:



amount tab and wire rotate with servo

amount arm attachment rotates with elbow

Assumptions:

no slack in wire

maximum rotation of shoulder is 10°

maximum rotation of elbow is 60°

wire doesn't stretch

length of arm is 12.57 in for upper and 9.647 in for lower

weight of arm is 1.38 lb for upper and 1.06 lb for lower

radius of lower arm is 1.969 in

Analysis:

$$d_t = 2\pi r\left(\frac{10°}{360°}\right)$$

$$d_t = 2\pi(.13in)\left(\frac{10°}{360°}\right) = 0.0226in$$ using the minimum distance of 0.13"

$$d_f = 2\pi f\left(\frac{60°}{360°}\right)$$

$$d_f = d_t$$

$$2\pi f\left(\frac{60°}{360°}\right) = 0.0226in$$

$$f = 0.0216in$$

∴ wire should be attached 0.0216inches down from the elbow

Finding tension in wire:

$\Sigma M_{elbow} = I\alpha$

$$Tf\cos 60^\circ - mg\left(\frac{l_l}{2}\right)\cos 60^\circ = \frac{1}{2} m_l r_l^2 \alpha$$

$$T = \frac{mg\left(\frac{l_l}{2}\right)\cos 60^\circ + \frac{1}{2} m_l r_l^2 \alpha}{f\cos 60^\circ}$$

Finding α:

- going up to 2.5 steps per second
- this means that ~ $\frac{\pi}{3}$ rads need to moved per second if 10° are moved for a half step

$\omega = \overset{0}{\cancel{\omega_0}} + \alpha t$

$\alpha = \frac{\omega}{t} = \frac{\pi/3}{1\,\text{sec}} = \frac{\pi}{3}\,\text{rad/s}^2$

Tension cont.

$$T = \frac{\overbrace{(1.06\,\text{lbf})}^{mg}\left(\frac{9.647\,\text{in}}{2}\right)\cos 60^\circ + \frac{1}{2}\left(\frac{1.06\,\text{lbf}}{32.2\,\text{ft/s}^2}\cdot\frac{\text{lbm ft/s}^2}{\text{lbf}}\right)(1.969\,\text{in})^2\left(\frac{\pi}{3}\,\text{rad/s}^2\right)}{(0.0216\,\text{in})\cos 60^\circ}$$

$T = 237\,\text{lbf}$

this is stronger than the fishing line we plan to use. If we change r from 0.13 inches to 2.5 inches

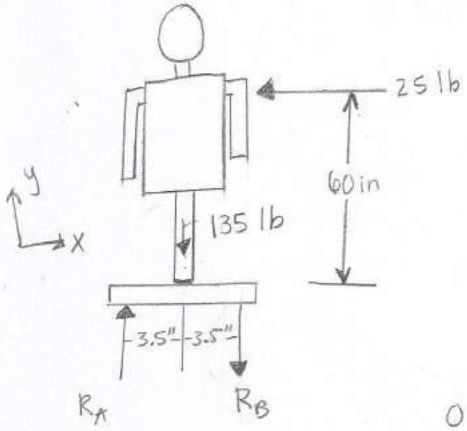
$f = \frac{r}{6} = \frac{2.5\,\text{inches}}{6} = 0.42\,\text{inches}$

$T = \frac{2.56\,\text{lbf}}{0.42\cos 60} = 12.3\,\text{lbf} < 20\,\text{lbf}$ fishing line we plan to use

Platform Analyses

total weight of mannequin = 135 lb
impact load at detachment = 25 lb
height of shoulder (impact location) = 60 in.

Loads onto top plate (ASTM A108, $\sigma_{yield} = 54$ ksi)



$$\circlearrowleft+ \ \Sigma M_A = 0$$

$$0 = 25\,lb(60\,in) - 135\,lb(3.5\,in) - R_B(7\,in)$$

$$R_B(7\,in) = 25\,lb(60\,in) - 135\,lb\,(3.5\,in)$$

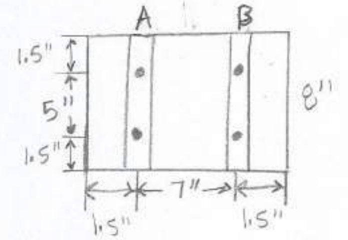
$$R_B = \frac{(1500 - 472.5)\,lb\cdot in}{7\,in}$$

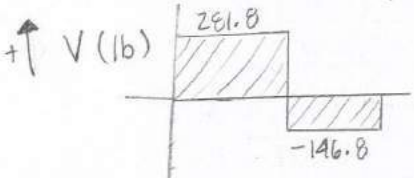
$$R_B = 146.8\,lb$$

$$\Sigma F_y = 0$$

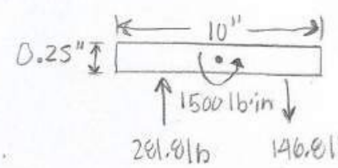
$$0 = R_A - 135\,lb - 146.8\,lb$$

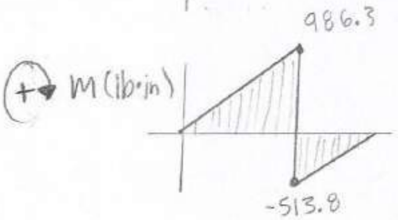
$$R_A = 281.8\,lb$$





Max shear force = 281.8 lb



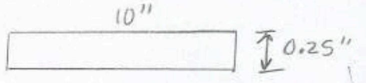


Max bending moment = 986.3 lb·in

②

$V_{max} = 281.6 \text{ lb}$ $\qquad M_{max} = 986.3 \text{ lb·in}$

$\tau_{shear} = \frac{VQ}{Ib}$ $\qquad \sigma_{bend} = \frac{My}{I}$



$I = \frac{bh^3}{12} = \frac{(10 in)(0.25 in)^3}{12}$

$I = 0.013 \text{ in}^4$

$\sigma_{bend} = \frac{(986.3 \text{ lb·in})(1/8 \text{ in})}{(0.013 \text{ in}^4)}$

$\sigma_{bend} = 9.48 \text{ ksi}$ ✓

$Q = 2(1/16 \text{ in})[(10 \text{ in})(1/8 \text{ in})]$

$Q \doteq 0.1563 \text{ in}^3$

$\tau_{shear} = \frac{(281.6 \text{ lb})(0.1563 \text{ in}^3)}{(0.013 \text{ in}^4)(0.25 \text{ in})}$

$\tau_{shear} = 13.52 \text{ ksi}$ ✓

Tubing: A, B, C, D

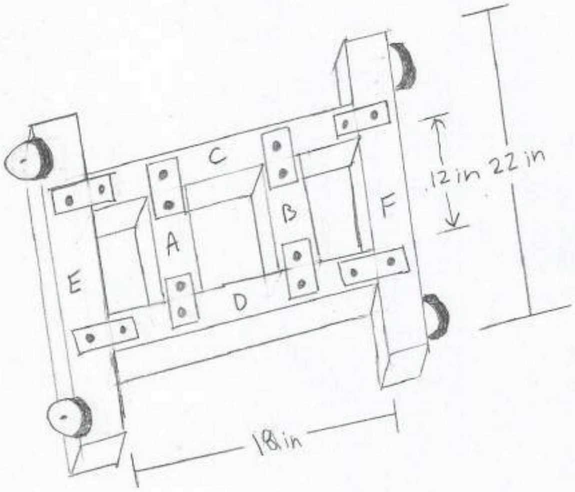
1" x 1", $t = 1/8$", A513

$\sigma_{yield} = 46$ ksi

Tubing: E and F

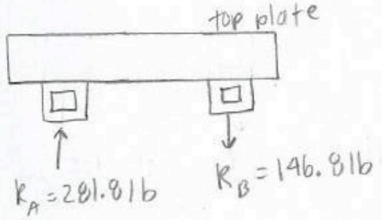
1.5" x 1.5", $t = 0.12$"

$\sigma_{yield} = 32$ ksi

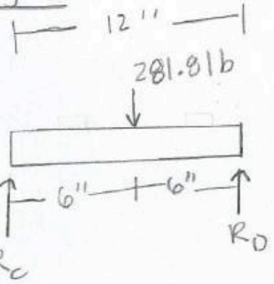


Loads onto Tubing A

③



Tubing A



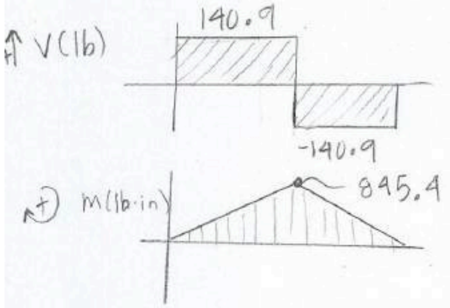
$(+\circlearrowleft)\ \Sigma M_c = 0$

$0 = R_D(12 in) - 281.8 lb(6 in)$

$R_D(12 in) = 1690.8 lb\cdot in$

$$R_D = \frac{1690.8 lb\cdot in}{(12 in)}$$

$R_D = 140.9 lb$

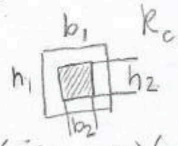


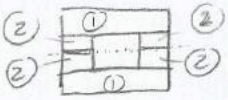
$\Sigma F_y = 0$

$0 = R_D + R_c - 281.8 lb$

$R_c = 281.8 lb - 140.9 lb$

$R_c = 140.9 lb$





$I = \frac{1}{12} b_1h_1^3 - \frac{1}{12} b_2h_2^3$

$I = \frac{1}{12}(1in)(1in)^3 - \frac{1}{12}(1-.25)(1-.25)^3$

$I_A = 0.057 in^4$

$Q = 2(1in)(.125)(.125/2) + 4(.125)(.375)(.375/2)$

$Q_A = .05078 in^3$

$$\tau_{shear} = \frac{VQ}{Ib} = \frac{(140.9 lb)(.05078 in^3)}{(.057 in^4)(.25 in)}$$

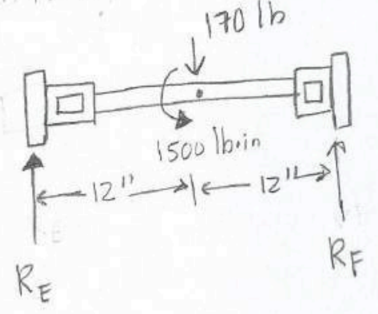
$\tau_{shear} = 502 psi$ ✓

$$\sigma_{bend} = \frac{My}{I} = \frac{(845.4 lb\cdot in)(0.5 in)}{(.057 in^4)}$$

$\sigma_{bend} = 7.42 ksi$ ✓

Reaction Forces at Wheels

- weight of mannequin = 135 lb
- weight of platform = 35 lb



$$\circlearrowleft + \quad \Sigma M_E = 0$$

$$0 = 1500\ \text{lb}\cdot\text{in} - 170\ \text{lb}(12\ \text{in}) + R_F(12\ \text{in})$$

$$R_F(12\ \text{in}) = 170\ \text{lb}(12\ \text{in}) - 1500\ \text{lb}\cdot\text{in}$$

$$R_F = \frac{2040\ \text{lb}\cdot\text{in} - 1500\ \text{lb}\cdot\text{in}}{12\ \text{in}}$$

$$R_F = 45\ \text{lb}$$

$$\Sigma F_y = 0$$

$$0 = R_E + R_F - 170\ \text{lb}$$

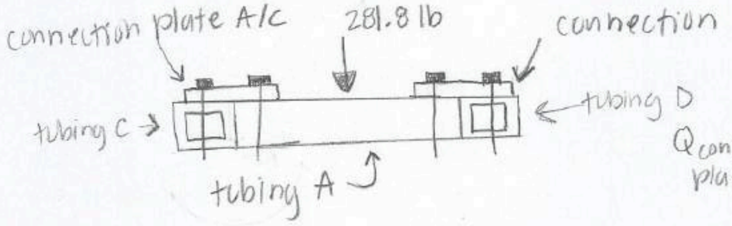
$$R_E = 170\ \text{lb} - 45\ \text{lb}$$

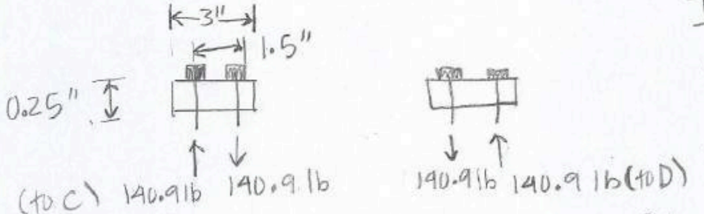
$$R_E = 125\ \text{lb}$$

- 2 wheels on E tubing, each with 62.5 lb reaction force
- 2 wheels on F tubing, each with 22.5 lb reaction force

Loads on Connection A/C and A/D

⑤





Bolts

$d = 3/8"$

$H_{nut} = 21/64"$

$width_{nut} = 9/16"$

$F_{tension} = 140.9\ lb$

See bolt analysis in Appendix

$\Rightarrow \sigma_{tensile,\,bolt} = 295\ psi$ ✓

$$Q_{\substack{connection\\plate}} = 2\left(\tfrac{1}{16}"\right)(3")\left(\tfrac{1}{8}"\right)$$

$$Q = .0469\ in^3$$

$$I_{\substack{connection\\plate}} = \tfrac{1}{12} bh^3 = \tfrac{1}{12}(3in)(0.25in)^3$$

$$I = .00391\ in^4$$

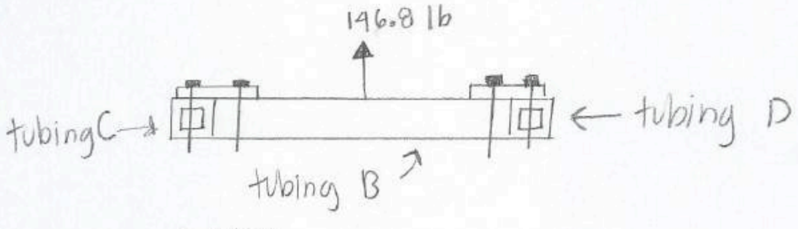
$$\tau_{\substack{shear\\connection\\plate}} = \frac{VQ}{Ib} = \frac{(140.9\ lb)(.0469\ in^3)}{(.00391\ in^4)(.25\ in)}$$

$$\tau_{\substack{shear\\connection\\plate}} = 6.76\ Ksi$$

$$\sigma_{\substack{bend\\connection\\plate}} = \frac{My}{I} \checkmark = \frac{(140.9 lb)(1.5 in)(.125 in)}{(.00391\ in^4)}$$

$$\sigma_{\substack{bend\\connection\\plate}} = 6.8\ Ksi \checkmark$$

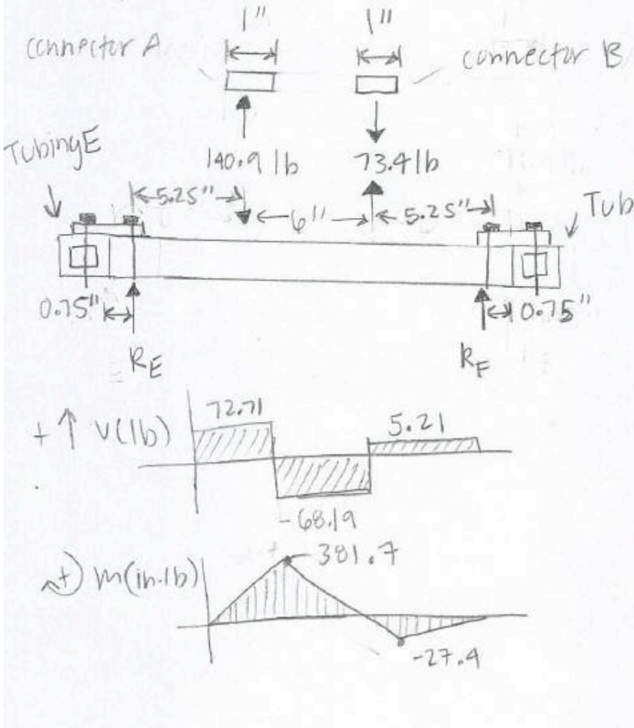
Loads on Connection B/C and B/D



- Loads on connector plate B/C + B/D are less than loads on connector plate A/C + A/D, will not yield.

Loads on Tubing C and D

length = 18 in



$$\circlearrowleft + \quad \Sigma M_E = 0$$

$$0 = R_F(16.5\text{ in}) + 73.4\text{ lb}(11.25\text{ in}) - 140.9\text{ lb}(5.25\text{ in})$$

$$R_F(16.5\text{ in}) = 140.9\text{ lb}(5.25\text{ in}) - 73.4\text{ lb}(11.25\text{ in})$$

$$R_F = \frac{-86.025\text{ in}\cdot\text{lb}}{16.5\text{ in}}$$

$$R_F = -5.21\text{ lb}$$

$$\Sigma F_y = 0$$

$$0 = R_E + R_F + 73.4\text{ lb} - 140.9\text{ lb}$$

$$R_E = (140.9 - 73.4 - R_F)\text{ lb}$$

$$R_E = 67.5 - (-5.21)\text{ lb}$$

$$R_E = 72.71\text{ lb}$$

Loads on Tubing C + D

$V_{max} = 72.71 \text{ lb}$

$M_{max} = 381.7 \text{ in}\cdot\text{lb}$

$\tau_{shear} = \frac{VQ}{Ib}$

$\tau_{shear} = \frac{(72.71\text{lb})(.05078 \text{ in}^3)}{(.057 \text{ in}^4)(0.25 \text{ in})}$

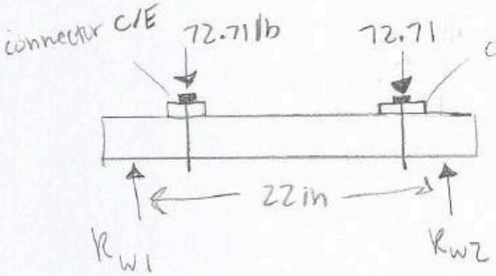
$\tau_{shear} = 259 \text{ psi}$ ✓

$\sigma_{bend} = \frac{My}{I}$

$\sigma_{bend} = \frac{(381.7 \text{in}\cdot\text{lb})(0.5 \text{in})}{(.057 \text{ in}^4)}$

$\sigma_{bend} = 3.35 \text{ ksi}$ ✓

Loads from C+D to E



$R_{w1} = R_{w2} = 72.71 \text{ lb}$

· loads on E are higher than on F

$I = 1/12 (1.5 \text{in})^4 - 1/12 (1.5 - .24 \text{in})^4$

$I = 0.212 \text{ in}^4$

$Q = 2(1.5 \text{in})(.12 \text{in})(.12/2) + 4(.12 \text{in})(.315)(\frac{.315}{2})$

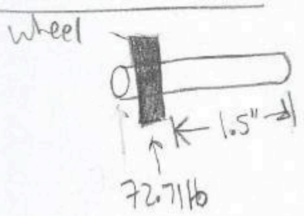
$Q = .045 \text{ in}^3$

$\tau_{shear} = \frac{(72.71 \text{ lb})(.045 \text{ in}^3)}{(.212 \text{in}^4)(.24 \text{in})} = 64 \text{ psi}$ ✓

$\sigma_{bend} = \frac{(72.71 \text{lb})(22 \text{in})(.75 \text{in})}{(.212 \text{ in}^4)}$

$\sigma_{bend} = 5.66 \text{ psi}$ ✓

Loads on Shaft



$d = 8\text{mm} = 0.315 \text{ in}$ $\quad \sigma_{yield} = 65 \text{ ksi}$

$I_z = 1/4 mr^2 + 1/12 mL^2$ $\quad m = .054 \text{ lb}$

$I_z = 1/4 (.054)(\frac{.315}{2}\text{in})^2 + 1/12 (.054 \text{ lb})(1.5 \text{in})^2$

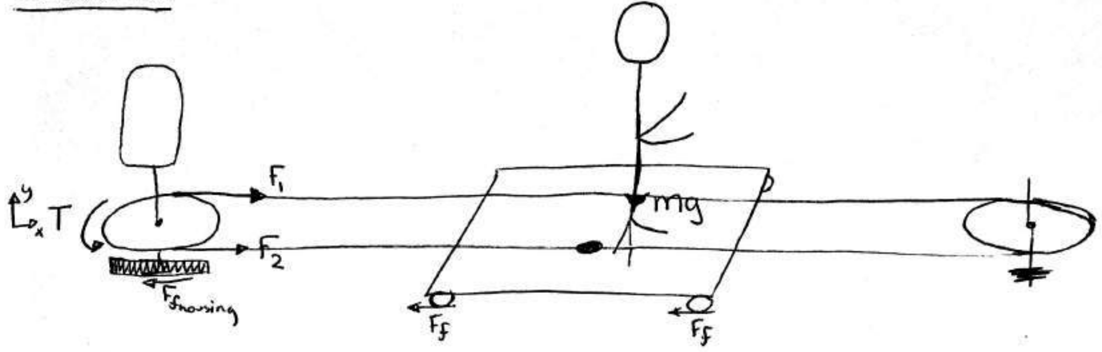
$I_z = .01046 \text{ in}^4$

$\sigma_{bend} = \frac{My}{I}$

$= \frac{(72.71 \text{ lb})(1.5 \text{ in})(.315/2 \text{ in})}{(.01046 \text{ in}^4)}$

$\sigma_{bend} = 1.642 \text{ ksi}$ ✓

Schematic:



Assumptions:

$f = 0.03$ → friction factor of wheels

$\omega_r = 0.018\,\text{lbm/ft}$ → weight per foot of manila rope

$V = 2.5\,\text{m/s} = 492.126\,\text{ft/min}$ → maximum velocity of platform and mannequin

$W = 200\,\text{lbf}$ → weight of platform and mannequin

Using same size pulley for each end so $\phi = \pi$ (angle of contact)

$f_{rope} = 0.23$ → friction of rope

$f_{rubber/asphalt} = 0.90$ → friction factor of rubber on asphalt

Analysis:

Finding initial tension based on force to start system

$$F_i = fW = (0.03)(200\,\text{lbf}) = 6\,\text{lbf}$$

Finding hoop tension

$$F_c = \frac{12\gamma\pi r^2}{g}\left(\frac{V}{60}\right)^2$$

$$F_c = \frac{12w}{g}\left(\frac{V}{60}\right)^2$$

$$F_c = \frac{(0.018\,\text{lbm/ft})(\text{lbf})}{(32.174\,\text{lbm ft/s}^2)}\left(\frac{492.126\,\text{ft/min}}{60}\right)^2$$

$$F_c = 0.0376\,\text{lbf}$$

Finding force in tight side (F_1)

$$F_1 = F_c + F_i \left(\frac{2e^{f\phi}}{e^{f\phi}+1} \right)$$

$$F_1 = 0.0367\,lbf + (6\,lbf)\left(\frac{2e^{(.23\pi)}}{e^{(.23\pi)}+1} \right)$$

$$F_1 = 8.11\,lbf$$

Finding force in loose side (F_2)

$$F_2 = F_c + F_i \left(\frac{2}{e^{\text{[illegible]}}+1} \right)$$

$$F_2 = 0.0367\,lbf + (6\,lbf)\left(\frac{2}{e^{(.23\pi)}+1} \right)$$

$$F_2 = 0.0367\,lbf + 3.922\,lbf$$

$$F_2 = 3.96\,lbf$$

Using a pulley for 3/8" rope will have a diameter of 2.25inches.

Finding Torque needed for this pulley

$$T = d \left(\frac{F_1 - F_2}{2} \right)$$

$$T = 2.25in \left(\frac{8.11\,lbf - 3.96\,lbf}{2} \right)$$

$$T = 4.669\ in\,lbf$$

Finding needed mass of motor housing with a rubber base

$\Sigma F_x = 0$ for no motion of housing

$$F_1 + F_2 - F_{f_{housing}} = 0$$

$$f_{housing} W_{housing} = F_1 + F_2$$

$$W_{housing} = \frac{8.11\,lbf + 3.96\,lbf}{0.9}$$

$$W_{housing} \approx 5\,lbf$$

Finding rpm of motor for max speed (2.5m/s)

$$n = \frac{12V}{\pi d}$$

$$n = \frac{12\,\text{in/ft}\,(492.126\ \text{ft/min})}{\pi\,(2.25\text{in})}$$

$$n = 835\ \text{rpm}$$

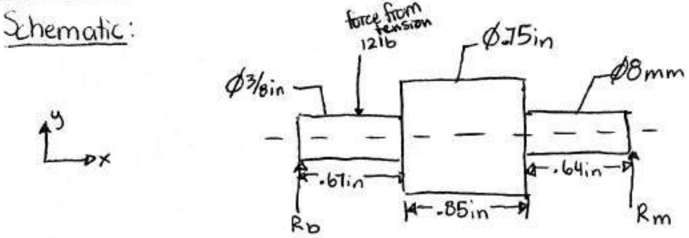
Finding rpm of motor for min speed (0.5m/s)

$$n = \frac{12\,V}{\pi d}$$

$$n = \frac{12\,\text{in/ft}\,(98.425\ \text{ft/min})}{\pi\,(2.25\text{in})}$$

$$n = 167\ \text{rpm}$$

Schematic:



Assumptions:

AISI 1050 steel for all parts

$K_c = K_d = K_e = K_f = 1$

$r = 0.0375\text{in}$ for connection between different shaft sizes

$S_{UT} = 100\text{ksi}$

$S_y = 84\text{ksi}$

$S_e' = 0.5S_{UT} = 50\text{ksi}$

$$\frac{\text{rev}}{\text{life}} = \left(\frac{157\text{rev}}{\text{test}}\right)\left(\frac{90\text{ tests}}{\text{day}}\right)\left(\frac{4\text{ days}}{\text{year}}\right)\left(\frac{5\text{years}}{\text{life}}\right) = 3\times10^5\,\frac{\text{rev}}{\text{life}}$$

from $\left(\frac{3.54\text{in travel (max)}}{2.25\text{in }\text{Ø of pulley}}\right)$

Analysis

$\Sigma M_b = 0$

$$(.67\text{in})(12\text{lb}) = (2\text{in})R_m$$

$$R_m = \frac{(.67\text{in})(12\text{lb})}{(2\text{in})}$$

$$R_m = 4.02\text{lb}$$

$$R_b = 12\text{lb} - 4.02\text{lb}$$

$$R_b = 7.98\text{lb}$$

Finding Correction factors:

$$K_a = aS_{UT}{}^b = 2.70(100\text{ksi})^{(-.265)} = 0.7968$$

$$K_b = 0.879(d)^{-.107} = 0.879(.31\text{in})^{-.107} = 0.9964$$

$$S_e = K_aK_bS_e' = (0.7968)(0.9964)(50\text{ksi}) =$$

$$S_e = 39.696\text{ ksi}$$

Find K_t:

$r/d = \frac{.031}{.31} = .1 \qquad D/d = \frac{.75}{.31} = 2.4$

$K_t = 2.2$

Finding K_f:

$\sqrt{a} = 0.246 - 3.08(10^{-3})(100) + 1.51(10^{-5})(100)^2 - 2.67(10^{-8})(100)^3$

$\sqrt{a} = 0.0622\sqrt{in}$

$K_f = 1 + \frac{K_t - 1}{1 + \sqrt{a}/\sqrt{r}}$

$K_f = 1 + \frac{2.2 - 1}{1 + 0.0622/\sqrt{0.31}} = 2.0794$

Finding moment at applied force:

$M_F = R_b x = (7.98\,lb)(.67\,in) = 5.35\,lb\,in$

Finding stress:

$\sigma_{rev} = K_f \frac{M_F}{I/c} = K_f \frac{M_F}{\pi d^3/32}$

$\sigma_{rev} = (2.0794) \frac{(5.35\,lb\,in)}{\pi(.31\,in)^3/32}$

$\sigma_{rev} = 3.803\,ksi$

Finding cycles:

$f = 0.844$

$a = \frac{(fS_{ut})^2}{Se} = \frac{(0.844 \cdot 100\,ksi)^2}{39.696\,ksi} = 179.4\,ksi$

$b = -\frac{1}{3}\log\left(\frac{fS_{ut}}{Se}\right) = -\frac{1}{3}\log\left(\frac{.844 \cdot 100\,ksi}{39.696\,ksi}\right) = -.1092$

$N = \left(\frac{\sigma_{rev}}{a}\right)^{1/b} = \left(\frac{3.803\,ksi}{179.4\,ksi}\right)^{1/-.1092} = 5.09(10^5)\text{ cycles} \ggg 3(10^5)\text{ cycles}$

Appendix I: FMEA

									Action Results
Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurence	Criticality	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken
Lateral Translation	Pedestrian test target experiences no lateral movement	Faulty test	3	Rope gets caught	5	15	Manual kill switch and/or sensors	Tiffany 1/23	Kill switch implemented between generator and driver
		Incorrect radar signature	5	Not enough friction on pulley	2	6	Operator's manual, specific set-up instructions	Tim 3/9/2017	In progress
		Never reaches point of impact	2	Rope comes off of the pulley	4	20	Ensure pulley grooves are deep enough to prevent rope from slipping off	Melanie 1/8/2017	Pulley selected for correct rope size
		Time is wasted	2	Pulley is frozen (cannot rotate)	3	15			
		Pedestrian test target battery has less energy	3	Inadequate power supplied to motor	2	10	Provide motor with adequate power	Tiffany 1/8/2017	Motor selected with torque greater than required
				Rope has insufficient tension	4	20			
				Clamping device does not have sufficient clamping force to allow rope to pull platform	2	10	Design for adequate clamping force	Chris 1/8/2017	Clamping device can be tighened with bolts and has three clampinig locations for redundancy
	Motor stalls	Damage the motor	8	Insufficient torque	4	32	Kill switch (Manual & Automatic)	Tiffany 1/23	Kill switch implemented between generator and driver
				Platform / hook stops against motor housing	8	64			
				Clip/hook do not disconnect	6	48			
				Not enough power	2	16			

Lateral Translation	Rope breaks	Rope whips and strikes someone	9	Platform doesn't detach upon impact	6	54	Ensure rope can take tension applied by weight of test target and impact	Melanie 1/8/2017	Calculations performed and rope selected with a large factor of safety
		Mannequin flys/falls and hurts someone	9	Incorrect set-up, too much tension	2	18	Provide clear and concise instructions	Tim 3/9/2017	In progress
	Rope breaks with platform still attached (with or without being hit by truck)	Motor experiences excessive torque caused by platform swinging about the motor housing	8	The truck impact causes the rope to break before the platform detaches	3	24	Ensure rope can take tension applied by weight of test target and impact	Melanie 1/8/2017	Calculations performed and rope selected with a large factor of safety
		Motor housing drags across floor due to platform swinging around motor housing	8						
		Pedestrian test target does not translate as desired	7	Rope not strong enough to support weight of test target and platform	2	16			
	Platform does not travel in straight path.	Radar system does not recognize the target as traveling at constant speed	7	High winds pushing on pedestrian test target	3	21	Provide adequate tensioners	Chris 1/8/2017	Tensioners out of scope. Tension will be applied by moving housing farther apart. Rubber placed on bottom of housing to reduce chance of sliding
		Execessive stress on motor housing and motor pulley due to different tension force	6						
		Unintended impact point	6						

Lateral Translation	Platform does not travel at constant speed	Incorrect radar signature	5	Extremely rough terrain causes test target to move in unpredictable manner	3	18	Select wheel of proper size	Chris 1/8/2017	Medium sized smooth skateboard wheel selected (similar application)
		Unintended impact point	6	Electrical issues with motor	3	18	Ensure proper wiring connections	Tim 2/20/2017	Wiring designed and double checked
	Truck tire is pinning rope to the ground while motor is still running	Motor may be damaged by extremely hight torque applied to the driver pulley.	7	Automated and manual shut off of the translation device fails before truck passes through test target track	4	32	Create automated and manual shut off	Tiffany 1/8/2017	Kill switch implemented between generator and driver
		Rope becomes damaged due to truck weight	7						Cheaper rope with high coefficient of friction selected and extra to be purchased
		Rope may break if no there is no slip on driver pulley and motor torque is high enough	8						
	Automated and/or manual shut off of the translation device fails	Pedestrian test target continues to translate until it hits the motor housing unit.	7	Faulty wiring	3	21	Ensure proper wiring connections	Tim 2/20/2017	Wiring designed and double checked. Will be revisited during manufactoring
		Energy from generator or power source is wasted	3	Operator error	7	49	Create automated and manual shut off	Tiffany 1/8/2017	Kill switch implemented between generator and driver

Mannequin	Insufficient impact resistance	Damage to electronics	8	Incorrect material choice	3	27	Higher factor of safety	Chris 1/8/2017	Larger tubing selected to account for FEA results
		Damage to skeleton	7	Truck impacts at high speed	3	27	Design for multiple impact points	Melanie 1/8/2017	Limbs absorb much energy with no deformation and torso structure is reenforced
		Rod yields or breaks	6	Platform doesn't detach upon impact	6	54	Ensure stability in all directions	Chris 1/8/2017	Stable attachement to platform; weight of mannequin evenly distributed
		Flying parts	9	Insufficient padding	3	27	Account for loads outside of expected range	Melanie 1/8/2017	Used large factors of safety
		Battery leakage	9	Lateral translation drives mannequin in a curved track	3	27	Multiple methods of energy dissipation	Melanie 1/8/2017	Limbs absorb much energy with no deformation and torso structure is reenforced. Pole dettaches allowing mannequin to fall to
		Exposed electronics	8	Mannequin spins after impact	4	36			
		Arm gets deformed	5	Wind load spins mannequin	2	18			
		Leg gets deformed	5	Mannequin tips upon impact	4	36			
		Torso gets deformed	5	Parts of the system get driven over by the truck	3	27			
		Housing of motors get deformed	8	Mannequin can not detach from track	3	27			
		Damage to motors	9	Not a sufficient factor of safety	3	27			
		Platform yields	6	Not enough energy dissipation	4	36			
		Mannequin wobbles during translation	3	Faulty wiring	3	27			
		Center of mass shifts	4						
		Bearings break	4						

Mannequin	Insufficient impact resistance	Broken connections (e.g. thigh to leg)	4				Higher factor of safety	Chris 1/8/2017	Larger tubing selected to account for FEA results
		Damage to reflective material	3						
		Incorrect radar signature	5						
		Shearing of bolts	3						
		Mannequin/platform unstable under static loads	5						
	Arm/leg articulates incorrectly	Incorrect radar signature	5	One motor dies	2	16	Ensure easy access to internal systems for repair/replacement	Melanie 1/23/2017	Structure of mannequin is an open box design that will be covered in easy to remove padding. Translation housing has removable cover for
		Unstable on platform (tips)	6	Motors not synced	4	32			
		Hits operator	8	Mech. tendon wire slips off/breaks	4	32			
		Mannequin gets damaged	7	Electrical failure	6	48			
		Unstable on platform (wiggles off track)	5	Damaged housing	5	40			
		Spring flys off and hits someone	7	Weak spring attachment	3	21	Kill switch (Manual & Automatic)	Tiffany 1/23	Kill switch implemented between generator and driver as well as on the back of the mannequin
		Mechanical Tendon gets wrapped around wheels and breaks them	5	Spring breaks	3	21			
		Limbs get stuck on body and permanently deform	7	Spring assembled incorrectly	4	28			
		Breaks pole	6	Hand gets stuck on the back	5	35	Ensure enough clearance between limbs, body, and platform	Tiffany 1/23	Clearance created by increasing pole length
		Rotates mannequin on pole and electrical components get full impact	8	Foot gets caught on the platform	5	35			

Mannequin	Arm/leg articulates incorrectly	Breaks the force of the magnets causing limbs to go flying	9	Limbs off balance	2	18	Ensure that body parts are appropriate and symmetric sizes and weights	Tim 1/23	To be accomplished in
		Unable to stop articulation and battery drains too quickly	5	Articulation cutoff does not work	4	32	Automatic kill switch	Tiffany 1/23	Out of Scope
		Mannequin falls over and continues to articulate, ruining motors	8						
Platform	Wheels do not roll	Mannequin tips	6	Wheels get stuck on rope	7	42	Large, stable platform	Chris 1/8/2017	Wheels large in comparsion to rope and rope is low to the ground
		Damage to wheels	5	Grime in wheels	4	24			Strong, single rolling surface skateboard wheels choosen
		Slowed lateral movement	3	Wheels break	2	12			
		Extra load on motor	5	Bumps in road	7	42			Large wheels
	Rod fails	Mannequin detaches	6	Weak rod joint	5	30	Ensure sufficient padding	Melanie 1/23/2017	Lots of batting to be place on entire design
				Insufficient rod strength	4	24	Select appopriate rod material & geometry	Chris 1/8/2017	Large strong rod selected
				Truck drives over platform	3	21	Minimize forces grounding in rod	Tim 1/23/2017	Forces transferred to platform and absorbed by limbs and fall
		Platform breaks	7				Large, strong platform	Chris 1/8/2017	Strong, large platform designed to take loads of mannequin dettaching

Platform	Platform does not roll in expected manner	Mannequin tips	8	Off-center impact causes rotation	8	64	Large, stable platform	Chris 1/8/2017	Large stable platform designed
		Damage to pulley system	7	Bumps in road	7	56	Select motor of appropriate size	Tiffany 1/8/2017	Motor selected with torque greater than required
				Insufficient motor torque	4	32			

APPENDIX J: CRITICAL DESIGN HAZARD CHECKLIST

Y	N	
☒	☐	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and shear points?
☒	☐	2. Can any part of the design undergo high accelerations/decelerations?
☒	☐	3. Will the system have any large moving masses or large forces?
☐	☒	4. Will the system produce a projectile?
☒	☐	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☐	☒	7. Will the system have any sharp edges?
☐	☒	8. Will any part of the electrical systems not be grounded?
☒	☐	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☒	☐	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☒	☐	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	14. Can the system generate high levels of noise?
☐	☒	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☒	☐	16. Is it possible for the system to be used in an unsafe manner?
☒	☐	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any “Y” responses a complete description, a list of corrective actions to be taken, and date to be completed can be found on the following page.

#	Description of Hazard	Planned Corrective Action	Planned Date of Completion
1	Motors in mannequin and those powering the pulley and belt system can cause pinch points.	Keep all motors contained and ensure that no one is in the pathway of the mannequin when it is turned on. A safe observation distance will be specified in the operator's manual.	2/7
2	High accelerations during impact.	Ensure that no one will be near the mannequin during test runs. This will be specified in the operator's manual.	3/9
3	The mannequin will weigh around 100 lb and will be moving up to 2.5 m/s (5.6 mph; 8.2 ft/s) before impact and possibly more after impact.	Required that no one is near the testing location during testing. A safe observation distance will be specified in the operator's manual.	3/9
5	Connection between mannequin and platform may become loose.	Provide replacement connectors. Specify criteria for replacement. Only allow fall in 1 direction	3/9
9	A motor will plug into a 110 V power source.	The large voltage system will be stock and we will not wire the electronics ourselves.	2/2
10	9V alkaline and 7.4V lithium ion batteries are within the body.	All batteries will be contained to protect electrical elements from contact.	2/15
13	Lift 150 lb mannequin to reset	Minimum of 3 people lift	3/9
16	Unsafe usage: not standing clear when in use	Specify safe distance in operator's manual	3/9
17	Rope may be caught in tires, damaging the pulley or truck.	Place rope low to the ground. Secure pulleys they will not move.	2/7

APPENDIX K: DESIGN VERIFICATION PLAN

DVP&R

Report Date	February 9, 2017		Sponsor	Daimler					Component/Assembly	Pedestrian Target	REPORTING ENGINEER:

Crosswalker TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference [1]	Test Description [2]	Acceptance Criteria [3]	Test Responsibility [4]	Test Stage [5]	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Quantity	ype [7	Start date	Finish date	est Result [6	Quantity Pass	Quantity Fail	
1	$3,500 production cost	Budget	Pass/Fail	Tiffany	DV	1	B	11/30/2016	2/7/2017				
2	10 min reset time	Time setup and reset time	Pass/Fail	Tiffany	PV	10	C	4/17/2017	4/20/2017				
3	Impact 35 ton truck at max velocity of 5 mph	Use pulley rig to apply known force to mannequin and platform	No permanent damage	Melanie	DV, PV	15		4/11/2017	4/16/2017				
4	Impact 35 ton truck at max velocity of 5 mph	Impact the mannequin with the ME dept. van at a low speed.	No permanent damage	Melanie	DV, PV	10	B, C	TBD	Same day				
5	Mannequin is not damaged when it falls	Apply forces to mannequin and see condition of mannequin when it falls	No permanent damage	Melanie	DV, PV	20	C	4/11/2017	4/16/2017				
6	Track supports vehicle weight	Drive over stationary track with a vehicle	Pass/Fail	Chris	PV	10	C	3/19/2017	3/19/2017				
7	10 m min. travel length	Measure mannequin travel distance	Pass/Fail	Chris	DV	1	B	3/25/2017	3/25/2017				
8	Adult human dimensions	Tape measure	"+- 5%"	Melanie	DV	1	B	3/19/2017	3/19/2017				
9	Hip angles: -35 to 35 deg.	Videotape articulation and measure the maximum and minimum angle for each articulation.Use Tracker to create plots to see if the correct angles have been obtained.	"+-5 deg"	Tim	DV	5	B, C	3/22/2017	3/29/2017				
10	Knee angles: 0 to 75 deg.		"-0 deg +5 deg"	Tim	DV	5	B, C	3/22/2017	3/29/2017				
11	Shoulder angles: -10 to 10 deg.		"+-3 deg"	Tim	DV	5	B, C	3/22/2017	3/29/2017				
12	Elbow angles: 0 to 60 deg.		"-0 deg +5 deg"	Tim	DV	5	B, C	3/22/2017	3/29/2017				
13	Step frequency	Experimentally measure the step frequency by measuring the time for 25 steps to occur.	"+-10%"	Tim	DV	15	B, C	3/29/2017	3/31/2017				
14	Lateral translation velocity range: 0.5 to 2.5 m/s	Experimentally measure the time it takes for the mannequin to travel 10 meters. Do this test for all chosen velocities and ensure it covers the entire range of 0.5-2.5 m/s	"+-0.1 m/s"	Chris	DV, PV	5	B, C	3/19/2017	3/22/2017				
15	Reaches desired speed 5m before impact location	Attach an accelerometer to the platform to get acceleration vs time data. Record a video of the test and use video and accelerometer data to determine location of constant speed.	"-0.5 m min."	Chris	PV	10	C	4/17/2017	4/20/2017				
16	Kill switch	Ensure that the kill switch shuts off all power for the system.	Pass/Fail	Tiffany	DV, PV	20	B, C	3/22/2017	4/24/2017				
17	Storage size of semi truck: 576"x102" x162"	Measure the maximum dimensions of the system when disassembled for transport.	Pass/Fail	Chris	PV	1	B, C	4/10/2017	4/10/2017				
18	Trigger input	Ensure that a trigger input (e.g. knob) allows for varying lateral translation speeds across the range of 0.5-2.5 m/s.	Pass/Fail	Tiffany	DV, PV	5	B, C	3/19/2017	3/22/2017				
19	Attach reflective materials	Ensure that given reflective materials can be attached and detached.	Pass/Fail	Tim	CV	1	A	3/22/2017	3/22/2017				
20	Wind speeds 7m/s max	Calculate the wind loads on the body and apply that load to the center of the mass.	Pass/Fail	Tiffany	PV	5	C	4/20/2017	4/22/2017				
21	Temperature range: 5-40 deg. Celsius	Place the arms, legs, and hook/nub in a walk in refrigerator and ensure basic functionality is maintained. Similarly, place the components under a heat gun until max temperature is reached and test for basic functionality.	Pass/Fail	Tiffany	PV	5	C	4/20/2017	4/22/2017				

APPENDIX L: BILL OF MATERIALS

Part of System	Item	Chosen Product	Source	Per unit cost	Amount	Shipping	Overall Cost	Subassembly Total
Mannequin	Fabric Covering	Upholstery	Jo-Anns	12	4	0	$48.00	
Mannequin	Batting	Pellon Quilters Touch 100 Percent Polyester Batting, 60" Wide, 20 Yard Roll	Walmart	45	1	0	$45.00	
Mannequin	Limb core	Sioux Chief 3/8 in. x 1/4 in. x 25 ft. Polyethylene Tubing	Home Depot	6.78	1	0	$6.78	
Mannequin	3/8 Inch Hex Bolts 3 1/2in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot	0.66	2	Bulk	$1.32	
Mannequin	3/8 Inch Hex Bolts 3in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot	0.5	4	Bulk	$2.00	
Mannequin	3/8 Inch Hex Bolts 2 1/4in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot	0.42	20	Bulk	$8.40	
Mannequin	3/8 Inch Hex Bolts 1 3/4in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot	0.33	4	Bulk	$1.32	
Mannequin	3/8 Inch Hex Bolts 1 1/4in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot	0.28	70	Bulk	$19.60	
Mannequin	3/8 Inch Hex Bolts 1in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot			Bulk	$0.00	
Mannequin	3/8 Inch Hex Bolts 1 1/2in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot	0.31	6	Bulk	$1.86	

Mannequin	3/8 Hex Locking Nuts	Nylon insert, Stainless Steel 18-8, Fine Thread	Bolt Depot	0.26	102	Bulk	$26.52	
Mannequin	3/8 USS Flat Washer	Zinc plated, grade 5 steel	Bolt Depot	0.11	204	Bulk	$22.44	
Mannequin	3/4 Inch Hex Bolts 1in Length	Zinc plated, grade 5 steel, Coarse	Bolt Depot	2.4	4	Bulk	$9.60	
Mannequin	3/4 USS Flat Washer	Stainless steel 18-8	Bolt Depot	0.63	4	Bulk	$2.52	
Mannequin	1/4 Inch Hex Bolts 1in Length	Zinc plated, grade 5 steel, Fine Thread	Bolt Depot	0.15	4	Bulk	$0.60	
Mannequin	1/4 Hex Locking Nut	Nylon insert, Stainless Steel 18-8, Fine Thread	Bolt Depot	0.13	4	Bulk	$0.52	
Mannequin	1/4 USS Flat Washer	Zinc plated, grade 5 steel	Bolt Depot	0.05	8	Bulk	$0.40	
Mannequin	#6-32 Phillips Flat Head Machine Screws 1/2in Length	Stainless steel 316	Bolt Depot	0.13	8	Bulk	$1.04	
Mannequin	#6-32 Phillips Flat Head Machine Screws 5/8in Length	Stainless steel 316	Bolt Depot	0.2	8	Bulk	$1.60	
Mannequin	#6-32 Phillips Flat Head Machine Screws 3/4in Length	Stainless steel 18-8	Bolt Depot	0.08	8	Bulk	$0.64	
Mannequin	#6-32 Screw Nuts	Stainless steel 18-8	Bolt Depot	0.05	16	Bulk	$0.80	

Mannequin	#8-32 Philips Flat Head Machine Screws 3/4" Length (Rod holder)	Stainless steel 18-8	Bolt Depot	0.06	12	Bulk	$0.72	
Mannequin	#8-32 Philips Flat Head Machine Screws 3/4" Length (Rod holder)			0	1	Bulk	$0.00	
Mannequin	#8-32 Screw Nuts	Stainless steel 18-8	Bolt Depot	0.05	8	Bulk	$0.40	
Mannequin	2x2in Steel Square Tubing 0.125in Thick 20 ft Length (15ft req.)		B&B Steel & Supply	52	1	0	$52.00	
Mannequin	1x1in Steel Square Tubing 0.125in Thick 20ft Length (3ft req.)		B&B Steel & Supply	25	1	0	$25.00	
Mannequin	12x8in Steel Plate 0.5in Thick		McMaster-Carr	55.44	1	Bulk	$55.44	
Mannequin	3in 6ft Length Steel Plate 0.25in Thick		McMaster-Carr	52.28	2	Bulk	$104.56	
Mannequin	Sandpaper	400-grit	Home Depot	3.97	1	0	$3.97	
Mannequin	Spray Adhesive	3M Super 77	Home Depot	9.99	1	0	$9.99	
Mannequin	Expanded Polyester Foam	4 pack 24x48x1in	Amazon	26.74	1	0	$26.74	
Mannequin	Electronics Housing	Hard Shell Case w/ Foam	Amazon	23.6	1	0	$23.60	

Mannequin	Anechoic Foam	Auralex 4" Studiofoam Pyramid 2'x2'x4" panels (6 pack) Charcoal	Musician's Friend	270	1	0	$270.00	
Mannequin	Flange Connection (pole to torso)	3" Floor Flange w/ 2 set screws	Chain Link Fittings	14.55	1	17.22	$31.77	
Mannequin	Pole Holder (bottom)	Clamping U-bolt	McMaster	2.35	1	Bulk	$2.35	
Mannequin	Pole Holder Walls	3/8"x 3" Low-Carbon Steel Bar	McMaster-Carr	16.49	2	Bulk	$32.98	
Mannequin	Pole Attachment Mounting	Corner Bracket	McMaster	26.78	6	Bulk	$160.68	
Mannequin	Magnets	1/4" thick magnets	AmazingMagnets	1.13	4	Bulk	$4.52	
Mannequin	Pole	2.75" HDPE rod	US Plastics Corps	21.65	4	42	$128.60	
								$1,134.28
Articulation	Servos (Articulation)	Digital Hi-Volt, Hi-Torque HS-5685MH	ServoCity	40	4	0	$160.00	
Articulation	Signal Board	Arduino Uno	Chris	0	0	0	$0.00	
Articulation	Attachment to limb core	90 degree 0.5" elbow	McMaster	4.5	4	0	$18.00	
Articulation	Mechanical Tendon Connection	Steel Eyebolt without Shoulder - for Lifting 1/4"-20 Thread Size, 3" Thread Length	McMaster	11.29	2	Bulk	$22.58	

Articulation	Nuts for tendon attachment	Zinc Yellow-Chromate Plated Steel Thin Hex Nut Grade 8, High-Strength, 1/4"-20 Thread Size (100 pack)	McMaster	9.55	1	Bulk	$9.55	
Articulation	Set screws	Cup Set Screws	McMaster	6.22	2	Bulk	$12.44	
Articulation	Servo Shaft & Bearing Block	.5" 6061-T6 aluminum	ServoCity	25	4	7	$107.00	
Articulation	Variable Resistor	Potentiometer	Adafruit	5	1	bulk	$5.00	
Articulation	Battery Clip	9V to 5.5mm/2.1mm plug	Chris	0	1	0	$0.00	
Articulation	Battery (Board)	7-12 V (9V battery)	Wal-Mart	3	1	0	$3.00	
Articulation	Batteries (Servos)	7.4 V LiPo	ValueHobby	30	2	4	$64.00	
Articulation	Battery Charger	Imax B6 Balance Charger	ValueHobby	20	1	3.99	$23.99	
Articulation	Kill Switch	Large Arcade Button	Adafruit	6	1	bulk	$6.00	
Articulation	Sensor for kill switch	Magnetic Contact or Force?	Adafruit	7	1	bulk	$7.00	
Articulation	Breadboard	Half-size	Adafruit	5	1	bulk	$5.00	
Articulation	Tendon (Wire)	20 lb Sufix Siege Monofilament Fishing Line	Dick's Sporting Goods	10	1	0	$10.00	
Articulation	Grommets	Grommet Installation Kit, 103pcs	Walmart	4	1	0	$4.00	
								$457.56
Linear Translation	Motor (Translation)	ACP-M-2IK6N-AUV	Anaheim Automation	109	1	14.8	$123.80	
Linear Translation	Motor Gearbox	ACP-G-2N36-K	Anaheim Automation	59	1	31.35	$90.35	

Linear Translation	Motor Driver	ACP-US-2I6A-AL	Anaheim Automation	134	1	0	$134.00	
Linear Translation	Thrust Bearing	Plastic Thrust Ball Bearing Plastic Thrust Ball Bearing Steel Washers, for 3/8" Shaft Diameter, 13/16" OD	McMaster-Carr	2.54	2	Bulk	$5.08	
Linear Translation	Pulley Shaft	Rotary Shaft 1566 Carbon Steel, 3/8" Diameter, 12" Long	McMaster-Carr	7.25	1	Bulk	$7.25	
Linear Translation	Shaft conversion 1	3/8" Slotted-Disc Flexible Shaft Coupling Set Screw Hub, 7/8" Overall Length	McMaster-Carr	13.08	1	Bulk	$13.08	
Linear Translation	Shaft conversion 2	Acetal Disc for 3/4" OD Slotted-Disc Flexible Shaft Coupling	McMaster-Carr	2.81	1	Bulk	$2.81	
Linear Translation	Shaft conversion 3	8mm Slotted-Disc Flexible Shaft Coupling Set Screw Hub, 7/8" Overall Length	McMaster-Carr	13.08	1	Bulk	$13.08	
Linear Translation	Pulleys	Stainless Steel Pulley for 3/8" Fibrous Rope	McMaster-Carr	18	2	Bulk	$36.00	
Linear Translation	Rope/Wire	3/8" Manila	Knot and Rope Supply	13	1	12	$25.00	

Linear Translation	Bolts from gearhead to supports	M4 x 40 mm Zinc-Plated Phillips Steel Pan-Head Machine Screw (2 per Bag)	Home Depot	0.74	17	0	$12.58	
Linear Translation	Nuts for bolts	4 mm-0.7 Zinc-Plated Metric Hex Nut (2-Piece)	Home Depot	0.37	21	0	$7.77	
Linear Translation	Contact Cement	Super Glue Corporation T-CC Contact Cement	Walmart	1.71	2	0	$3.42	
Linear Translation	Corner Bracket	Zinc-Plated Steel Corner Bracket with 7/8" Long Sides	McMaster-Carr	0.43	4	Bulk	$1.72	
Linear Translation	Flat Plate for base	1x1ft 3/16 (.1875) thick T304 Stainless Steel Plate - Dull Mill Finish	Metal Depot	37.17	1	Bulk	$37.17	
Linear Translation	Mounted Bearing for slave side	Low-Profile Mounted Ball Bearing with Aluminum Housing Double Shielded, for 3/8" Shaft Diameter	McMaster-Carr	23.5	1	Bulk	$23.50	
Linear Translation	Nuts for Mounted bearing	5 mm - 0.8 Zinc-Plated Metric Hex Nut (2-Piece)	Home Depot	0.43	1	0	$0.43	

Linear Translation	Bolts for corner bracket to base	4 mm-0.7 x 12 mm Zinc-Plated Steel Pan-Head Phillips Machine Screw (3 per Pack)	Home Depot	0.74	3	0	$2.22	
Linear Translation	Bolts for Mounted Bearing	JIS Steel Phillips Rounded Head Screws M5 x 0.8 mm Thread, 40 mm Long (10 pack)	McMaster-Carr	6.3	1	Bulk	$6.30	
Linear Translation	Sheet for covering	1x2ft 24 GA. (.024 thick) Cold Rolled Steel Sheet	Metal Depot	10.2	1	20.1	$30.30	
								$575.86
Platform	Steel Tubing - combined w torso above	1"x1", 1/8" thickness	B&B steel & supply	0	0	0	$0.00	
Platform	Wheels (4)	70 mm diameter	Warehouse Skateboards	41	1	7	$48.00	
Platform	Wheel Ball Bearings	22 mm OD, 8mm ID	McMaster-Carr	4.32	4	Bulk	$17.28	
Platform	Wheel Thrust Bearings	8 mm ID, 19 mm OD	Amazon	6.53	4	0	$26.12	
Platform	Square Tubing Flanges	for 1" tubing	King Metals	1.35	8	14.52	$25.32	
Platform	Plate connecting tubing (3ft)	.5" thick, 1" wide	McMaster-Carr	18.61	1	Bulk	$18.61	
Platform	1.5" square tubing	t=.12"	McMaster-Carr	36	1	Bulk	$36.00	
Platform	Bracket	bracket	McMaster-Carr	31	4	Bulk	$124.00	
Platform	bushing	8mm ID, 12 mm OD	McMaster-Carr	2.58	4	Bulk	$10.32	
Platform	Rope Clamp & thimble	3/8" rope clamp set	Home Depot	4.57	2	0	$9.14	

Platform	Screw-set Snap Hook	snap hook	McMaster-Carr	6.1	1	Bulk	$6.10	
Platform	Top plate	.25 in thick, 8"x12" sheet	mcmaster-carr	55.44	1	Bulk	$55.44	
Platform	.5in thick, 1in wide steel	steel	Mcmaster-carr	52.87	1	Bulk	$52.87	
Platform	Flanged Axle Mount	for 8mm shaft	Misumi	41	4	16	$180.00	
Platform	Shaft Collar	8mm ID, 25mm OD	McMaster-Carr	4.52	4	Bulk	$18.08	
Platform	Axle	8mm rod (1ft)	McMaster-Carr	3.52	1	Bulk	$3.52	
Platform	Tap bolt for flanged shaft collar	M4x0.7, 25mm length, Zinc plated, class 8.8 steel	Bolt Depot	0.13	16	5	$7.08	
Platform	Nut for flanged shaft collar	for M4x.07, zinc plated, class 8.8	Bolt Depot	0.05	16	5	$5.80	
								$643.68
Bulk Shipping Estimate								
							Total	Budget
							$2,811.38	$3,500.00

APPENDIX M: PSEUDO CODE FOR ARTICULATION

```
Loop {
        leftArm.write( la[i] );
        rightArm.write( ra[i] );
        tendon.write( tn[i] );
        leftLeg.write( ll[i] );
        rightLeg.write( rl[i] );

        delay( time[analogRead(potentiometer)] );

        i = (i + 1) % 61;
}
```

APPENDIX N: DRAWINGS (FOUND IN SEPARATE DOCUMENT)

CALIFORNIA · POLYTECHNIC · STATE · UNIVERSITY · 1901

Critical Design Review: Detailed Drawings

Team Crosswalker, #13

Tim Lee

Melanie Lim

Tiffany Prather

Chris Welch

Advisor: Dr. Birdsong

ME 429-09

Appendix M - Drawing List and Detailed Part Drawings

100 – Top Level Assembly

200 – Torso Structure Assembly

201 - Exploded Structure Assembly

201A - Exploded Structure Assembly 2

210A – Torso Subassembly Exploded Detail

210B – Torso Subassembly Standard View

211 - ⅜in Hex Bolt 1 ¼in Length

212 - ⅜in Washer

213 - ⅜in Locking Nut

214 - ¼in Hex Bolt

215 - ¼in Washer

216 - ¼in Locking Nut

217 - Vertical Column

218 - Top Horizontal Column

219 - Bottom Horizontal Column

211A- Shoulder Backplate

212A - Top Width Column

213A - Bottom Width Column

214A- Body Triangle

215A - Shoulder Servo Plate

216A - Electrical Housing Plate

220 - Shoulder Subassembly

221 - Shoulder Plate

222 - Shoulder Front Tube

223 - Shoulder Side Length

224 - ⅜in Hex Bolt 2 ¼in Length

225 - ⅜in Hex Bolt 1 ¾in Length

226 - Shoulder L Bracket

230 - Neck Subassembly

231 - ⅜in Hex Bolt 3in Length

232 - Foam Head

233 - Neck

234 - Neck Bottom

235 - Neck Plate

240 - Electronics Housing Subassembly

241 - Hard Shell Case

242 - 9V Battery

243 - Permanent Bread Board

244 - Arduino

245 - 7.4V LiPo Battery

250 - Pole Subassembly

251 - ⅜ in Hex Bolt 3 ½in Length

252 - Torso Bottom Plate

253 - #6-32 Hex Nut

254 - #6-32 Phillips Flat Head Screw ¾in Length

255 - ¾in Washer

256 - ¾in Hex Bolt

257 - Pole Flange

258 - Polypropylene Pole

260 - Control Panel Subassembly

261 - Emergency Stop Button

        - 262 - Control Knob
        - 263 - Potentiometer
        - 264 - Control Panel Plate
    - 270 - Servo Subassembly
        - 271 - Servo
        - 272 - Bearing Block
- 300 – Limb Assembly: Arm
    - 301 - Exploded View
    - 310 - Eye Bolt
    - 311 - 90° Clamping Mount
    - 312 - Humerus Core
    - 313 - Upper Arm Padding
    - 314 - Forearm
- 400 – Limb Assembly: Leg
    - 401 - Exploded View
    - 410 - 90° Clamping Mount
    - 411 - Femur Core
    - 412 - Thigh Padding
    - 413 - Calf
- 500 – Platform Assembly
    - 501 - Side Frame Exploded View
    - 502 - Side Frame Connection Exploded View
    - 503 - Bracket to center frame exploded view
    - 504 - Top plate to center frame exploded view
    - 510 - Tube 1
    - 511 - Wheel

512 - Shaft

513 - Ball Bearing

514 - Flanged Shaft Collar

515 - Bushing

516 - Thrust Bearing

517 - Shaft Collar

518 - M3 x 0.5 mm, 50 mm Long Machine Screw

519 - M3 x 0.5 mm Hex Nut

520 - Corner Bracket

521 - 8-32 Hex Nut

522 - 8-32 x 2in Phillips Screw

523 - Tube 2

524 - Top Plate

525 - Connector 1

526 - Connector 2

527 - ⅜-24 Hex Nut

528 - ⅜ - 24 x 2in Hex Bolt

529 - ⅜-24 x 2.5in Hex Bolt

530 - ⅜-24 Thin Hex Nut

531 - Tube 3

532 - Hook

533 - 8-32 X 1.5in Phillips Screw

534 - ⅜-24 X 1.75in Hex Bolt

535 - 8-32 X ⅝ in Phillips Screw

- 600 – Pole Connection to Platform
    - 601 - Exploded View
    - 610 - U-bolt clamp
    - 611 - Clamp Plate
    - 612 - Back Wall
    - 613 - Side Walls
    - 614 - Top
    - 615 - Magnets
- 700 – Translation Assembly
    - 701 - Translation Assembly
    - 710 - Motor Housing Subassembly
        - 711 - Vertical Support
        - 712 - Cross Support
        - 713 - Base Plates
        - 714 - Corner Bracket
        - 715 - M4 40mm Bolts
        - 716 - M4 12mm Bolts
        - 717 - M4 nuts
        - 718 - Back Casing
        - 719 - Side Casing and Front Strips
    - 720 - Slave Pulley Housing Subassembly
        - 721 - Front Vertical Support

722 - Cross Support

723 - Back Vertical Support

724 - Base Plates

725 - M5 40mm Bolts

726 - M5 Nuts

727 - Back Casing

728 - Side and Top Casing

729 - Base Extension

730 - Motor and Pulley Subassembly

731 - Motor and Driver

732 - ⅜" Shaft Conversion

733 - ⅞" Shaft Conversion

734 - Center for Shaft Conversion

735 - 5/16" - 24 5 inch long, Bolts

736 - 5/16" - 24 Nuts

737 - 5/16" Washer

738 - Pulley for ⅜" Shaft

739 - Plastic Thrust Ball Bearing Plastic Thrust Ball Bearing Steel Washers, for 3/8" Shaft Diameter, 13/16" OD

740 - Slave Pulley Subassembly

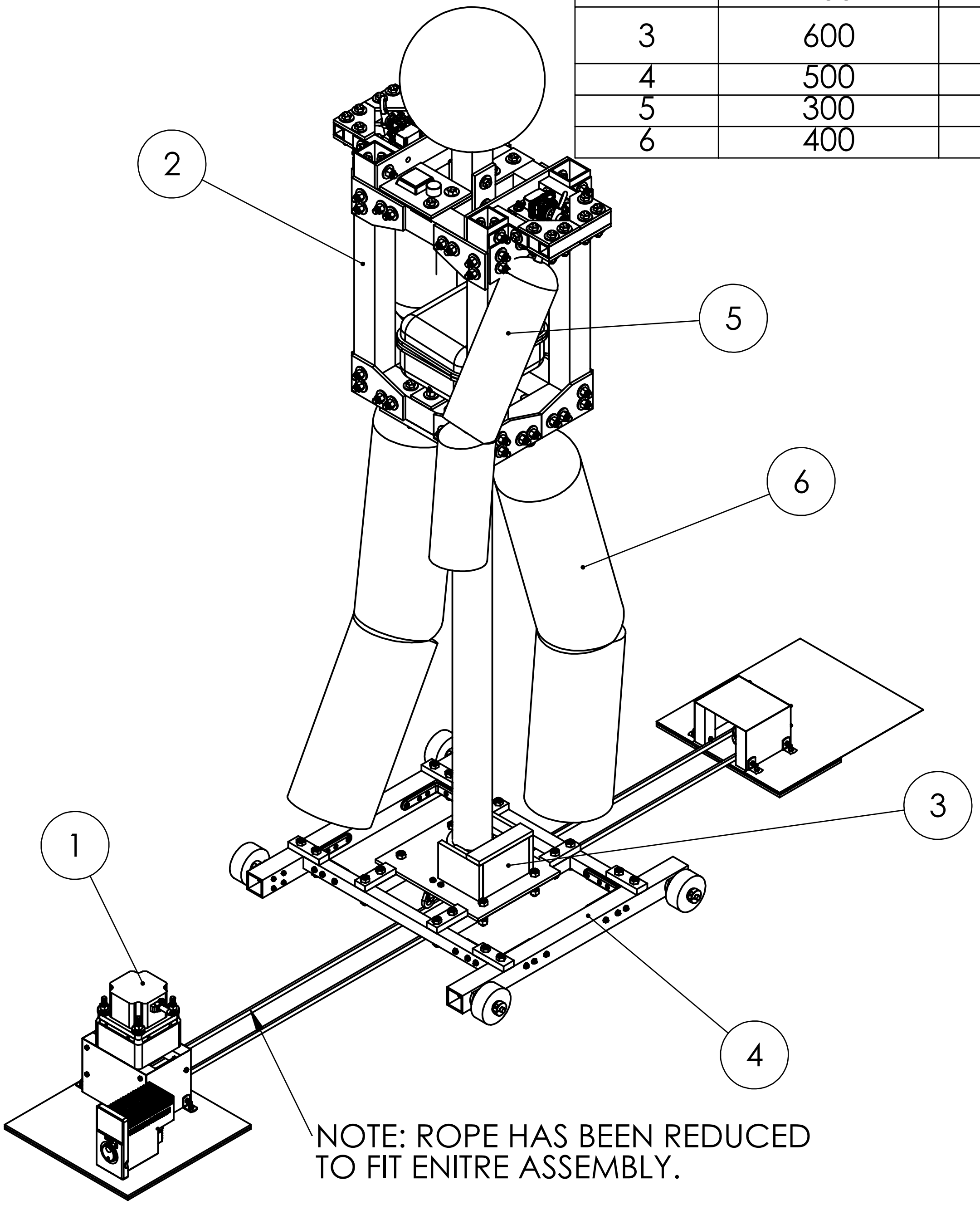
741 - ⅜" Manila Rope

742 - Low-Profile Mounted Ball Bearing with Aluminum Housing Double Shielded, for 3/8" Shaft Diameter

743 - Pulley Shaft

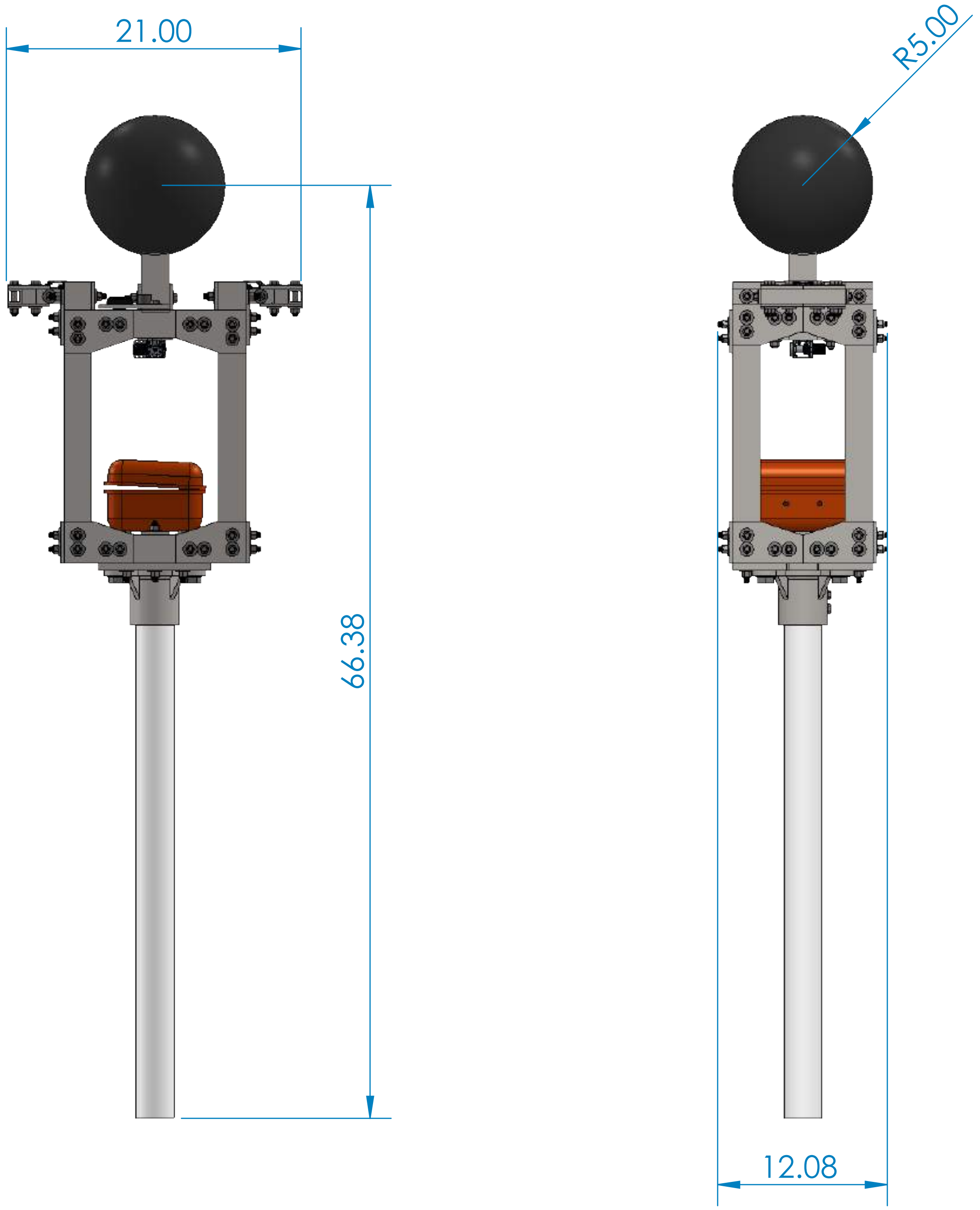
800 – Wiring Diagram

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	700	Tranlation Assembly	N/A	1
2	200	Torso Assembly	N/A	1
3	600	Pole Connection To Platfrom	N/A	1
4	500	Platform Assembly	N/A	1
5	300	Limb Assembly: Arm	N/A	2
6	400	Limb Assembly: Leg	N/A	2



NOTE: ROPE HAS BEEN REDUCED
TO FIT ENITRE ASSEMBLY.

TITLE: Top Level Assembly		
SIZE A	DWG. NO. 100	REV 1
SCALE: 1:12		SHEET 1 OF 1



All dimensions in inches

TITLE:

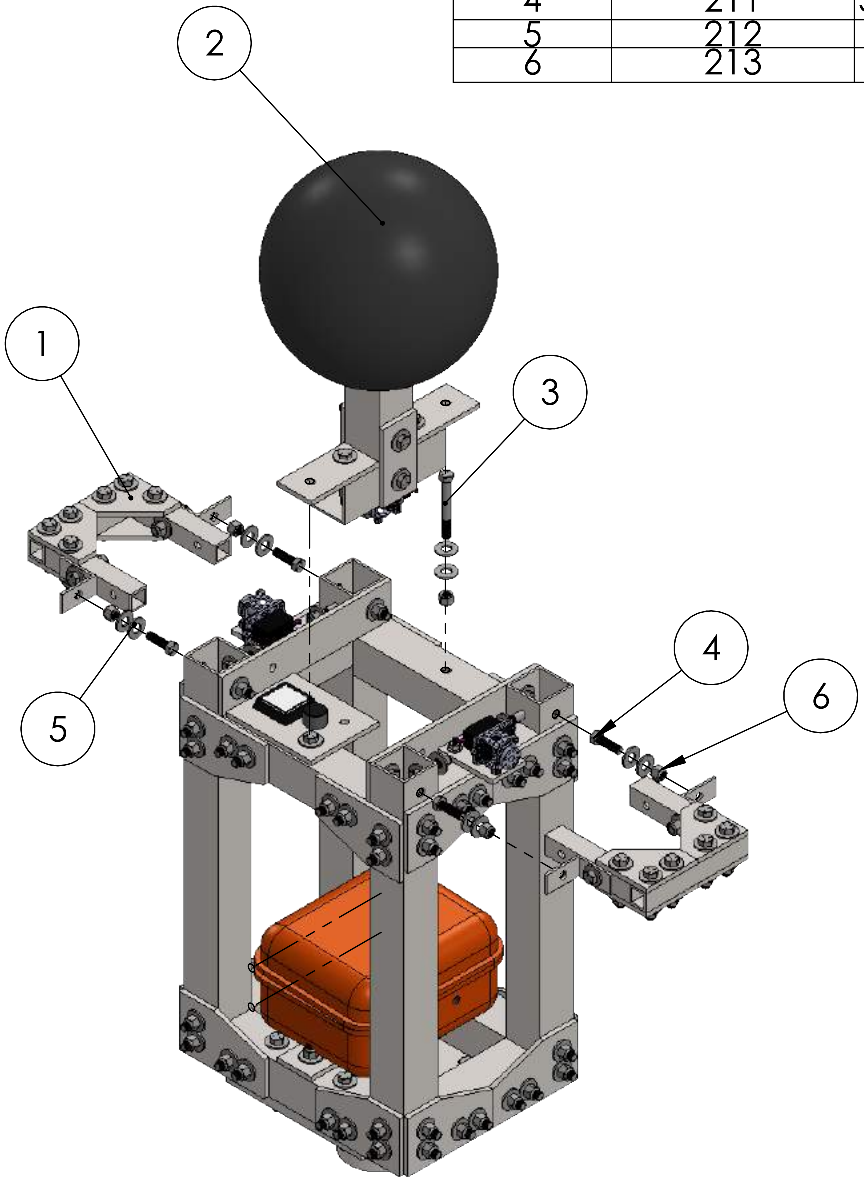
Torso Structure Assembly

SIZE	DWG. NO.	REV
A	200	1

SCALE: 1:12

SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	220	Shoulder Subassembly	N/A	2
2	230	Neck Subassembly	N/A	1
3	231	3/8in Hex Bolt 3in Length	Steel Grade 5	2
4	211	3/8in Hex Bolt 1 1/4in Length	Steel Grade 5	6
5	212	3/8in Washer	Steel Grade 5	16
6	213	3/8in Locking Nut	Stainless Steel 18-8	8



TITLE:

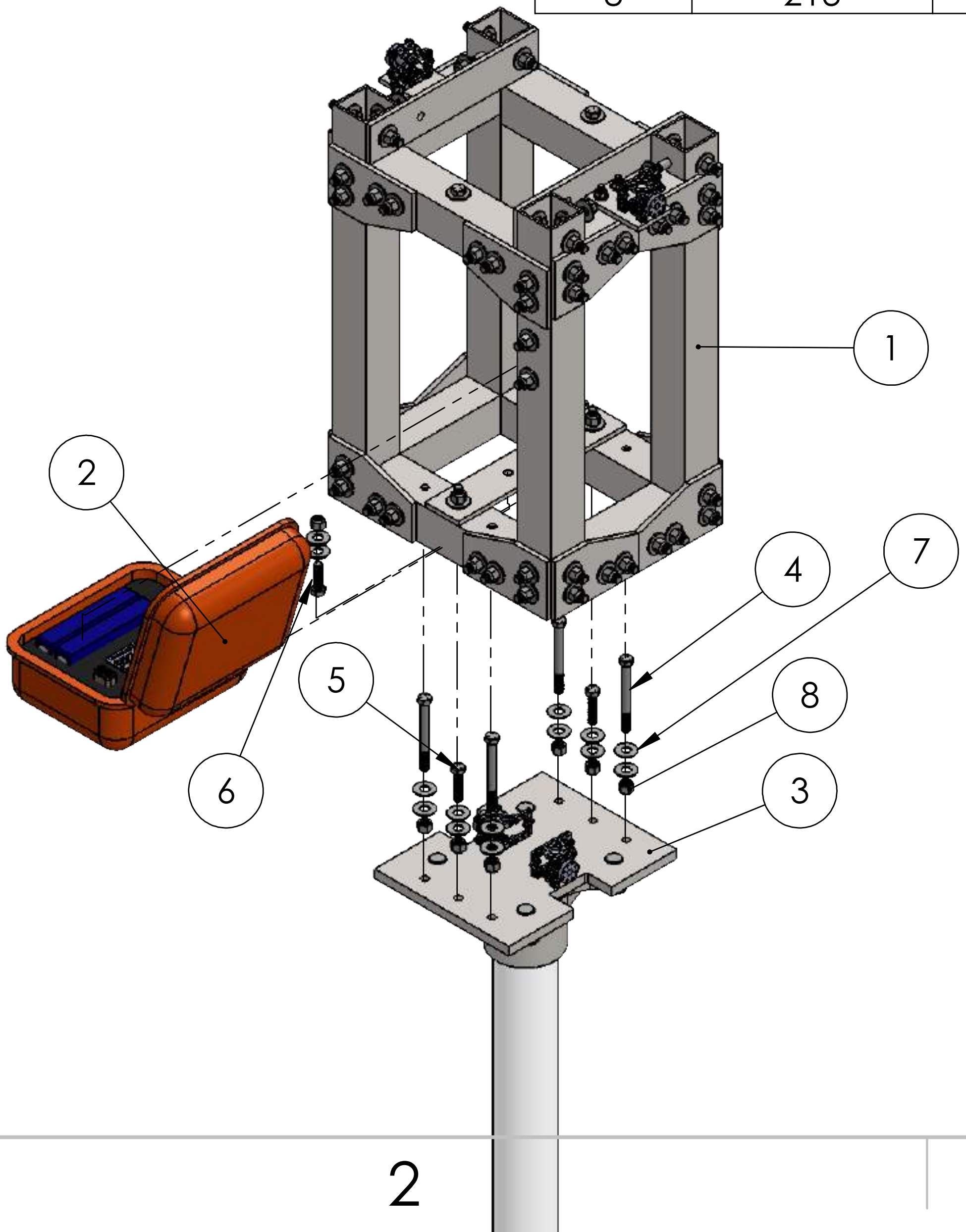
Exploded Structure Assembly

SIZE	DWG. NO.	REV
A	201	1

SCALE: 1:8

SHEET 1 OF 1

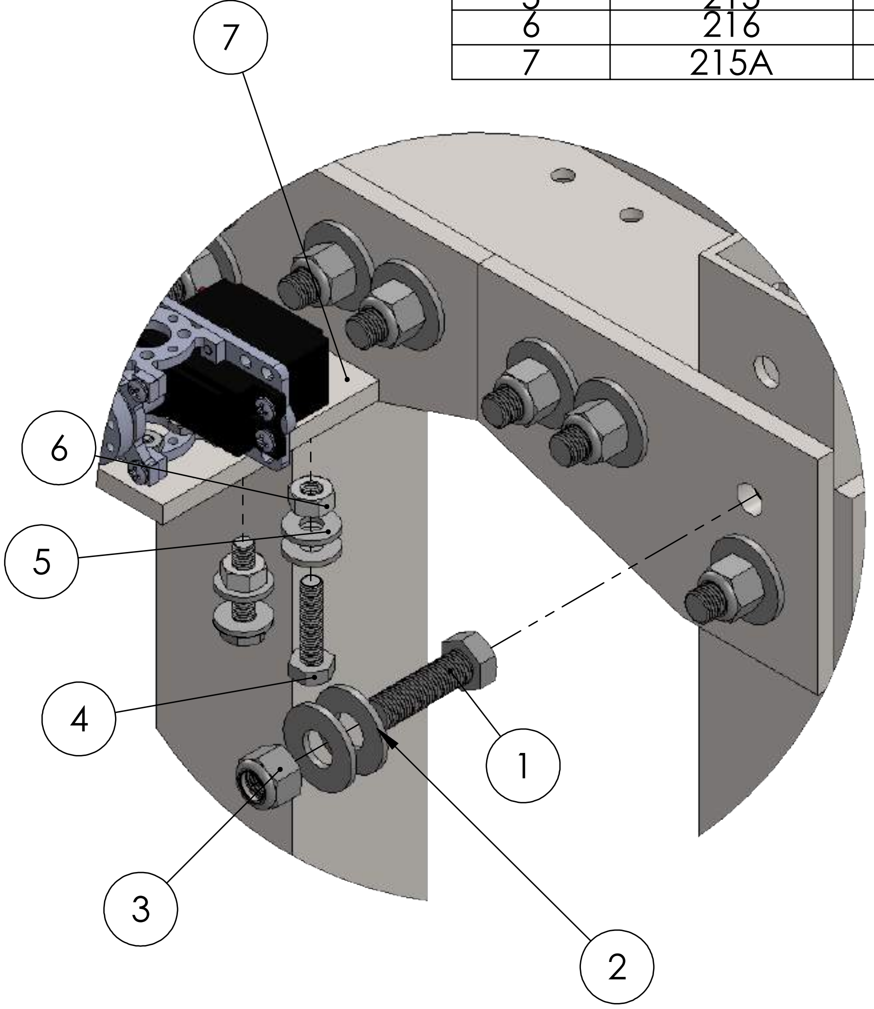
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	210	Torso Subassembly	N/A	1
2	240	Electronic Housing Subassembly	N/A	1
3	250	Pole Subassembly	N/A	1
4	231	3/8in Hex Bolt 3 1/2in Length	Steel Grade 5	4
5	251	3/8in Hex Bolt 1 1/2in Length	Steel Grade 5	2
6	211	3/8in Hex Bolt 1 1/4in Length	Steel Grade 5	2
7	212	3/8in Washer	Steel Grade 5	16
8	213	3/8in Locking Nut	Stainless Steel 18-8	8



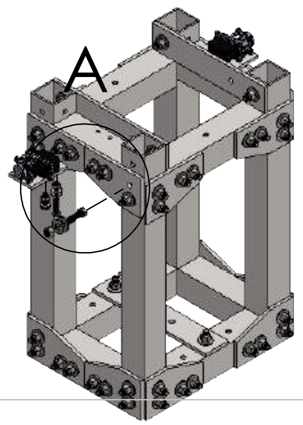
TITLE: Exploded Structure Assembly 2

SIZE: A
DWG. NO. 201A
REV 1
SCALE: 1:8
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	211	3/8 Hex Bolt 1 1/4in Length	Carbon Steel	70
2	212	3/8in Washer	Carbon Steel	140
3	213	3/8 Locking Nut	Carbon Steel	70
4	214	1/4in Hex Bolt	Carbon Steel	4
5	215	1/4in Washer	Carbon Steel	8
6	216	1/4in Locking Nut	Carbon Steel	4
7	215A	Shoulder Servo Plate	Carbon Steel	2



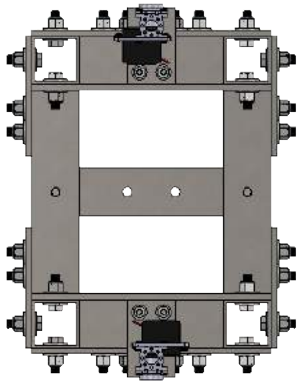
DETAIL A
SCALE 1 : 2

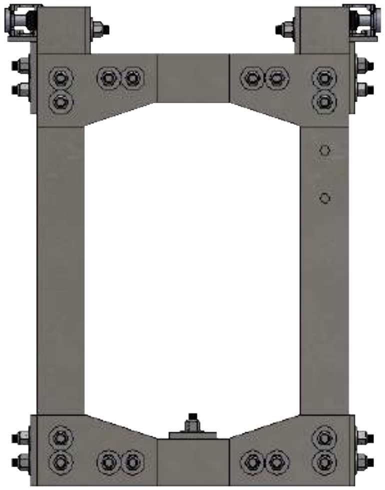


TITLE:

Torso Subassembly Exploded Detail

SIZE A
DWG. NO. 210A
REV 1
SCALE: 1:2
SHEET 1 OF 1





TITLE:

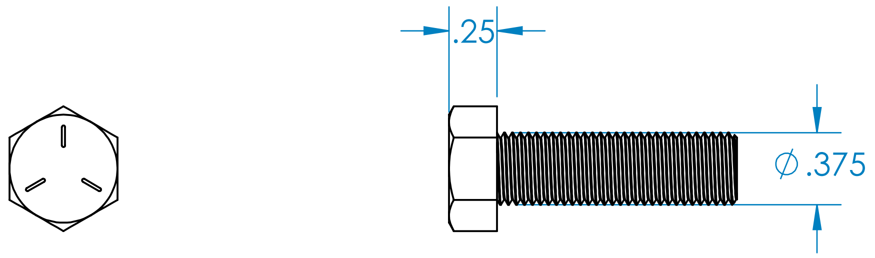
Torso Subassembly Standard View

SIZE	DWG. NO.	REV
A	210B	1

SCALE: 1:8

SHEET 1 OF 1

B



A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

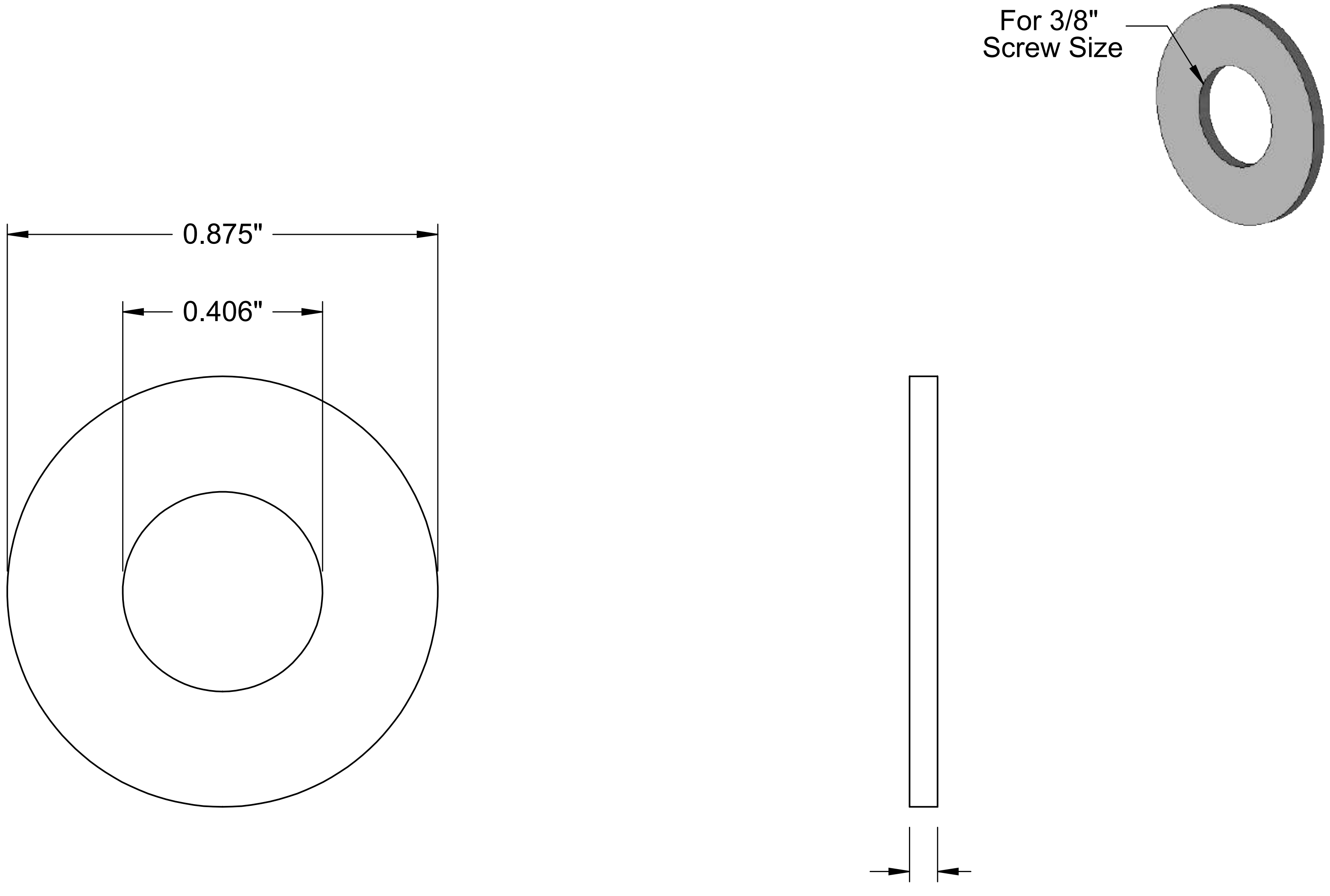
MATERIAL
Steel Grade 5

DO NOT SCALE DRAWING

TITLE:
3/8in Hex Bolt 1 1/4in Length

SIZE	DWG. NO.	REV
A	211	1

SCALE: 1:1
SHEET 1 OF 1



Washer may vary from
0.043" to 0.057" in thickness.

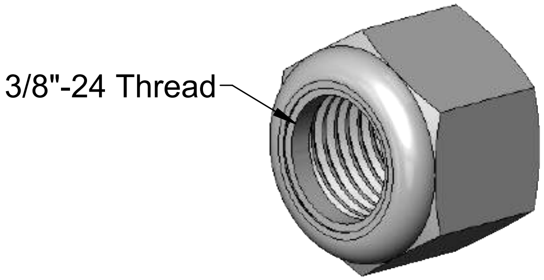
McMASTER-CARR® CAD

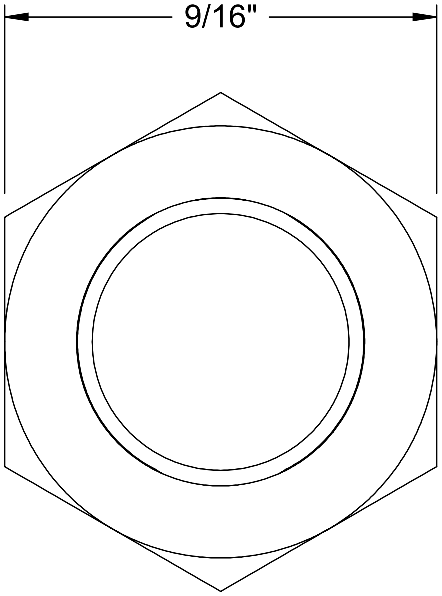
PART
NUMBER

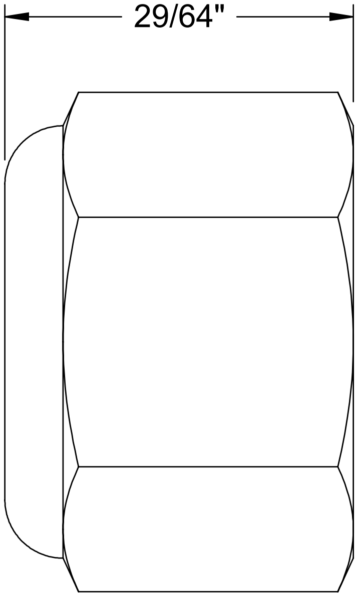
212

http://www.mcmaster.com

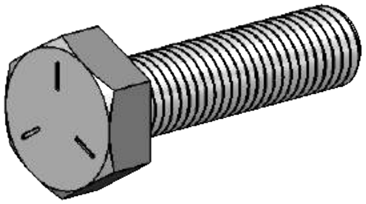
General Purpose
Washer

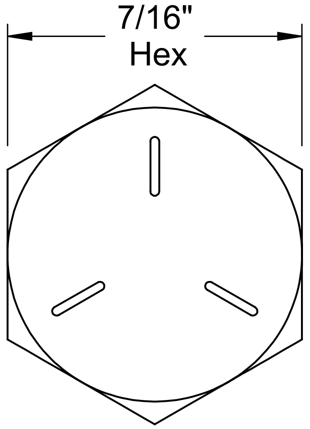


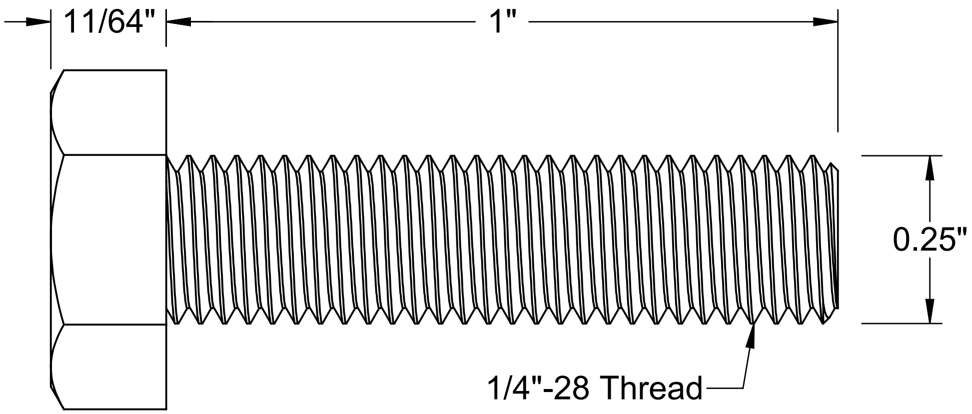




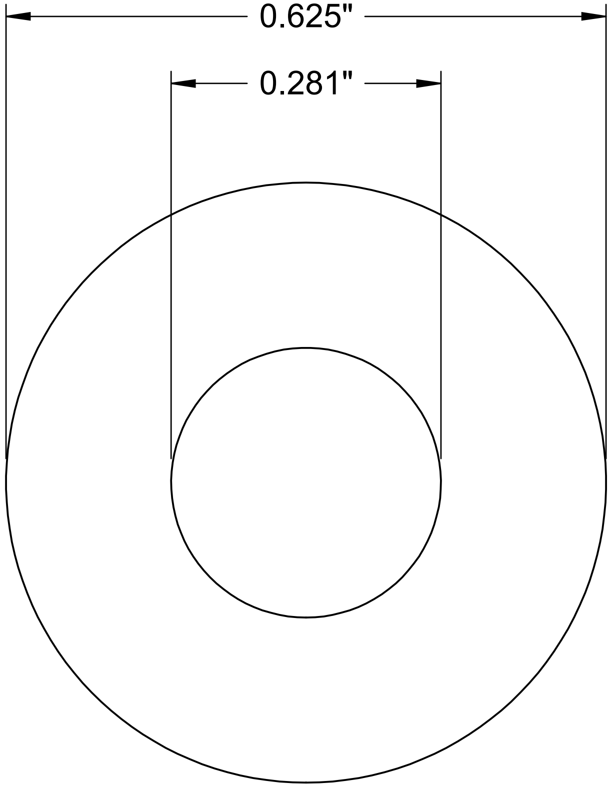
McMASTER-CARR® CAD	PART NUMBER	213
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Nylon-Insert Locknut	

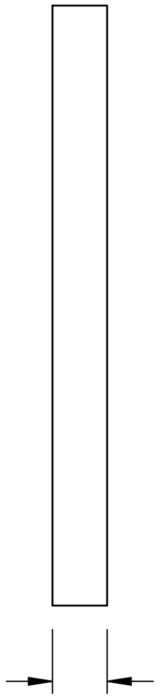




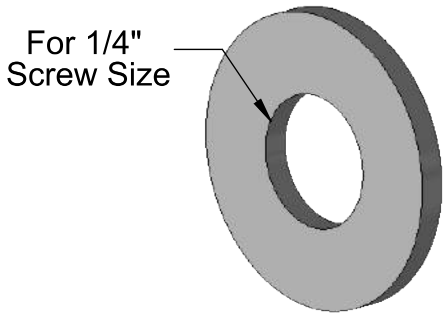


McMASTER-CARR® CAD	PART NUMBER	214
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Medium-Strength Steel Cap Screw - Grade 5	

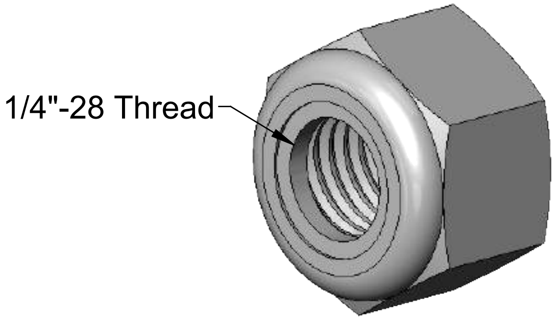


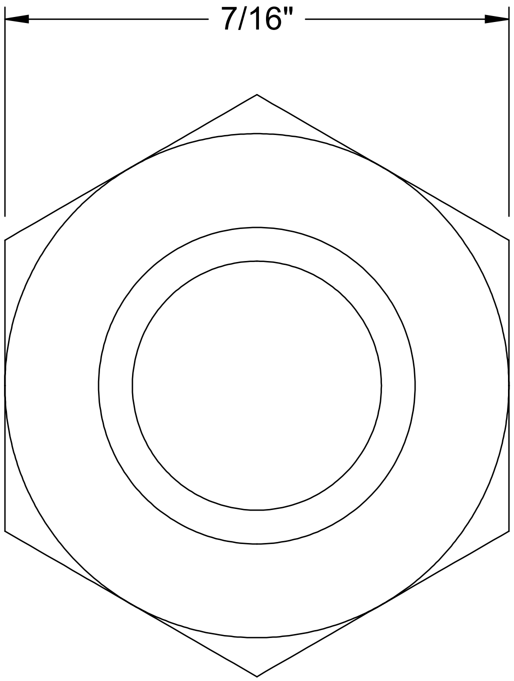


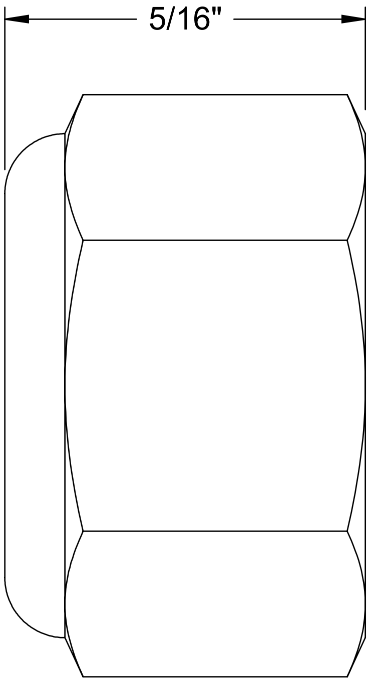
Washer may vary from
0.043" to 0.057" in thickness.



McMASTER-CARR® CAD	PART NUMBER	**215**
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	General Purpose Washer	

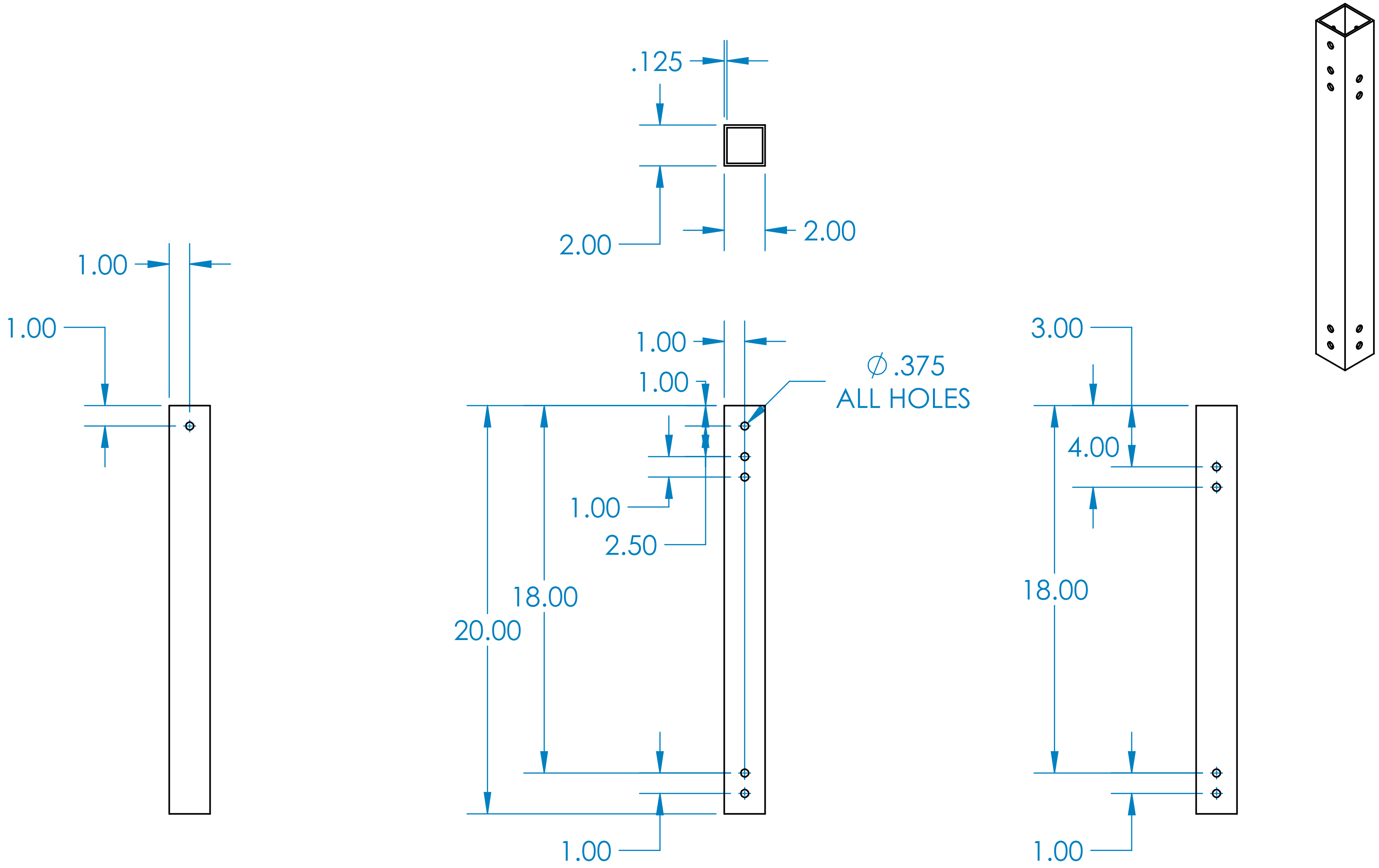






McMASTER-CARR® CAD

PART NUMBER	**216**
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Nylon-Insert Locknut



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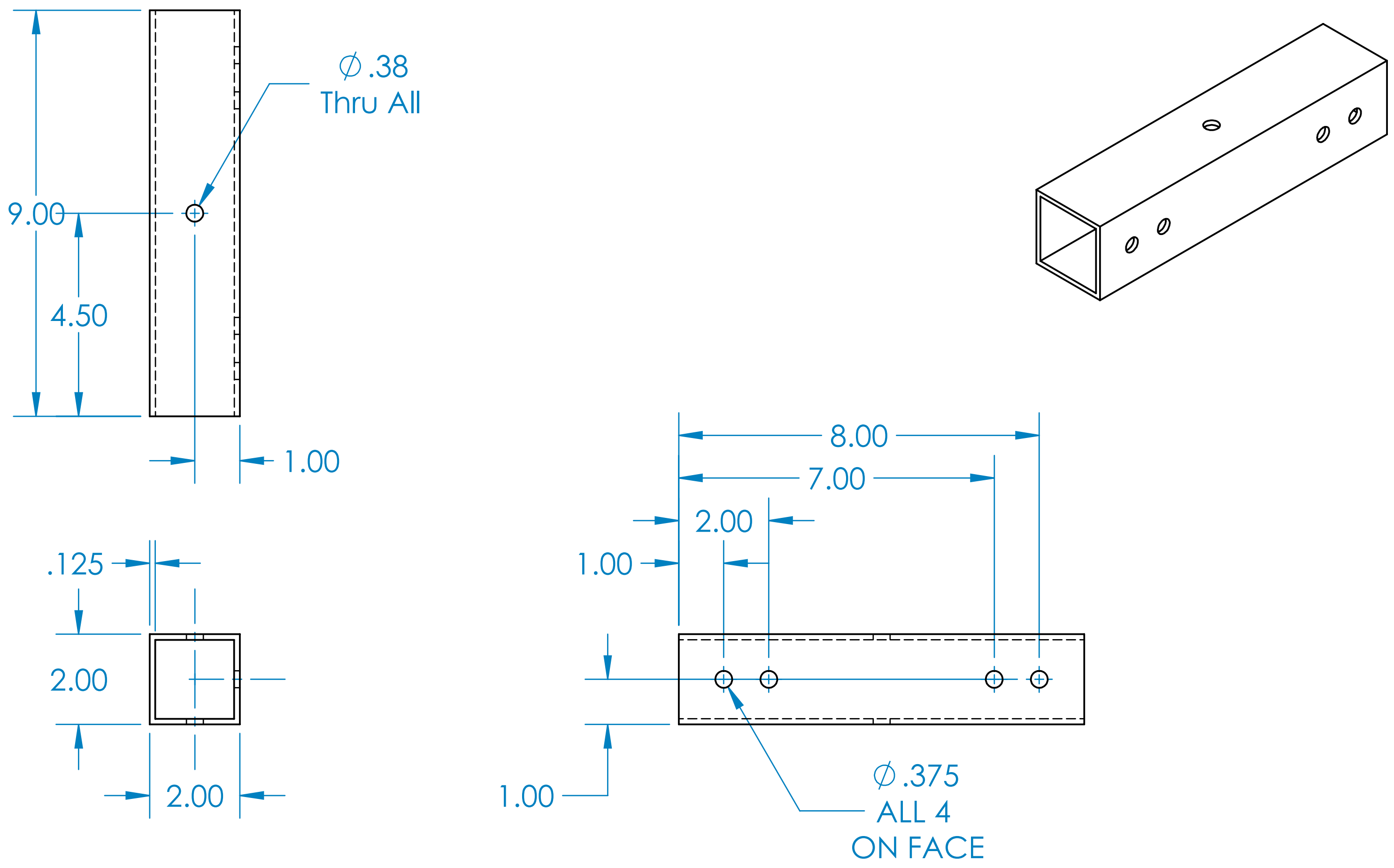
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL Carbon Steel	COMMENTS:		
DO NOT SCALE DRAWING			

TITLE:
Vertical Column

SIZE **A**
DWG. NO. 217
REV 1
SCALE: 1:8
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

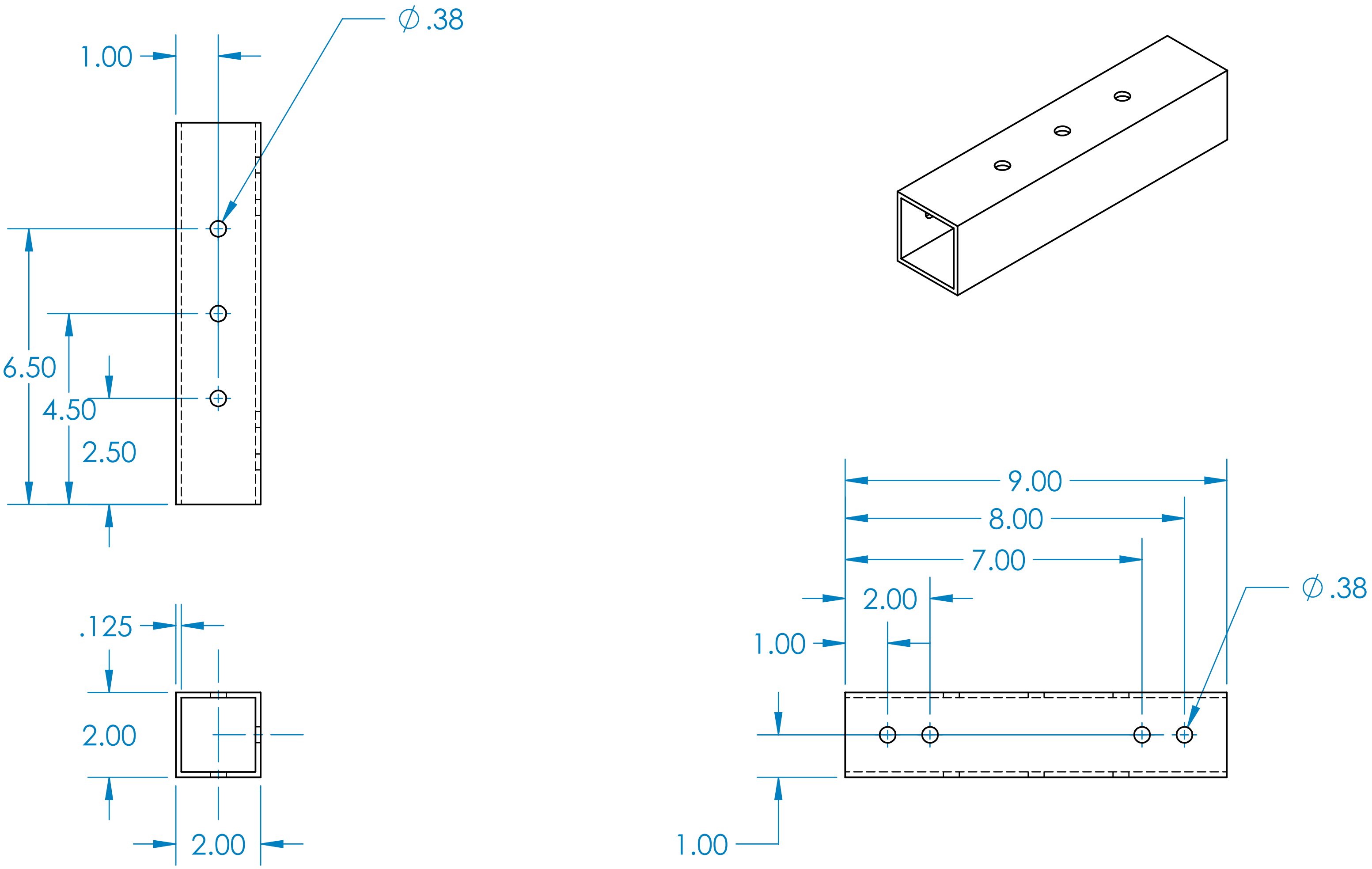
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Top Horizontal Column

SIZE	DWG. NO.	REV
A	218	1

SCALE: 1:4
SHEET 1 OF 1



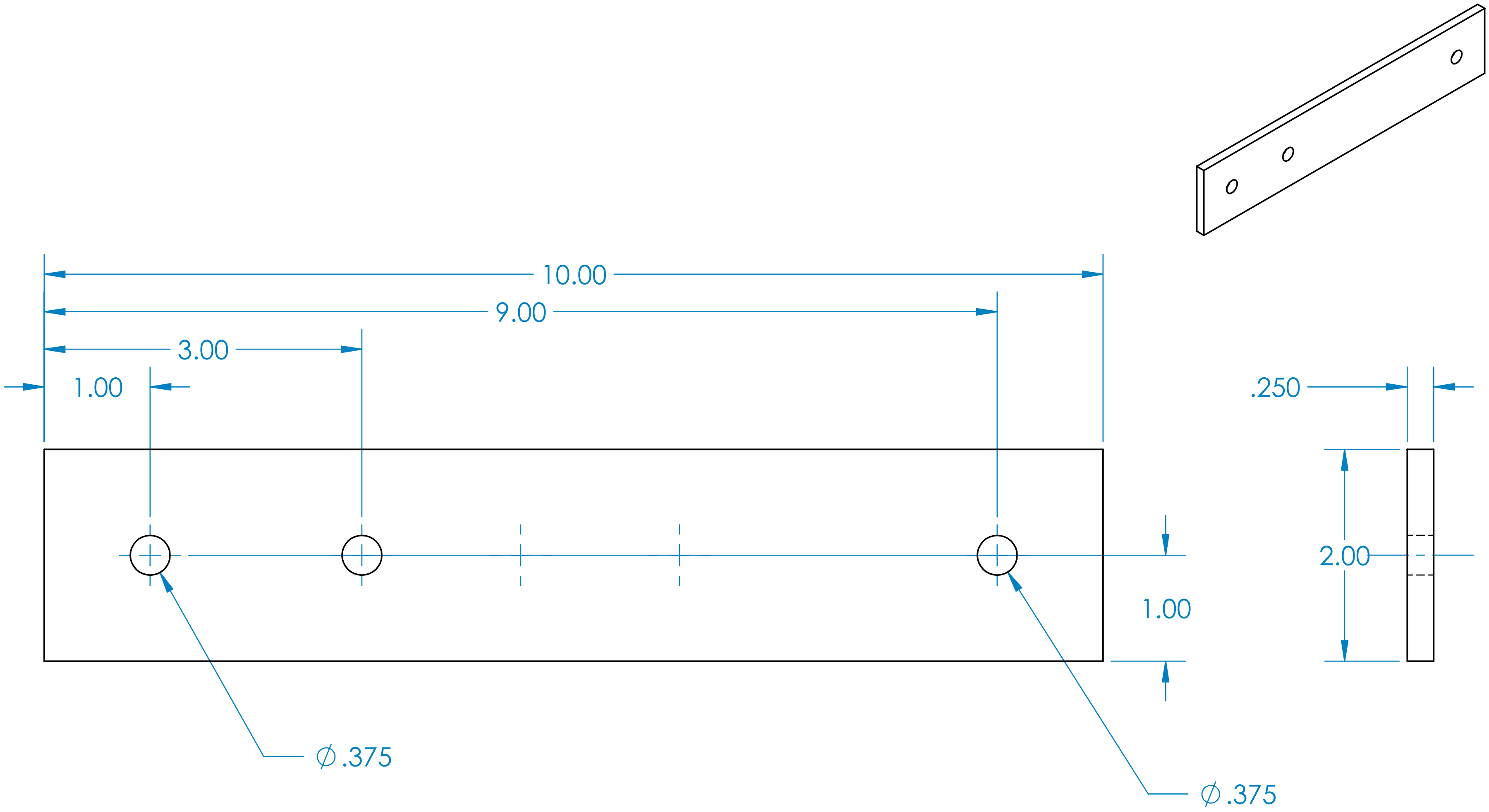
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL Carbon Steel	COMMENTS:		
DO NOT SCALE DRAWING			

TITLE: Bottom Horizontal Column

SIZE	DWG. NO.	REV
A	219	1

SCALE: 1:4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

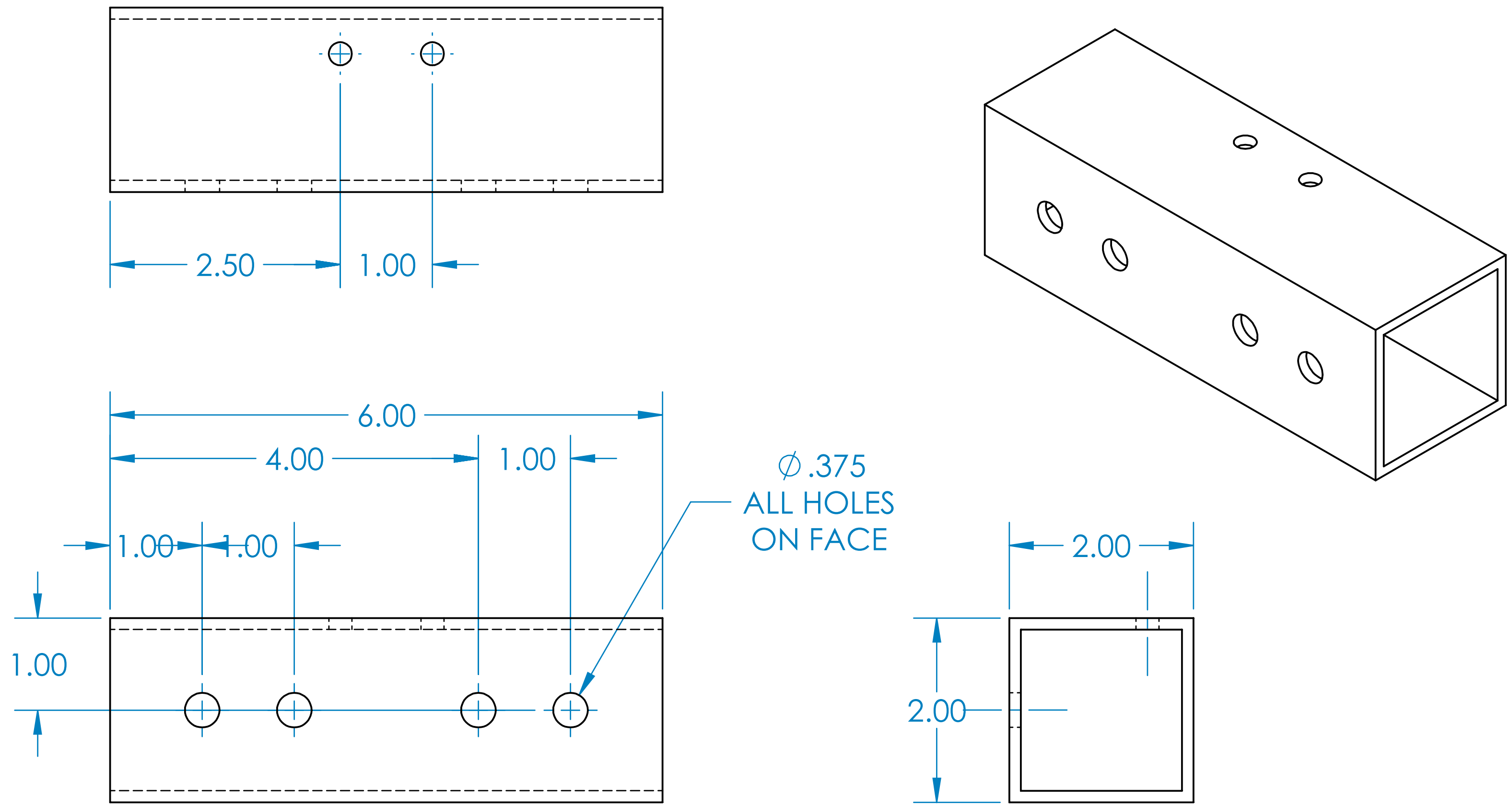
COMMENTS:

TITLE:

Shoulder Backplate

SIZE	DWG. NO.	REV
A	211A	1

SCALE: 2:3
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

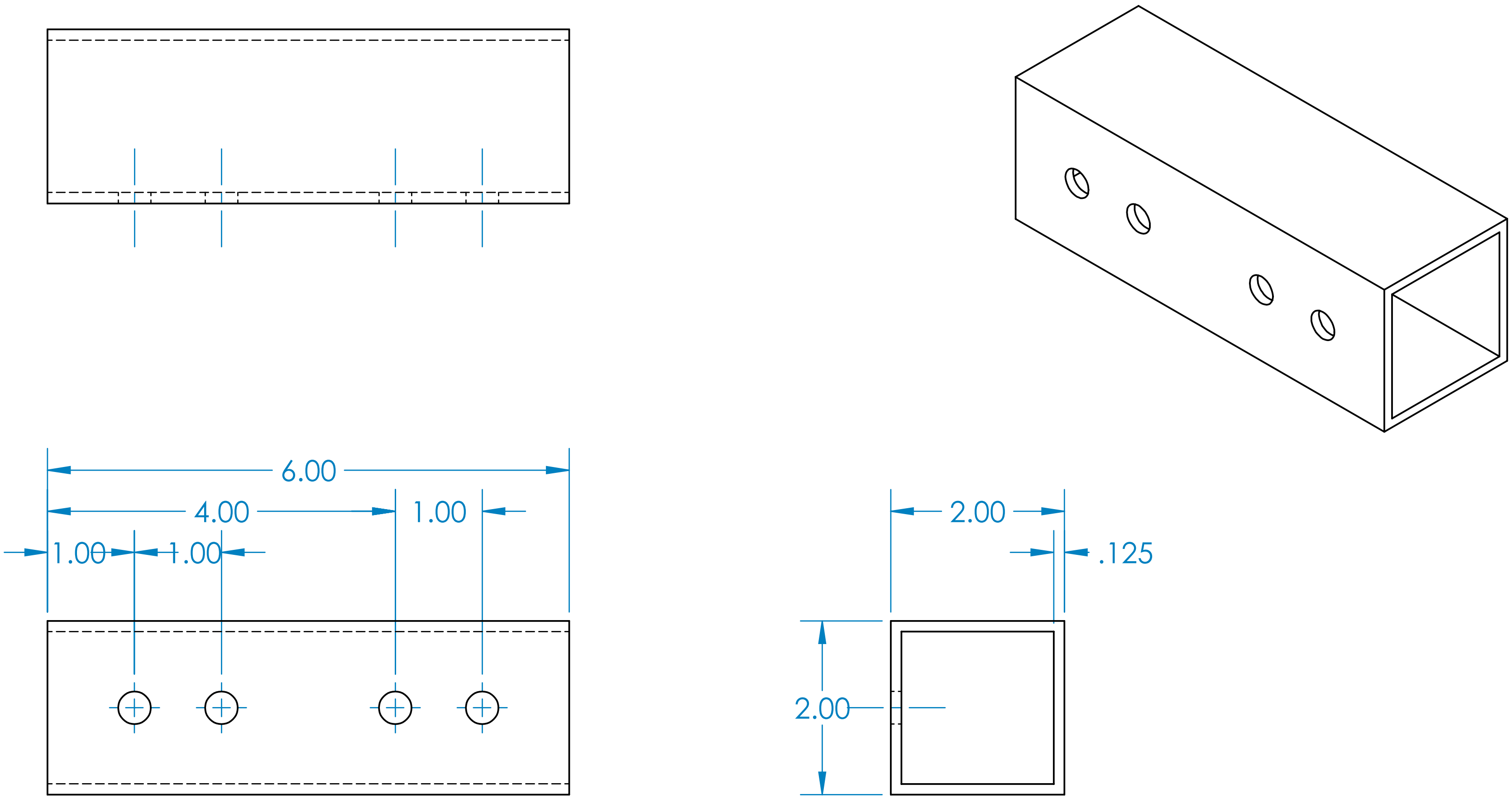
COMMENTS:

TITLE:

Top Width Column

SIZE	DWG. NO.	REV
A	212A	1

SCALE: 1:2
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

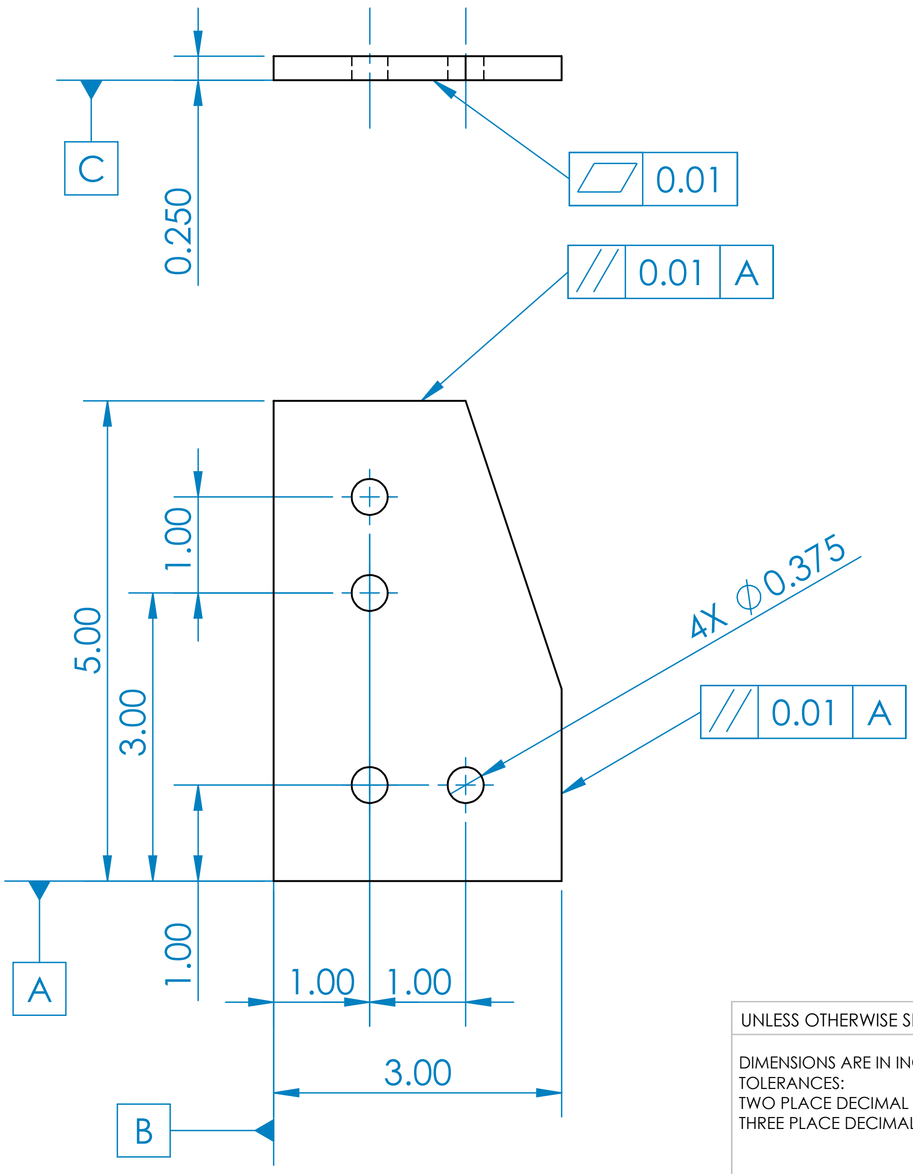
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

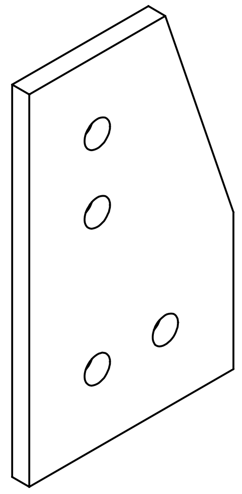
COMMENTS:

TITLE:
Bottom Width Column

SIZE	DWG. NO.	REV
A	213A	1

SCALE: 1:2
SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.001

MATERIAL
ASTM A108 Steel

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

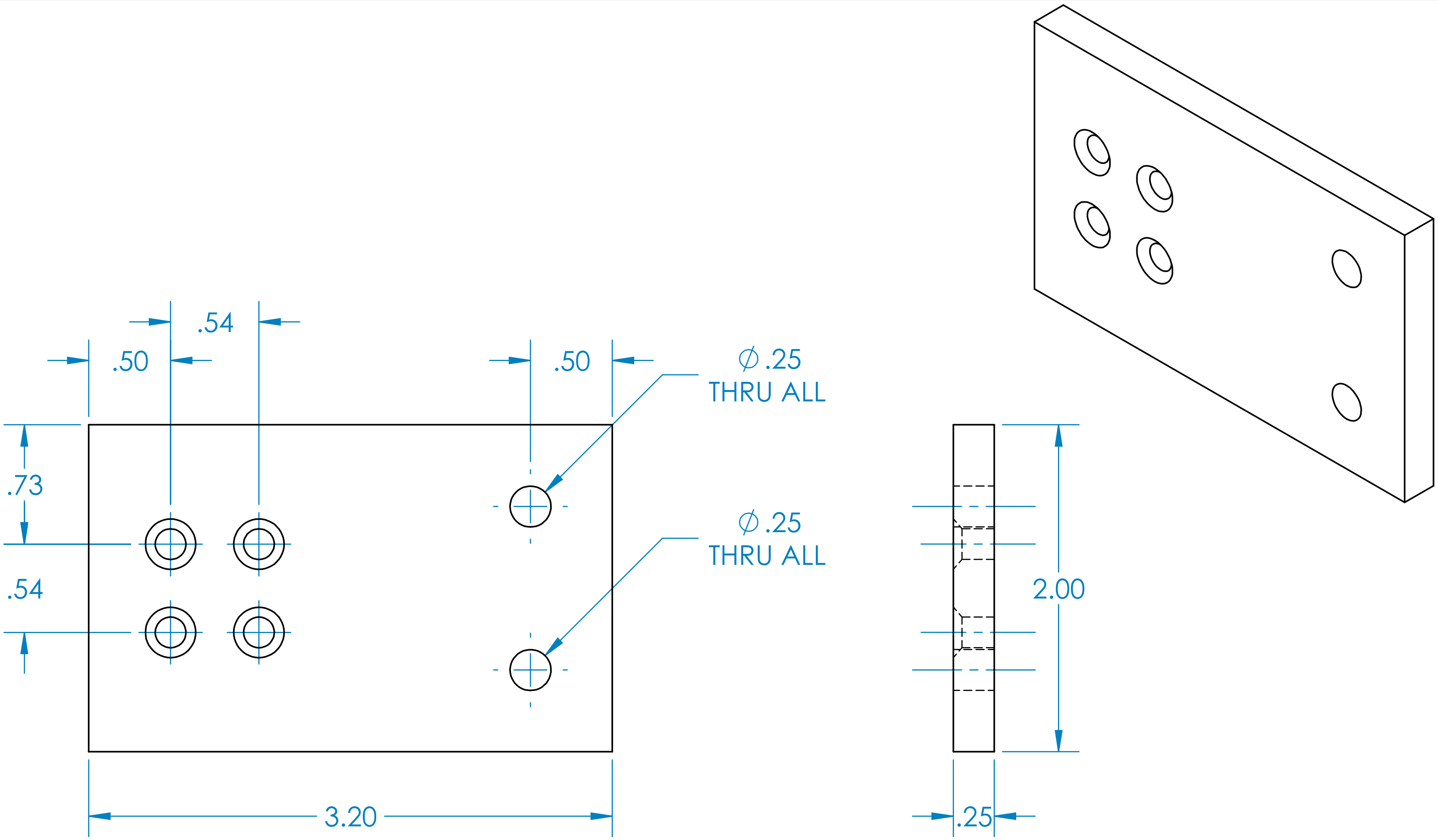
COMMENTS:

TITLE:
Body Triangle

SIZE	DWG. NO.	REV
A	214A	1

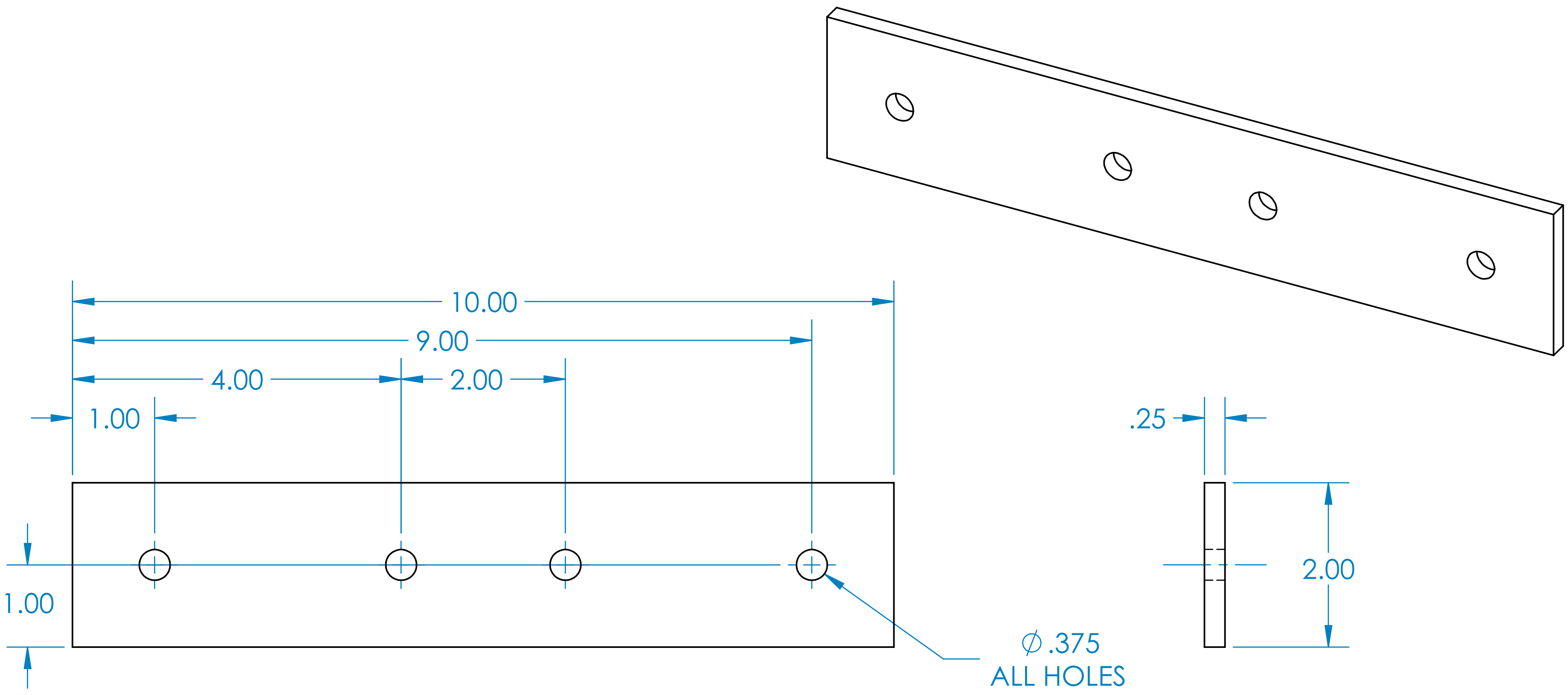
SCALE: 1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL Carbon Steel	COMMENTS:		
DO NOT SCALE DRAWING			

TITLE: Shoulder Servo Plate		
SIZE **A**	DWG. NO. 217A	REV 1
SCALE: 1:1		SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL Carbon Steel	COMMENTS:		
DO NOT SCALE DRAWING			

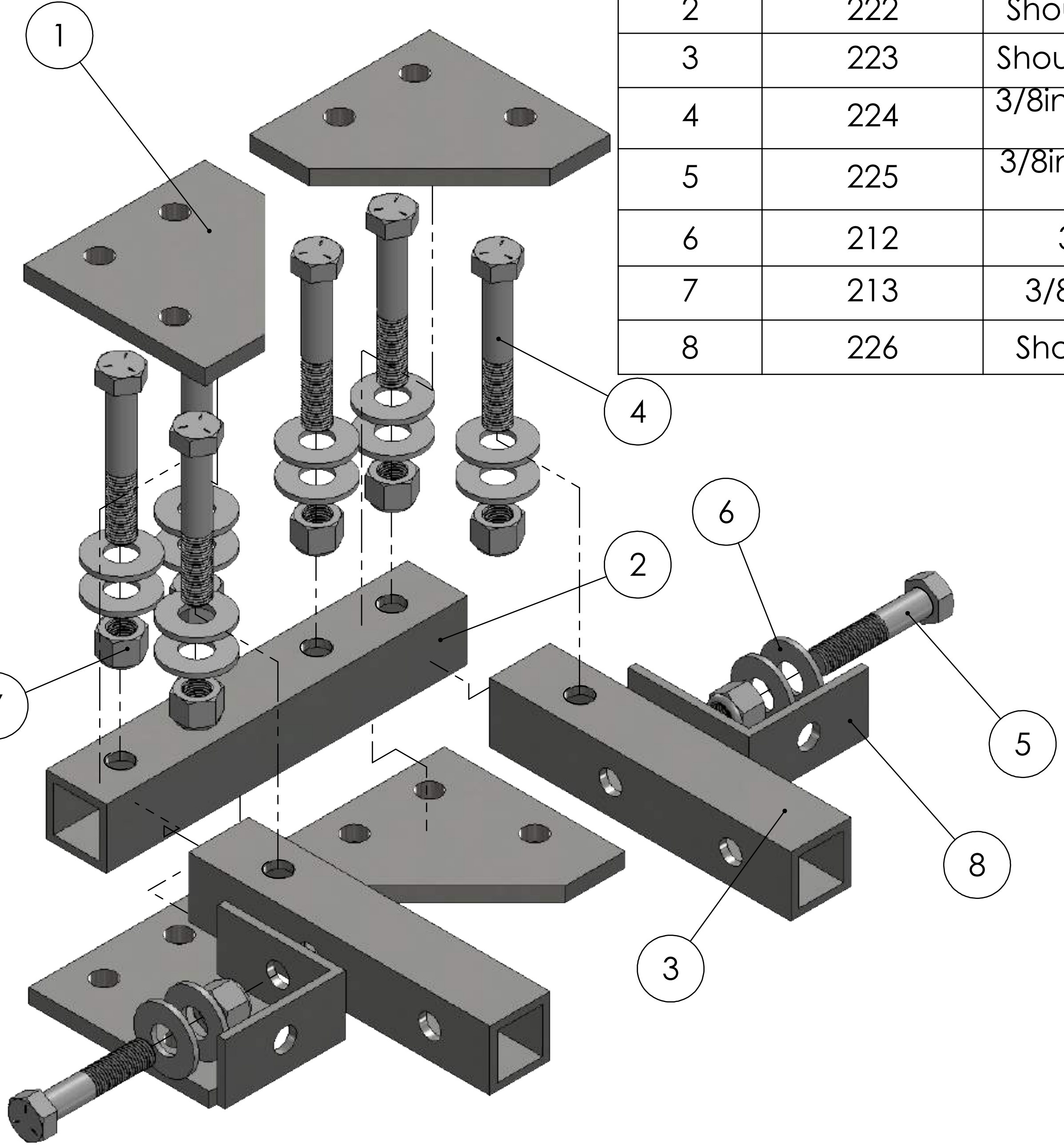
TITLE:

Electrical Housing Plate

SIZE	DWG. NO.	REV
A	216A	1
SCALE: 1:2		SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	221	Shoulder Plate	Carbon Steel	4
2	222	Shoulder Front Tube	Carbon Steel	1
3	223	Shoulder Side Length	Carbon Steel	2
4	224	3/8in Hex Bolt 2 1/4in Lenght	Carbon Steel	6
5	225	3/8in Hex Bolt 1 3/4in Length	Carbon Steel	2
6	212	3/8in Washer	Carbon Steel	16
7	213	3/8in Locking Nut	Carbon Steel	8
8	226	Shoulder L Bracket	Carbon Steel	2

B B

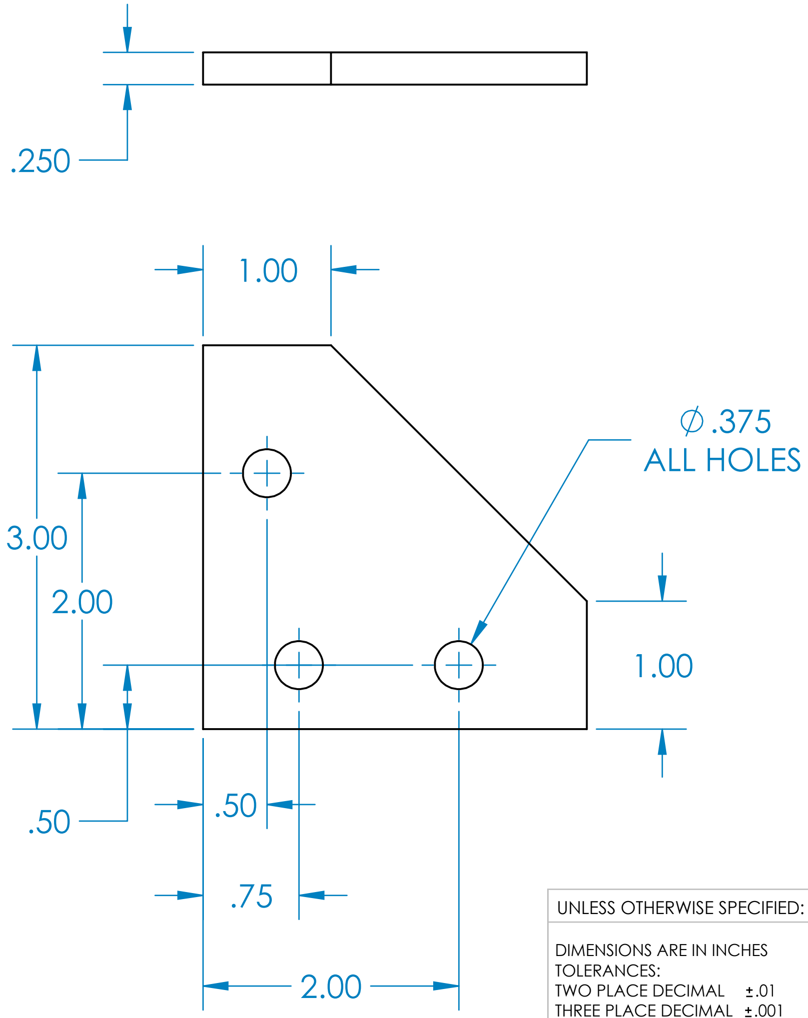


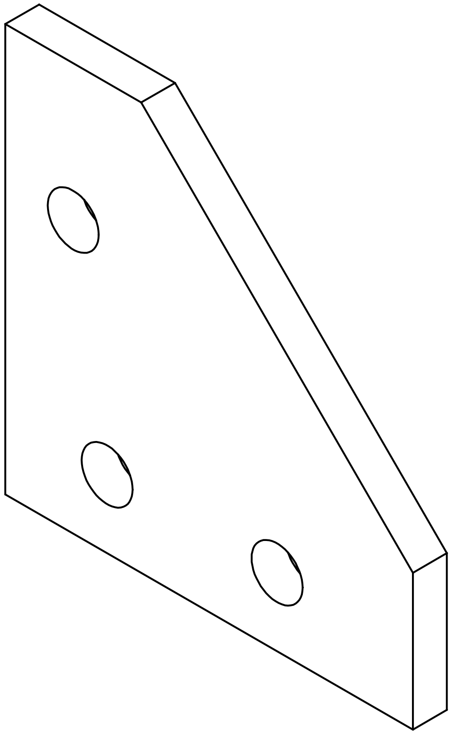
A A

TITLE:

Shoulder Subassembly

SIZE A
DWG. NO. 220
REV 1
SCALE: 1:2
SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

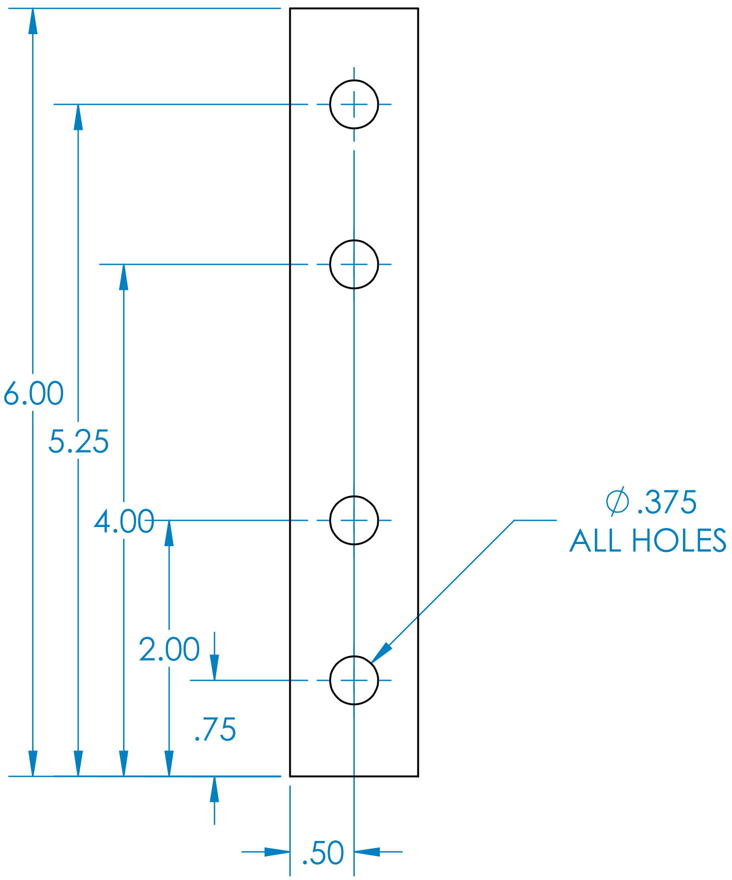
COMMENTS:

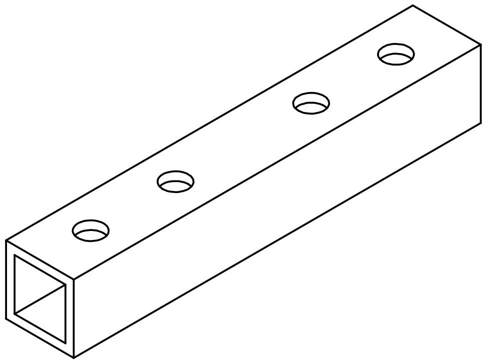
TITLE:
Shoulder Plate

SIZE	DWG. NO.	REV
A	221	1

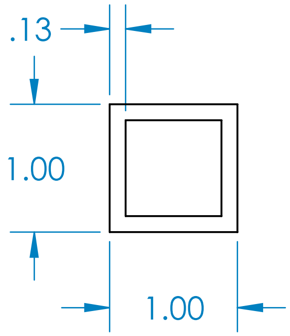
SCALE: 2:3
SHEET 1 OF 1

B





A



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

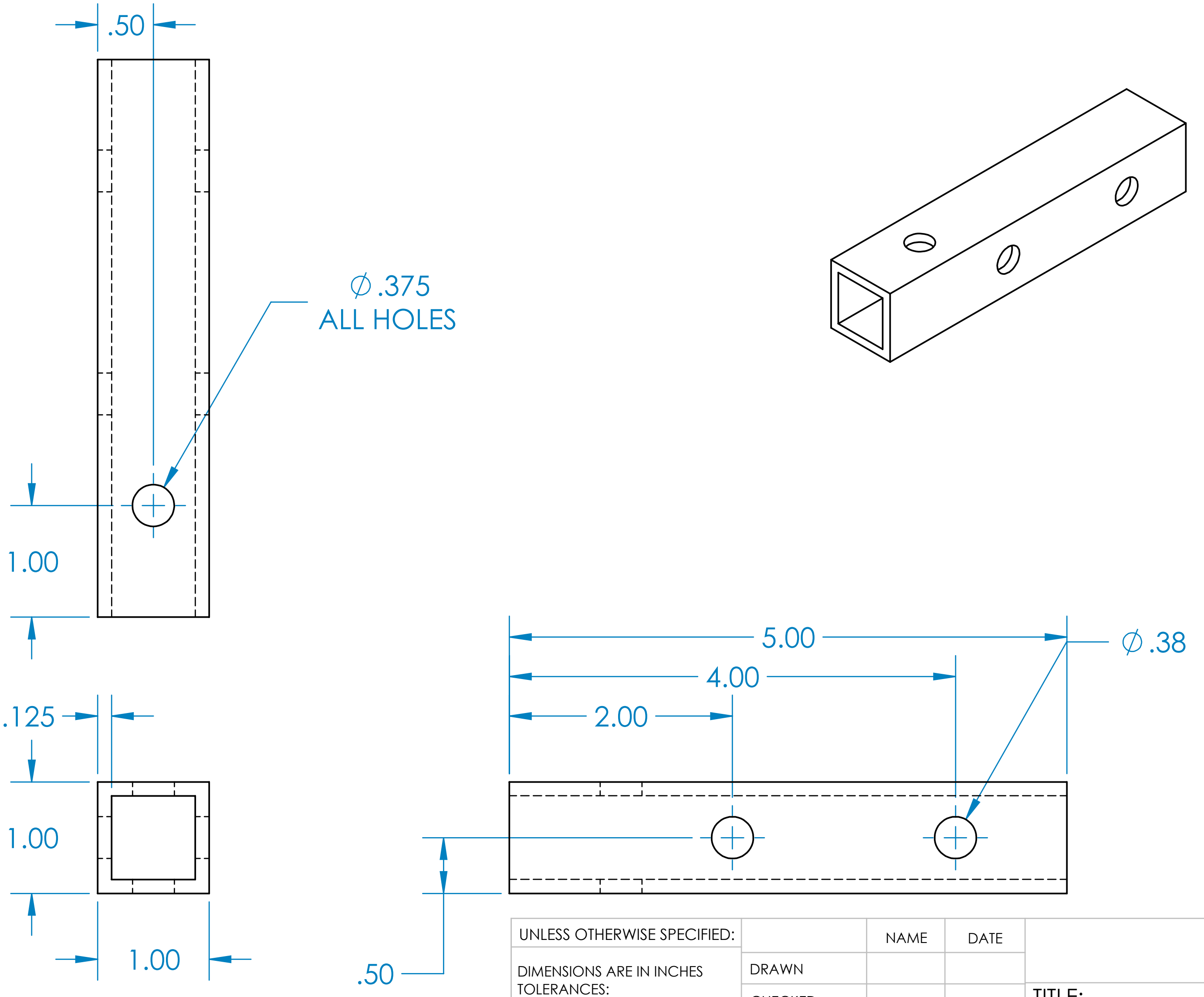
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Shoulder Front Tube

SIZE	DWG. NO.	REV
A	222	1

SCALE: 2:3
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Shoulder Side Length

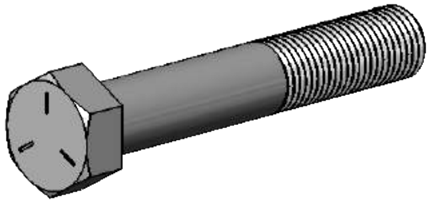
SIZE
A

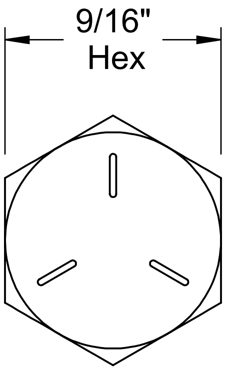
DWG. NO.
223

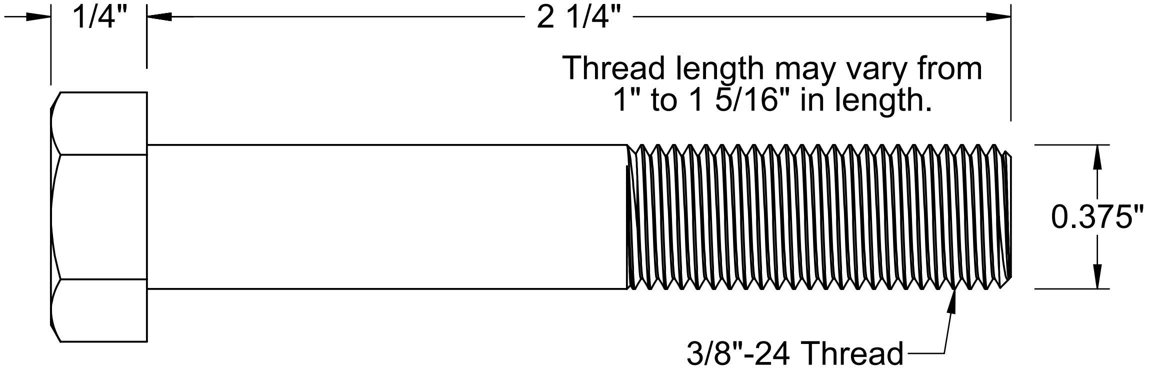
REV
1

SCALE: 2:3

SHEET 1 OF 1





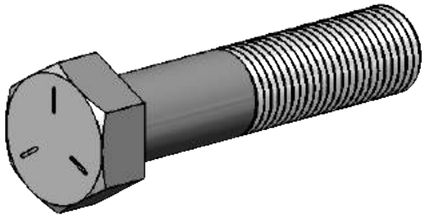


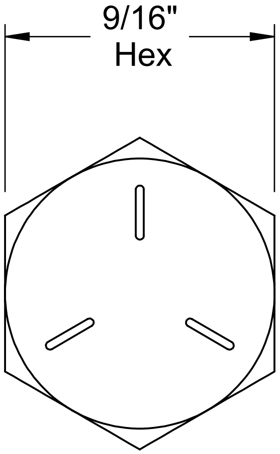
McMASTER-CARR® CAD

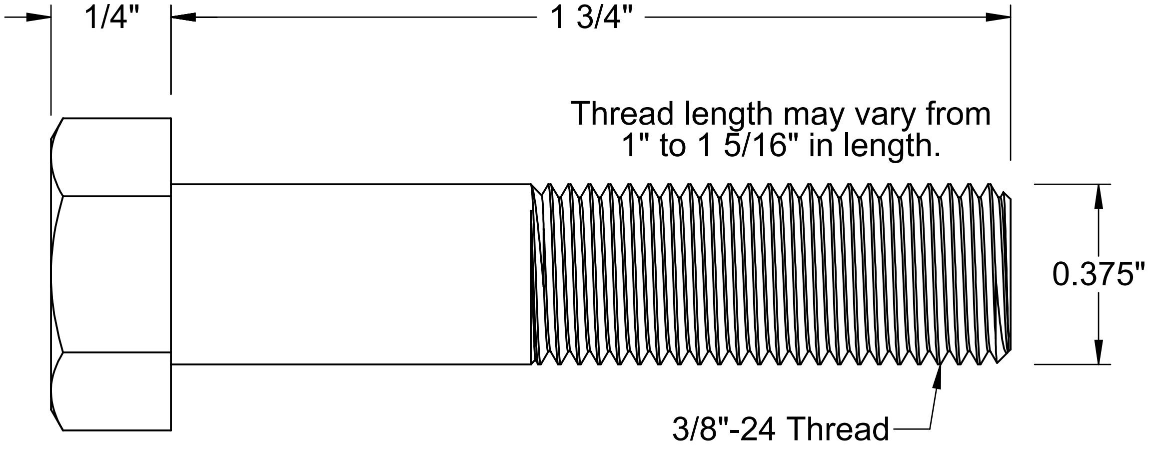
PART
NUMBER
224

http://www.mcmaster.com

Medium-Strength Steel
Cap Screw -Grade 5





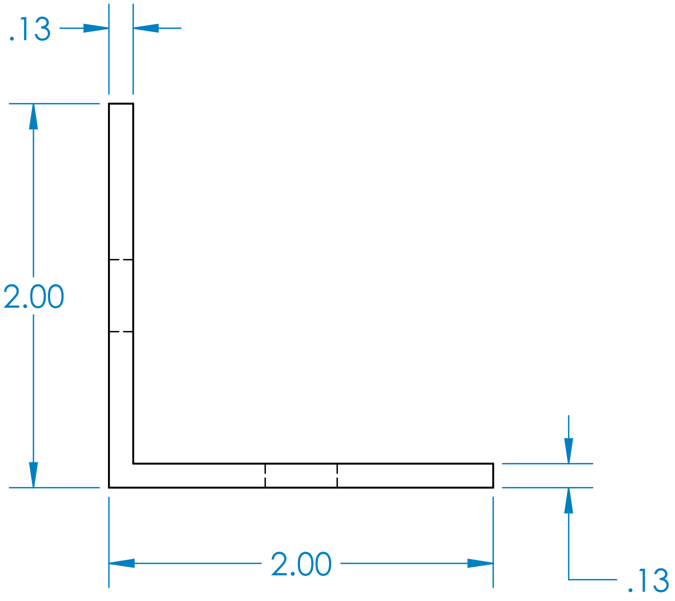


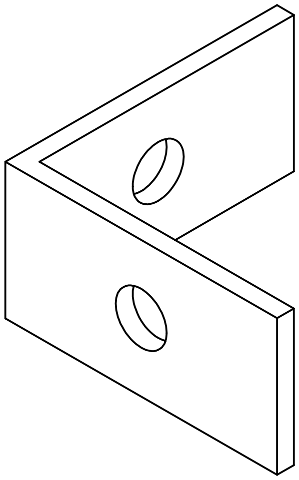
McMASTER-CARR. CAD

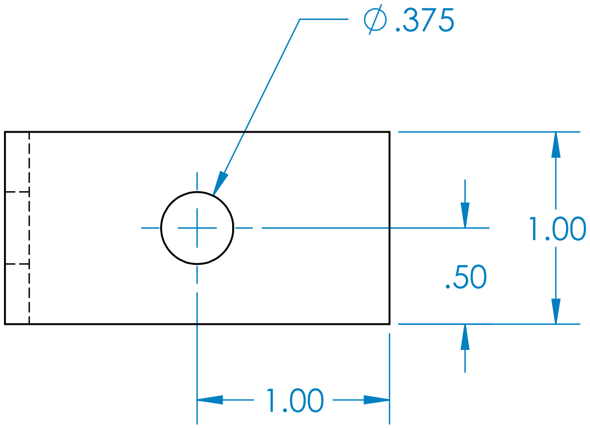
PART NUMBER **225**

http://www.mcmaster.com

Medium-Strength Steel
Cap Screw -Grade 5







UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

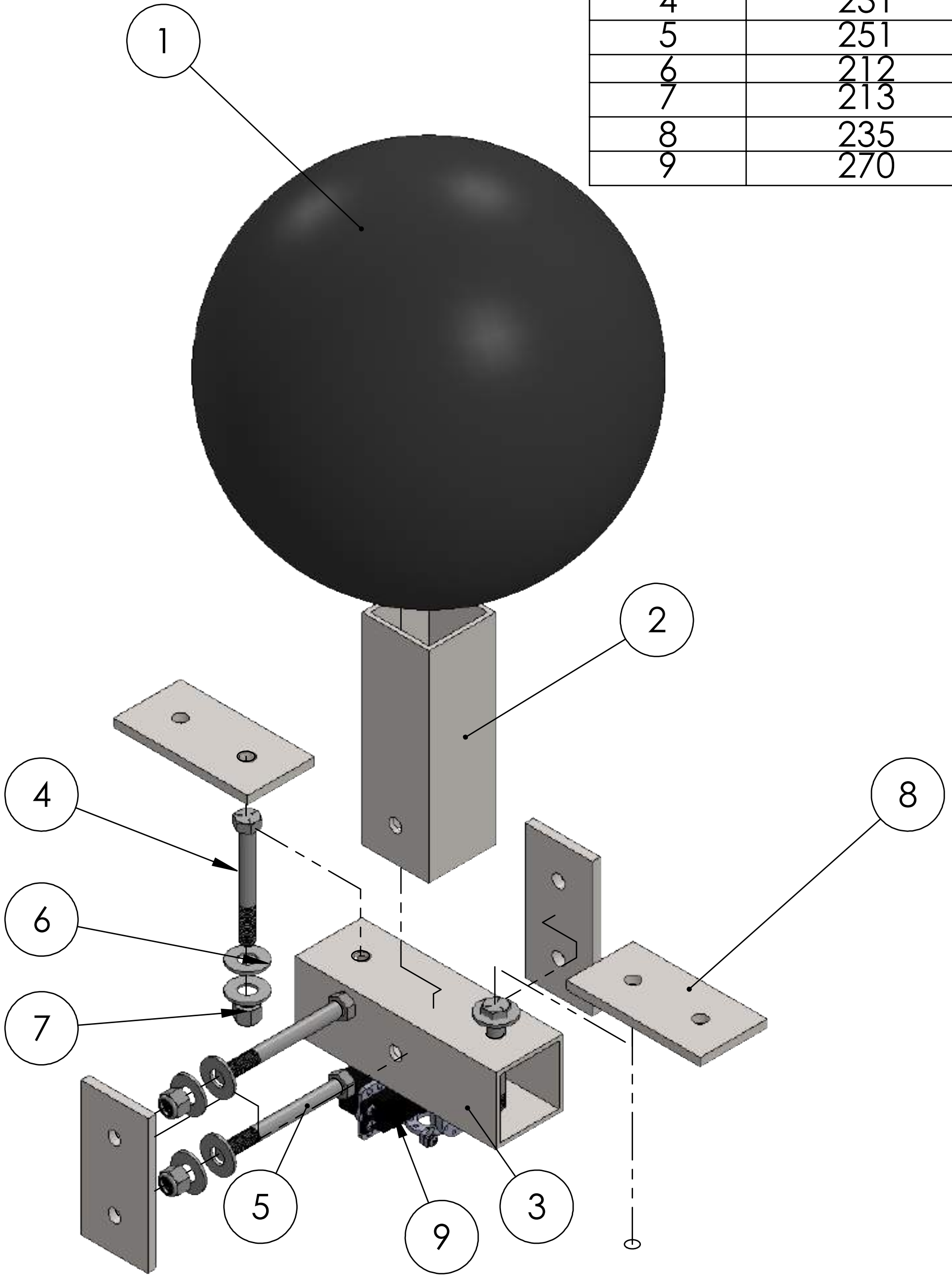
TITLE:

Shoulder L
Bracket

SIZE	DWG. NO.	REV
A	226	1

SCALE: 1:1
SHEET 1 OF 1

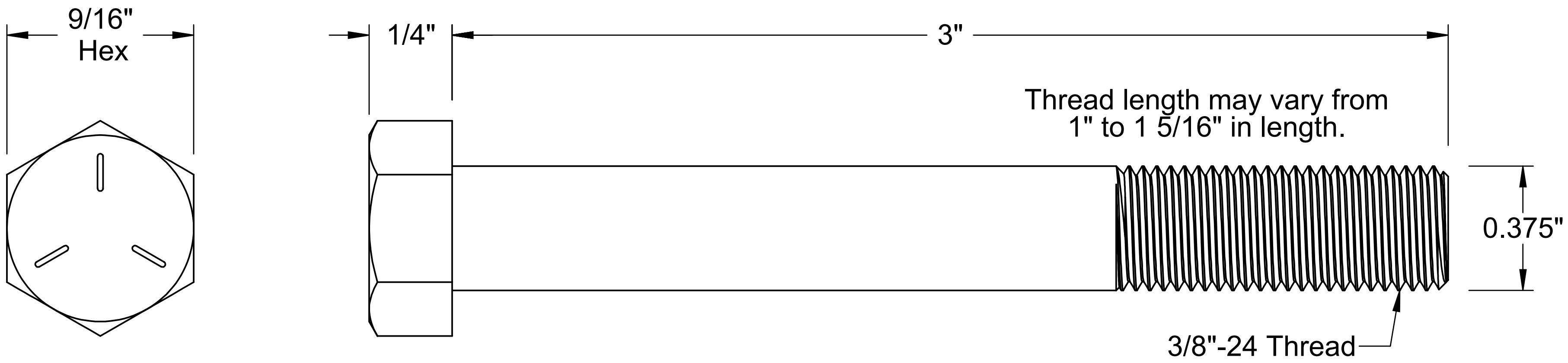
ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	232	Foam Head	Foam	1
2	233	Neck	Carbon Steel	1
3	234	Neck Bottom	Carbon Steel	1
4	231	3/8in Hex Bolt 3in Length	Carbon Steel	2
5	251	3/8in Hex Bolt 3 1/2in Length	Carbon Steel	2
6	212	3/8in Washer	Carbon Steel	8
7	213	3/8in Locking Nut	Carbon Steel	4
8	235	Neck Plate	Carbon Steel	4
9	270	Servo Subassembly	Many	1



TITLE:

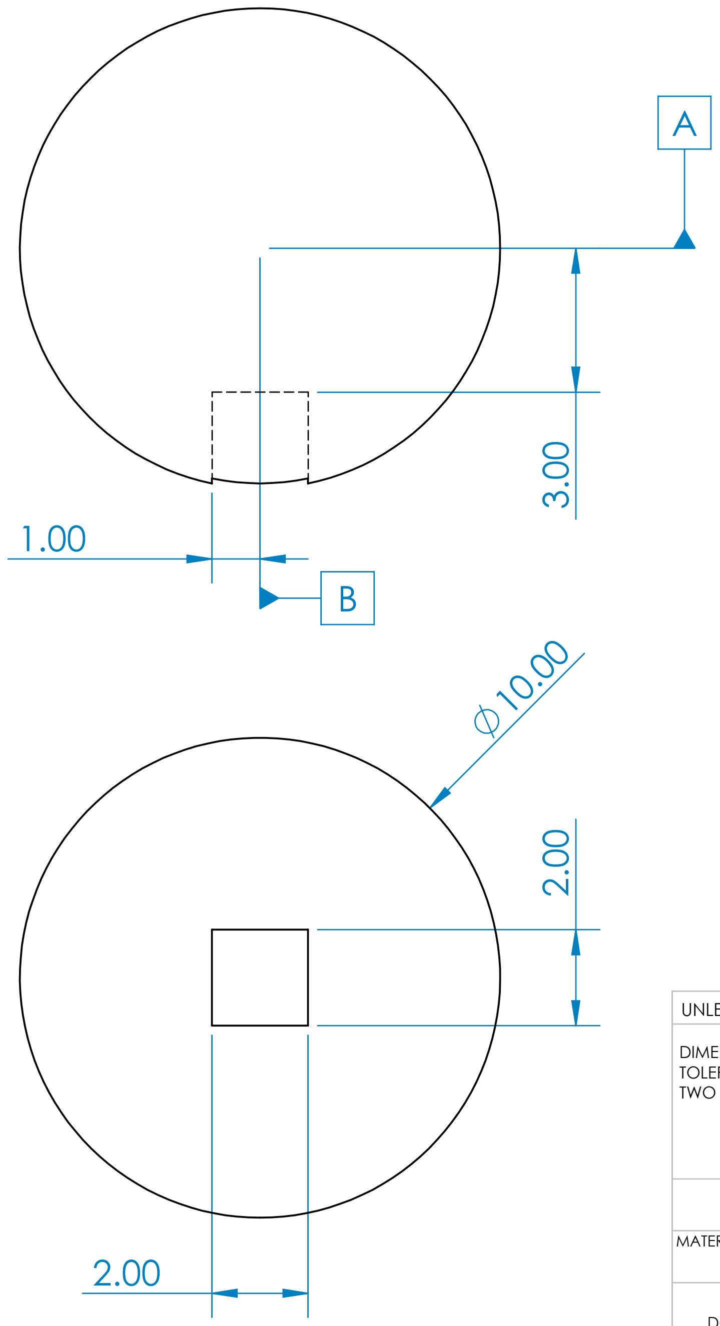
Neck Subassembly

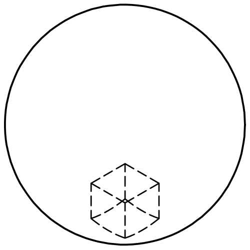
SIZE A
DWG. NO. 230
REV 1
SCALE: 1:4
SHEET 1 OF 1



Thread length may vary from 1" to 1 5/16" in length.

McMASTER-CARR® CAD	PART NUMBER **231**
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Medium-Strength Steel Cap Screw -Grade 5





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.01

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

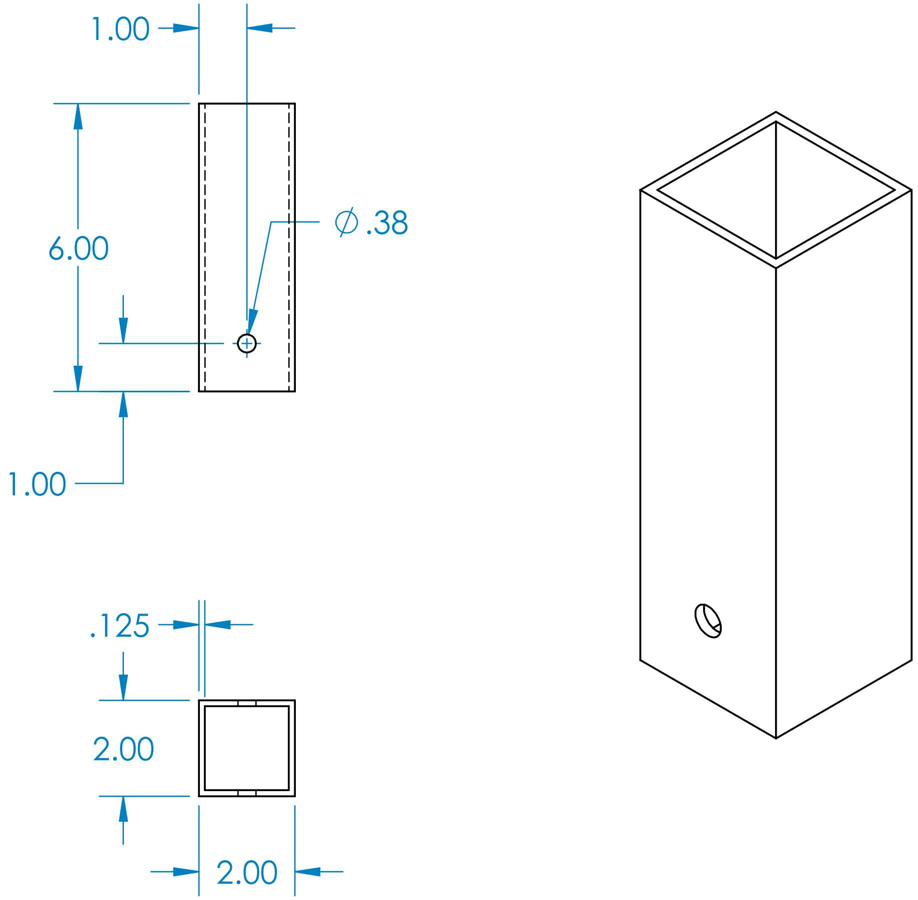
MATERIAL
Foam

DO NOT SCALE DRAWING

TITLE:
Foam Head

SIZE	DWG. NO.	REV
A	232	1

SCALE: 1:4 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
MATERIAL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

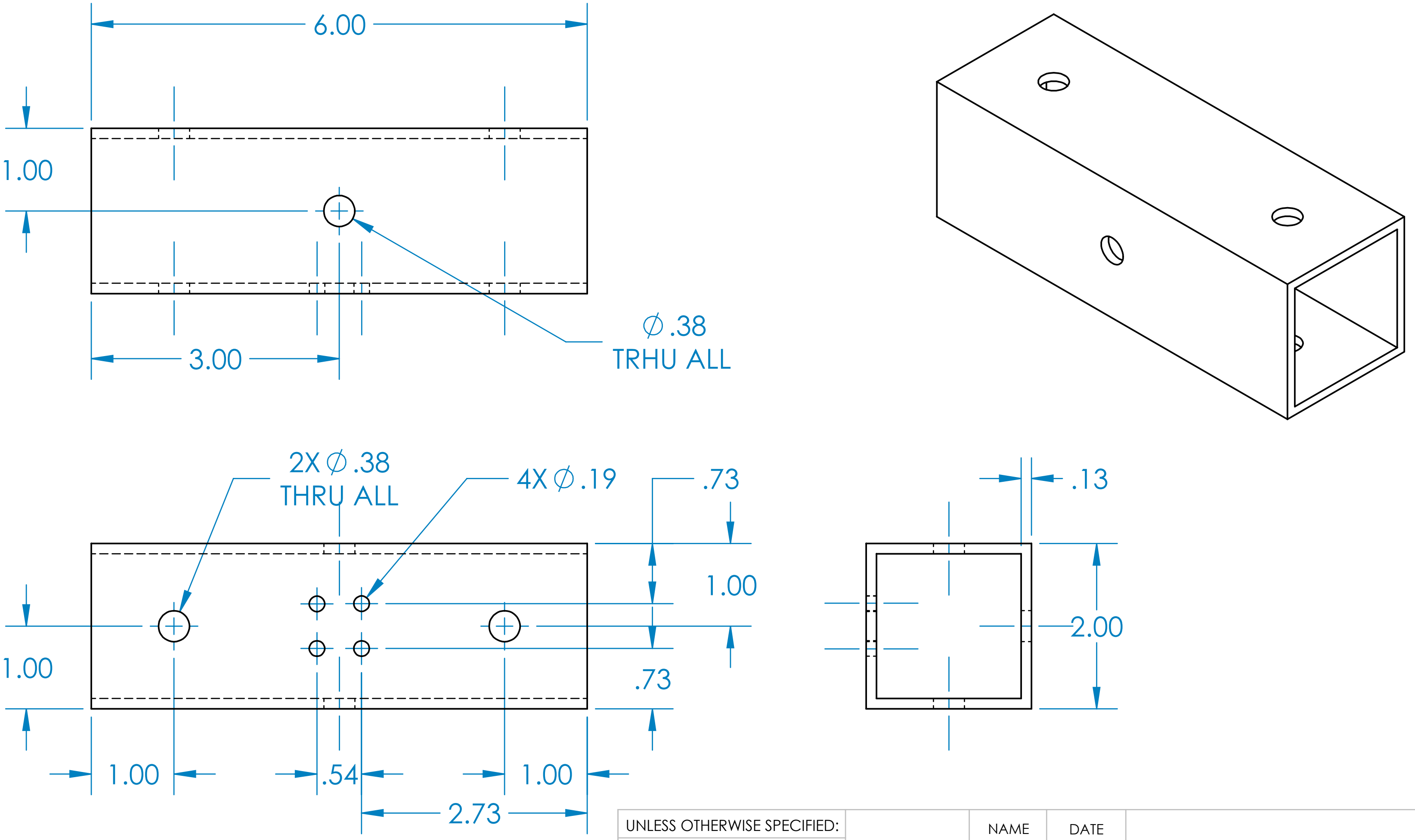
TITLE:

Neck

SIZE	DWG. NO.	REV
A	233	1

SCALE: 1:4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
MATERIAL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

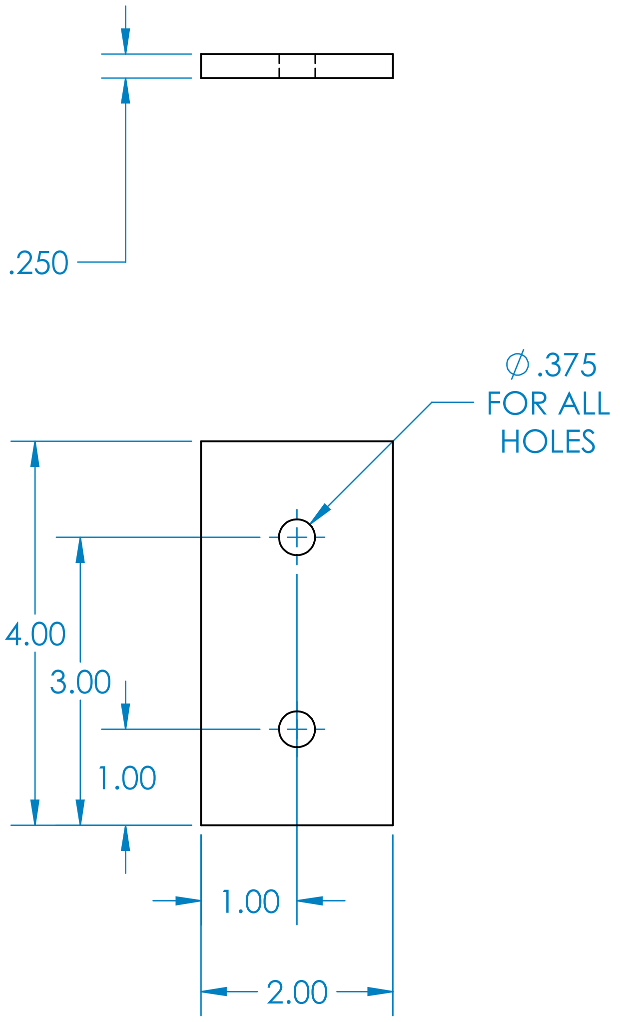
COMMENTS:

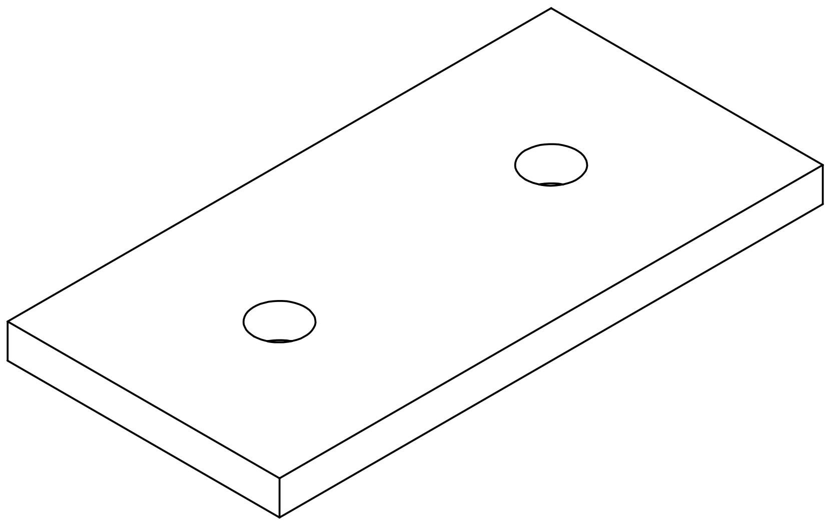
TITLE:

Neck Bottom

SIZE **A** DWG. NO. 234 REV 1

SCALE: 1:2 SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL
Carbon Steel

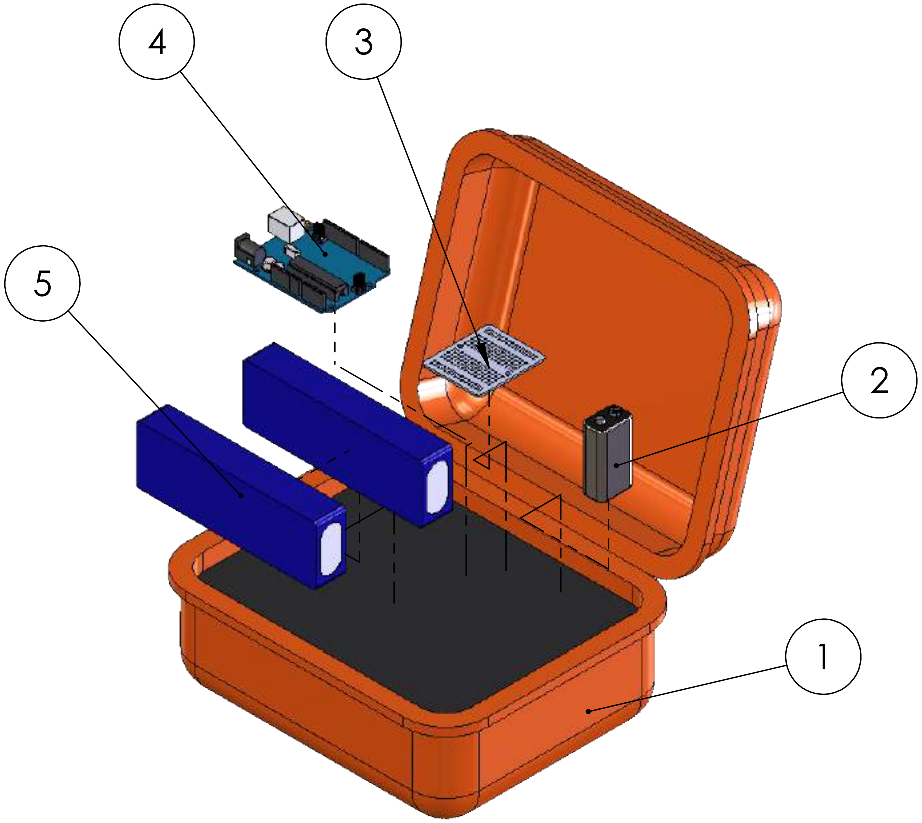
DO NOT SCALE DRAWING

TITLE:
Neck Plate

SIZE	DWG. NO.	REV
A	235	1

SCALE: 1:2
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	241	Hard Shell Case	Plastic	1
2	242	9V Battery	Metal	1
3	243	Permanent Bread Board	Plastic	1
4	244	Arduino	Plastic	1
5	245	7.4V LiPo Battery	Metal	1



TITLE:

Electronic Housing Subassembly

SIZE	DWG. NO.	REV
A	240	1

SCALE: 1:4
SHEET 1 OF 1

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

Hard Shell Case

SIZE	DWG. NO.	REV
A	241	1

SHEET 1 OF 1

PRODUCT DATASHEET

Energizer

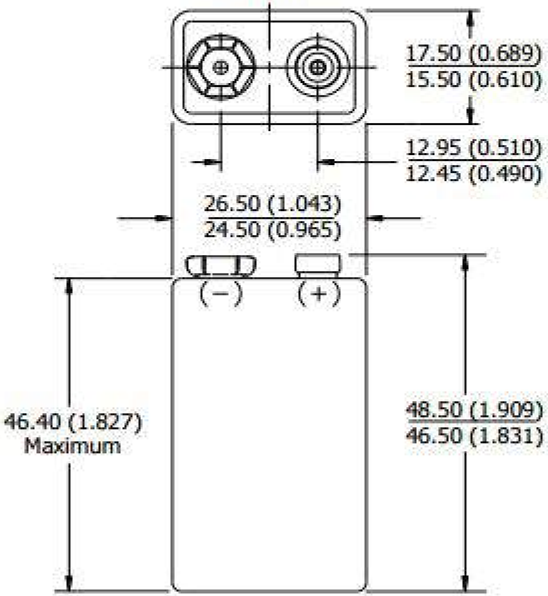
1-800-383-7323 USA/CAN
www.energizer.com

ENERGIZER 522

9V

Industry Standard Dimensions

mm (inches)

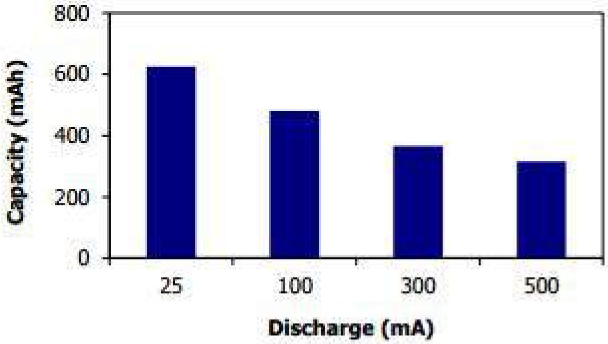


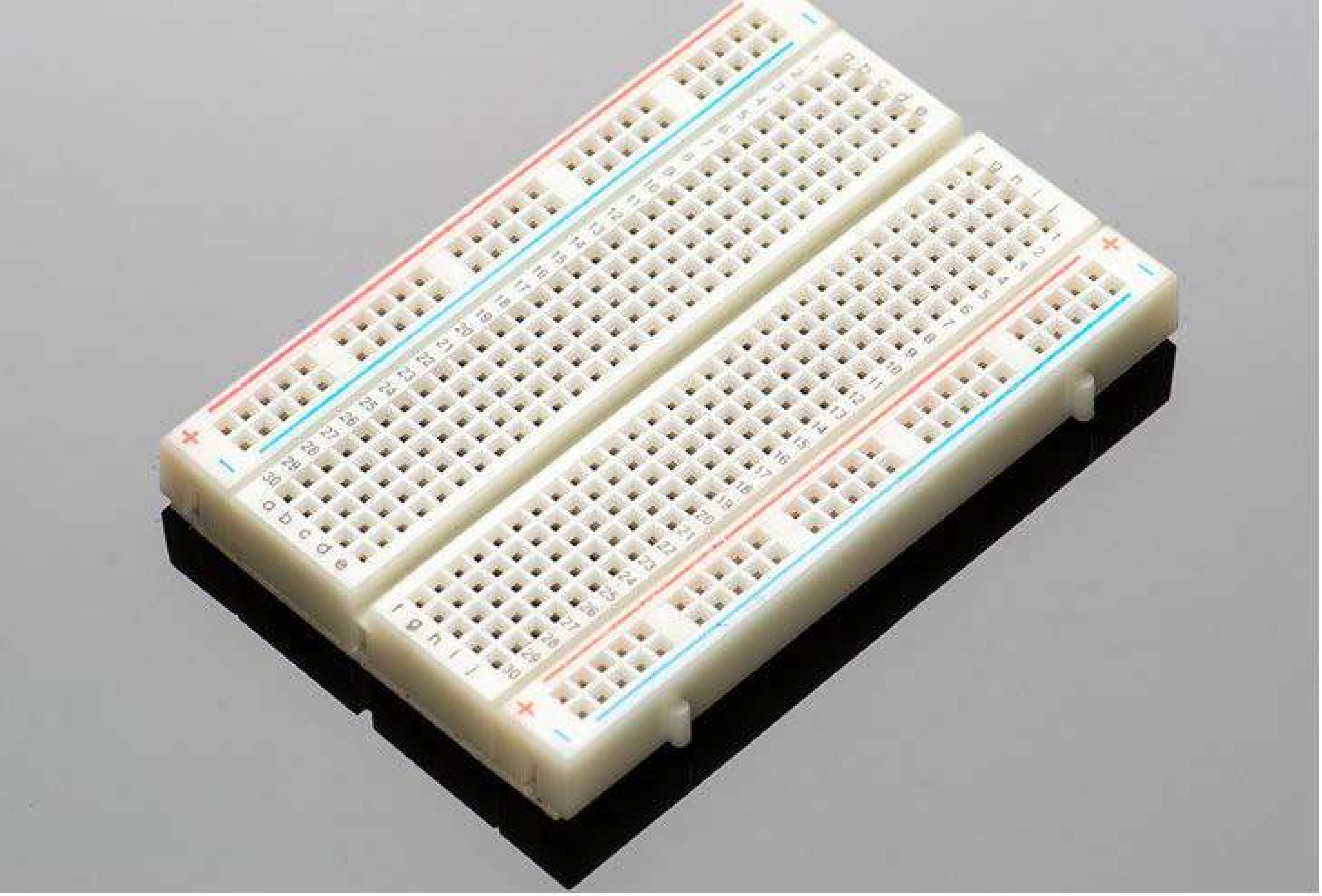
Specifications

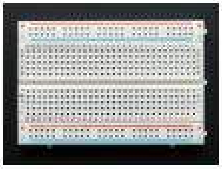
Classification:	Alkaline
Chemical System:	Zinc-Manganese Dioxide (Zn/MnO_2) No added mercury or cadmium
Designation:	ANSI-1604A, IEC-6LR61
Nominal Voltage:	9.0 volts
Operating Temp:	-18°C to 55°C (0°F to 130°F)
Typical Weight:	45.6 grams (1.6 oz.)
Typical Volume:	21.1 cubic centimeters (1.3 cubic inch)
Jacket:	Metal
Shelf Life:	5 years at 21°C
Terminal:	Miniature Snap

Milliamp-Hours Capacity

Continuous discharge to 4.8 volts at 21°C







DESCRIPTION

This is a cute half size breadboard, good for small projects. It's 2.2" x 3.4" (5.5 cm x 8.5 cm) with a standard double-strip in the middle and two power rails on both sides. You can pull the power rails off easily to make the breadboard as thin as 1.4" (3.5cm) and stick it onto an Arduino protoshield. You can also cut these in half with a saw to create 2 tiny breadboards, or "snap" these breadboards together either way to make longer and/or wider breadboards.

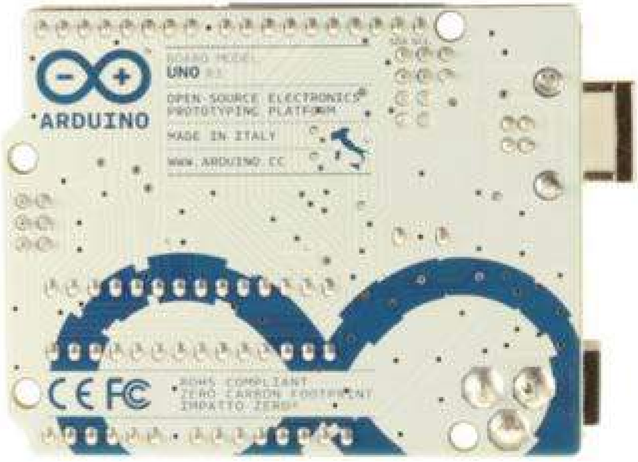
TECHNICAL DETAILS

Dimensions:

- 2.2" x 3.4" (5.5 cm x 8.5 cm)
- 9.7mm(0.38in) thick, including sticky foam on the bottom
- Weight: 38.9g(1.27oz)

Arduino Uno

Arduino Uno R3 Front

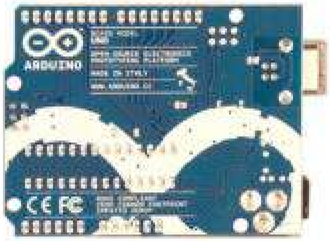


Arduino Uno R3 Back

Arduino Uno R2 Front

Arduino Uno SMD

Arduino Uno Front



Arduino Uno Back

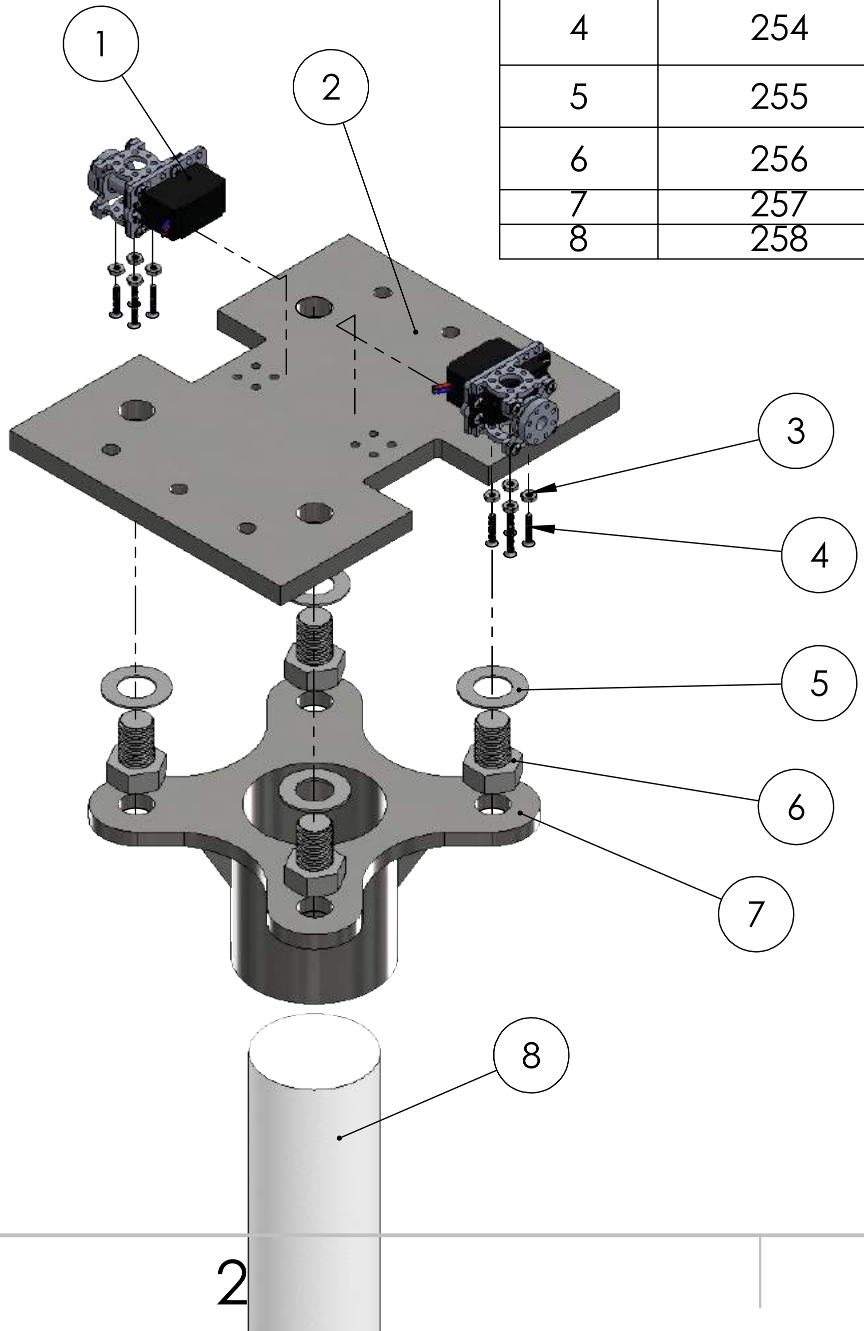
Overview

The Arduino Uno is a microcontroller board based on the ATmega328 (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.
The Uno differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega16U2 (Atmega8U2 up to version R2) programmed as a USB-to-serial converter.

PRODUCT DESCRIPTION SPECIFICATIONS REVIEWS

SKU	FLM-LP-2226
Applicable Airplane	No
Type	LiPO
Voltage	2S
Discharge Rate	40C
Discharge Connector	T-Connector
Battery Capacity	6500
Capacity Range	3700mAh and Above

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	270	Servo Subassembly	N/A	1
2	252	Torso Bottom Plate	Low Carbon Steel	1
3	253	#6-32 Hex Nut	Stainless Steel 18-8	8
4	254	#6-32 Phillips Flat Head Screw 3/4in Length	Stainless Steel 18-8	8
5	255	3/4in Washer	Low Carbon Steel	4
6	256	3/4in Hex Bolt	Low Carbon Steel	4
7	257	Pole Flange	Cast Steel	1
8	258	Polypropylene Pole	Polypropylene	1



TITLE:

Pole Subassembly

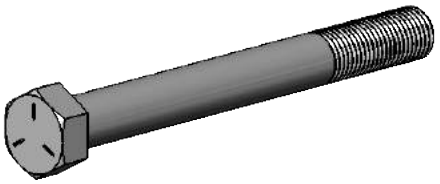
SIZE A

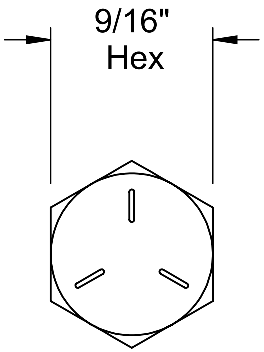
DWG. NO. 250

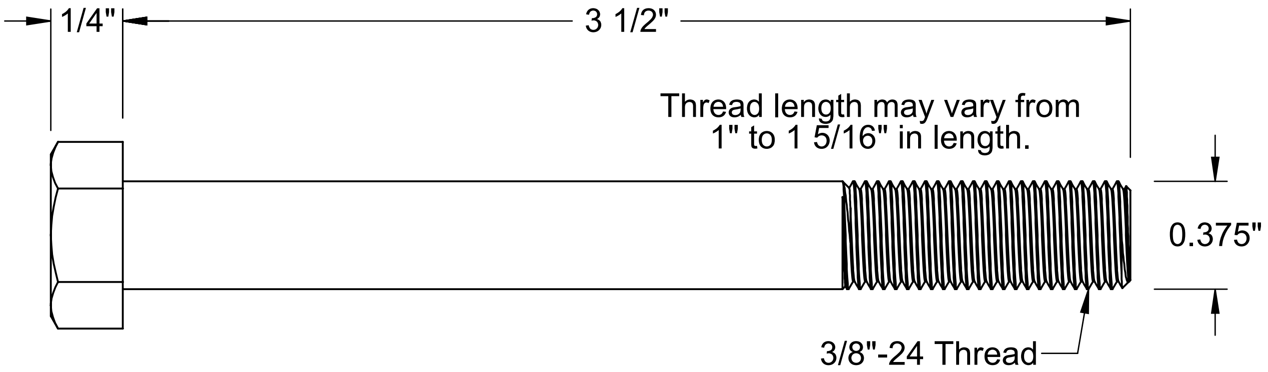
REV 1

SCALE: 1:4

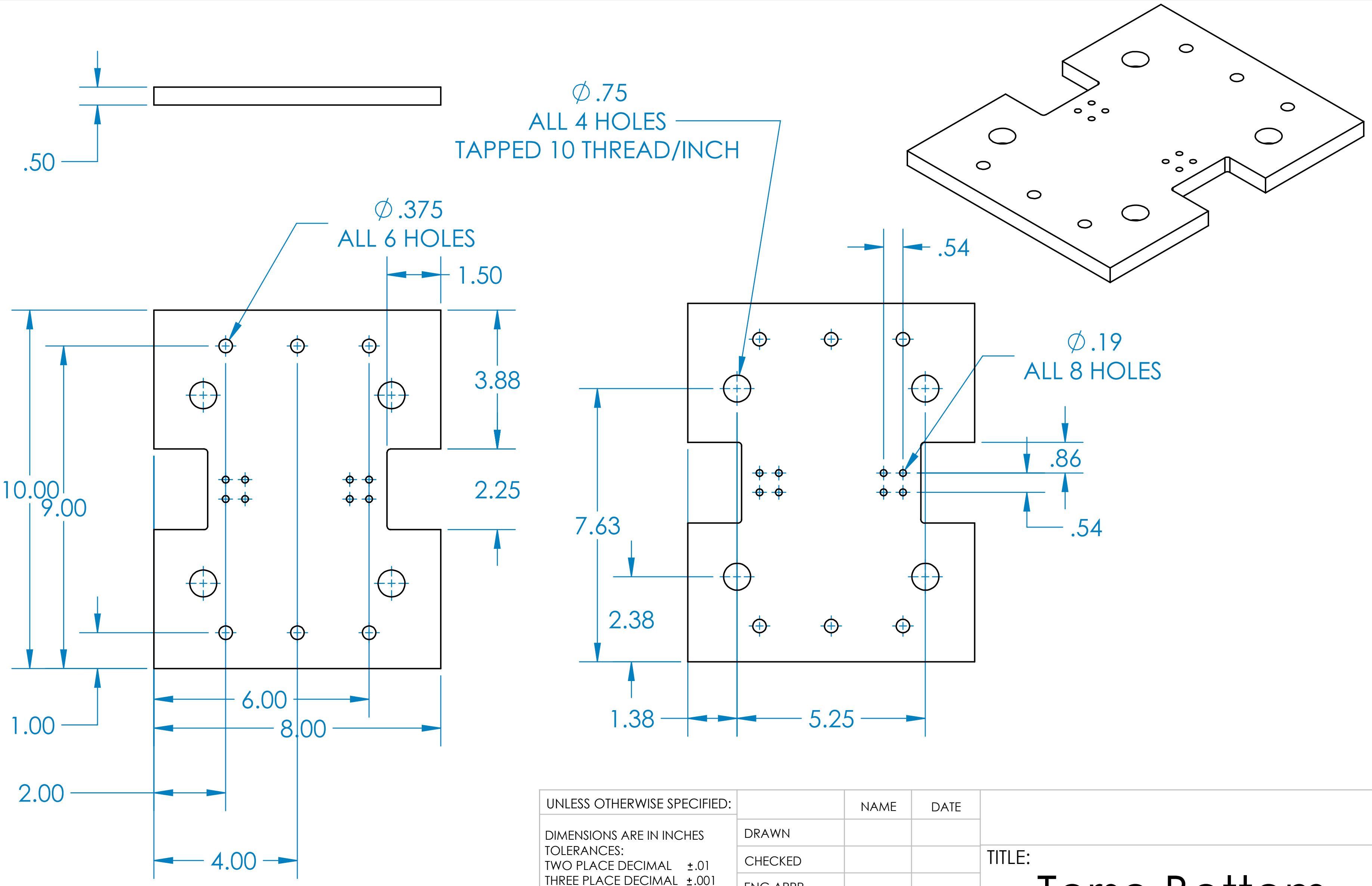
SHEET 1 OF 1



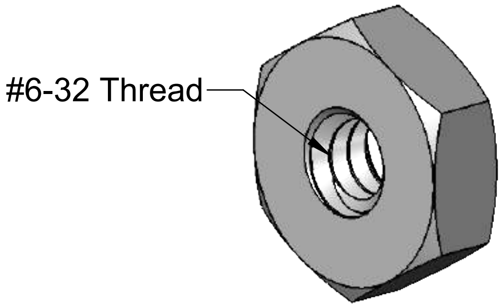


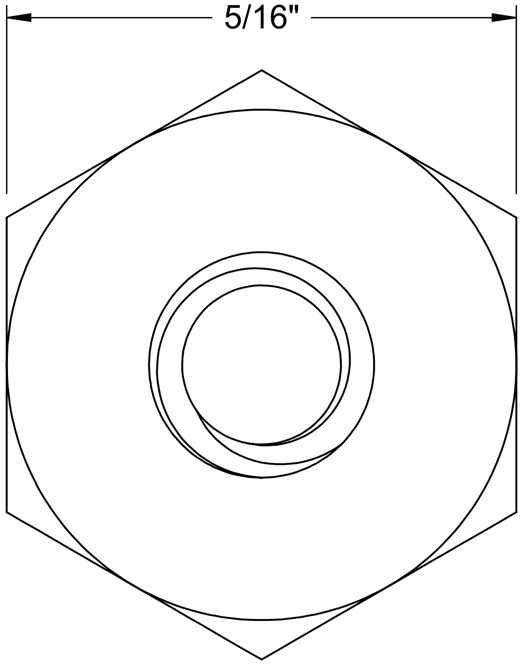


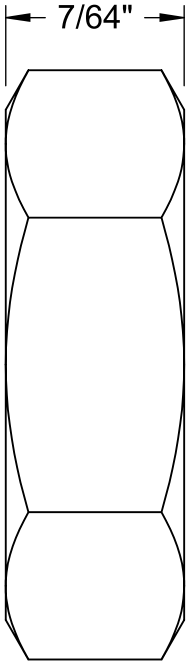
McMASTER-CARR® CAD	PART NUMBER **251**
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Medium-Strength Steel Cap Screw -Grade 5



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	DRAWN			TITLE: Torso Bottom Plate
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL Carbon Steel	COMMENTS:			SIZE A · DWG. NO. 252 · REV 1
DO NOT SCALE DRAWING				SCALE: 1:4 · SHEET 1 OF 1





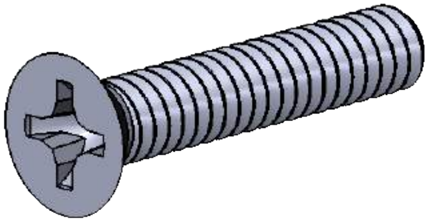


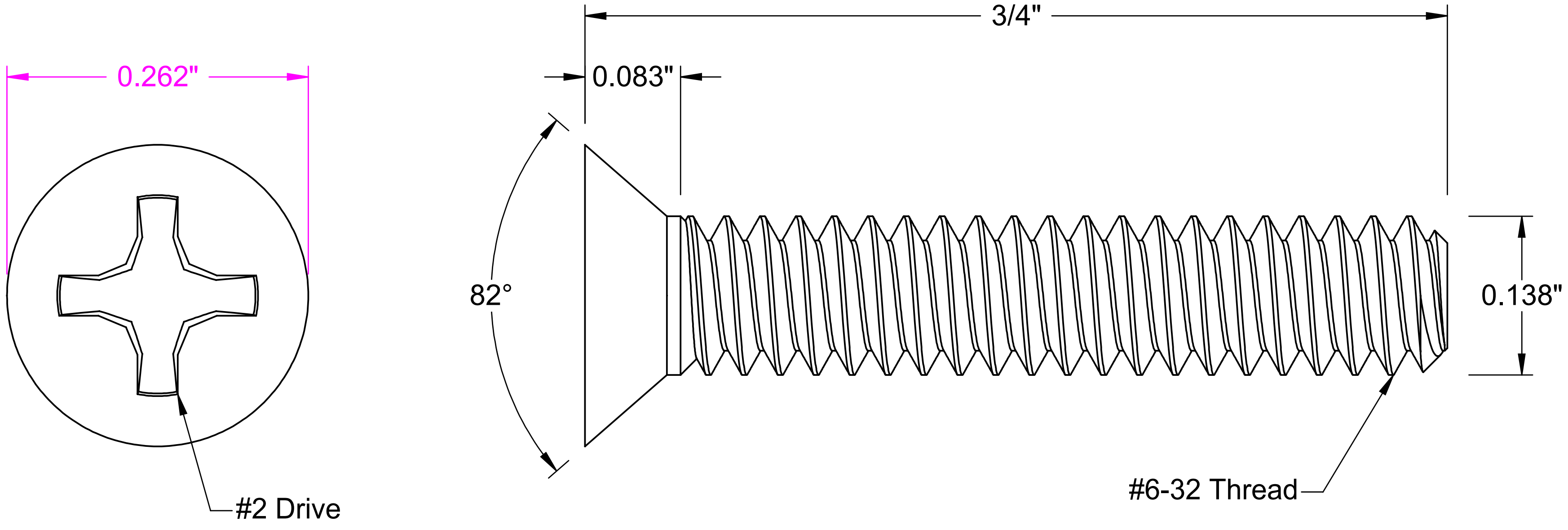
McMASTER-CARR® CAD

PART NUMBER **253**

http://www.mcmaster.com

Hex
Nut



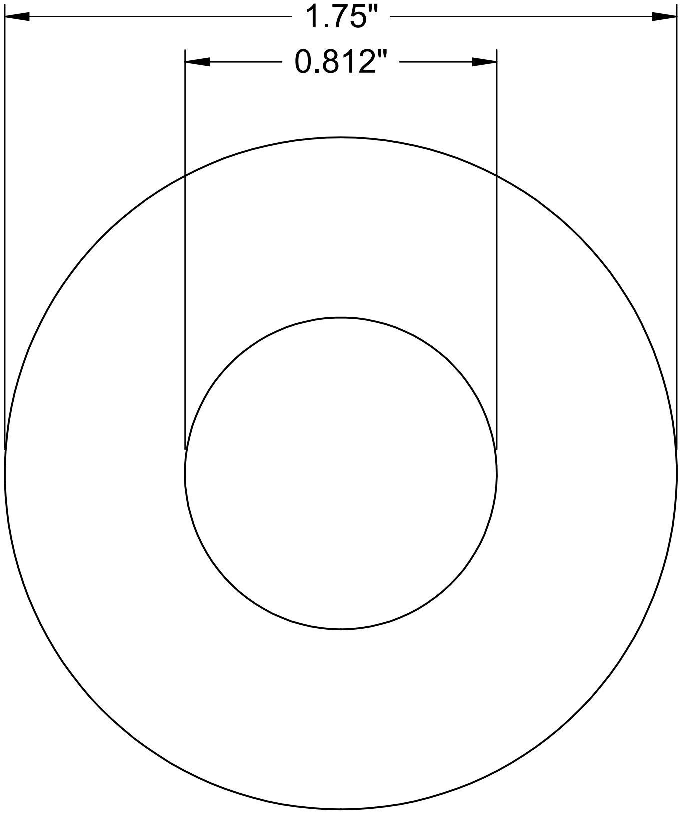


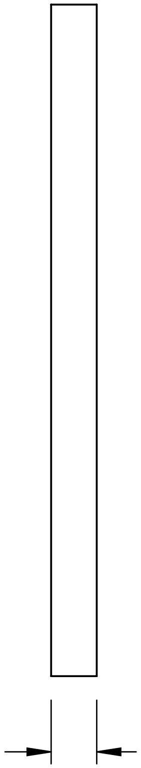
McMASTER-CARR® CAD

PART NUMBER **254**

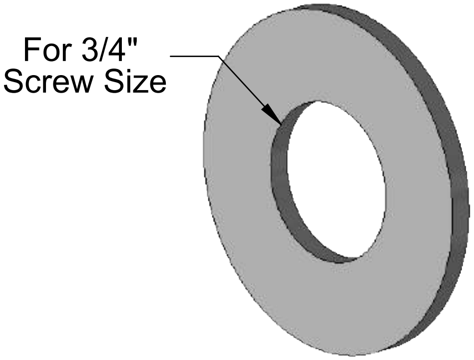
http://www.mcmaster.com

Flat Head Phillips
Machine Screw

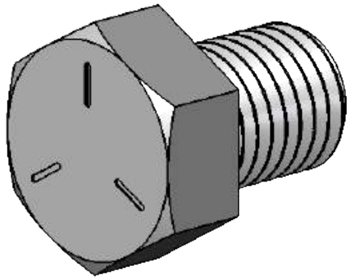


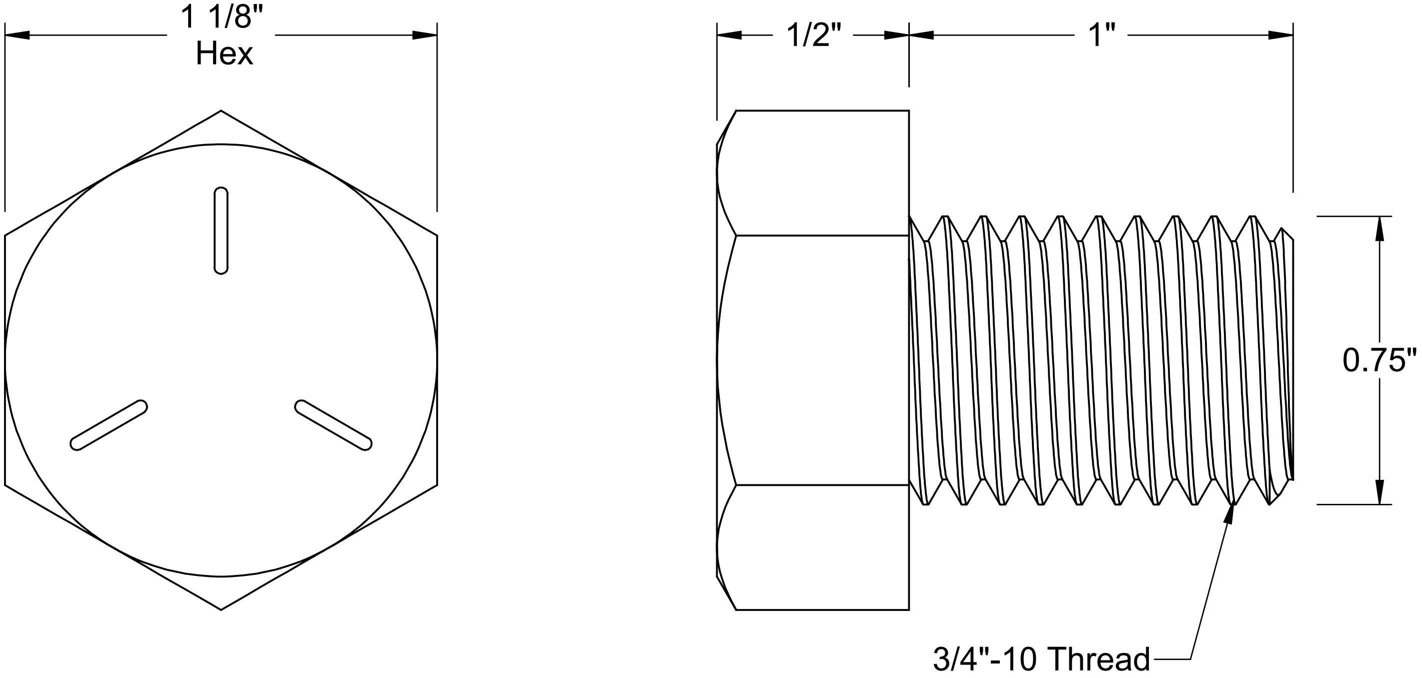


Washer may vary from
0.099" to 0.119" in thickness.



McMASTER-CARR® CAD	PART NUMBER	255
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	General Purpose Washer	



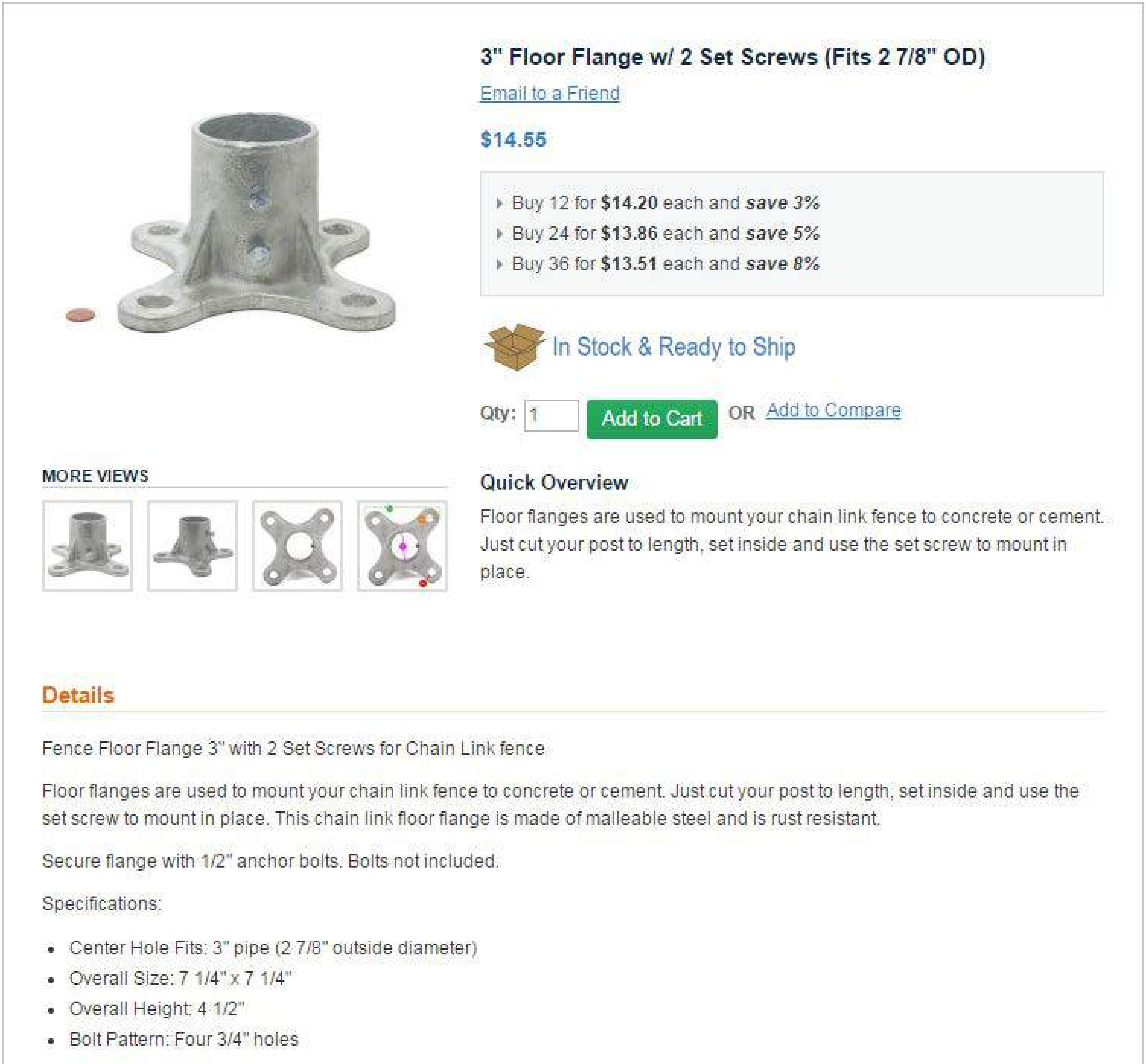


McMASTER-CARR® CAD

PART NUMBER **256**

http://www.mcmaster.com

Medium-Strength Steel
Cap Screw - Grade 5



3" Floor Flange w/ 2 Set Screws (Fits 2 7/8" OD)

Email to a Friend

$14.55

- Buy 12 for **$14.20** each and ***save 3%***
- Buy 24 for **$13.86** each and ***save 5%***
- Buy 36 for **$13.51** each and ***save 8%***

In Stock & Ready to Ship

Quick Overview

Floor flanges are used to mount your chain link fence to concrete or cement. Just cut your post to length, set inside and use the set screw to mount in place.

Details

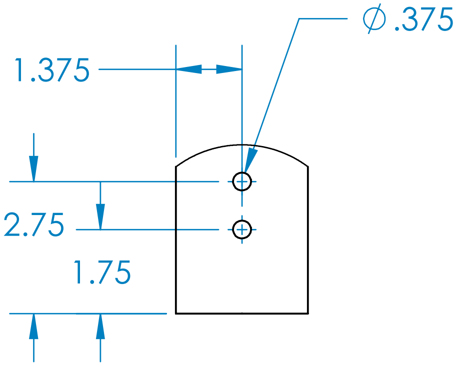
Fence Floor Flange 3" with 2 Set Screws for Chain Link fence

Floor flanges are used to mount your chain link fence to concrete or cement. Just cut your post to length, set inside and use the set screw to mount in place. This chain link floor flange is made of malleable steel and is rust resistant.

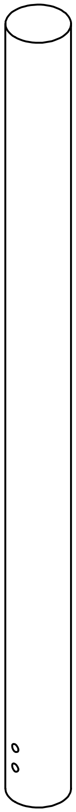
Secure flange with 1/2" anchor bolts. Bolts not included.

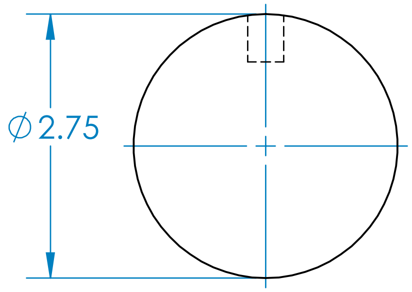
Specifications:

- Center Hole Fits: 3" pipe (2 7/8" outside diameter)
- Overall Size: 7 1/4" x 7 1/4"
- Overall Height: 4 1/2"
- Bolt Pattern: Four 3/4" holes



DETAIL A
SCALE 1 : 4



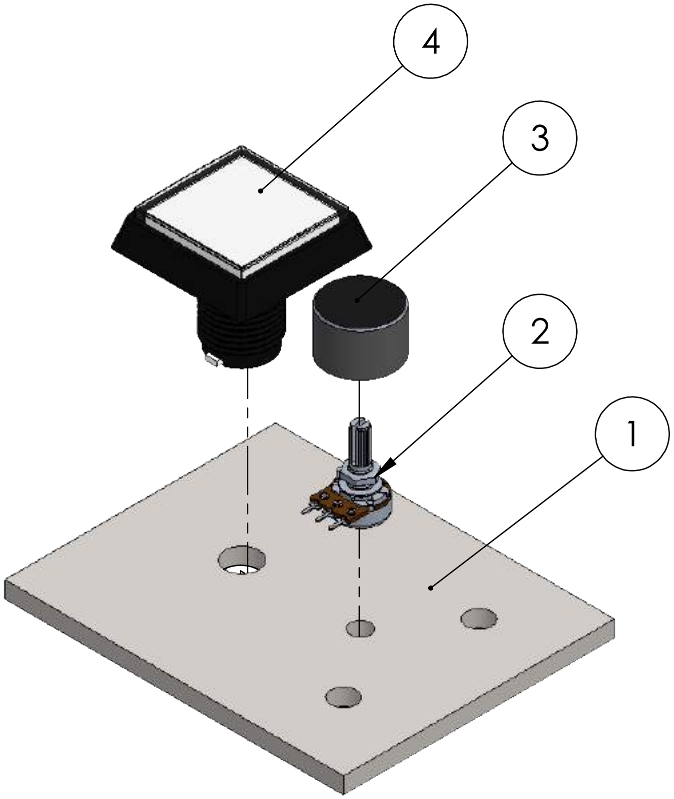


SCALE 1:2

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	DRAWN			
	CHECKED			TITLE: Polypropylene Pole
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL Polypropylene	COMMENTS:			SIZE A · DWG. NO. 258 · REV 1
DO NOT SCALE DRAWING				SCALE: 1:2 · SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	264	Emergency Stop Button	Plastic	1
2	263	Control Knob	Aluminum	1
3	262	Potentiometer	Steel	1
4	261	Control Panel Back Plate	Cold Drawn Steel	1

B B



A A

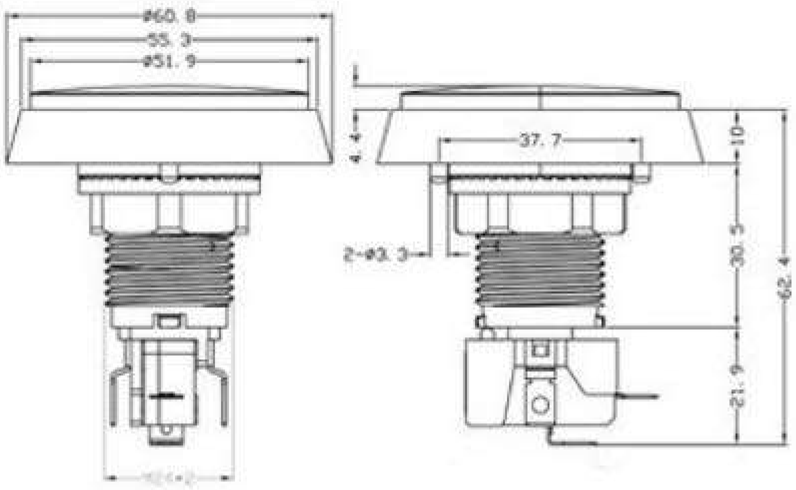
TITLE:
Control Panel Subassembly

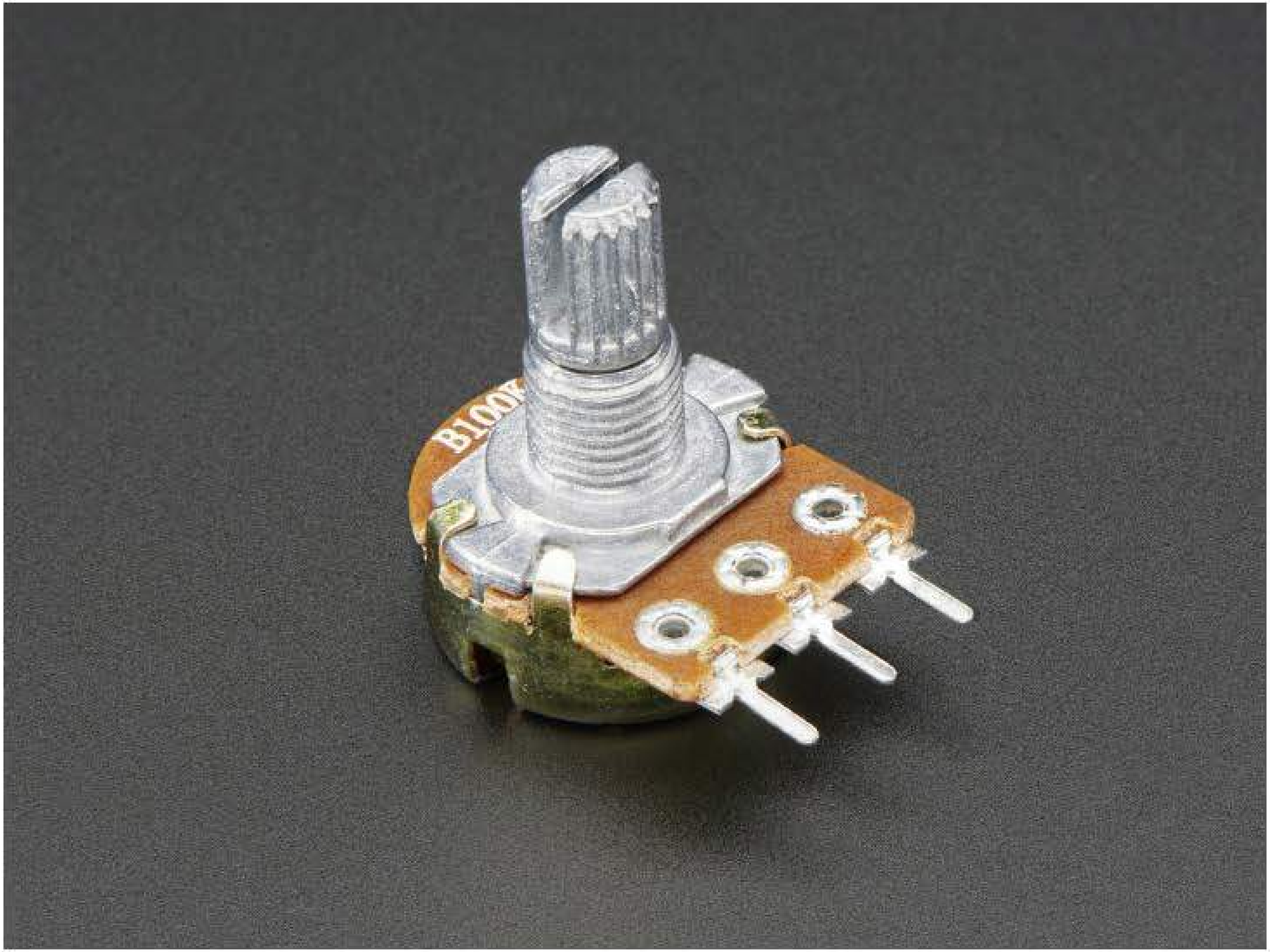
SIZE	DWG. NO.	REV
A	260	1

SCALE: 1:2
SHEET 1 OF 1

TECHNICAL DETAILS

- 12mm / .5" height when pressed
- 15.2mm / .6" height when not pressed
- 52.5mm / 2.1" long stem with switch installed





Panel Mount 100K potentiometer (Breadboard Friendly) - 100KB

PRODUCT ID: 1831

$0.95

IN STOCK

1 ADD TO CART

☐ Also include 1 x Potentiometer Knob - Soft Touch T18 - Blue ($0.50)

☐ Also include 1 x Potentiometer Knob - Soft Touch T18 - Red ($0.50)

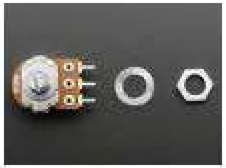
☐ Also include 1 x Potentiometer Knob - Soft Touch T18 - White ($0.50)

QTY	DISCOUNT
1-9	$0.95
10-99	$0.86
100+	$0.76

ADD TO WISHLIST

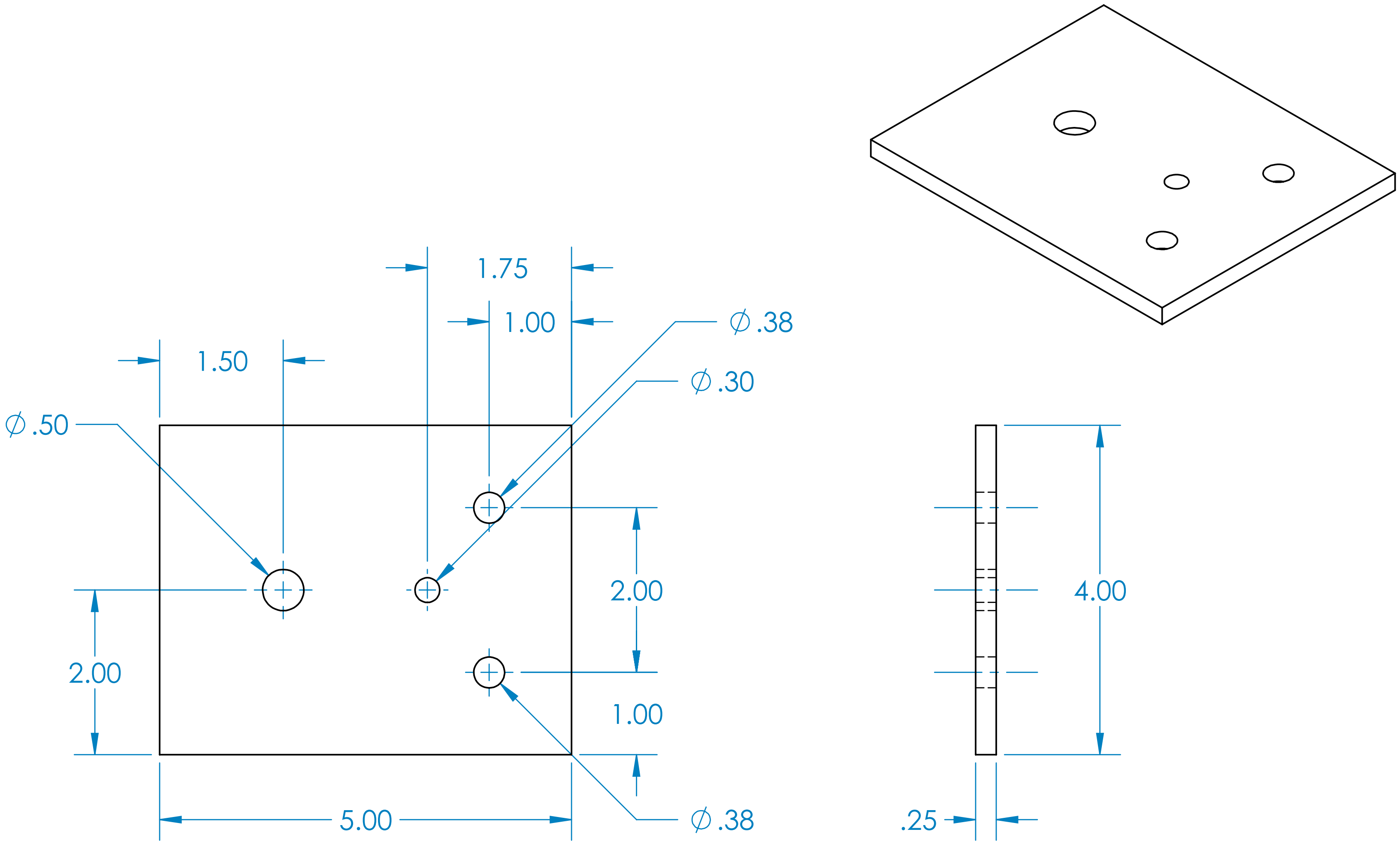
DESCRIPTION

TECHNICAL DETAILS



DESCRIPTION

This potentiometer is a two-in-one, good in a breadboard or with a panel. It's a fairly standard linear taper 100K ohm potentiometer, with a grippy shaft. It's smooth and easy to turn, but not so loose that it will shift on its own. We like this one because the legs are 0.2" apart with pin-points, so you can plug it into a breadboard or perfboard. Once you're done prototyping, you can drill a hole into your project box and mount the potentiometer that way.



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
Carbon Steel

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

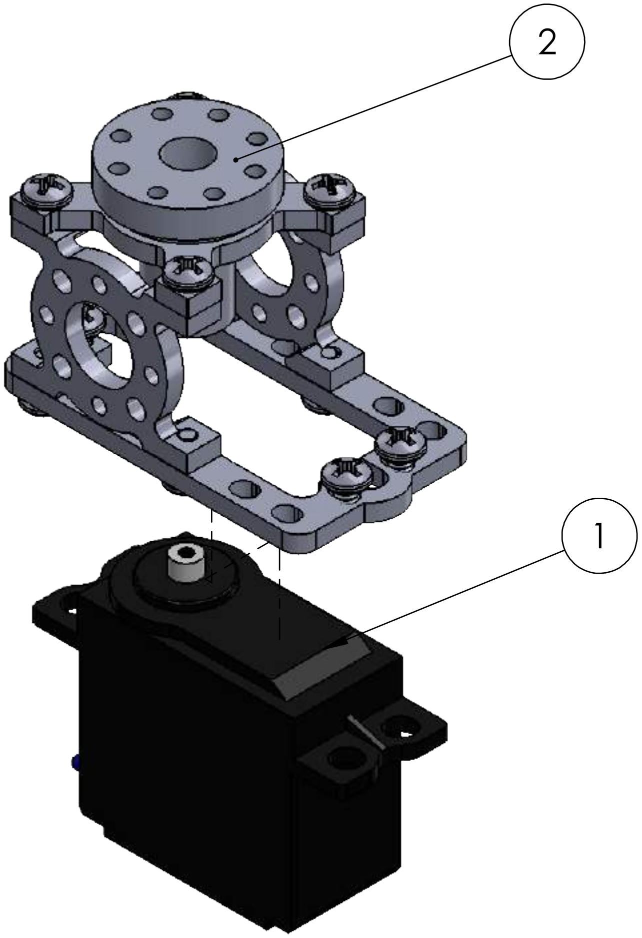
COMMENTS:

TITLE:
Control Panel Plate

SIZE	DWG. NO.	REV
A	264	1

SCALE: 1:2
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	271	Servo	Plastic	1
2	272	Bearing Block	Steel	1



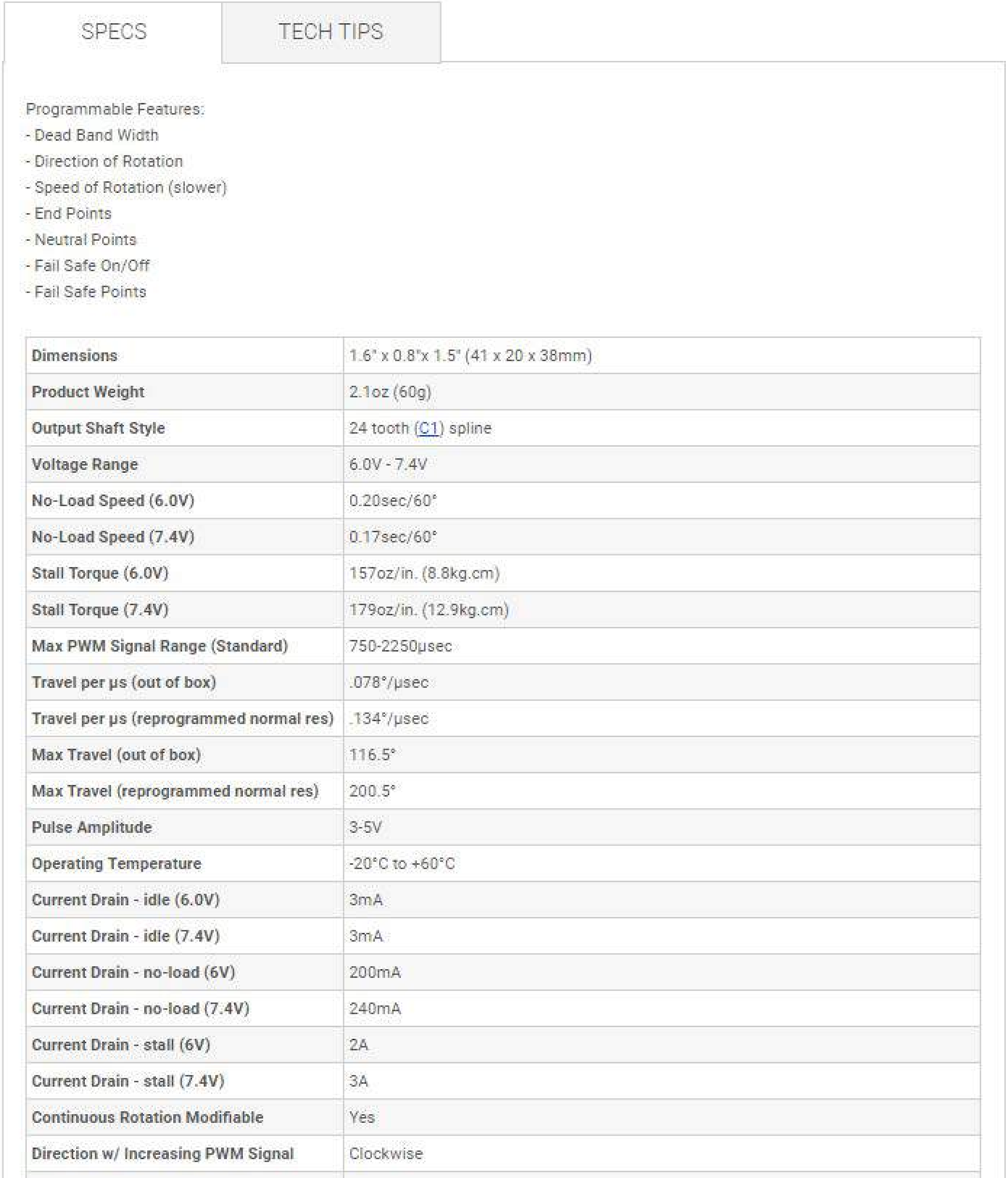
TITLE:

Servo Subassembly

SIZE	DWG. NO.	REV
A	270	1

SCALE: 1:1

SHEET 1 OF 1



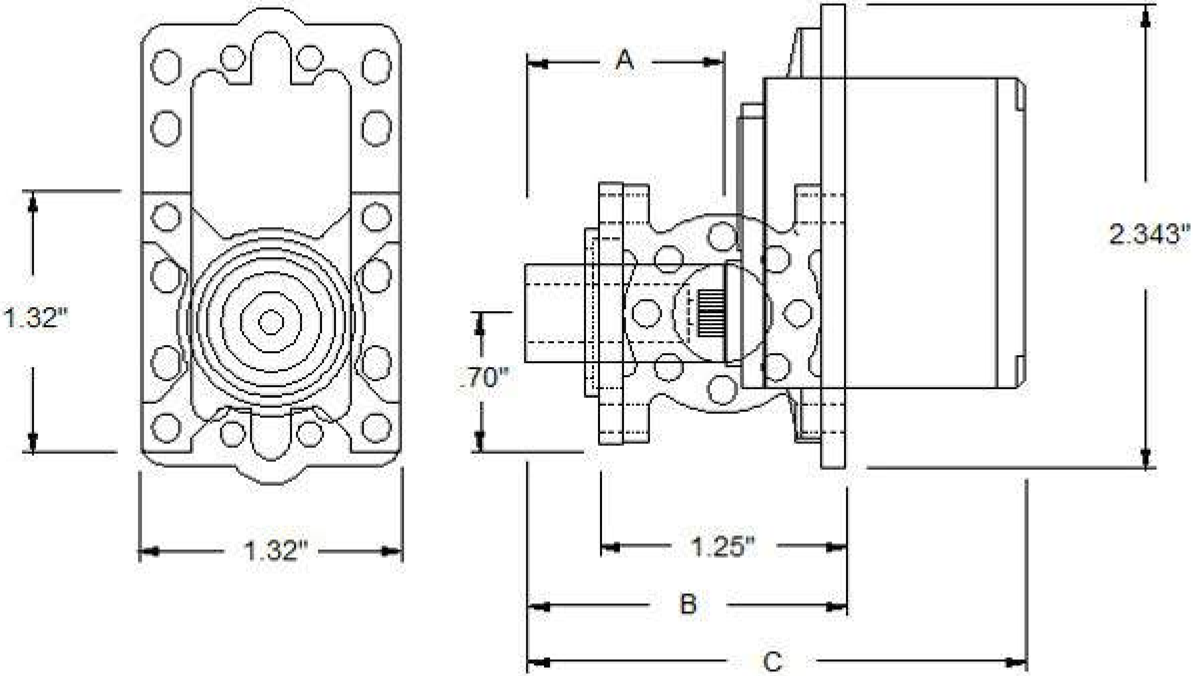
Programmable Features:
- Dead Band Width
- Direction of Rotation
- Speed of Rotation (slower)
- End Points
- Neutral Points
- Fail Safe On/Off
- Fail Safe Points

Dimensions	1.6" x 0.8"x 1.5" (41 x 20 x 38mm)
Product Weight	2.1oz (60g)
Output Shaft Style	24 tooth (C1) spline
Voltage Range	6.0V - 7.4V
No-Load Speed (6.0V)	0.20sec/60°
No-Load Speed (7.4V)	0.17sec/60°
Stall Torque (6.0V)	157oz/in. (8.8kg.cm)
Stall Torque (7.4V)	179oz/in. (12.9kg.cm)
Max PWM Signal Range (Standard)	750-2250µsec
Travel per µs (out of box)	.078°/µsec
Travel per µs (reprogrammed normal res)	.134°/µsec
Max Travel (out of box)	116.5°
Max Travel (reprogrammed normal res)	200.5°
Pulse Amplitude	3-5V
Operating Temperature	-20°C to +60°C
Current Drain - idle (6.0V)	3mA
Current Drain - idle (7.4V)	3mA
Current Drain - no-load (6V)	200mA
Current Drain - no-load (7.4V)	240mA
Current Drain - stall (6V)	2A
Current Drain - stall (7.4V)	3A
Continuous Rotation Modifiable	Yes
Direction w/ Increasing PWM Signal	Clockwise

SPECS

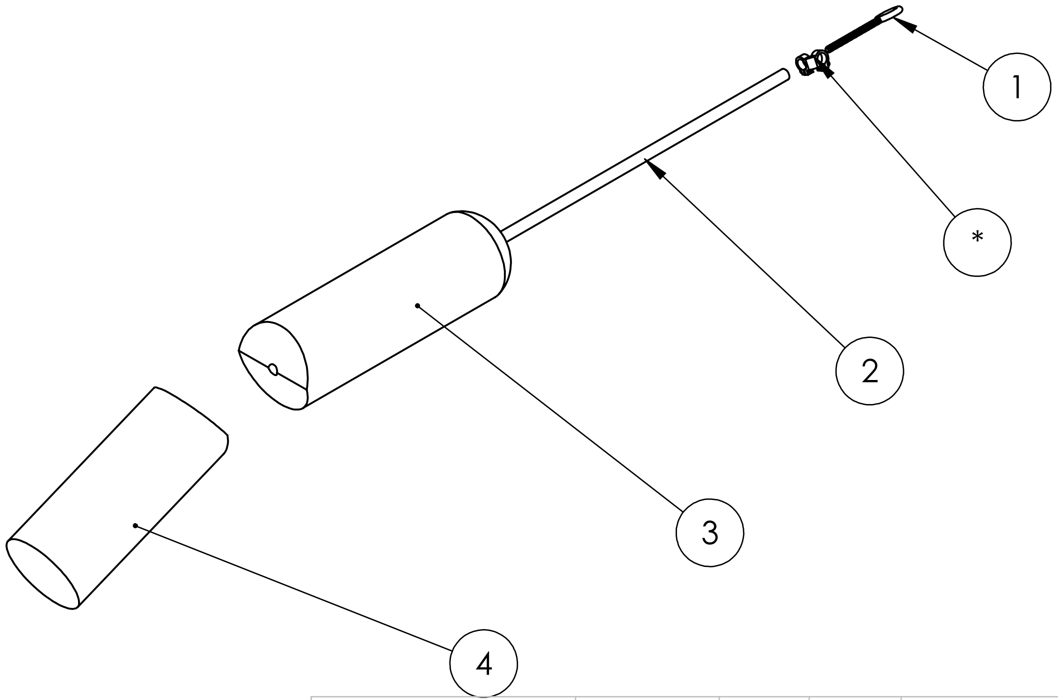
RESOURCES

TECH TIPS



Product Weight	1.3 oz (no servo)
Servo Spline Compatibility	24T spline
Servo Size Compatibility	Standard Size Servo

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	EXPLODED/QTY.
1	310	EYE BOLT	STEEL	1
2	312	HUMERUS CORE	POLYETHYLENE	1
3	313	UPPER ARM PADDING	BATTING	1
4	314	FOREARM	BATTING	1



		NAME	DATE
UNLESS OTHERWISE SPECIFIED:	DRAWN		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL	COMMENTS:		
DO NOT SCALE DRAWING	Fishing wire runs from shoulder to forearm		

TITLE:

ARM

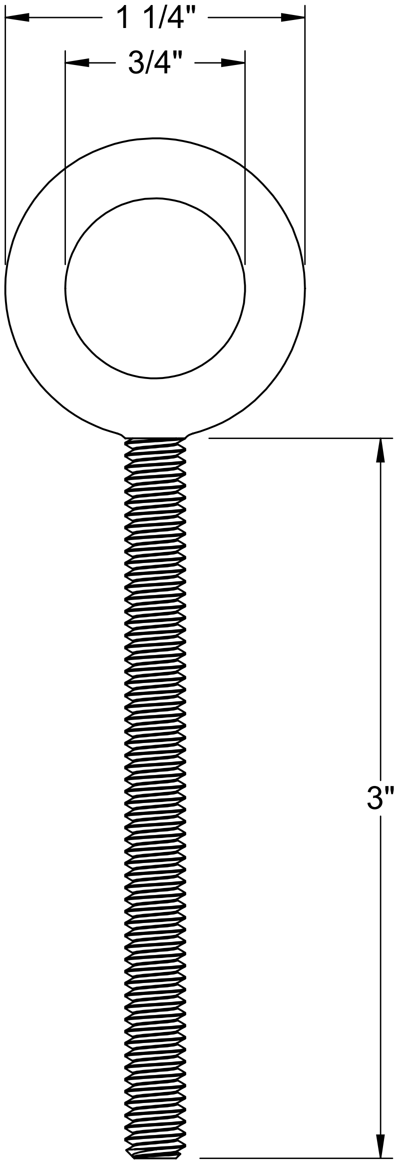
SIZE **A**

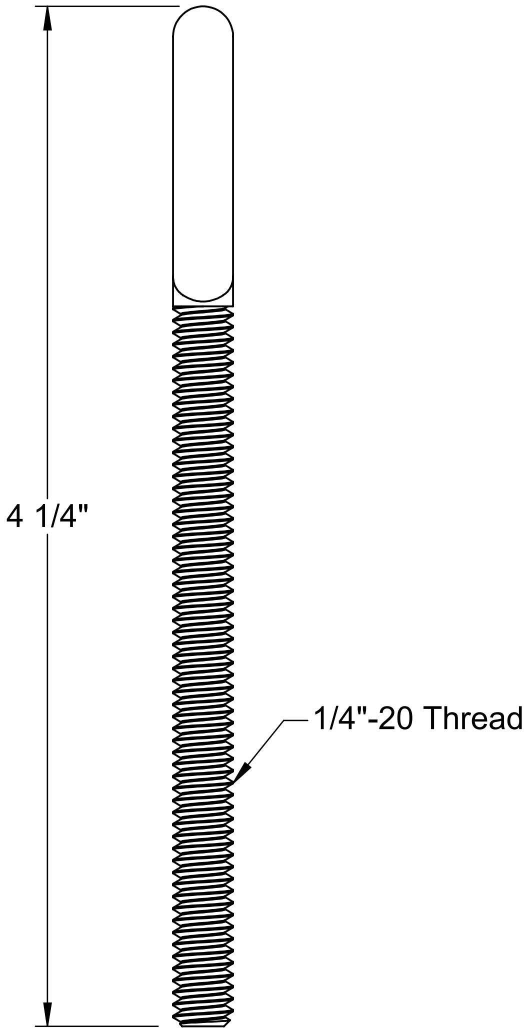
DWG. NO. 301

REV 1

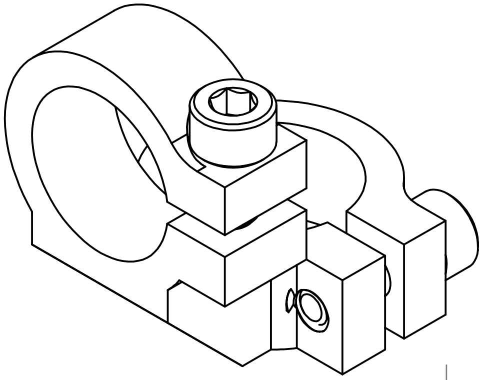
SCALE: 1:8

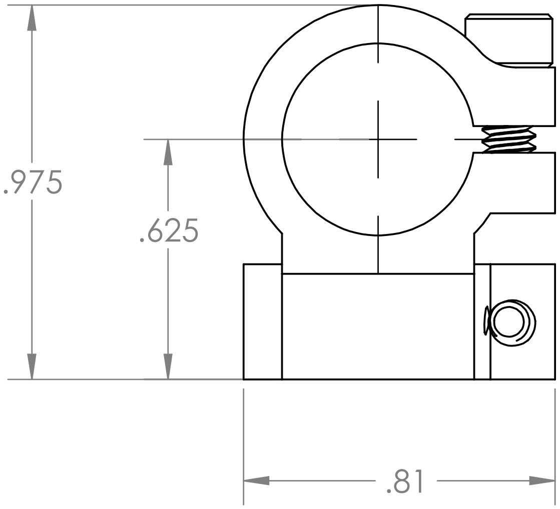
SHEET 1 OF 1

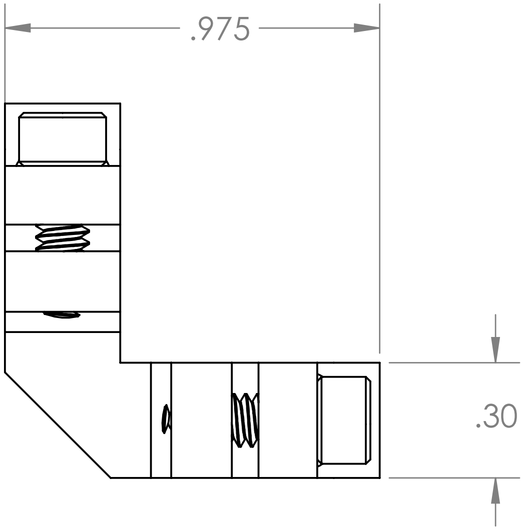




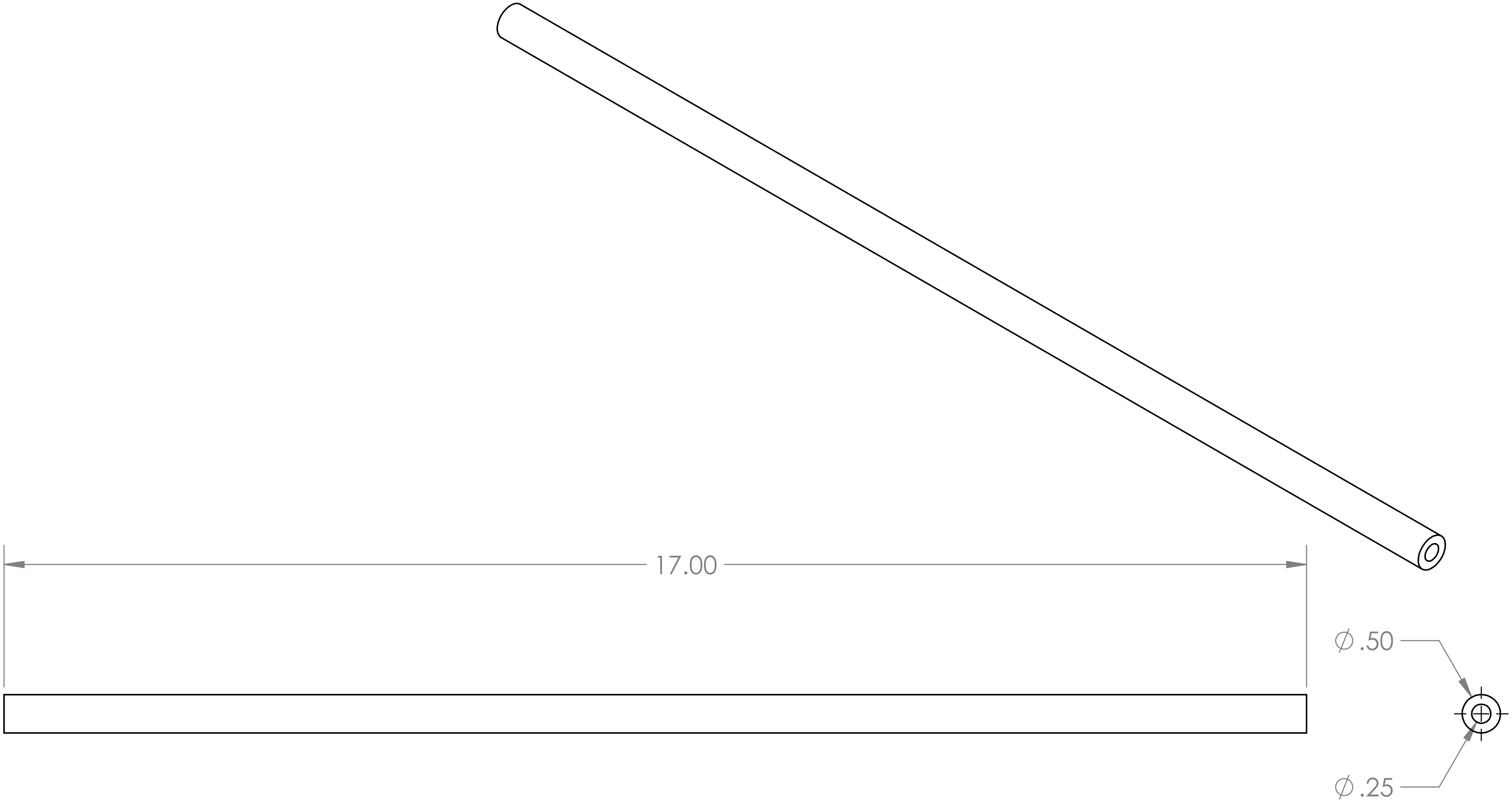
McMASTER-CARR® CAD	PART NUMBER 310
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Eyebolt - For Lifting







UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE: Clamping Mount
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL ALUMINUM	COMMENTS:			SIZE A
				DWG. NO. 311
				REV 1
DO NOT SCALE DRAWING				SCALE: 2:1
				SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL POLYETHYLENE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
HUMERUS CORE

SIZE	DWG. NO.	REV
A	312	1

SCALE: 1:2
SHEET 1 OF 1

2 1

B B

A A

2 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL BATTING

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

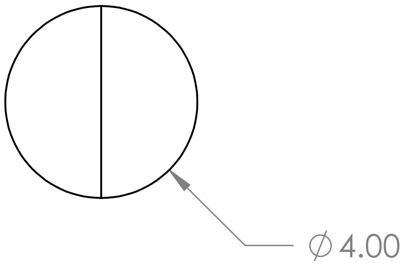
TITLE:

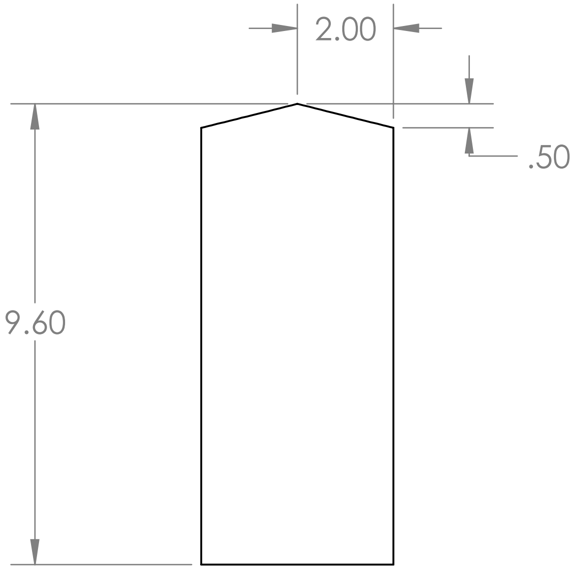
HUMERUS PADDING

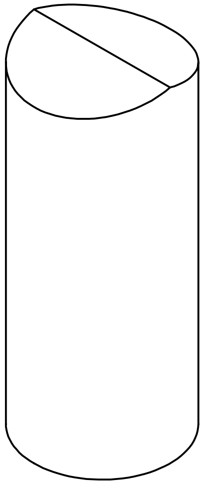
SIZE	DWG. NO.	REV
A	313	1

SCALE: 1:4

SHEET 1 OF 1

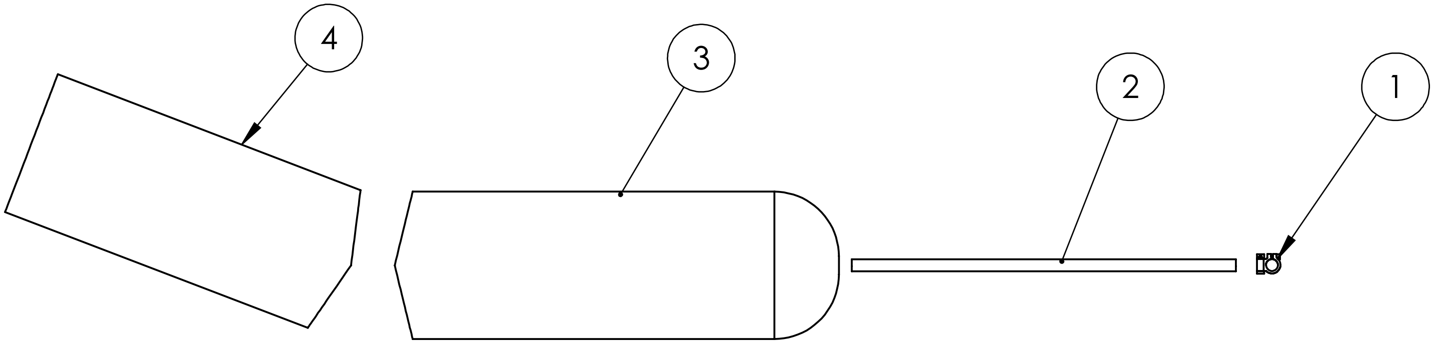






UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE:
	CHECKED			FOREARM
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL BATTING	COMMENTS:			SIZE A DWG. NO. 314 REV 1
DO NOT SCALE DRAWING				SCALE: 1:4 SHEET 1 OF 1

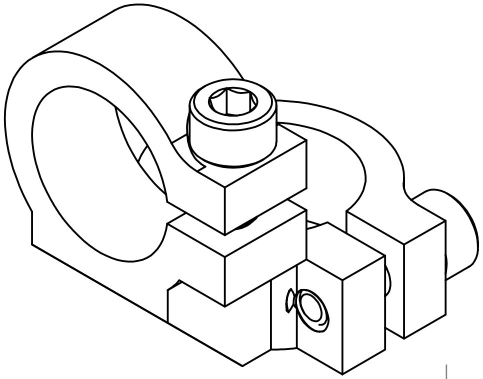
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	Exploded/QTY.
1	410	CLAMPING MOUNT	ALUMINUM	1
2	411	FEMUR CORE	ALUMINUM	1
3	412	THIGH PADDING	BATTING	1
4	413	CALF	BATTING	1

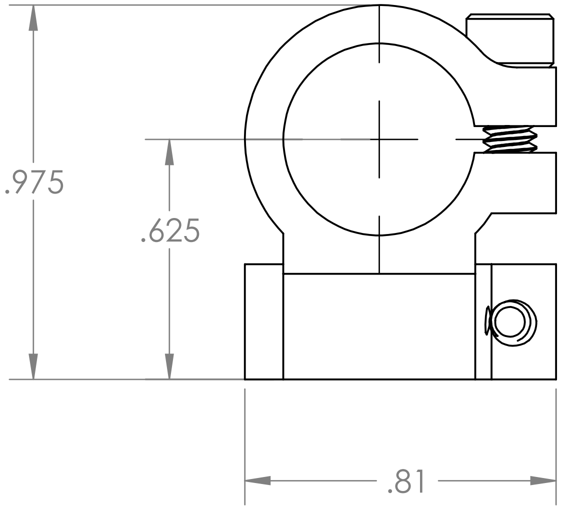


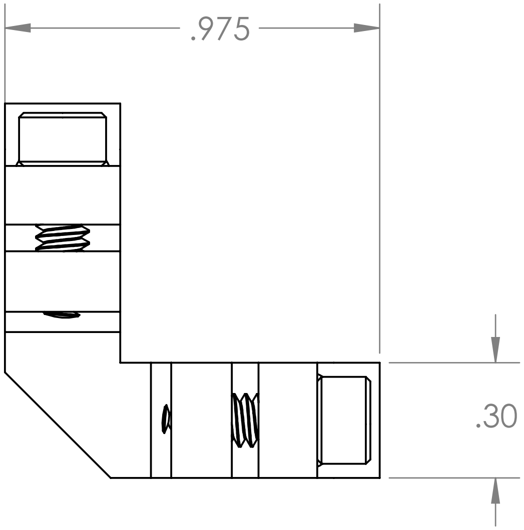
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE: LEG
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL	COMMENTS:			
DO NOT SCALE DRAWING				

SIZE	DWG. NO.	REV
A	401	1

SCALE: 1:8 SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
ALUMINUM

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

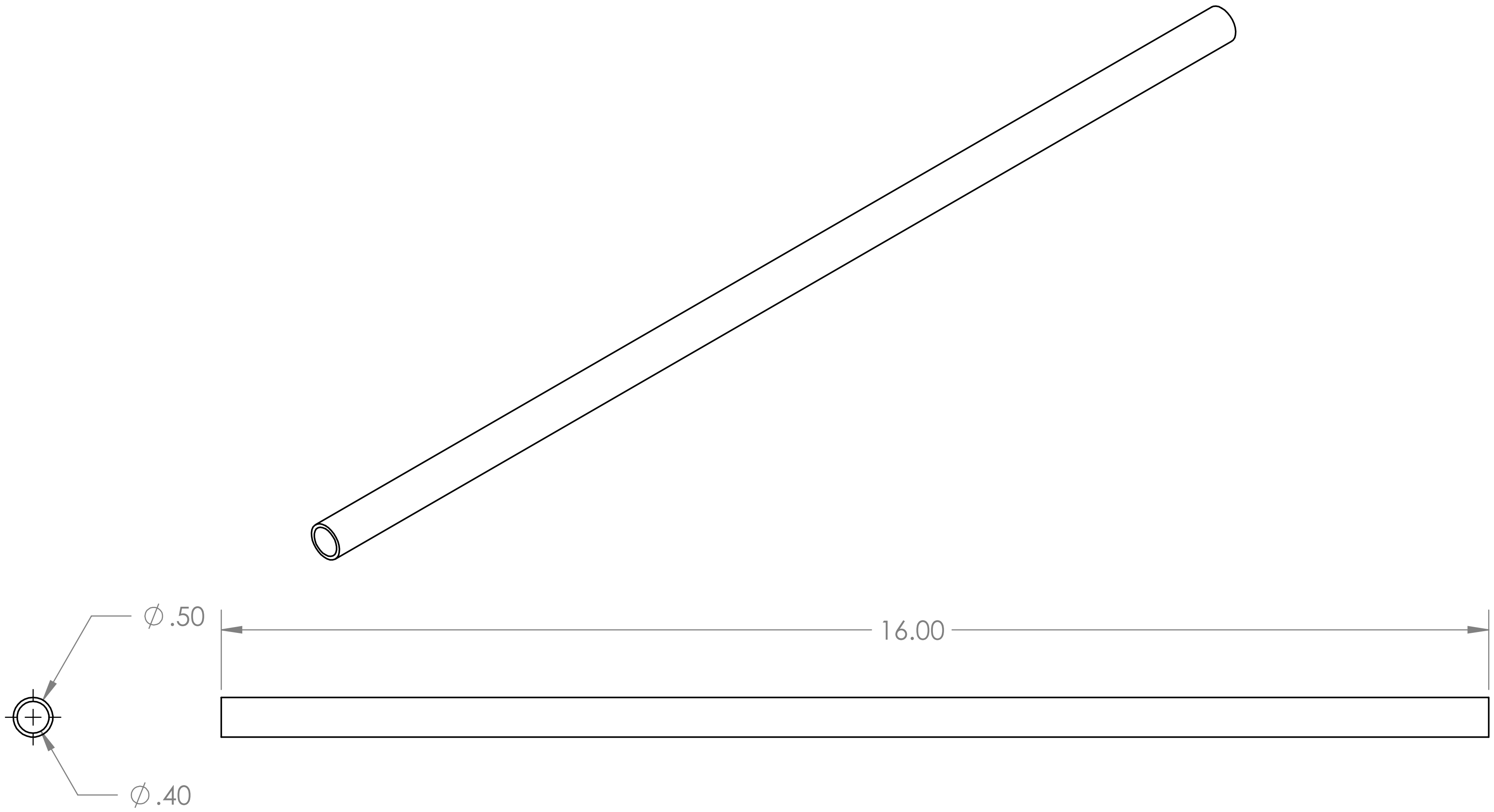
COMMENTS:

TITLE:
Clamping Mount

SIZE	DWG. NO.	REV
A	410	1

SCALE: 2:1
SHEET 1 OF 1

B B



A A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
ALUMINUM

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

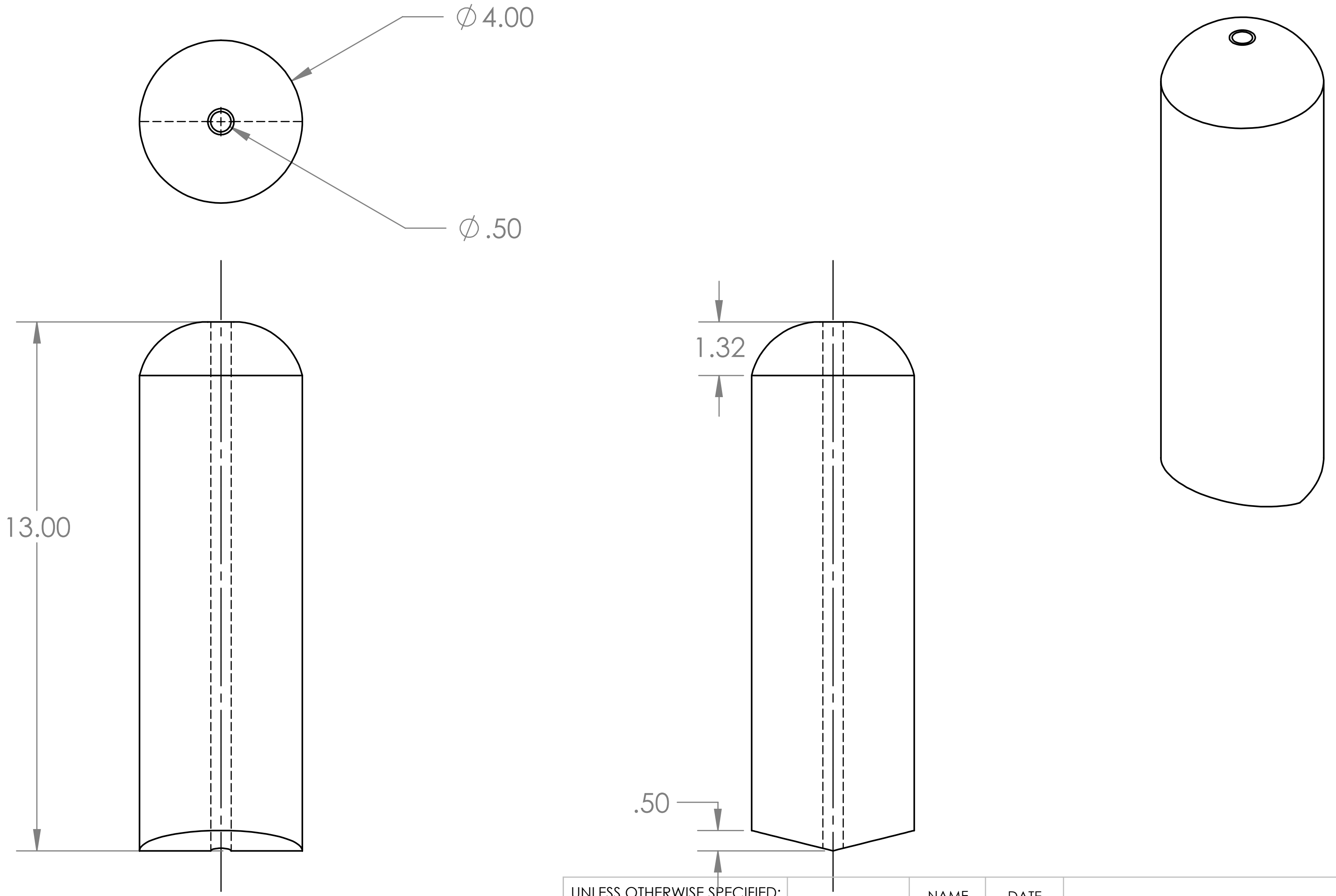
COMMENTS:

TITLE:

FEMUR CORE

SIZE	DWG. NO.	REV
A	411	1

SCALE: 1:2 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
BATTING

DO NOT SCALE DRAWING

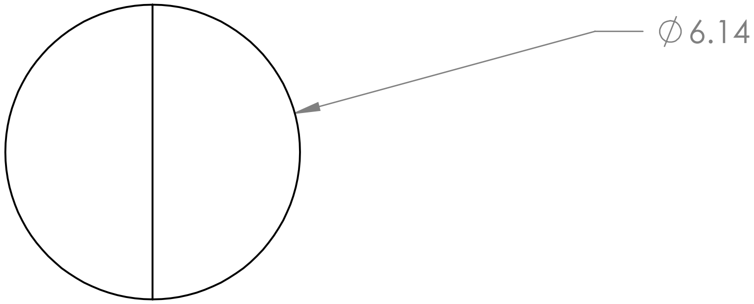
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

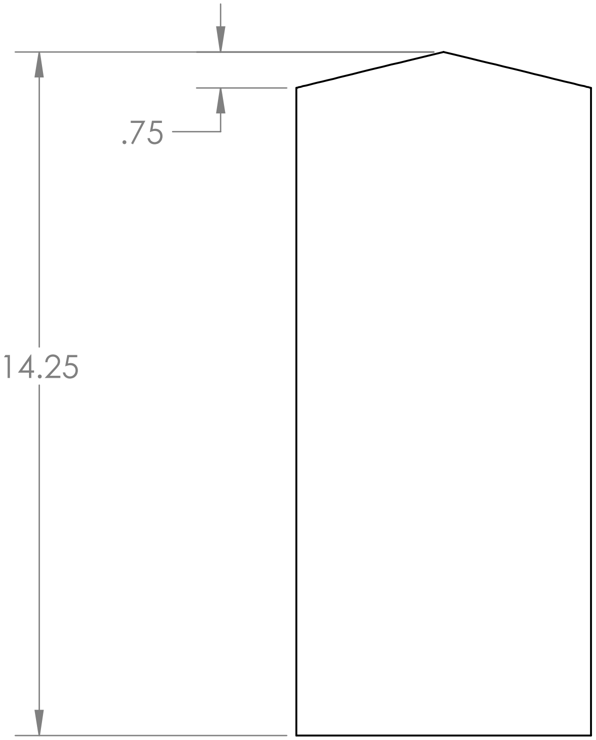
COMMENTS:

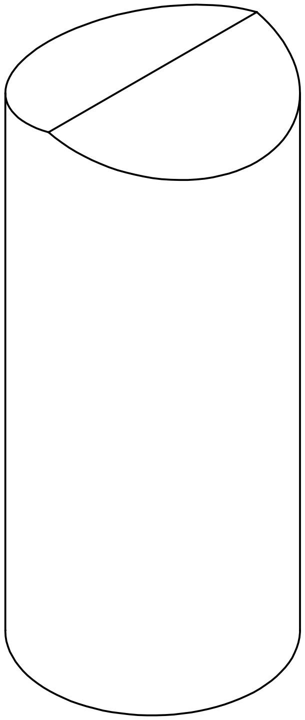
TITLE:
THIGH PADDING

SIZE A
DWG. NO. 412
REV 1
SCALE: 1:4
SHEET 1 OF 1

B B







A A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
BATTING

DO NOT SCALE DRAWING

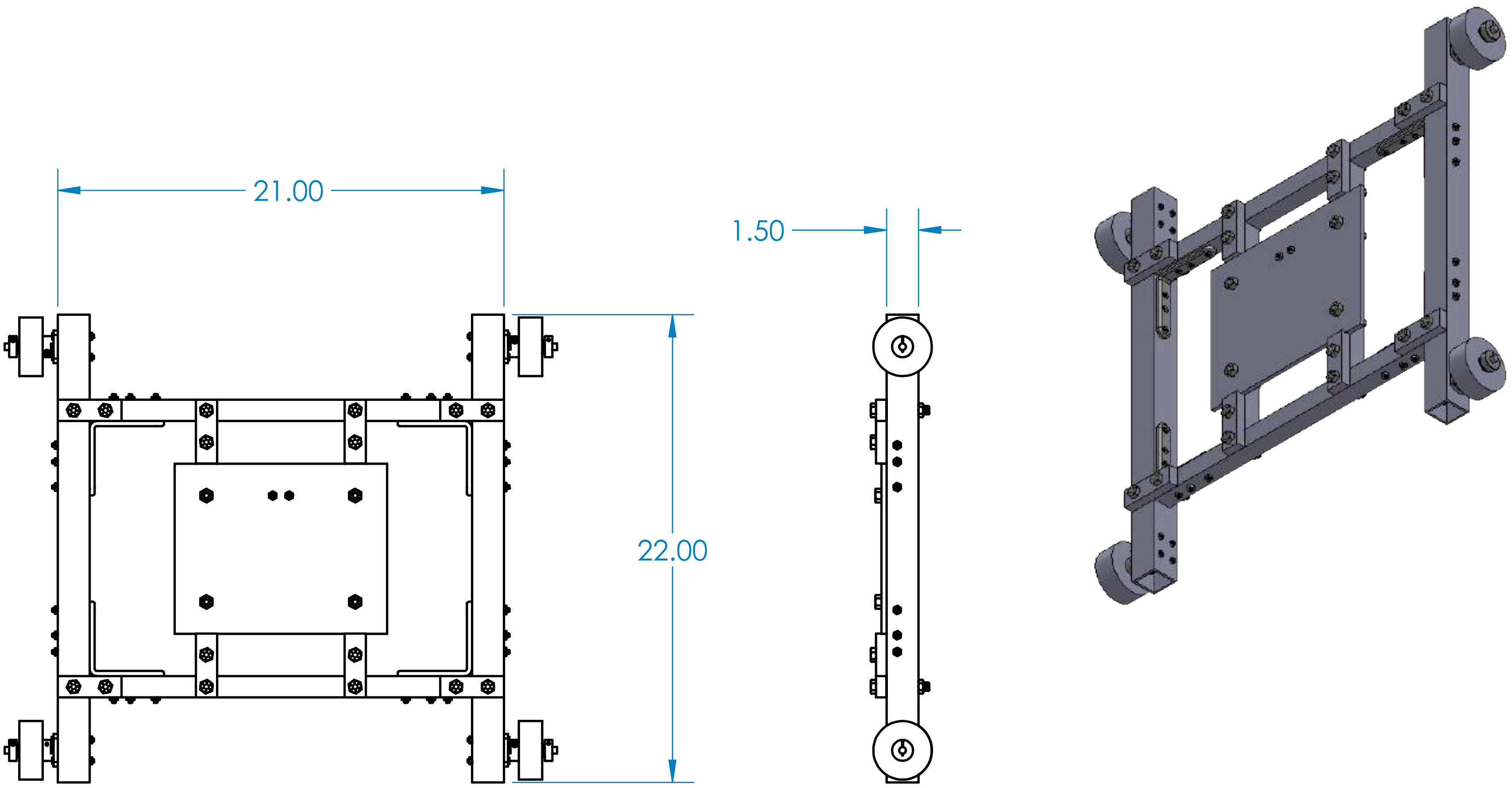
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

CALF

SIZE **A**
DWG. NO. 413
REV 1
SCALE: 1:4
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: X.XX=±.01 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL VARIOUS	COMMENTS:		
DO NOT SCALE DRAWING			

TITLE:

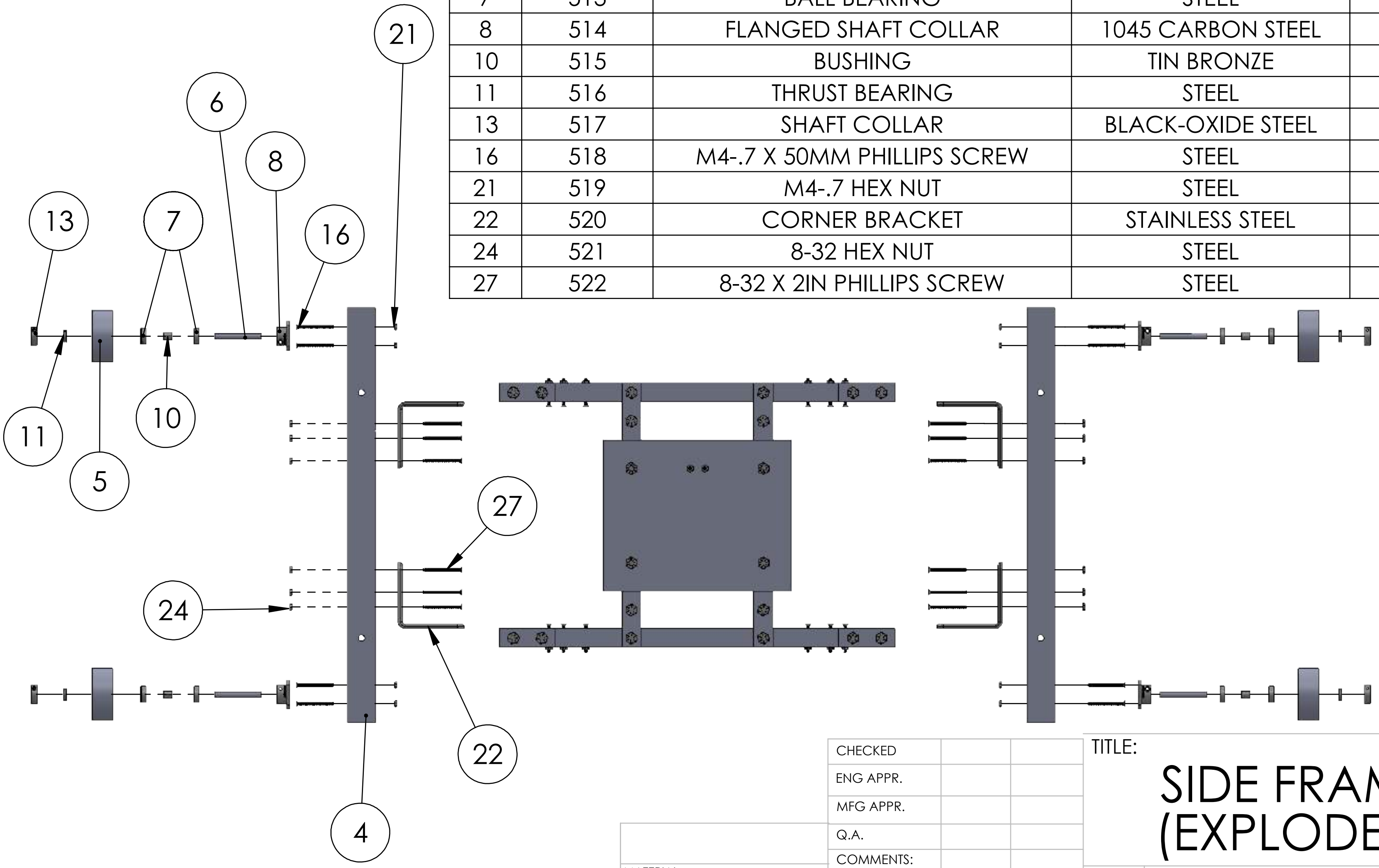
PLATFORM ASSEMBLY

SIZE	DWG. NO.	REV
A	500	1

SCALE: 1:8

SHEET 1 OF 1

ITEM	PART NUMBER	DESCRIPTION	MATERIAL	QUANTITY
4	510	TUBE 1	A513 STEEL	2
5	511	WHEEL	RUBBER	4
6	512	SHAFT	12L14 STEEL	4
7	513	BALL BEARING	STEEL	8
8	514	FLANGED SHAFT COLLAR	1045 CARBON STEEL	4
10	515	BUSHING	TIN BRONZE	4
11	516	THRUST BEARING	STEEL	4
13	517	SHAFT COLLAR	BLACK-OXIDE STEEL	4
16	518	M4-.7 X 50MM PHILLIPS SCREW	STEEL	16
21	519	M4-.7 HEX NUT	STEEL	16
22	520	CORNER BRACKET	STAINLESS STEEL	4
24	521	8-32 HEX NUT	STEEL	26
27	522	8-32 X 2IN PHILLIPS SCREW	STEEL	12



CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

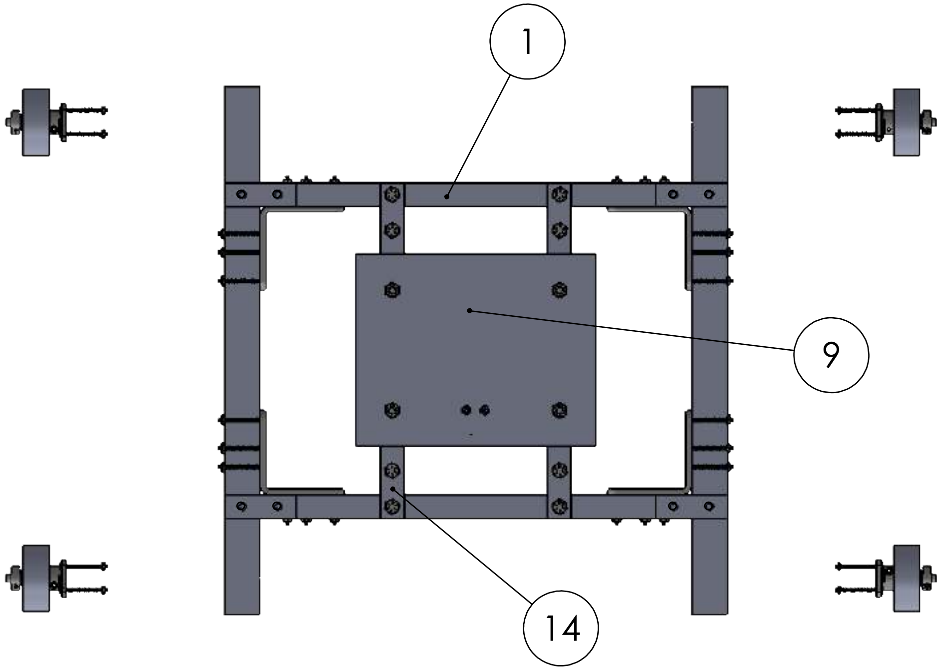
MATERIAL
VARIOUS

DO NOT SCALE DRAWING

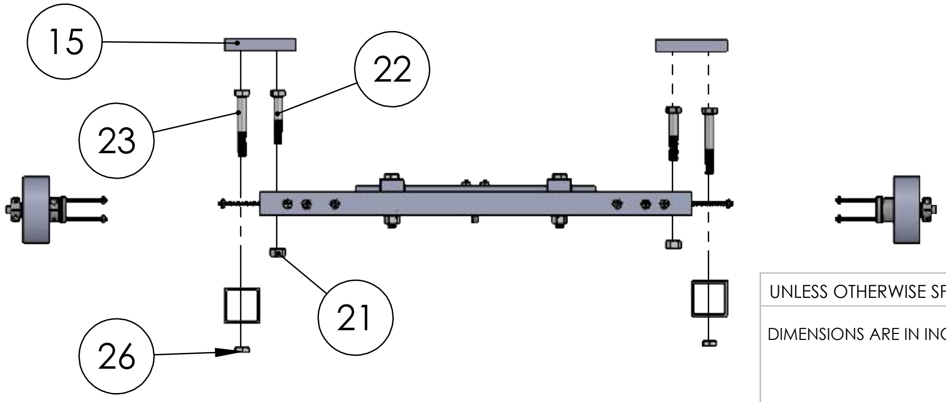
TITLE:

SIDE FRAME (EXPLODED)

SIZE **A**
DWG. NO. 501
REV 1
SCALE: 1:8
SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY,
1	523	TUBE 2	A513 STEEL	2
9	524	TOP PLATE	ASTM 108 STEEL	1
14	525	CONNECTOR 1	ASTM A681	1
15	526	CONNECTOR 2	ASTM A681	4
21	527	3/8 - 24 HEX NUT	STEEL	16
22	528	3/8 - 24 X 2IN HEX BOLT	STEEL	12
23	529	3/8 - 24 X 2.5 IN HEX BOLT	STEEL	4
26	530	3/8 - 24 THIN HEX NUTS	STAINLESS STEEL	4



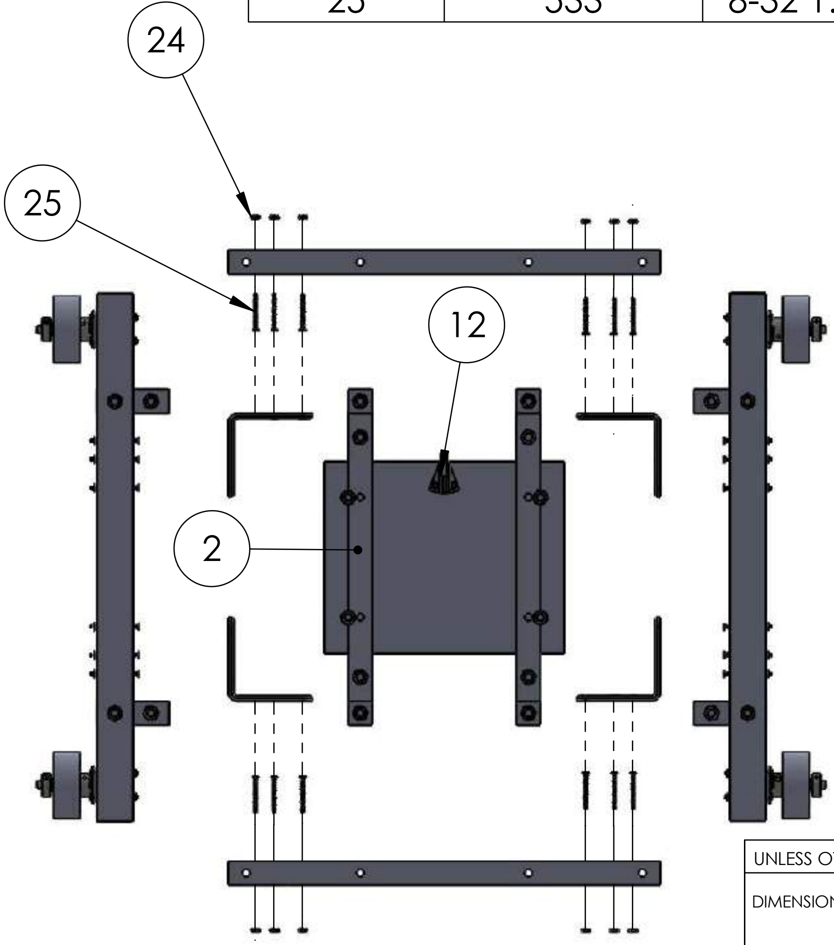
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL VARIOUS	COMMENTS:		
DO NOT SCALE DRAWING			

TITLE: **Side Frame Connection (Exploded View)**

SIZE A DWG. NO. 502 REV 1

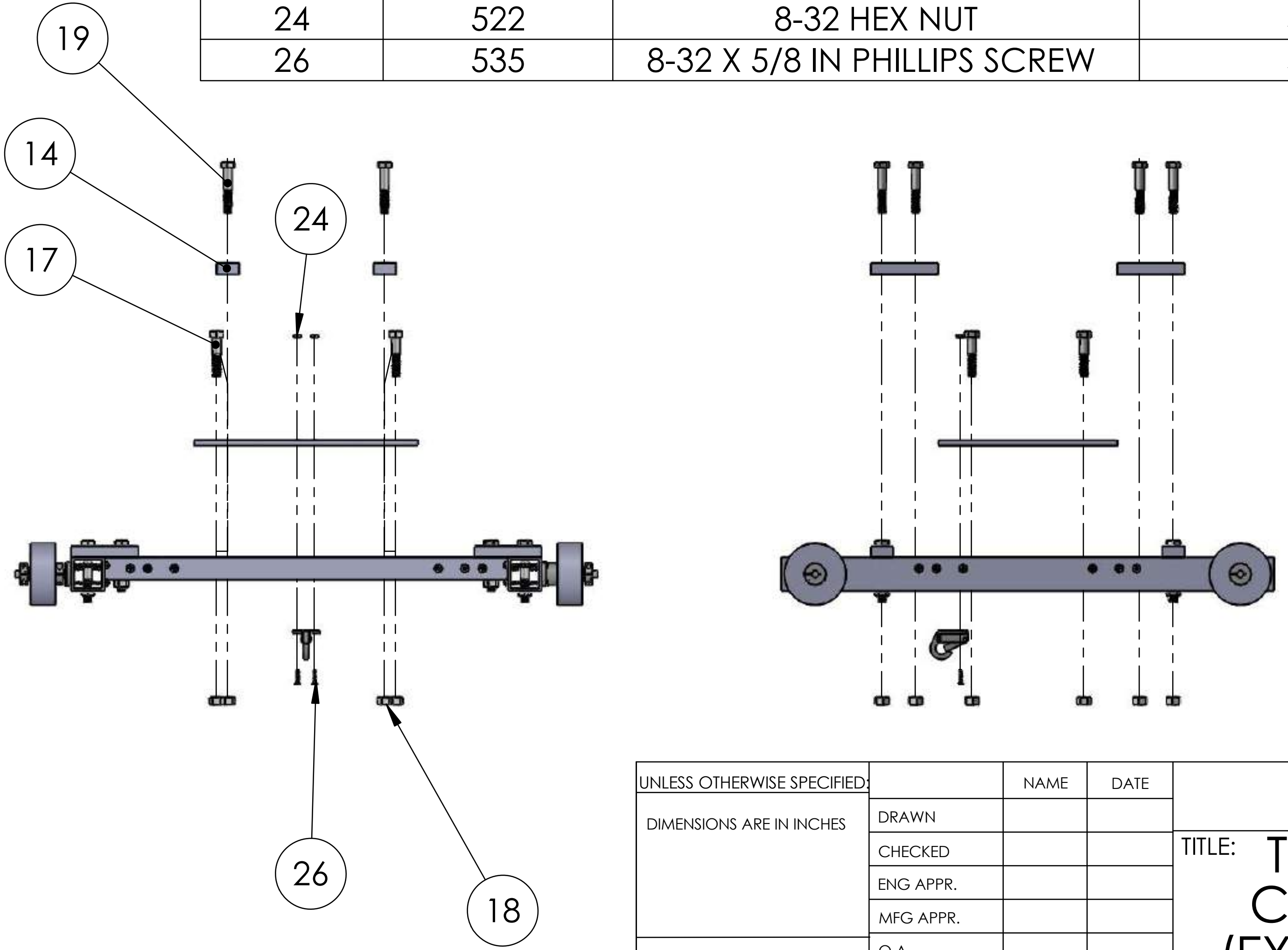
SCALE: 1:8 SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	Default/ QTY.
2	531	TUBE 3	A513 STEEL	2
12	532	HOOK	CHROME-PLATED BRASS	1
24	521	8-32 HEX NUT	STEEL	26
25	533	8-32 1.5 IN PHILLIPS SCREW	STEEL	12



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES	DRAWN			
	CHECKED			TITLE: BRACKET TO CENTER FRAME (EXPLODED VIEW)
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL VARIOUS	COMMENTS:			SIZE A — DWG. NO. 503 — REV 1
DO NOT SCALE DRAWING				SCALE: 1:8 — SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	Default/ QTY.
14	525	CONNECTOR 1	ASTM A681 STEEL	4
17	534	3/8-24 X 1.75 IN HEX BOLT	STEEL	4
18	527	3/8-24 HEX NUT	STEEL	16
19	528	3/8-24 X 2 IN HEX BOLT	STEEL	12
24	522	8-32 HEX NUT	STEEL	26
26	535	8-32 X 5/8 IN PHILLIPS SCREW	STEEL	2



		NAME	DATE
UNLESS OTHERWISE SPECIFIED:			
DIMENSIONS ARE IN INCHES	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL VARIOUS	COMMENTS:		
DO NOT SCALE DRAWING			

TITLE: TOP PLATE TO CENTER FRAME (EXPLODED VIEW)

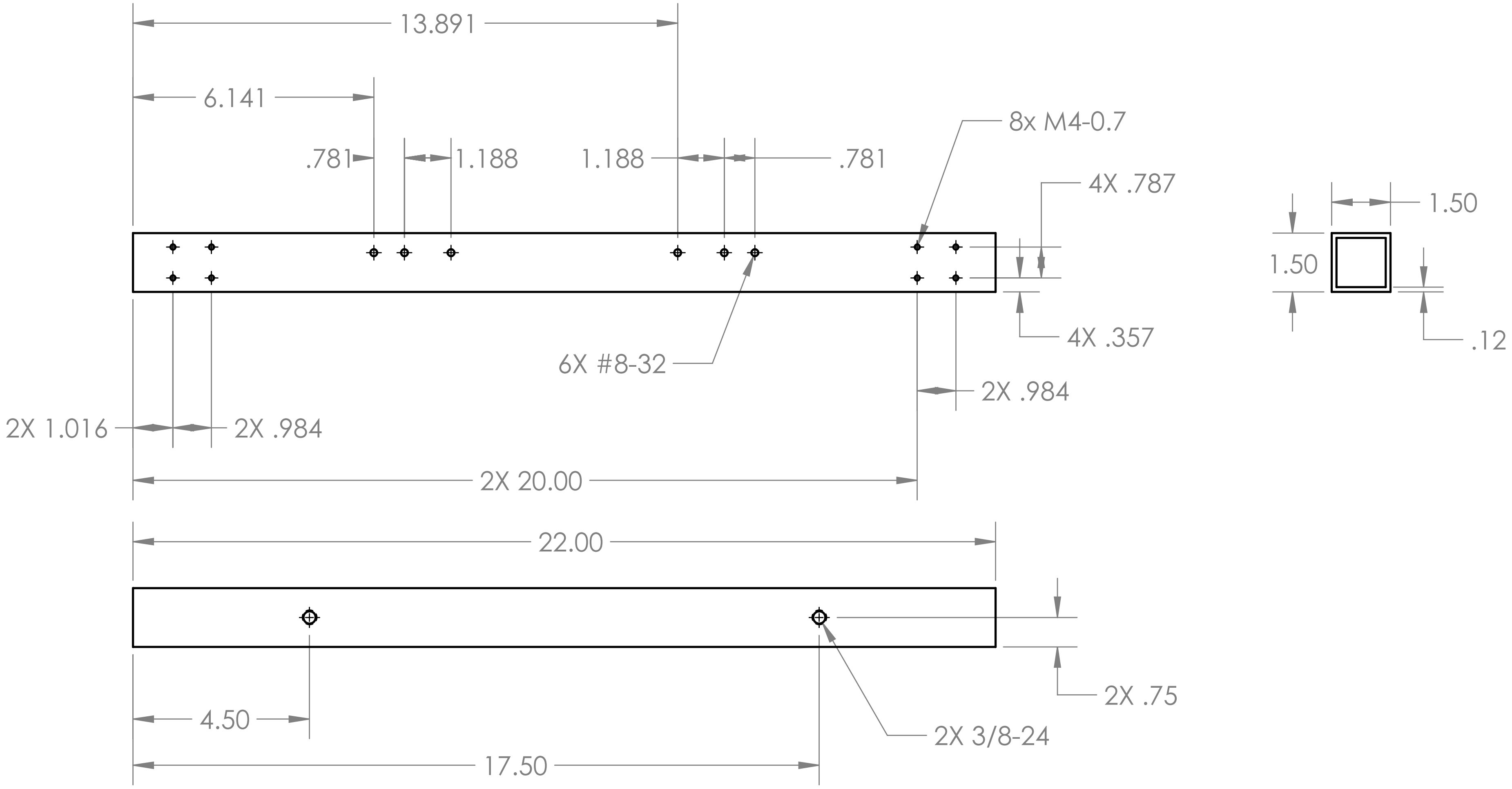
SIZE A

DWG. NO. 504

REV 1

SCALE: 1:4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES: X.XX=±.01
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
A513 STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

TUBE 1

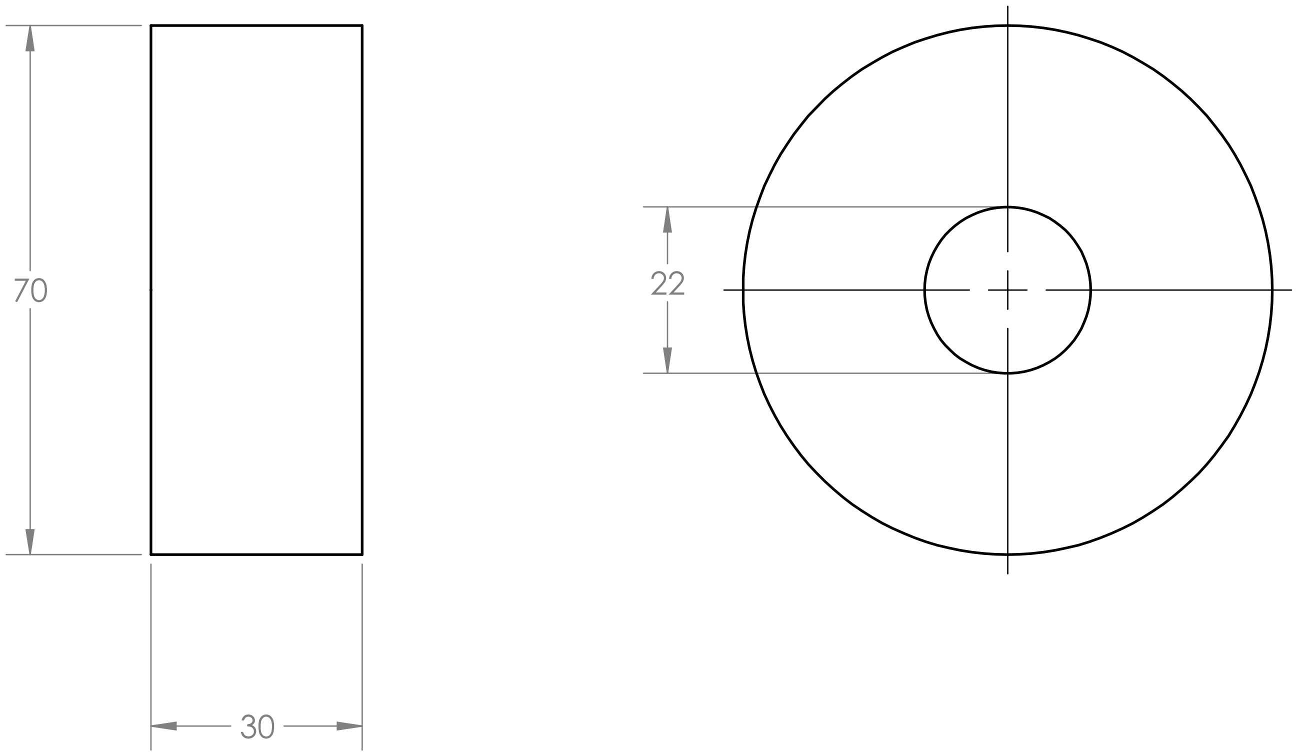
SIZE
A

DWG. NO.
510

REV
1

SCALE: 1:4

SHEET 1 OF 1



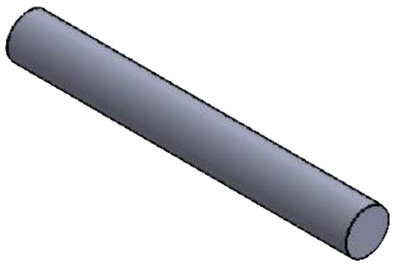
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MILLIMETERS TOLERANCES: X.XX=±.01 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL RUBBER	COMMENTS:		
DO NOT SCALE DRAWING			

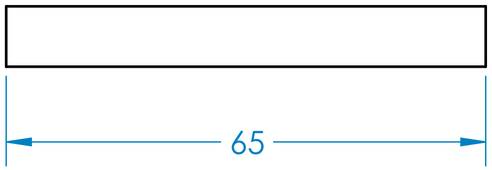
TITLE:

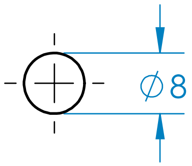
WHEEL

SIZE	DWG. NO.	REV
A	511	1
SCALE: 1:1		SHEET 1 OF 1

B







A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS
TOLERANCES: X.XX ±.01
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
12L14 STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

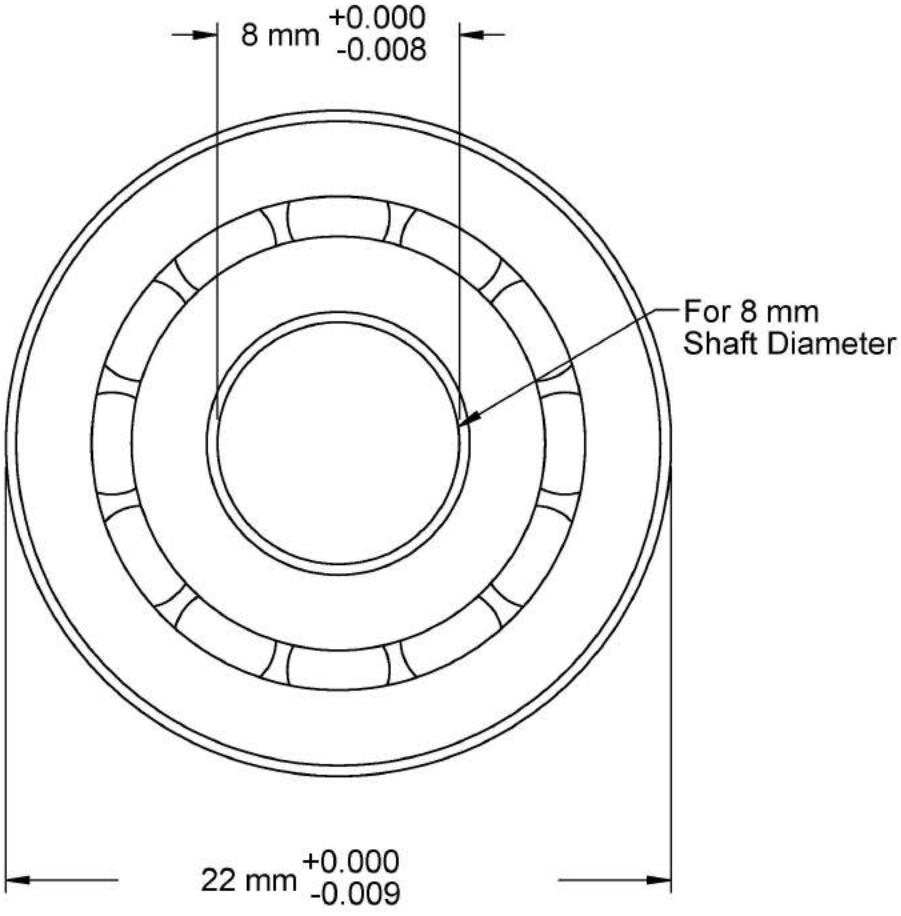
SHAFT

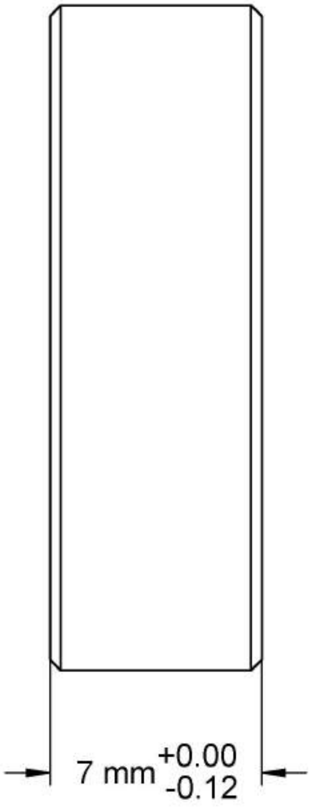
SIZE	DWG. NO.	REV
A	512	1

SCALE: 1:1

SHEET 1 OF 1

Trade Number: 608

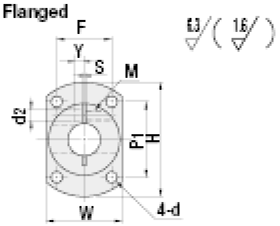




McMASTER-CARR® CAD	PART NUMBER 513
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company	Ball Bearing
Information in this drawing is provided for reference only.	

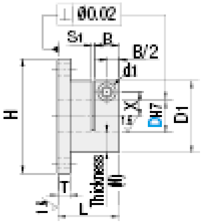
PART 514

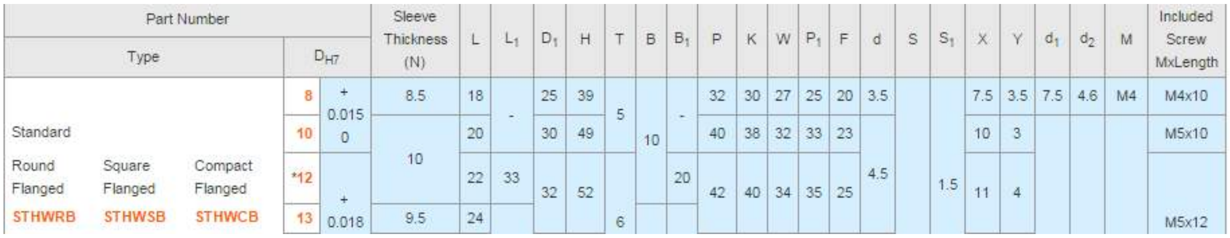
■Compact Flanged



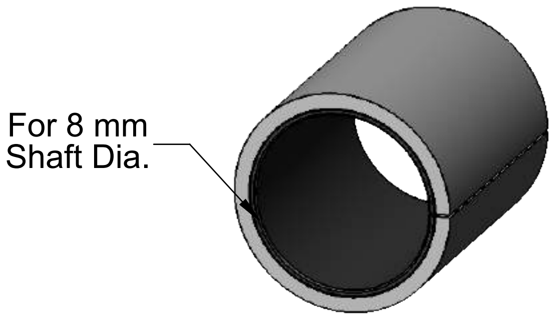
■Standard
with Through Mounting Holes

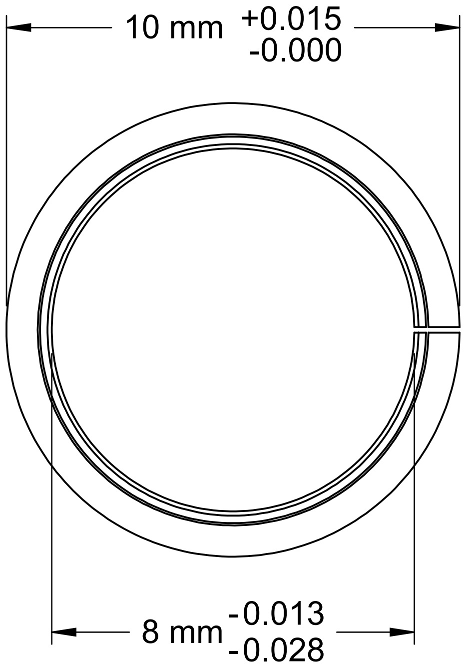
■Rou

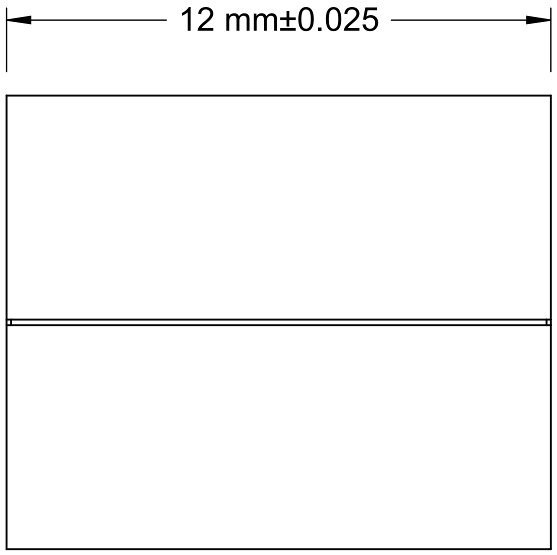




Part Number			Sleeve Thickness (N)	L	L_1	D_1	H	T	B	B_1	P	K	W	P_1	F	d	S	S_1	X	Y	d_1	d_2	M	Included Screw MxLength
Type	D_{H7}																							
Standard Round Flanged STHWRB Square Flanged STHWSB Compact Flanged STHWCB	8	+ 0.015 0	8.5	18	-	25	39	5	10	-	32	30	27	25	20	3.5		1.5	7.5	3.5	7.5	4.6	M4	M4x10
	10		10	20		30	49				40	38	32	33	23	4.5			10	3				M5x10
	*12	+ 0.018		22	33	32	52	6		20	42	40	34	35	25				11	4				M5x12
	13		9.5	24																				





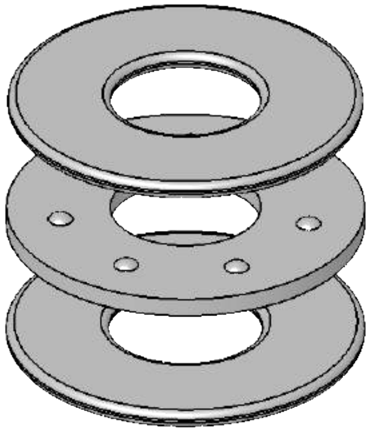


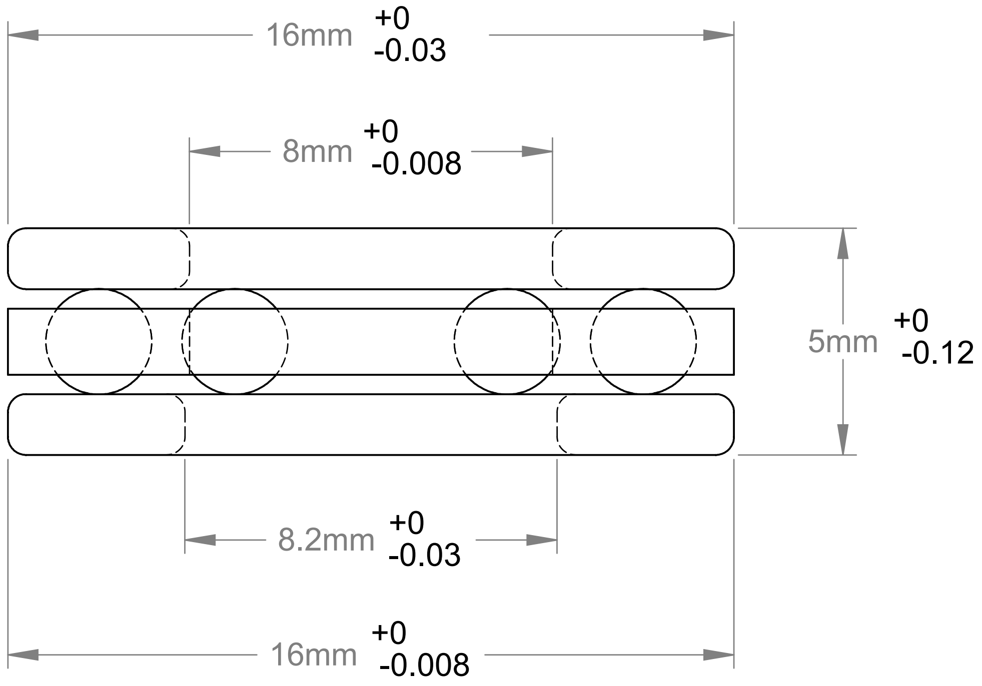
McMASTER-CARR®

PART NUMBER **515**

http://www.mcmaster.com

Dry-Running
Sleeve Bearing with Metal Shell



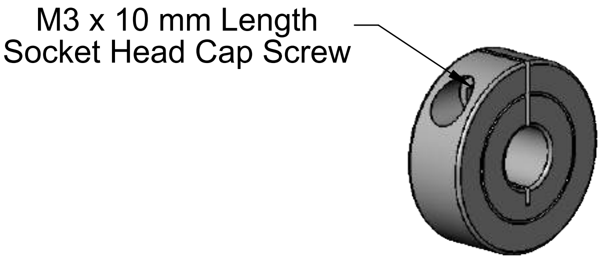


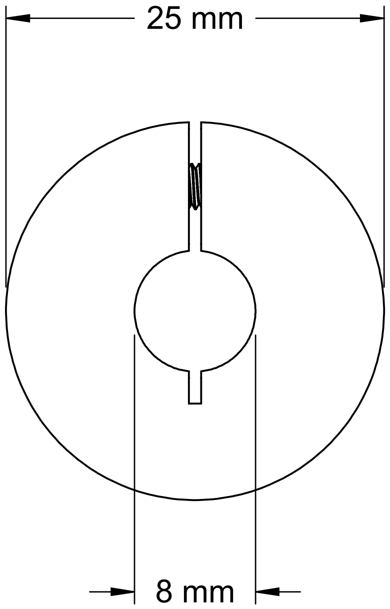
McMASTER-CARR® CAD

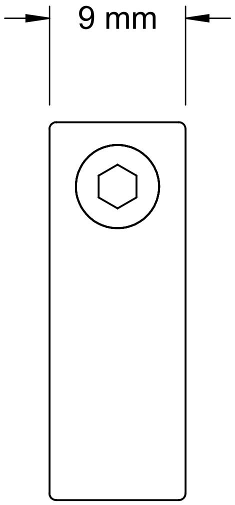
http://www.mcmaster.com

PART NUMBER **516**

Steel
Thrust Ball Bearing





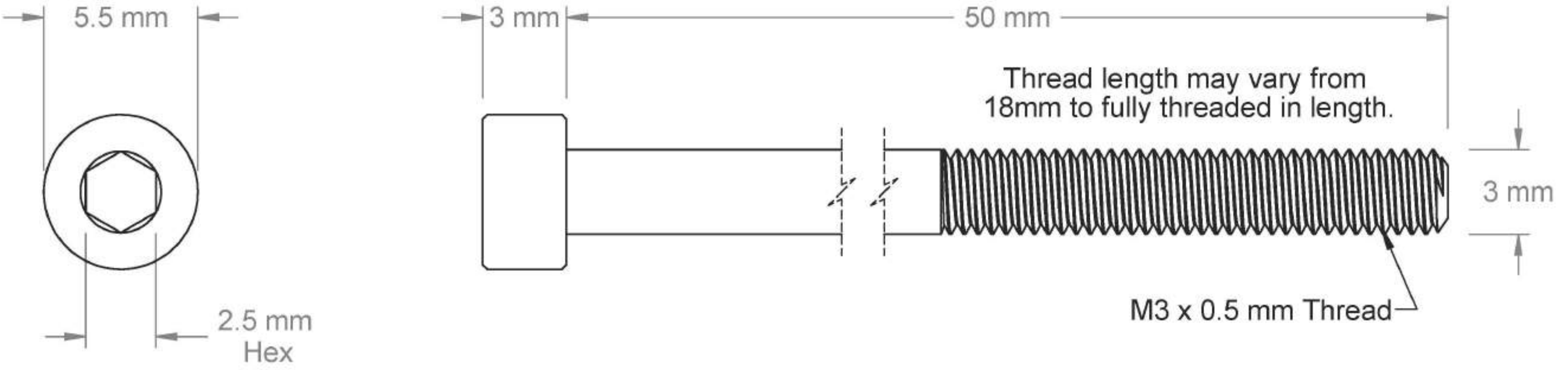


McMASTER-CARR® CAD

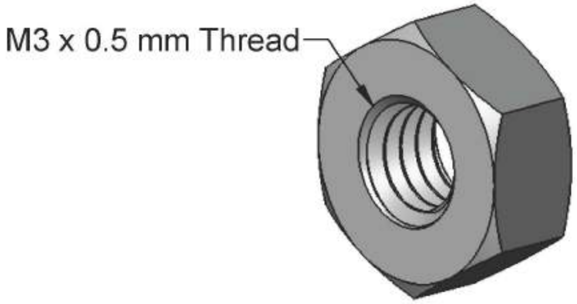
http://www.mcmaster.com

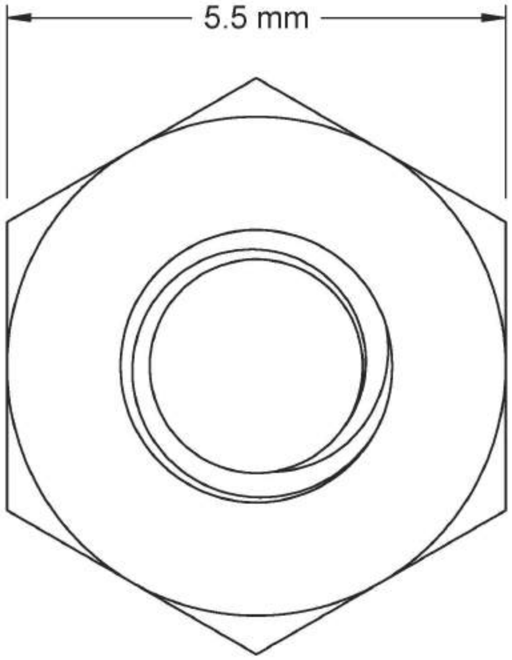
PART NUMBER **517**

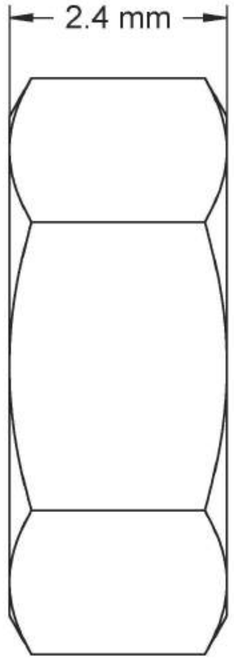
One-Piece Clamp-On
Shaft Collar



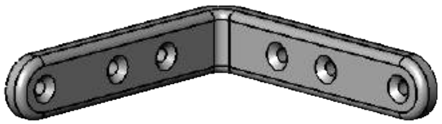
McMASTER-CARR® CAD	PART NUMBER	518
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric Alloy Steel Socket Head Cap Screw	

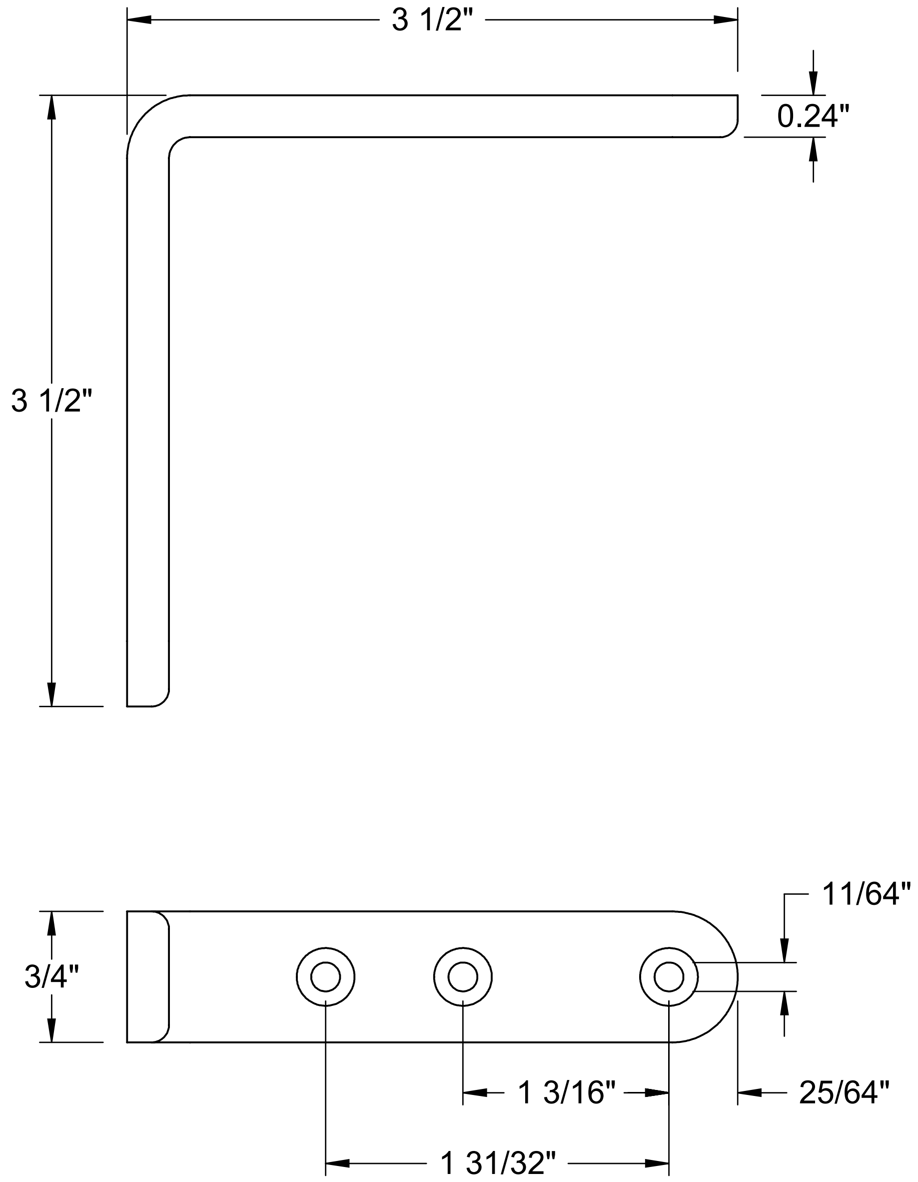






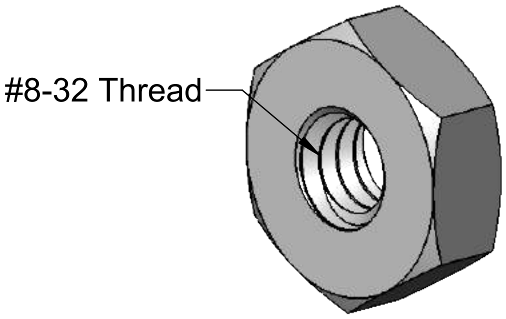
McMASTER-CARR® CAD	PART NUMBER 519
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric Hex Nut

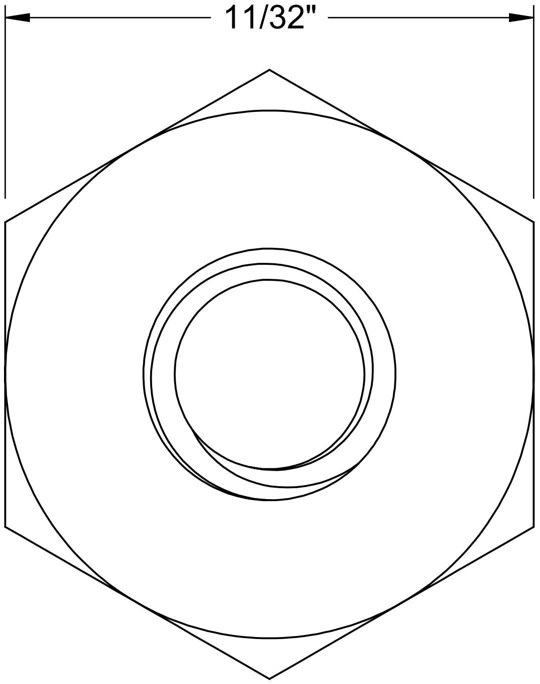


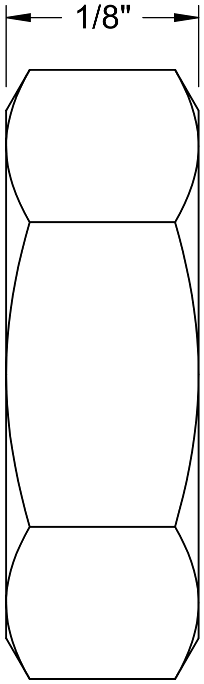


Bracket has 6 holes.
Mounting screws included.

McMASTER-CARR® CAD	PART NUMBER	520
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Load-Rated Corner Bracket	







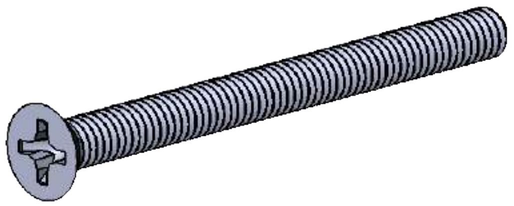
Military Specification: MS-35649-282

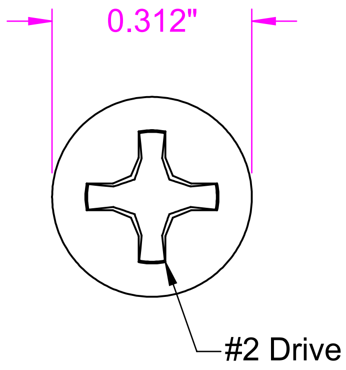
McMASTER-CARR

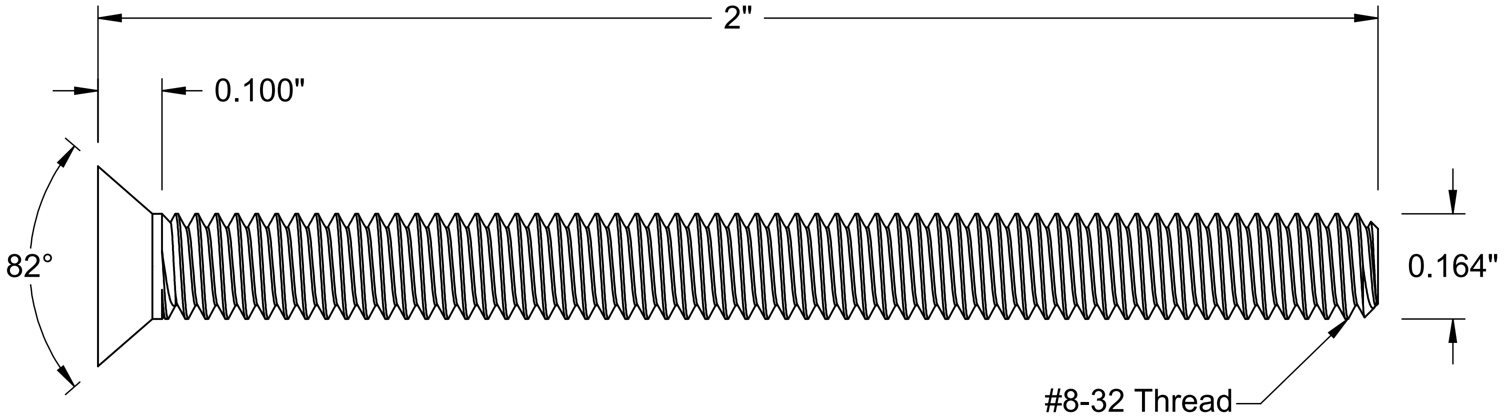
PART NUMBER **521**

http://www.mcmaster.com

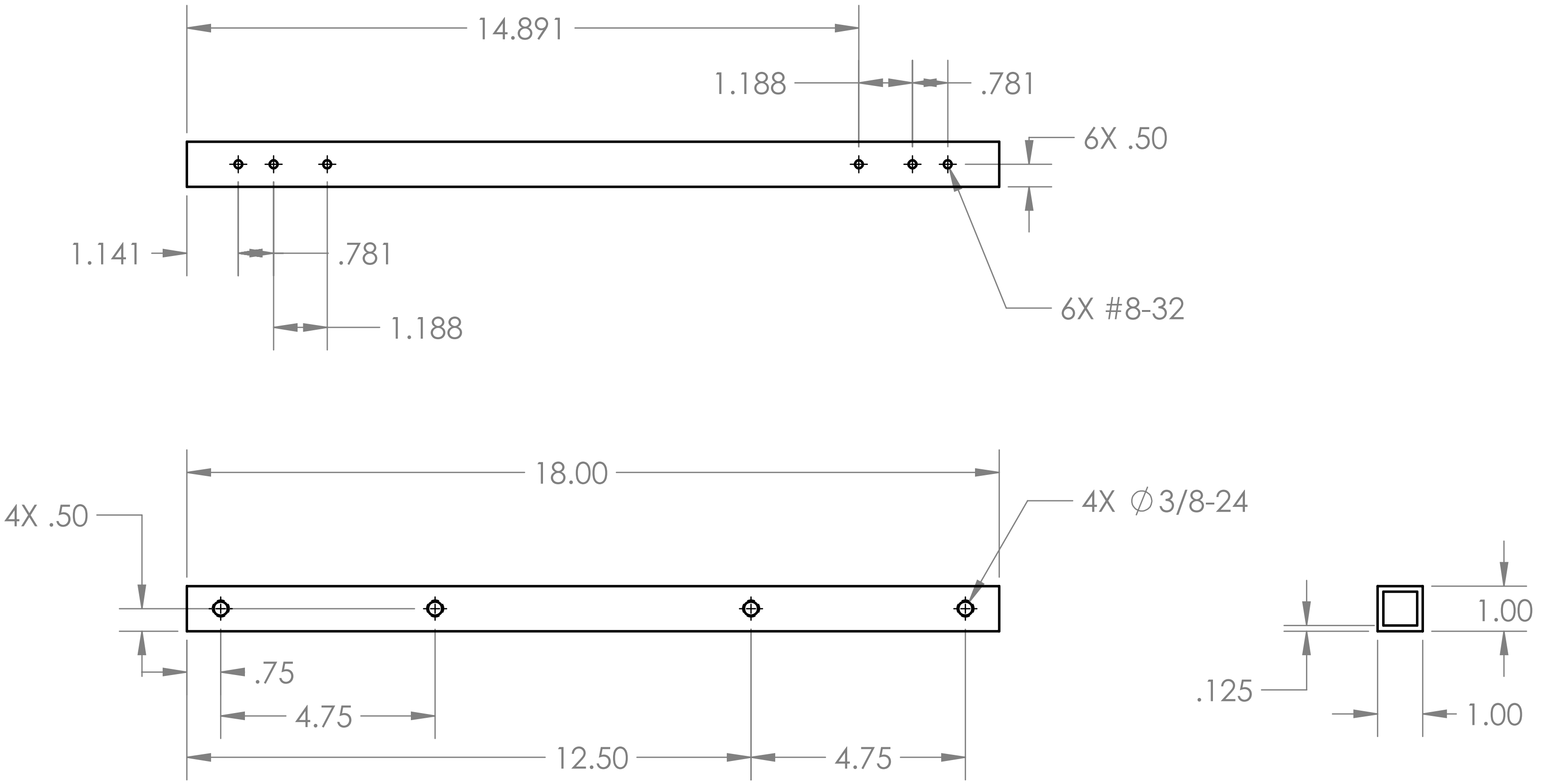
Mil Spec.
Hex Nut







McMASTER-CARR® CAD	PART NUMBER 522
http://www.mcmaster.com © 2012 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Flat Head Phillips Machine Screw



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: X.XX ±.01 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL A513 STEEL	COMMENTS:		
DO NOT SCALE DRAWING			

TITLE:

TUBE 2

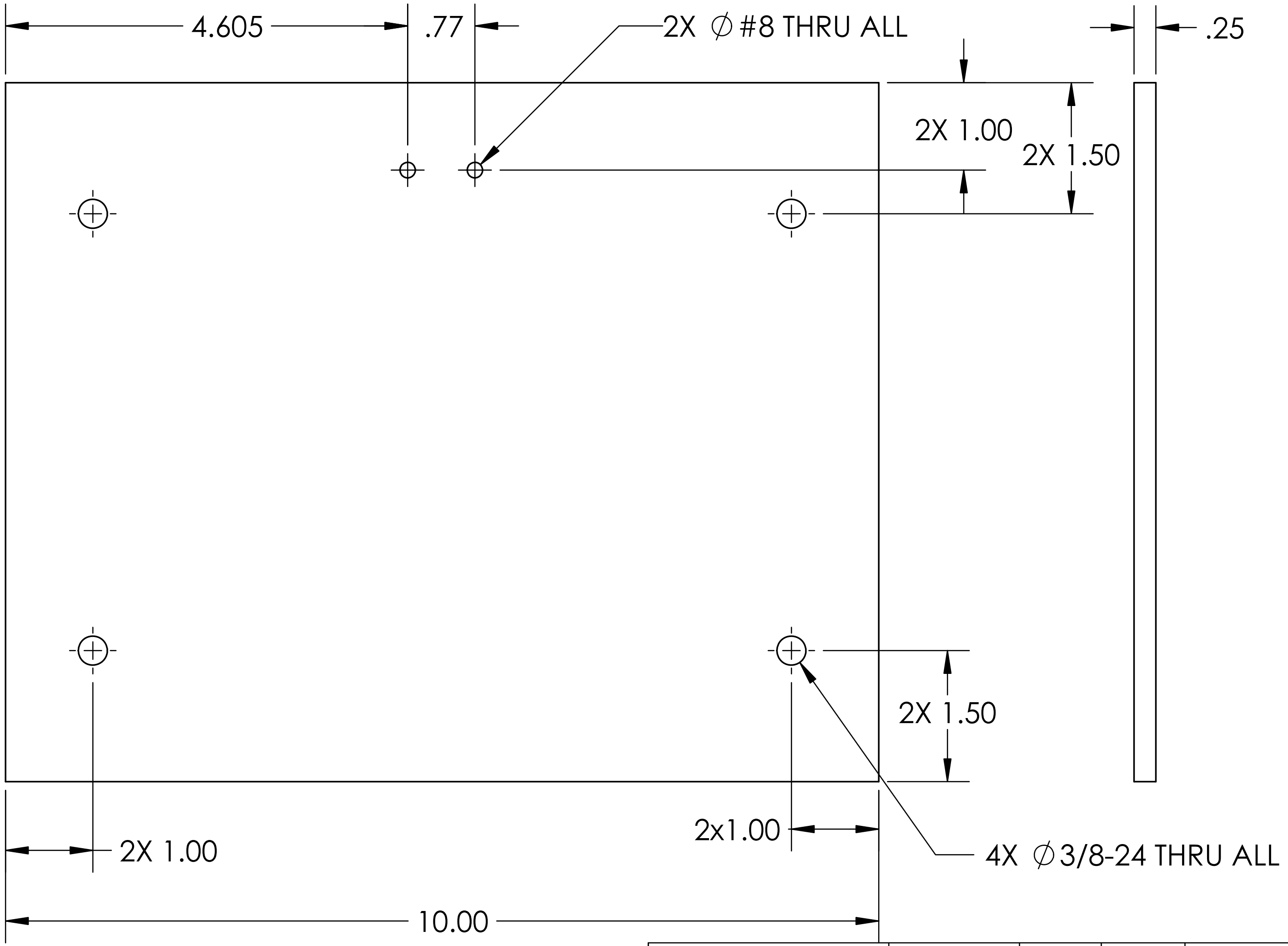
SIZE	DWG. NO.	REV
A	523	1

SCALE: 1:4

SHEET 1 OF 1

2 1

B B



A A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005

MATERIAL
ASTM 108

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

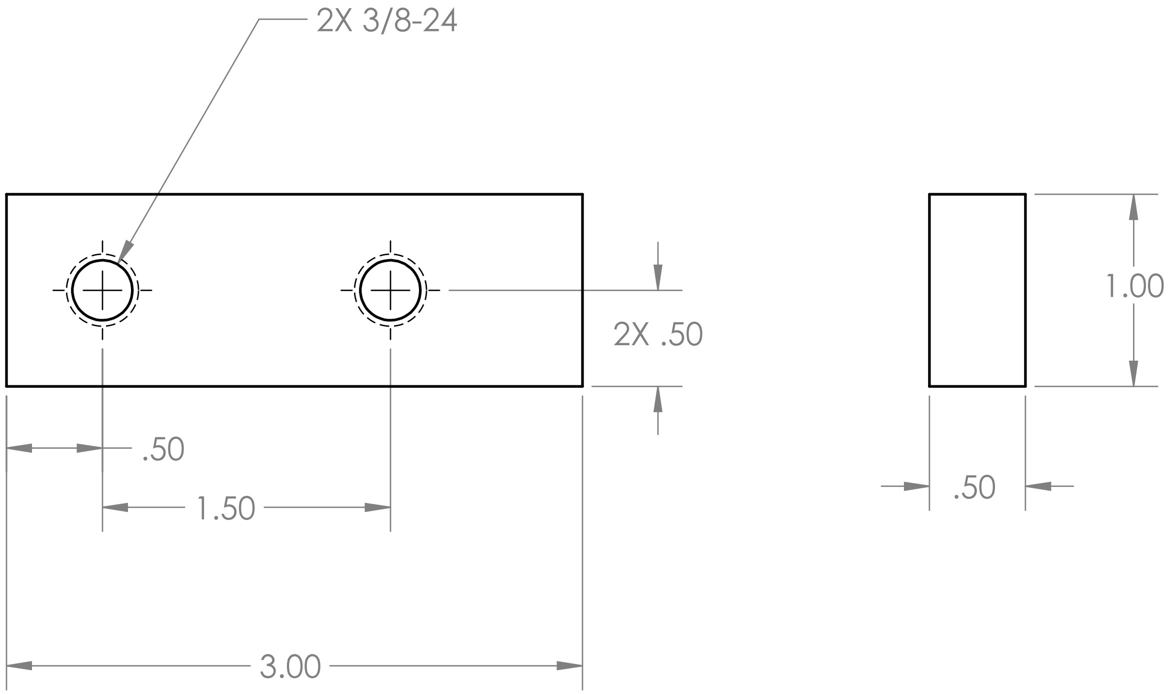
COMMENTS:

TITLE:
TOP PLATE

SIZE	DWG. NO.	REV
A	524	1

SCALE: 1:2
SHEET 1 OF 1

2 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES: X.XX ±.01
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005

MATERIAL
ASTM A681 STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

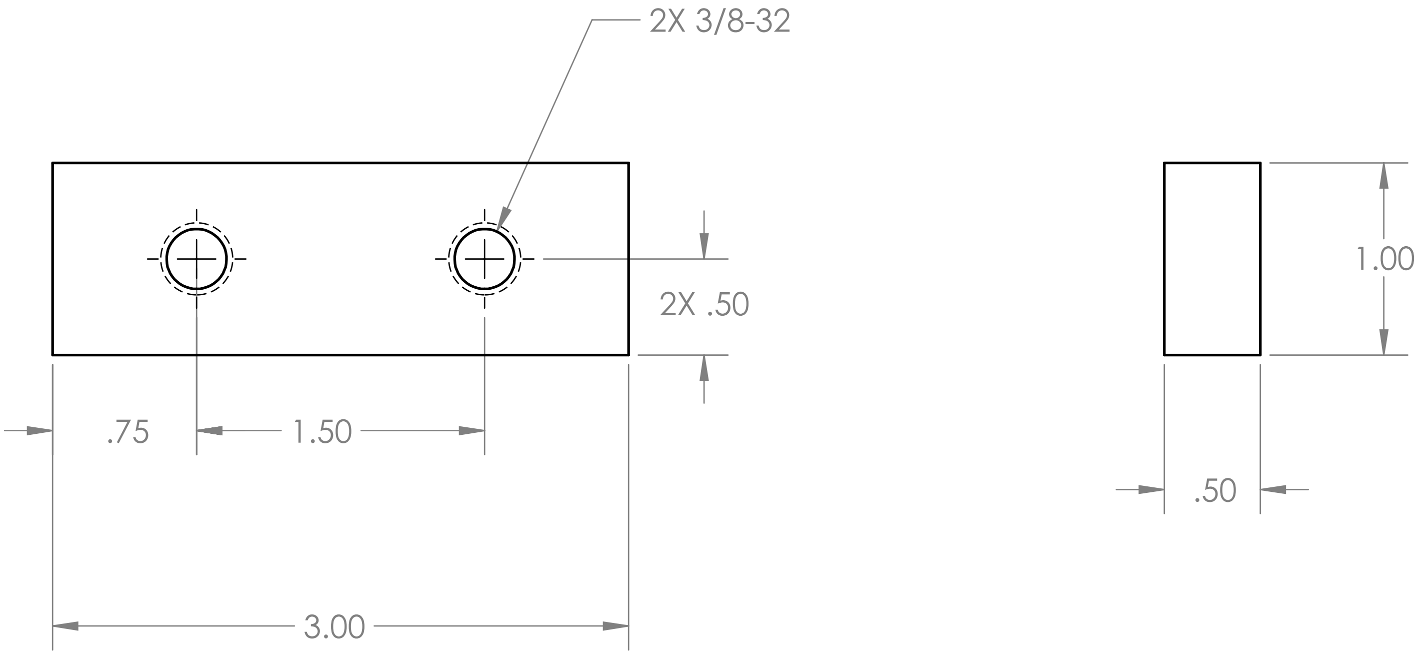
COMMENTS:

TITLE:
CONNECTOR 1

SIZE	DWG. NO.	REV
A	525	1

SCALE: 1:1
SHEET 1 OF 1

B B



A A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:X.XX ±.01
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005

MATERIAL
ASTM A681 STEEL

DO NOT SCALE DRAWING

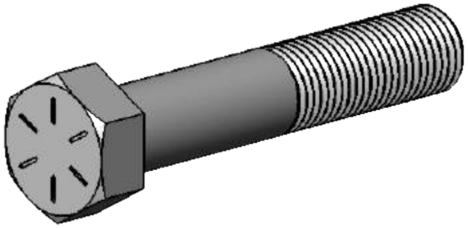
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

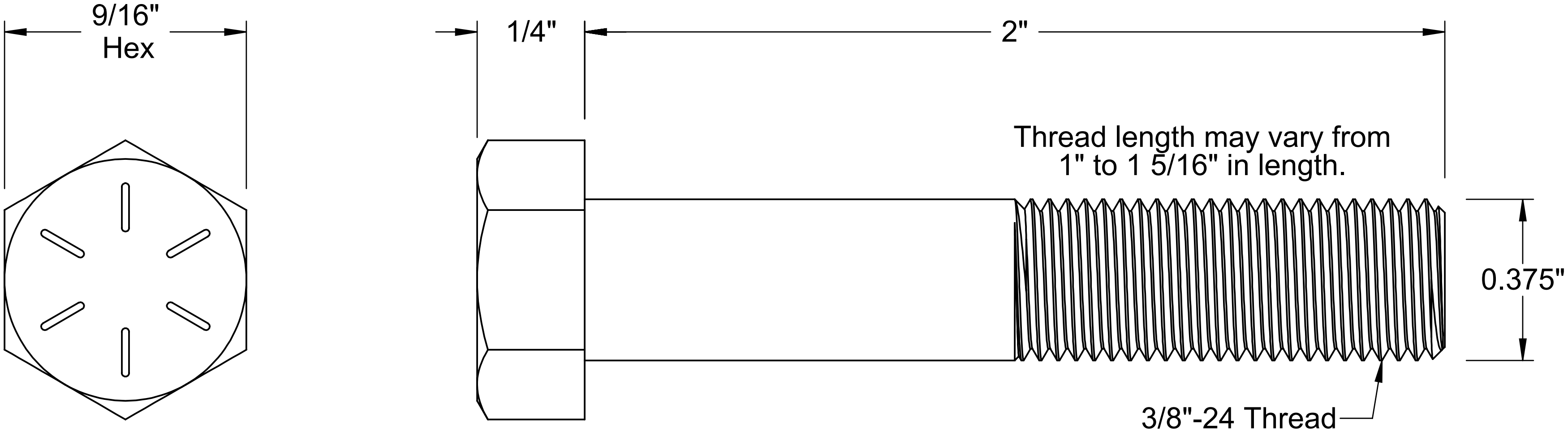
COMMENTS:

TITLE:
CONNECTOR 2

SIZE	DWG. NO.	REV
A	526	1

SCALE: 1:1
SHEET 1 OF 1



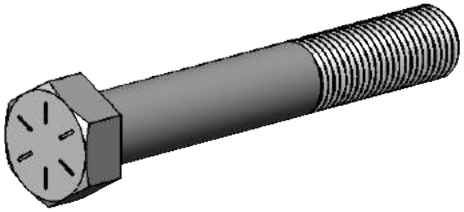


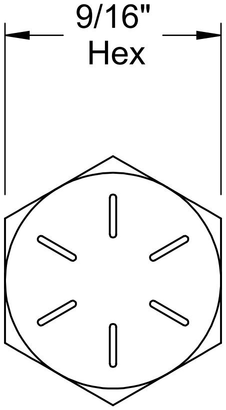
McMASTER-CARR. CAD

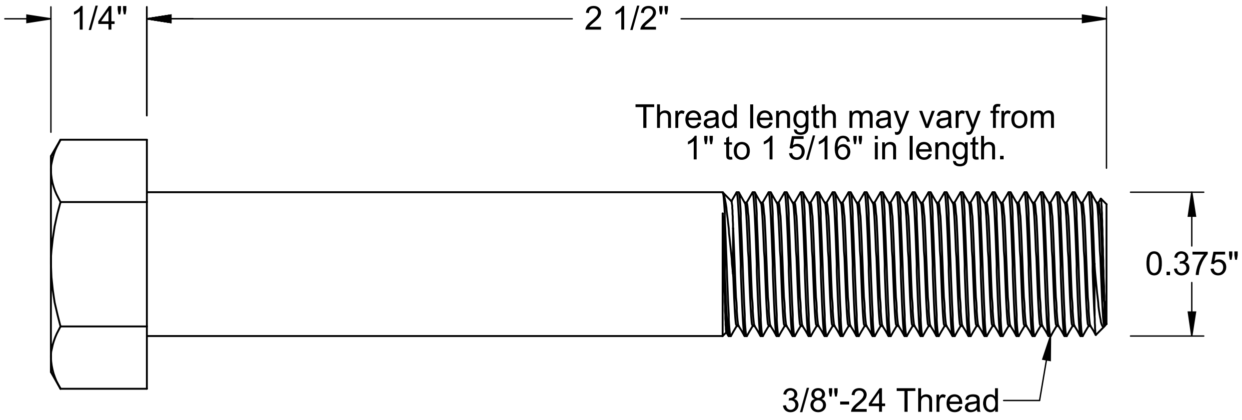
PART NUMBER **528**

http://www.mcmaster.com

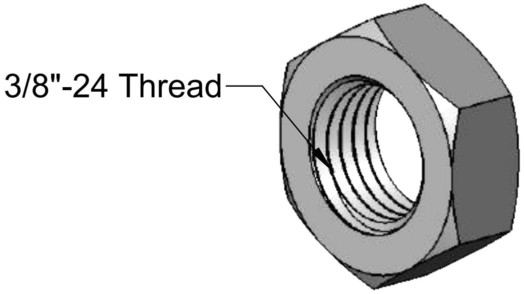
High-Strength Steel
Cap Screw-Grade 8

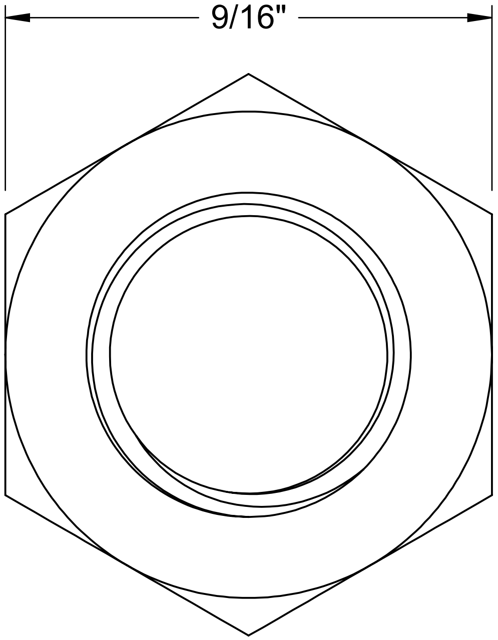


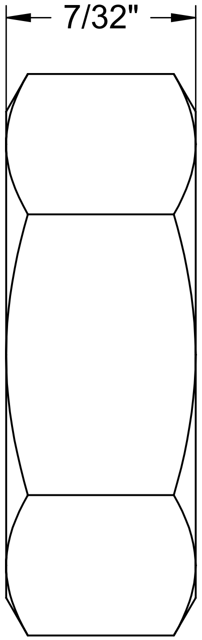




McMASTER-CARR. CAD	PART NUMBER	**529**
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company	High-Strength Steel Cap Screw-Grade 8	
Information in this drawing is provided for reference only.		





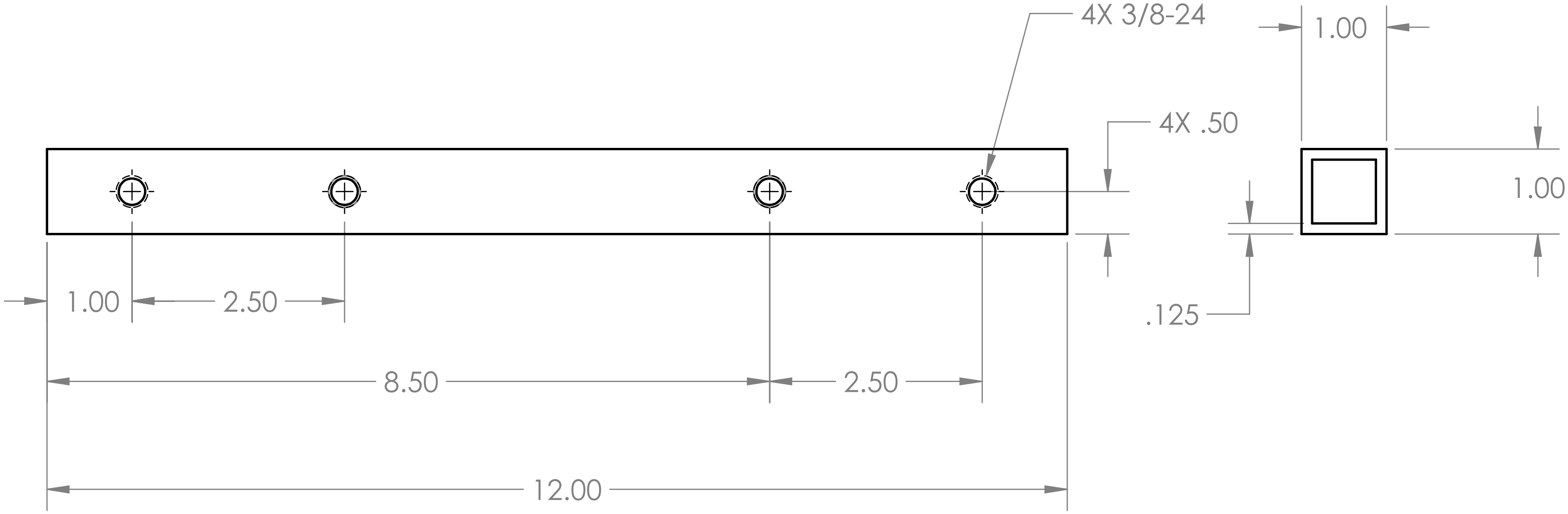


McMASTER-CARR® CAD

PART
NUMBER
530

http://www.mcmaster.com

Thin
Hex Nut



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:X.XX ±.01
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL
A513 STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

TUBE 3

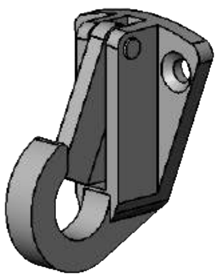
SIZE
A

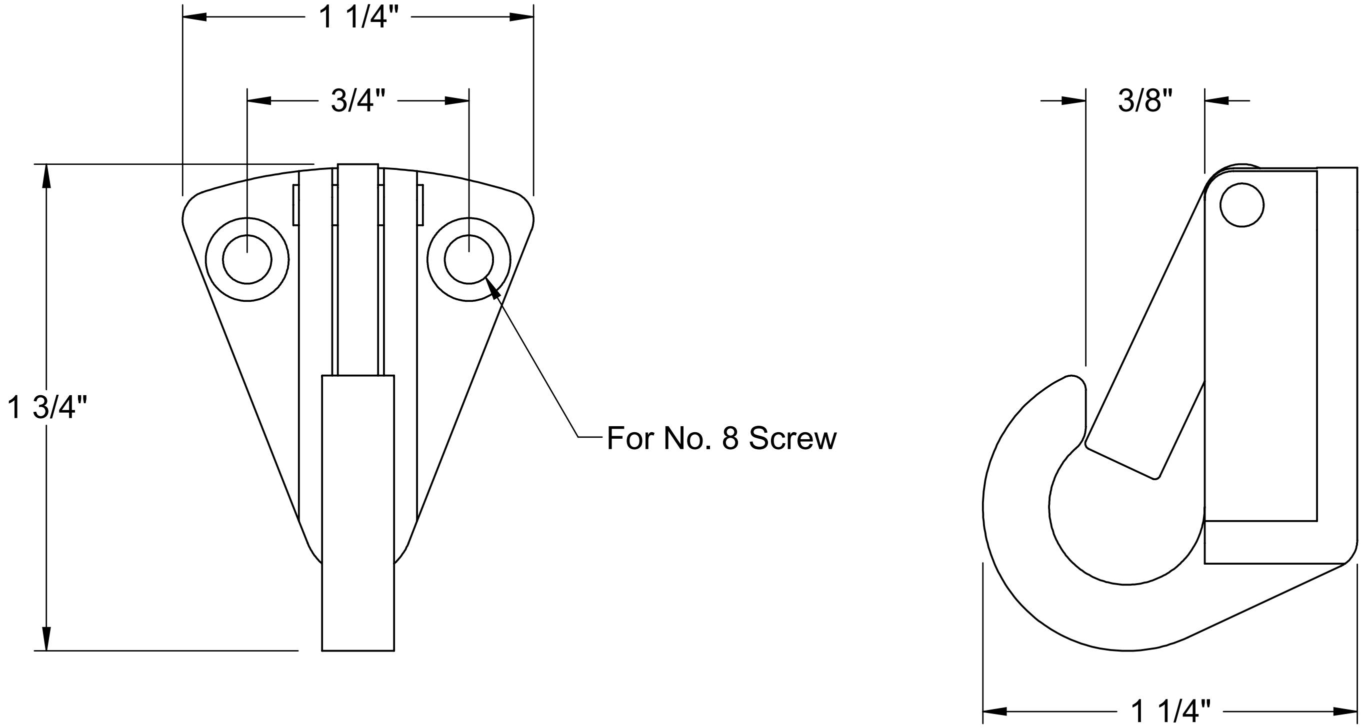
DWG. NO.
531

REV
1

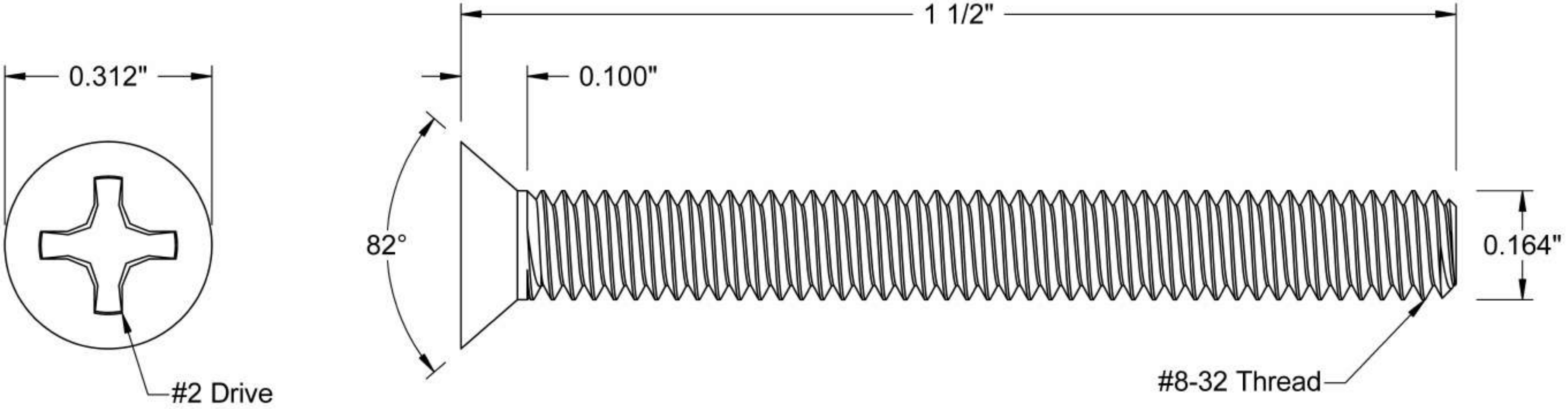
SCALE: 1:2

SHEET 1 OF 1





McMASTER-CARR® CAD	PART NUMBER	532
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company	Hook	
Information in this drawing is provided for reference only.		

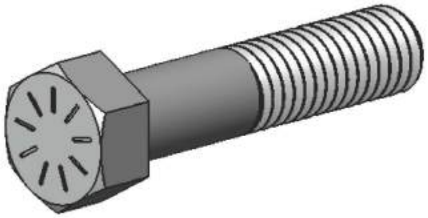


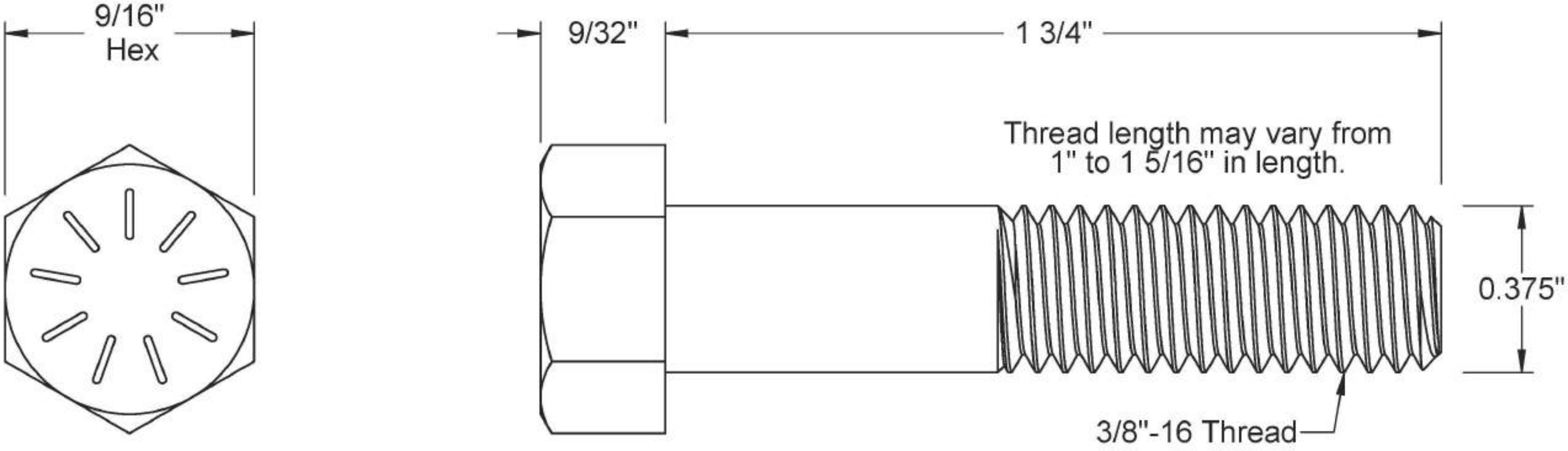
McMASTER-CARR® CAD

PART NUMBER 533

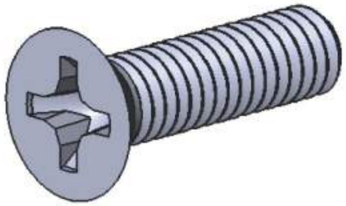
http://www.mcmaster.com

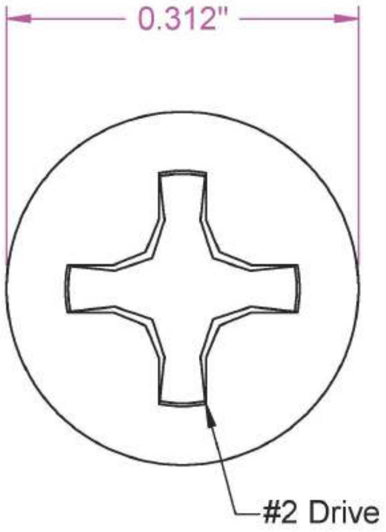
Flat Head Phillips
Machine Screw

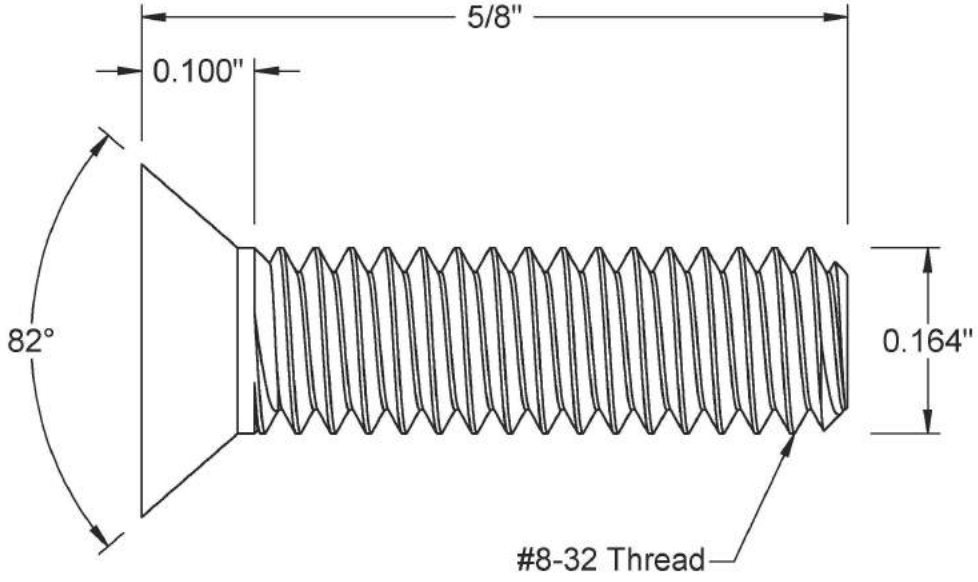




McMASTER-CARR.® CAD	PART NUMBER 534
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Extreme-Strength Steel Cap Screw-Grade 9

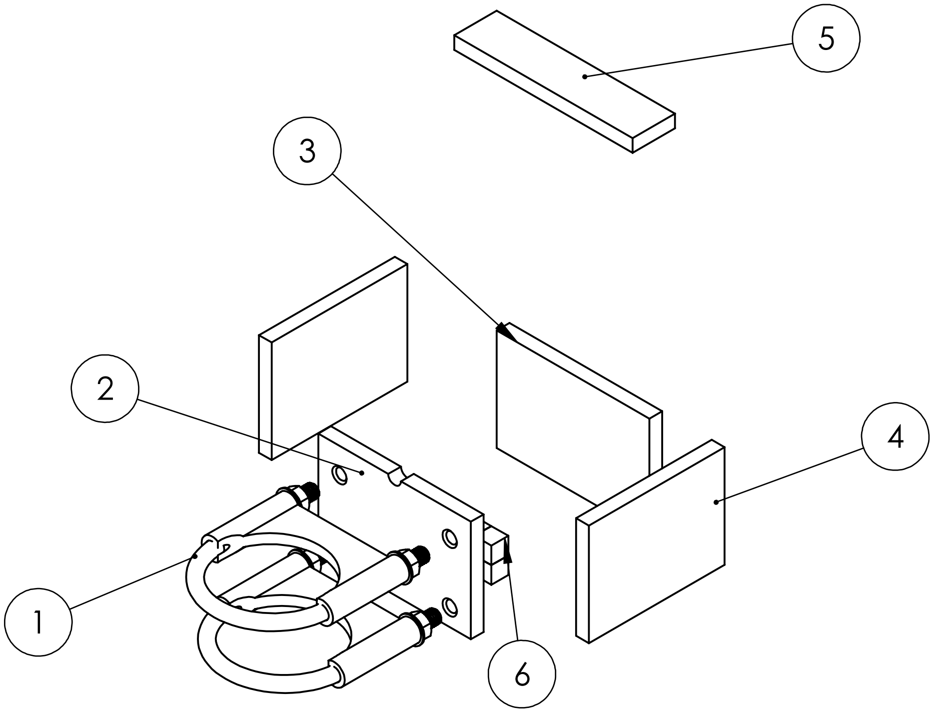






McMASTER-CARR. CAD	PART NUMBER 535
http://www.mcmaster.com © 2012 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Flat Head Phillips Machine Screw

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	Explosion/QTY.
1	610	U-BOLT CLAMP	STEEL	2
2	611	CLAMP PLATE	STEEL	1
3	612	BACK WALL	STEEL	1
4	613	SIDE WALL	STEEL	2
5	614	TOP	STEEL	1
6	615	MAGNETS	NEODYMIUM	10



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL	COMMENTS:		
DO NOT SCALE DRAWING			

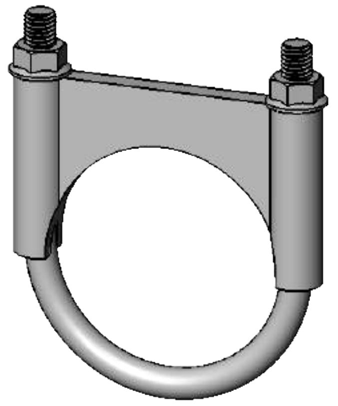
TITLE:

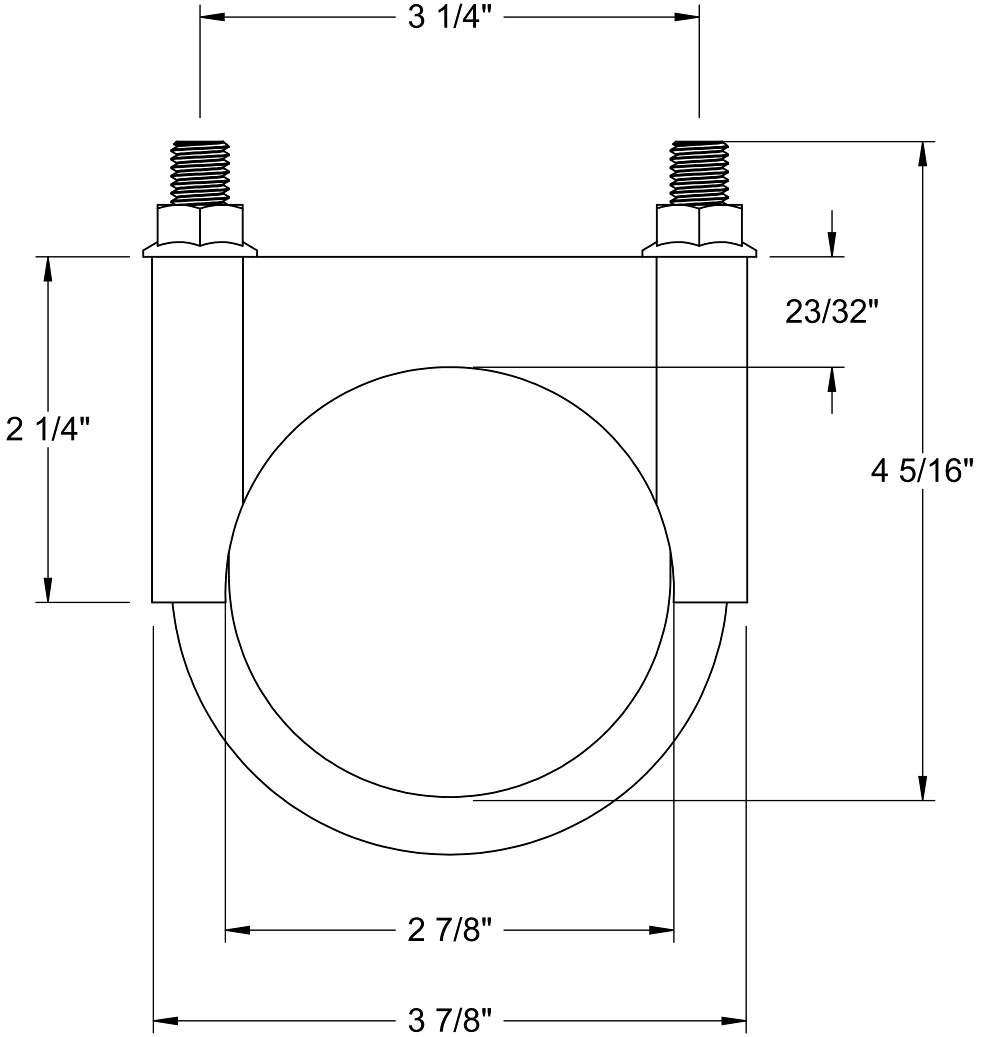
POLE CONNECTION

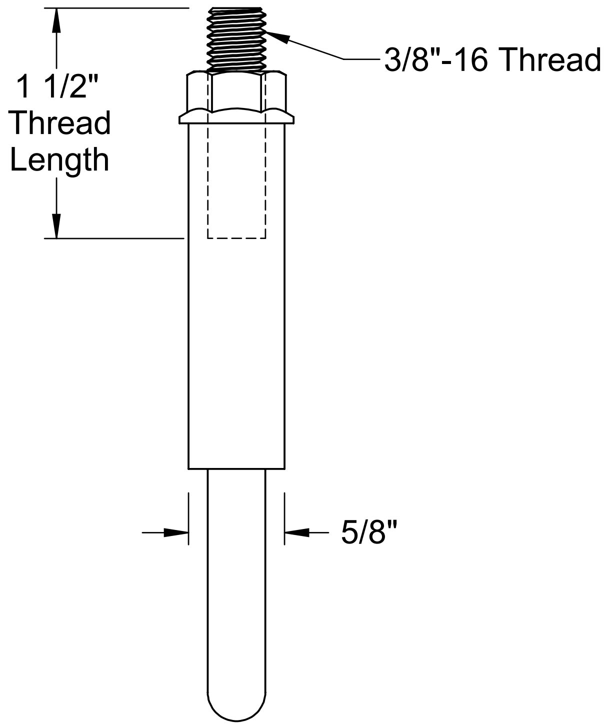
SIZE	DWG. NO.	REV
A	601	1

SCALE: 1:4

SHEET 1 OF 1





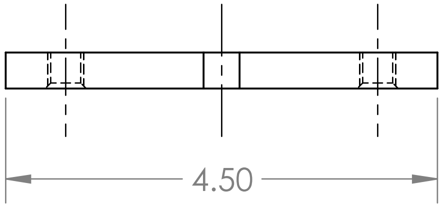


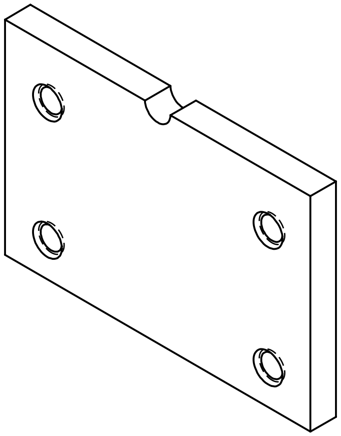
McMASTER-CARR CAD

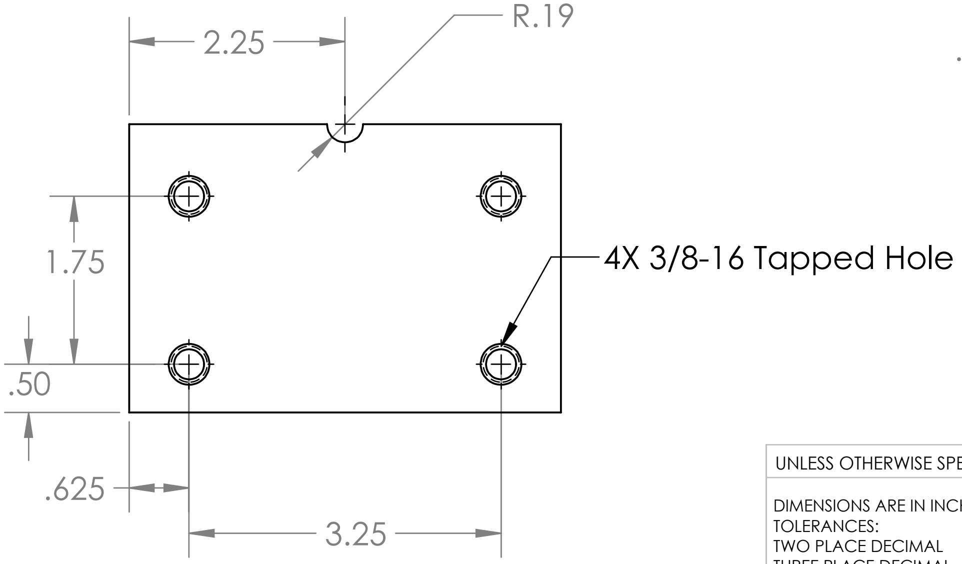
PART NUMBER **610**

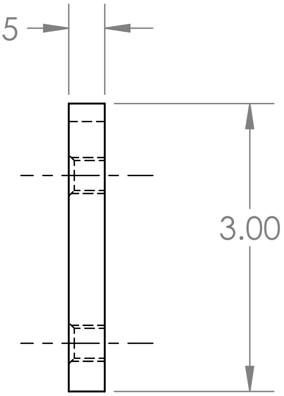
http://www.mcmaster.com

Clamping
U-Bolt









UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL 1018 STEEL

DO NOT SCALE DRAWING

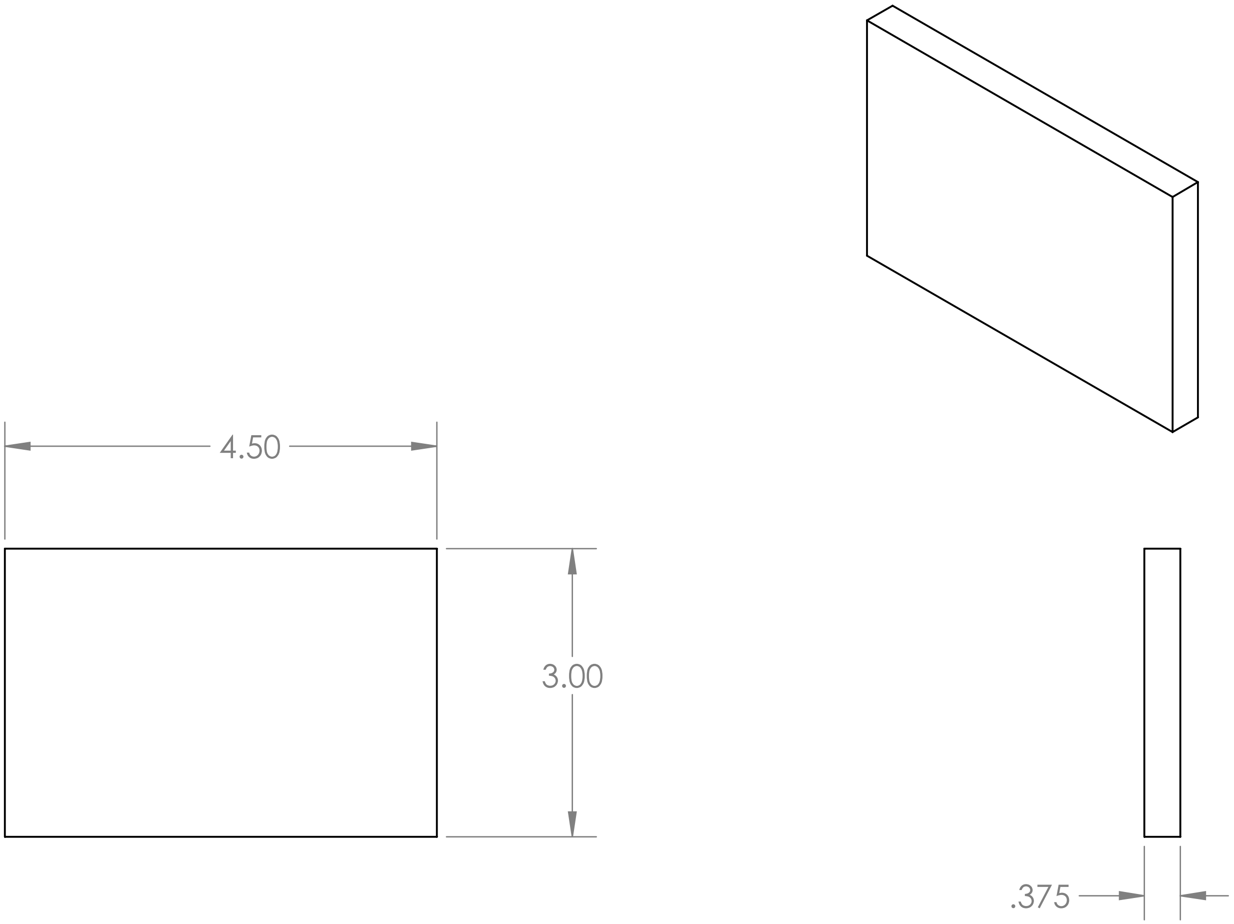
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
CLAMP PLATE

SIZE	DWG. NO.	REV
A	611	1

SCALE: 1:2 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL 1018 STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

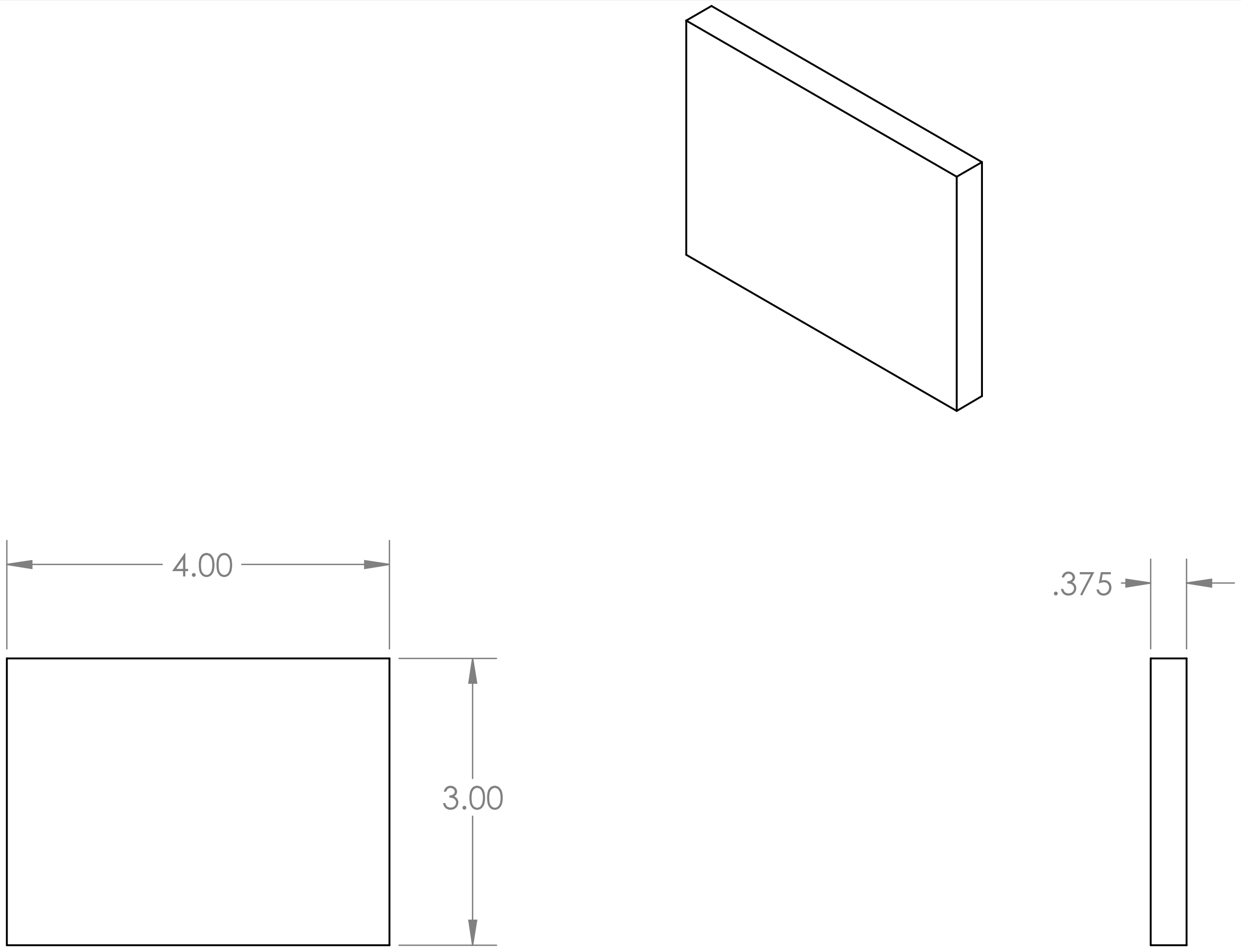
COMMENTS:

TITLE:

BACK WALL

SIZE	DWG. NO.	REV
A	612	1

SCALE: 1:2
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL 1018 STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

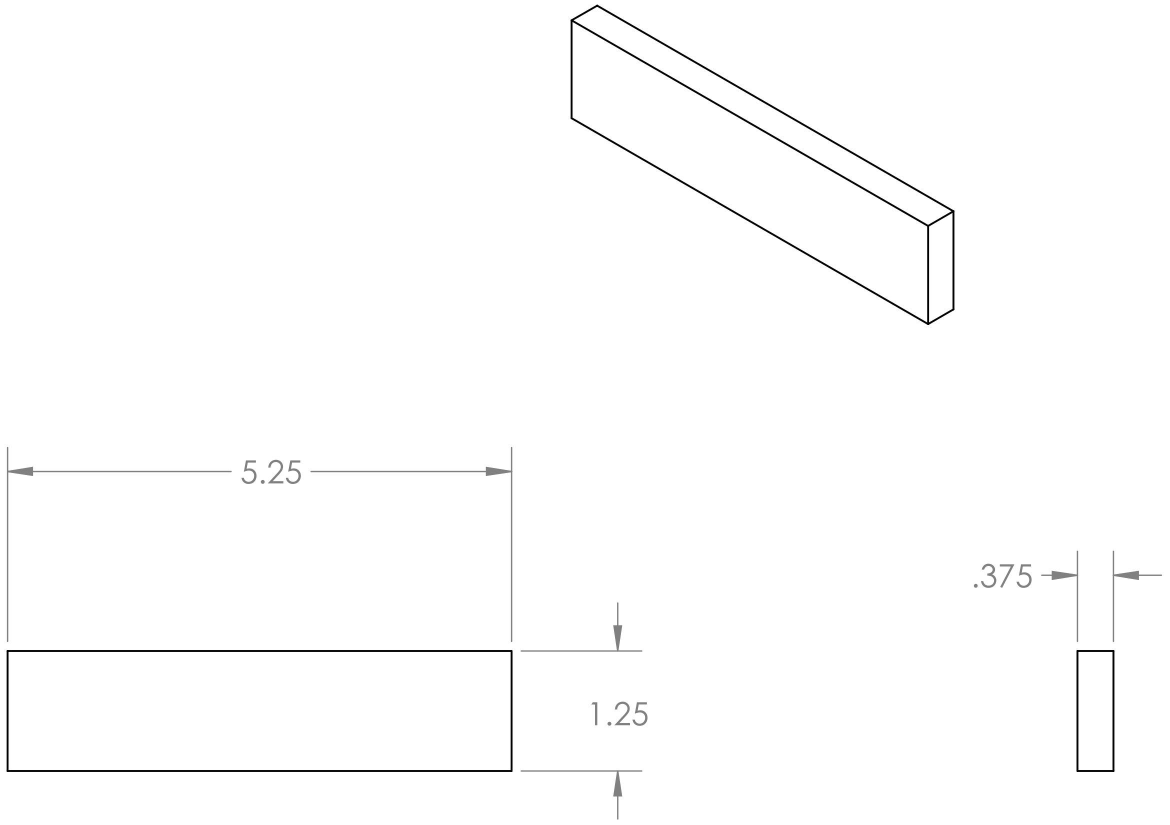
TITLE:

SIDE WALL

SIZE	DWG. NO.	REV
A	613	1

SCALE: 1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL 1018 STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

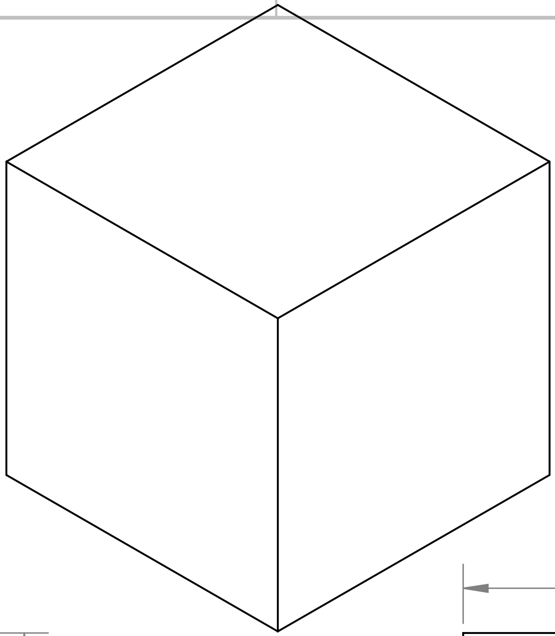
TOP

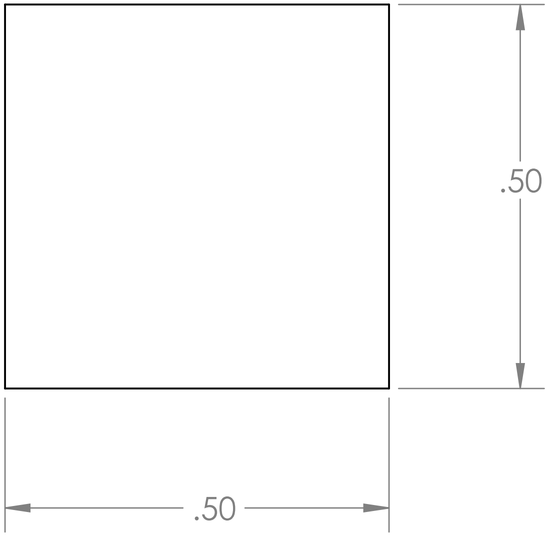
SIZE	DWG. NO.	REV
A	614	1

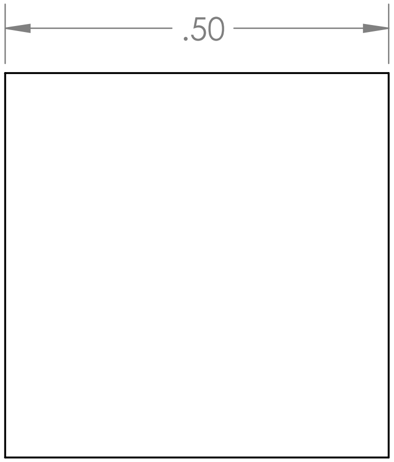
SCALE: 1:2

SHEET 1 OF 1

B B







A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE: MAGNET
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL NEODYMIUM	COMMENTS:			SIZE A
DO NOT SCALE DRAWING				DWG. NO. 615
				REV 1
				SCALE: 4:1
				SHEET 1 OF 1

2 1

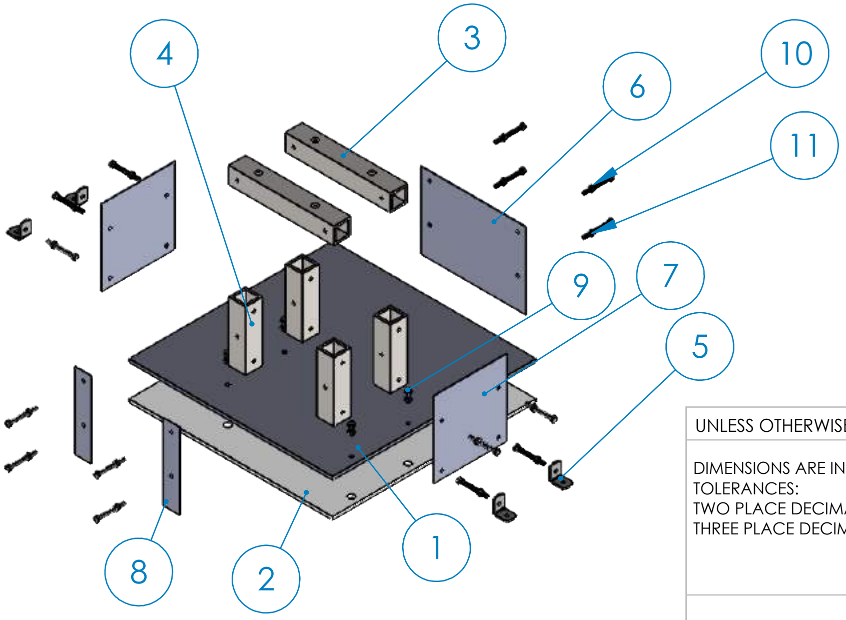
B B

A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE: Translation Assembly
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL VARIOUS	COMMENTS:			SIZE A DWG. NO. 701 REV 1
				SCALE: 1:1 SHEET 1 OF 1

2 1

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	Base Plate	Stainless Steel Base Plate	Stainless Steel	1
2	Rubber base	Rubber Base Plate	Rubber	1
3	Cross Support	Cross Support	Steel	2
4	Vertical Support	Vertical Support	Steel	4
5	1556A24	Corner Bracket	Steel	4
6	Back Casing	Steel Sheet Metal Covering	Steel	1
7	Side Casing	Steel Sheet Metal Covering	Steel	2
8	FrontStrip	Steel Sheet Metal Covering	Steel	2
9	91280A134	12mm M4 Bolt	Steel	4
10	91280A152	40mm M4 Bolt	Steel	16
11	92497A250	M4 Nut	Steel	20



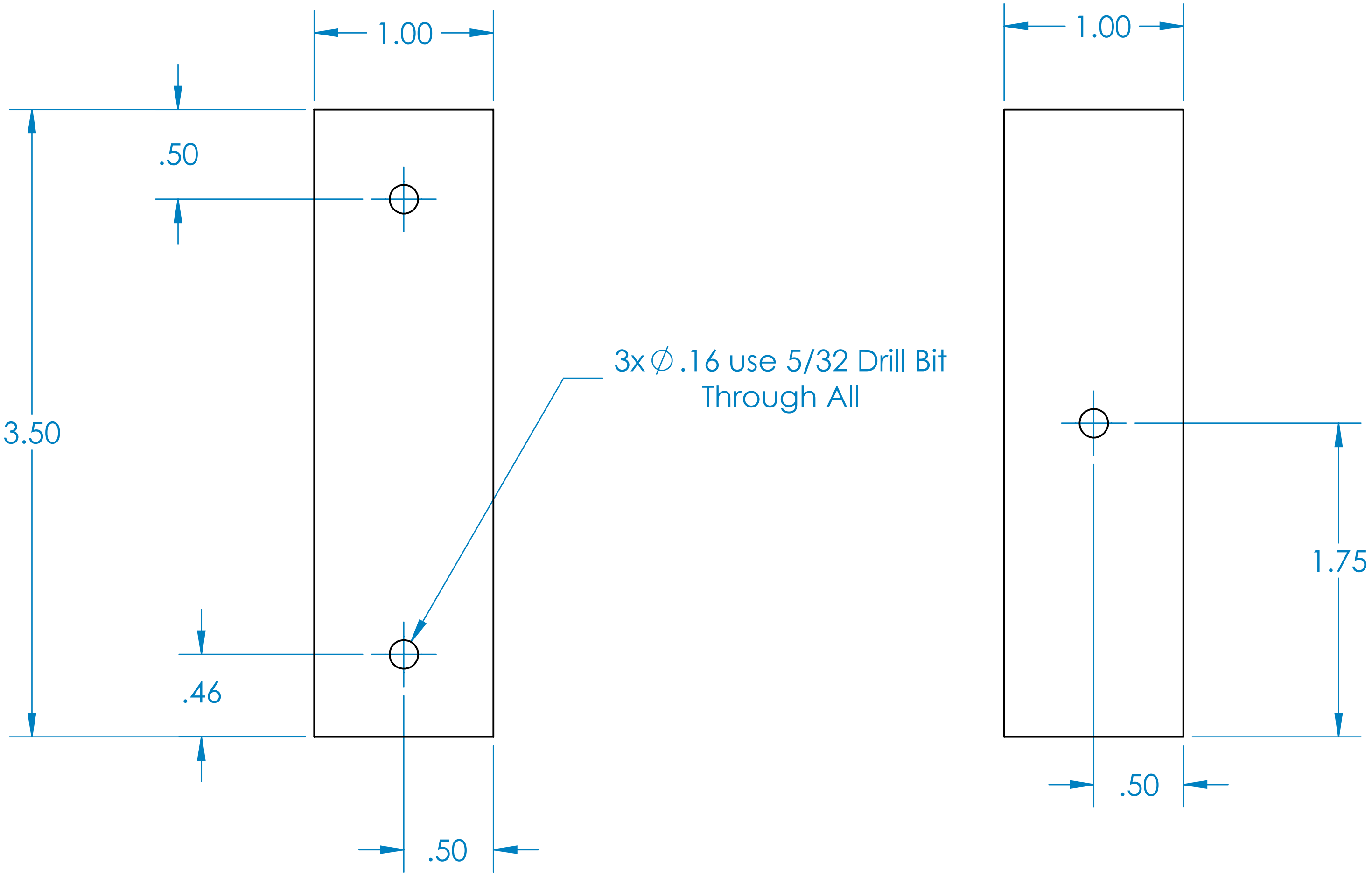
		NAME	DATE
UNLESS OTHERWISE SPECIFIED:			
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL VARIOUS	COMMENTS:		

TITLE:

Motor Housing Subassembly

SIZE	DWG. NO.	REV
A	710	1

SCALE: 1:1 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
1inch Steel tubing

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

Motor Housing Vertical Support

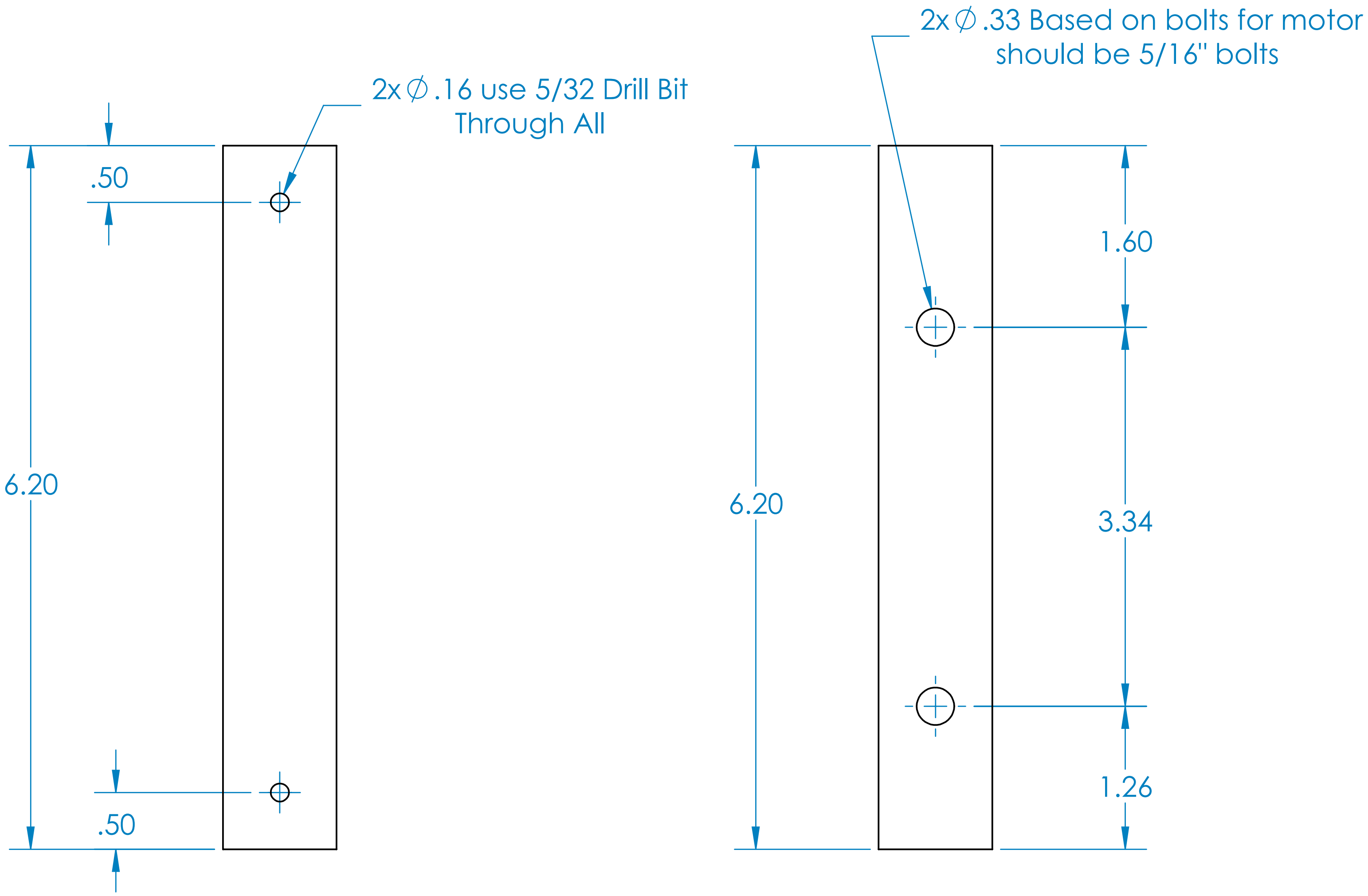
SIZE **A**

DWG. NO. 711

REV 1

SCALE: 1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
1inch Steel Tubing

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

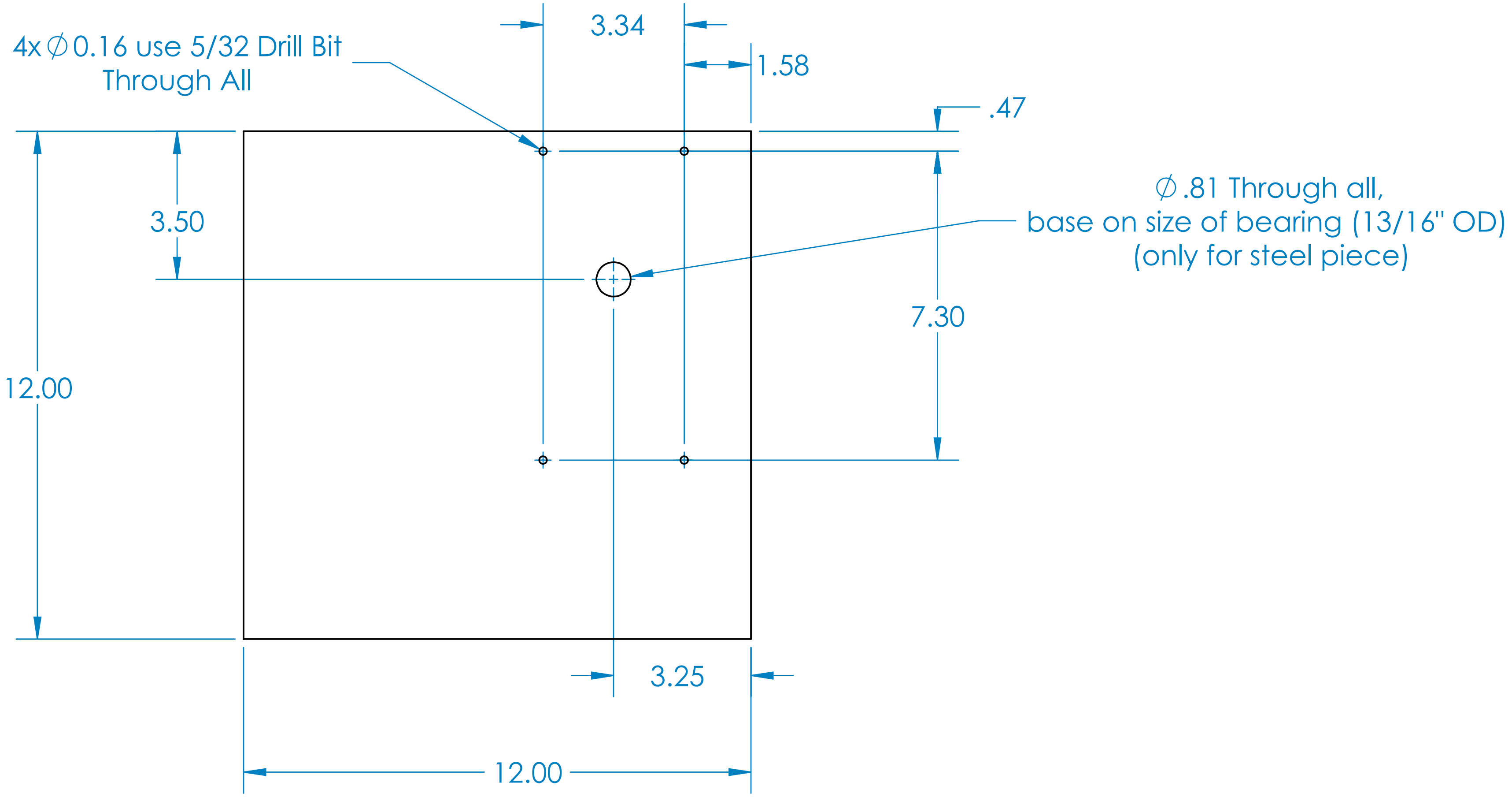
COMMENTS:

TITLE:

Motor Housing Cross Support

SIZE	DWG. NO.	REV
A	712	1

SCALE: 1:1 SHEET 1 OF 1



4x ∅0.16 use 5/32 Drill Bit
Through All

∅.81 Through all,
base on size of bearing (13/16" OD)
(only for steel piece)

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL

.1875 in thick
T304 Stainless Steel Plate
and one of Rubber

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

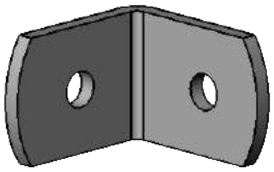
TITLE:

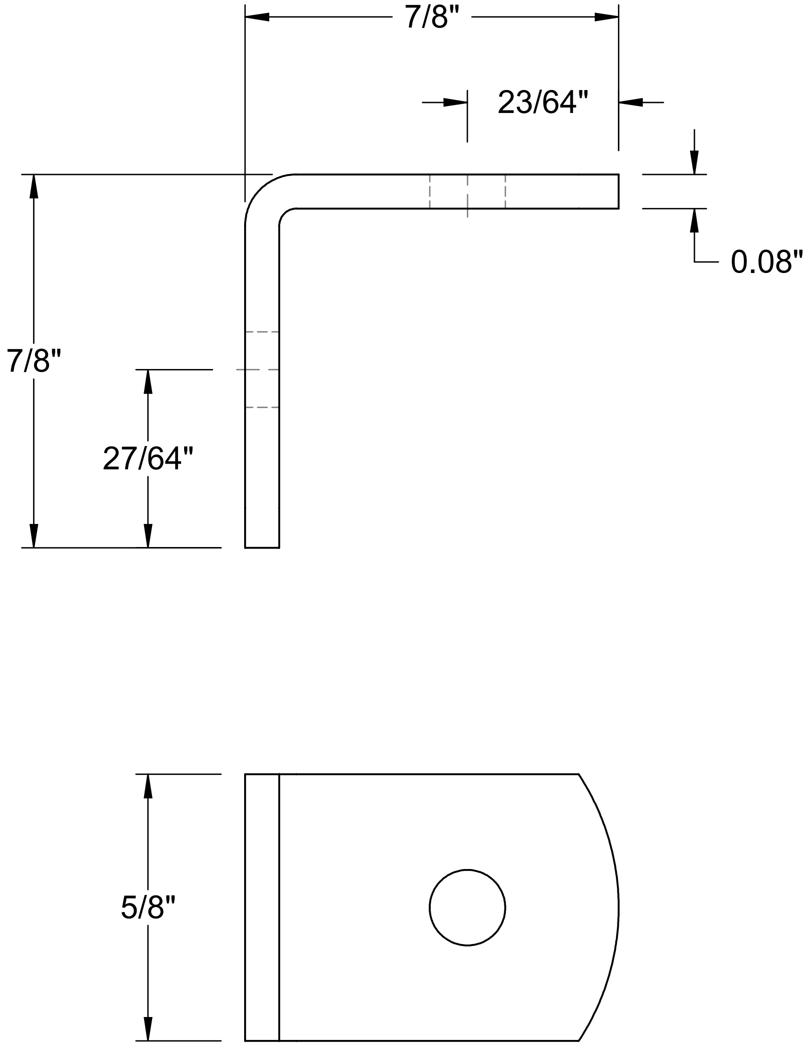
Motor Housing Base Plates

SIZE	DWG. NO.	REV
A	713	1

SCALE: 1:1

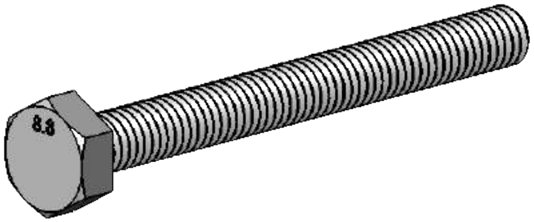
SHEET 1 OF 1

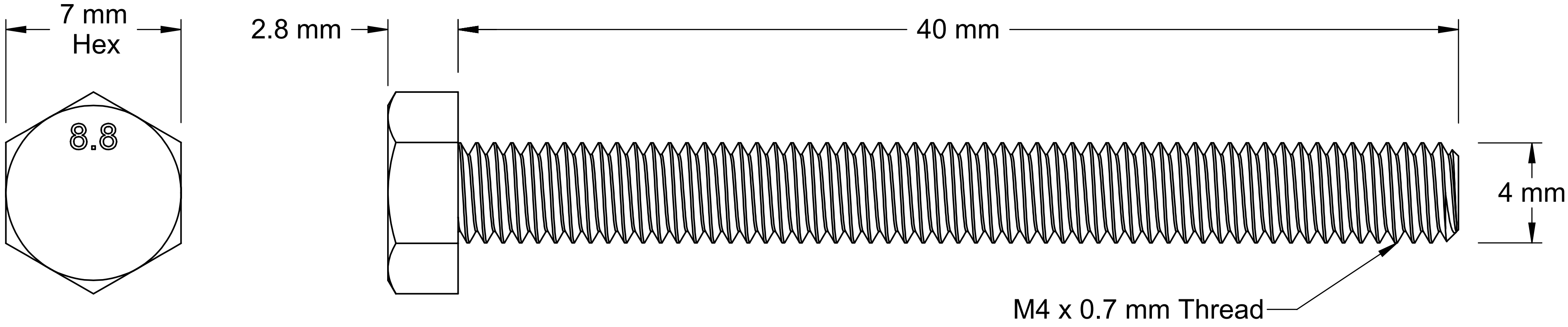




Bracket has 2 holes.
Bracket uses No. 9 screws.

McMASTER-CARR	PART NUMBER 714
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Bracket



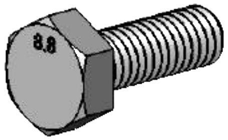


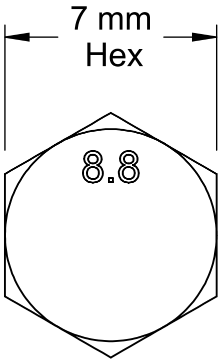
McMASTER-CARR CAD

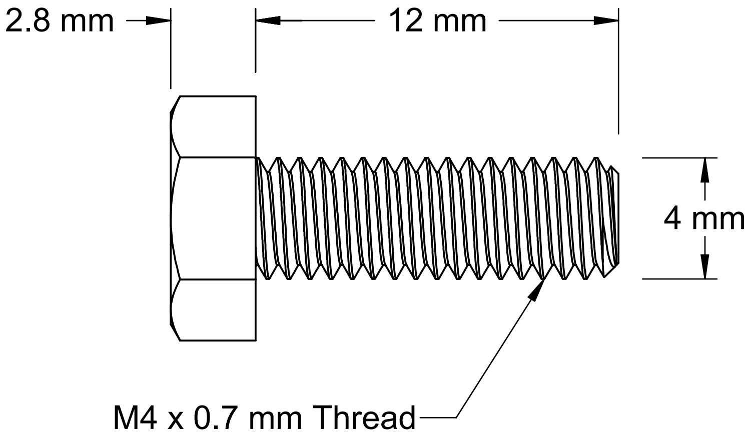
PART NUMBER **715**

http://www.mcmaster.com

Metric Medium-Strength Steel
Cap Screw - Class 8.8





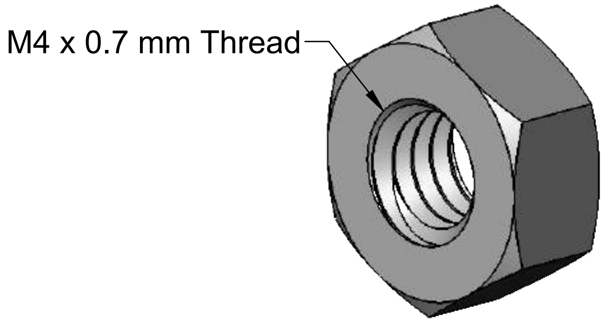


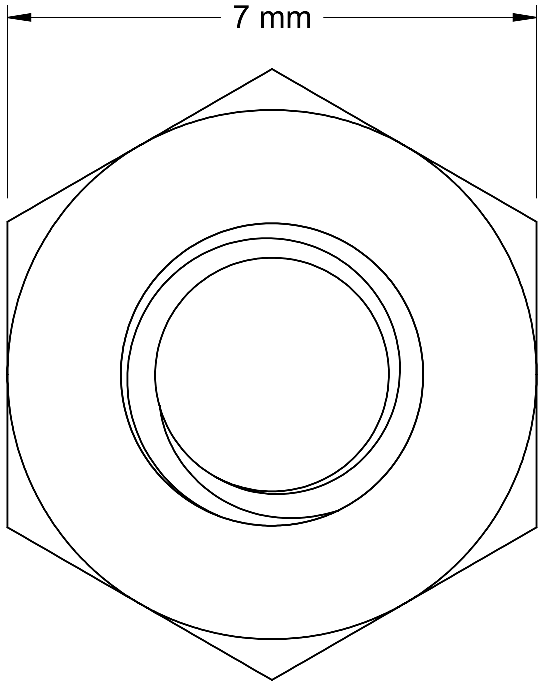
McMASTER-CARR® CAD

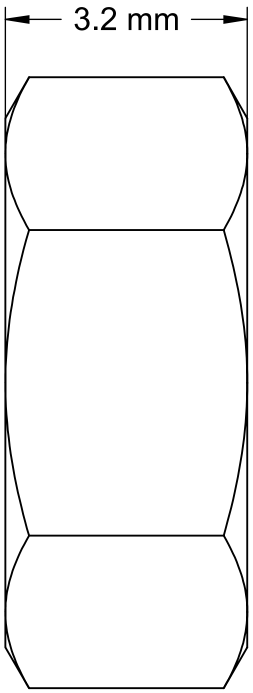
http://www.mcmaster.com

PART NUMBER **716**

Metric Medium-Strength Steel
Cap Screw - Class 8.8





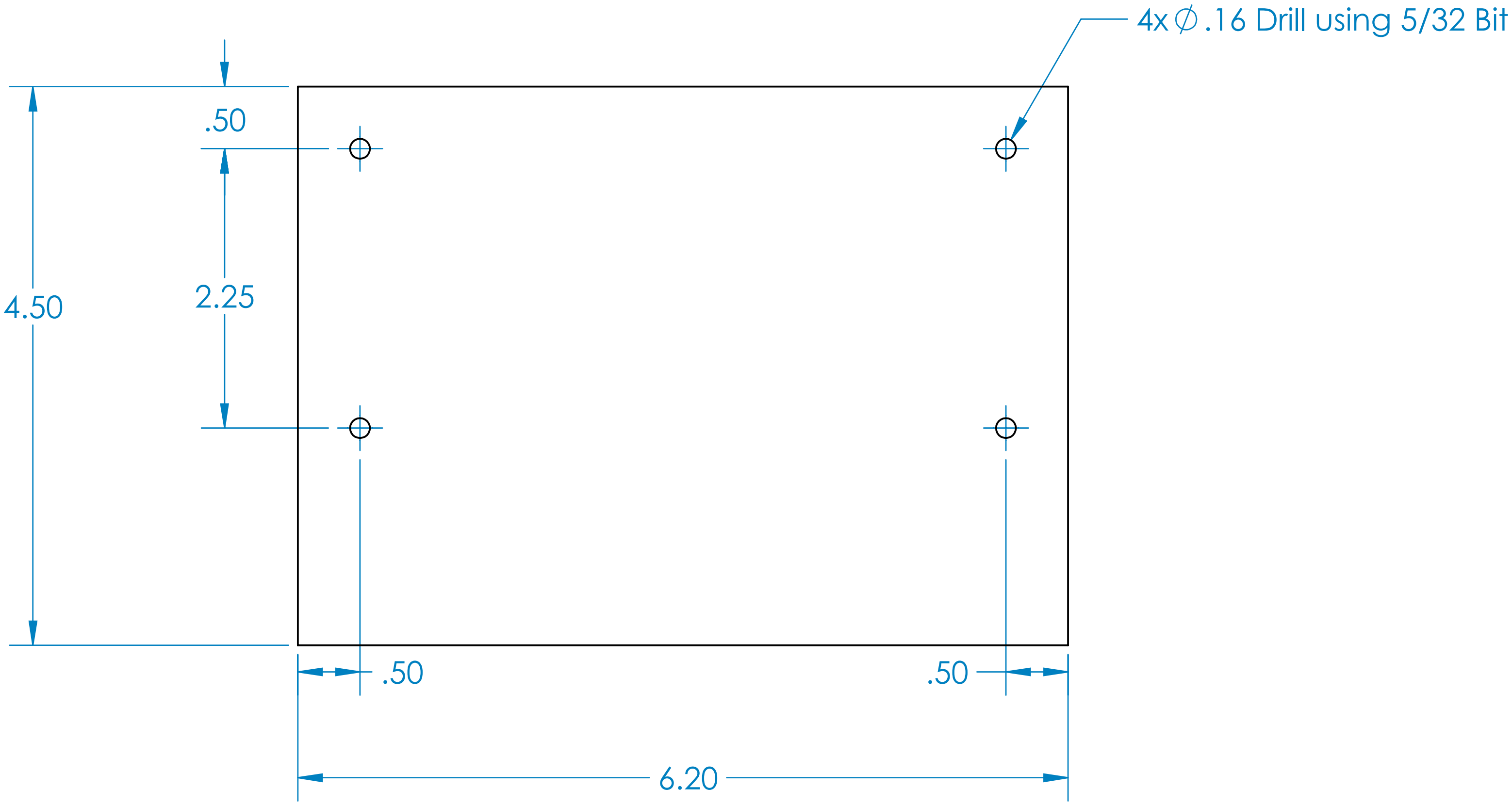


McMASTER-CARR. CAD

PART NUMBER **717**

http://www.mcmaster.com

Metric
Hex Nut



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL

.024in thick
cold rolled steel

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

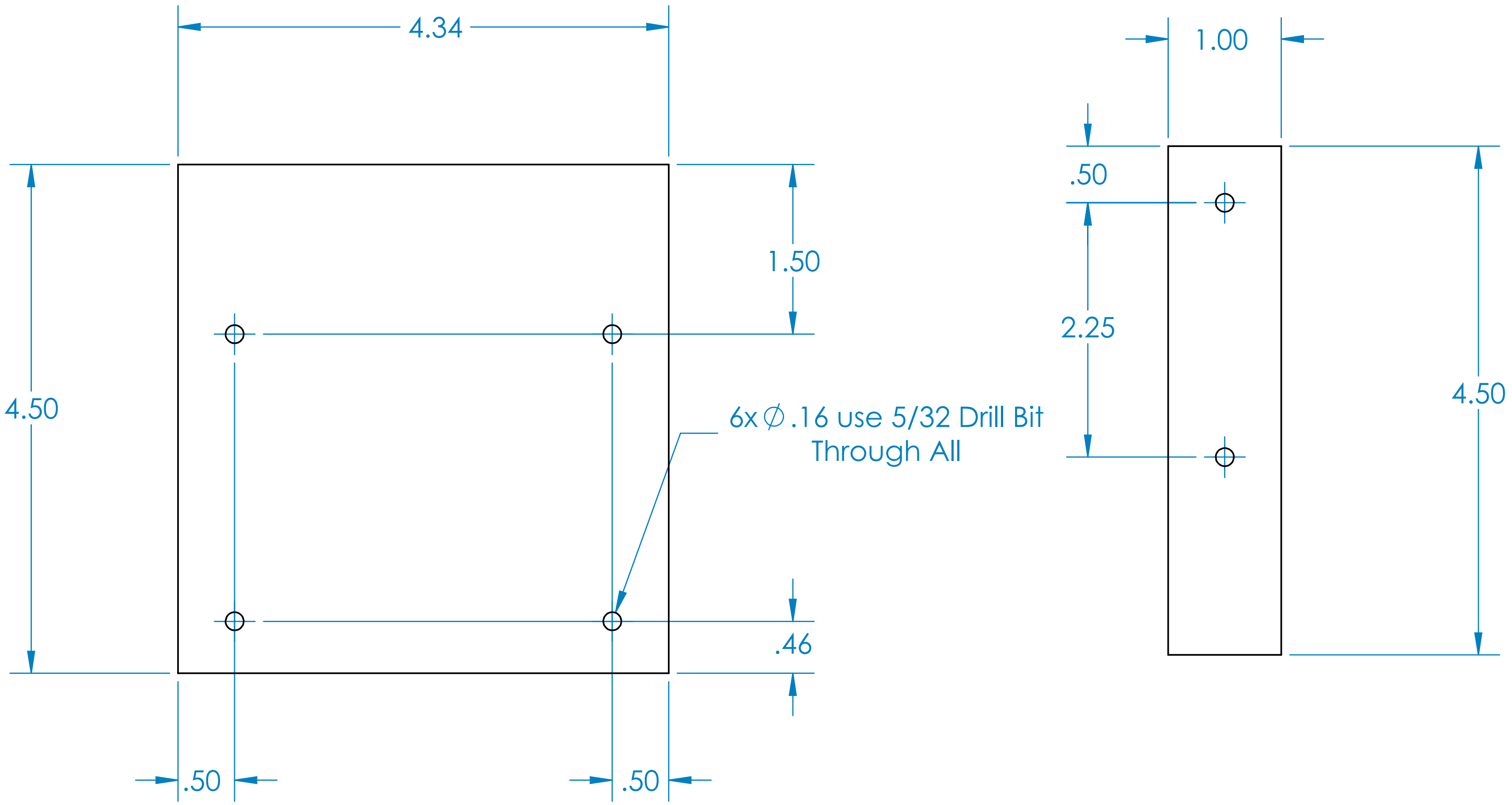
TITLE:

Motor Housing Back Casing

SIZE	DWG. NO.	REV
A	718	1

SCALE: 1:1

SHEET 1 OF 1



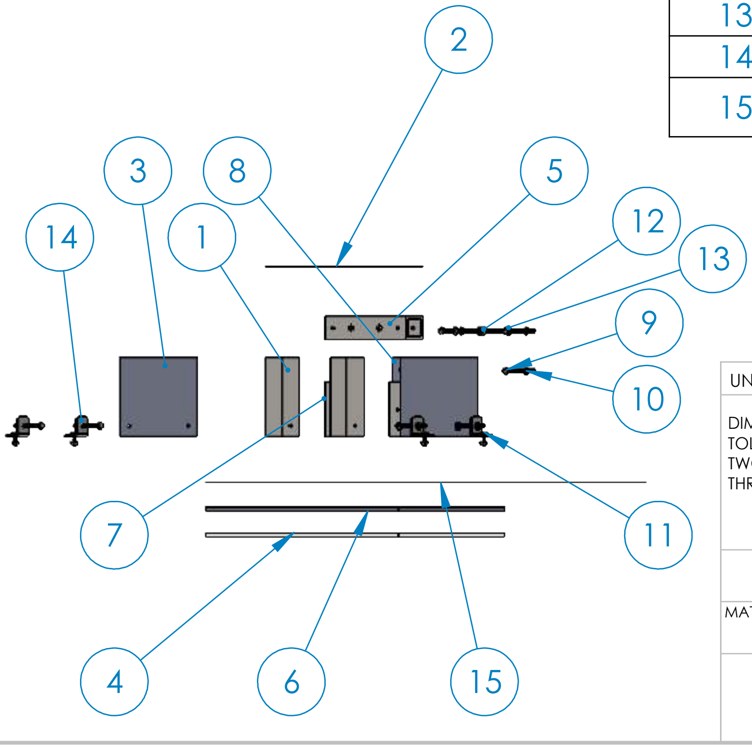
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL	COMMENTS:		
.024 in thick Cold Rolled Steel	1 of Back plate and 2 of the front strip to be made		

TITLE:
Motor Housing Side Casing and Front Strips

SIZE	DWG. NO.	REV
A	719	1

SCALE: 1:1
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	Slave Side Vertical Support	Front Vertical Support	Steel	2
2	Slave Side Top Casing	Top Covering	Steel	1
3	Slave Side Side Casing	Side Covering	Steel	2
4	Slave Side Rubber Base Plate	Rubber Base Plate	Rubber	1
5	Slave Side Cross Support	Cross Support	Steel	1
6	Slave Side Base Plate	Metal Base Plate	Stainless Steel	1
7	Slave Side Back Vertical	Back Vertical Support	Steel	2
8	Slave Side Back Casing	Back Covering	Steel	1
9	91280A152	40mm M4 Bolt	Steel	8
10	92497A250	M4 Nut	Steel	12
11	91280A134	12mm M4 Bolt	Steel	4
12	94387A344	40mm M5 Bolt	Steel	2
13	92497A300	M5 Nut	Steel	2
14	1556A24	Corner Bracket	Steel	4
15	Slave Side Base Extension	Extension for Cinder Blocks	Steel	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
VARIOUS

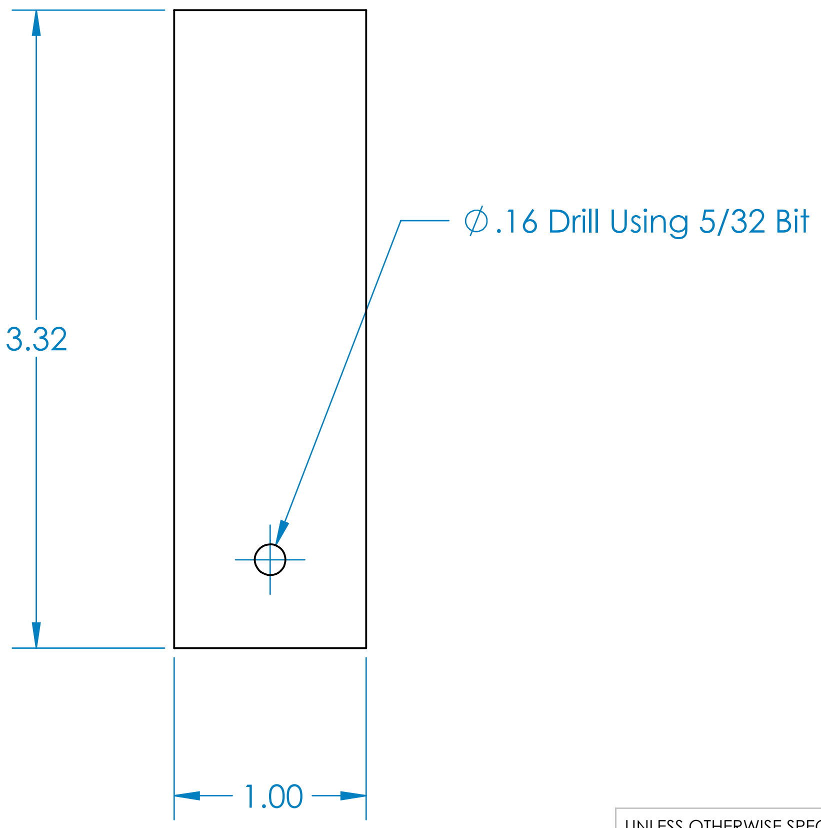
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

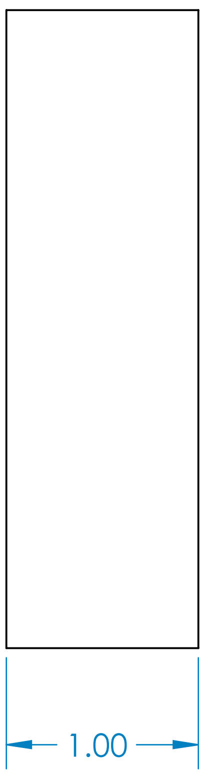
COMMENTS:

TITLE:
Slave Pulley Housing Subassembly

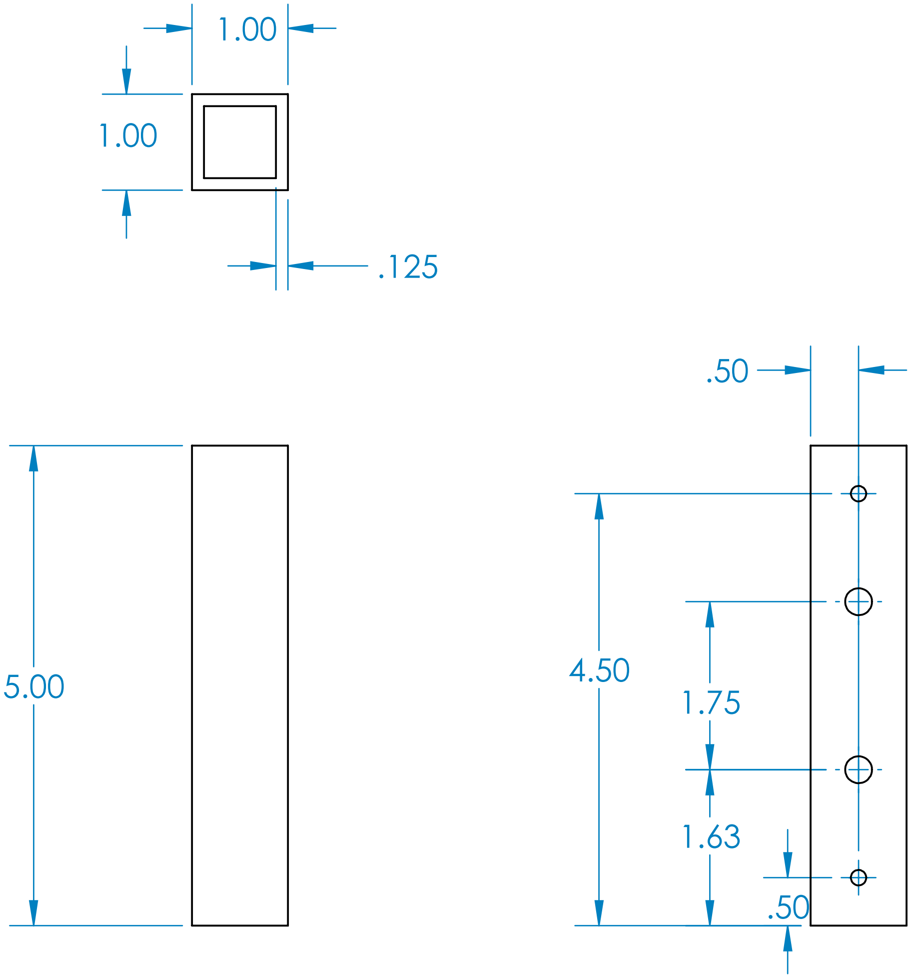
SIZE	DWG. NO.	REV
A	720	1

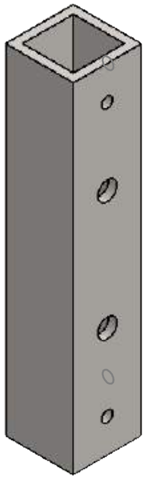
SCALE: 1:4
SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE: Slave Side Front Vertical Support
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 1inch Steel Tubing	COMMENTS:			SIZE A DWG. NO. 721 REV 1
				SCALE: 1:1 SHEET 1 OF 1





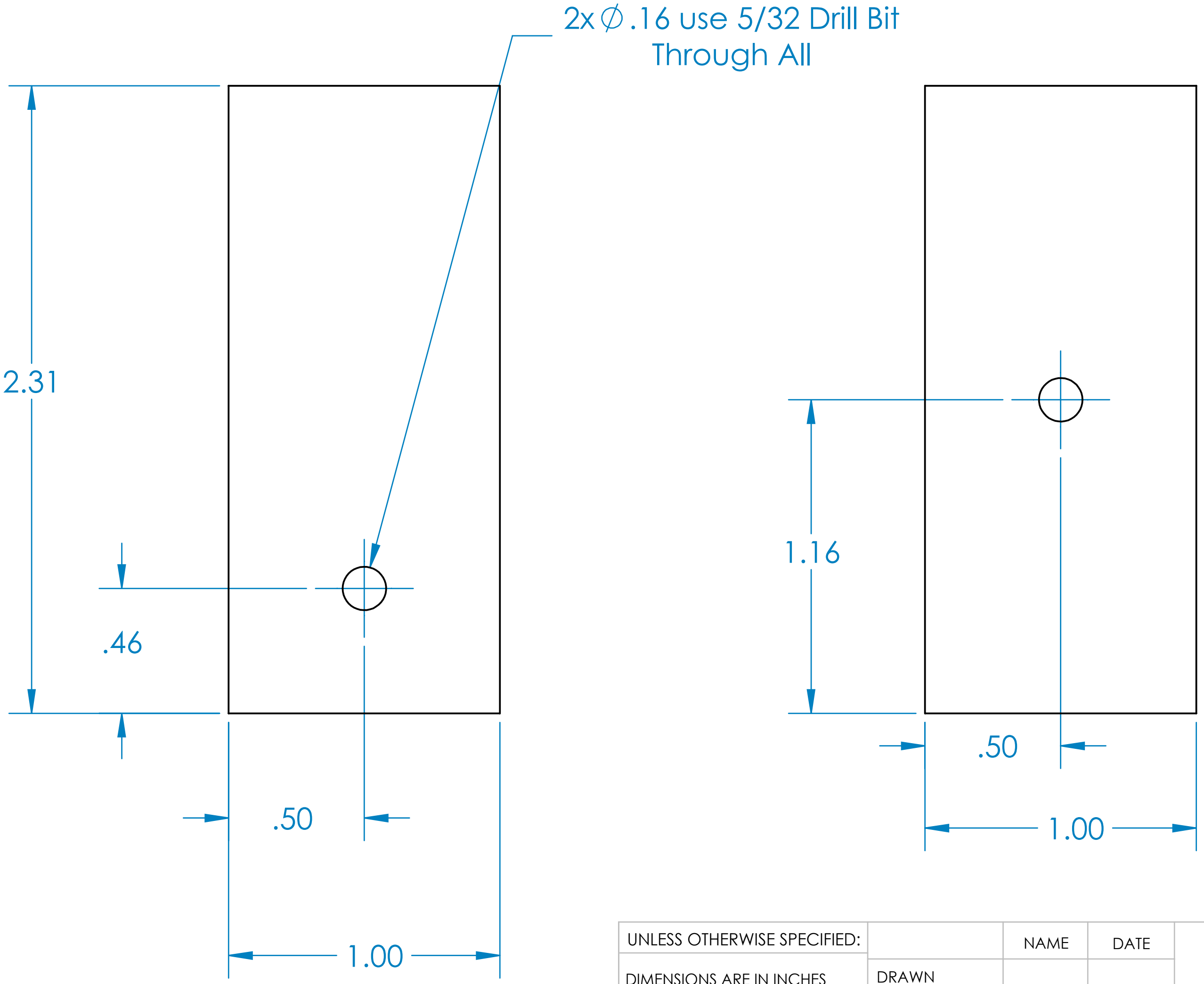
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL STEEL	COMMENTS:		

TITLE:

CROSS SUPPORT FOR
SLAVE PULLEY HOUSING

SIZE	DWG. NO.	REV
A	722	1

SCALE: 1:2 SHEET 1 OF 1

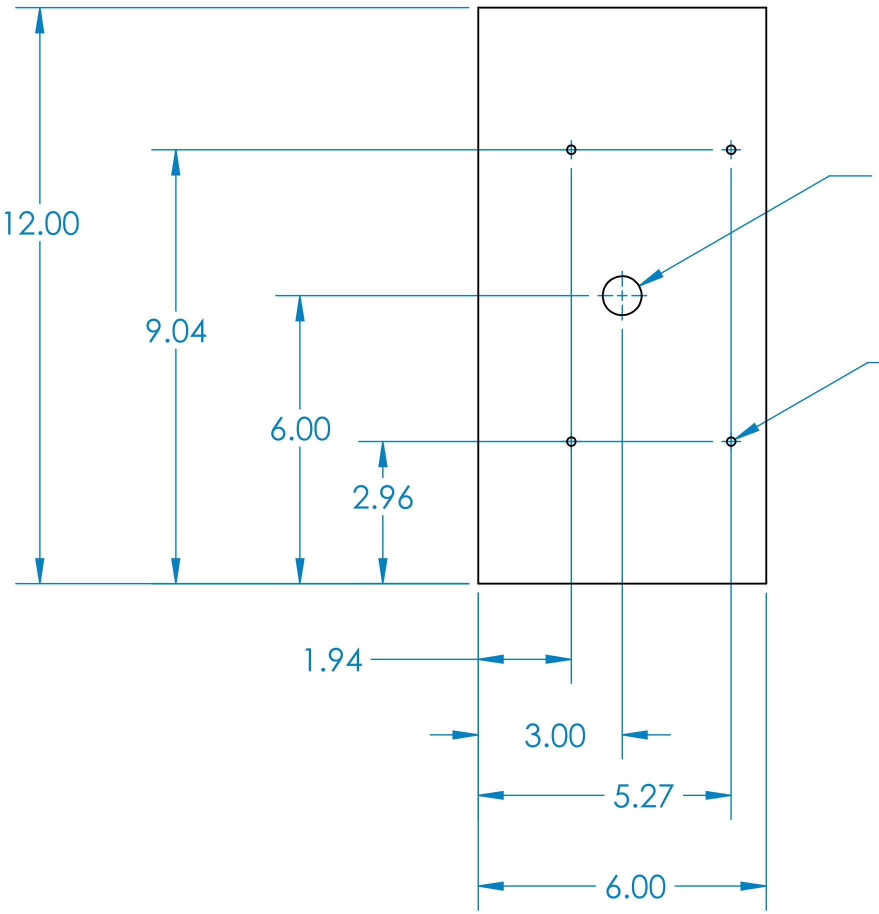


B

A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE: Back Vertical Support Slave Side
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 1inch Steel Tubing	COMMENTS:			

SIZE	DWG. NO.	REV
A	723	1
SCALE: 1:1		SHEET 1 OF 1



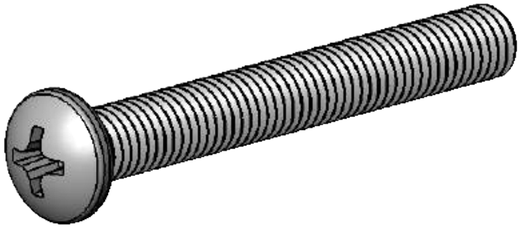
∅.81 Through all,
base on size of bearing (13/16" OD)
(only for steel piece)

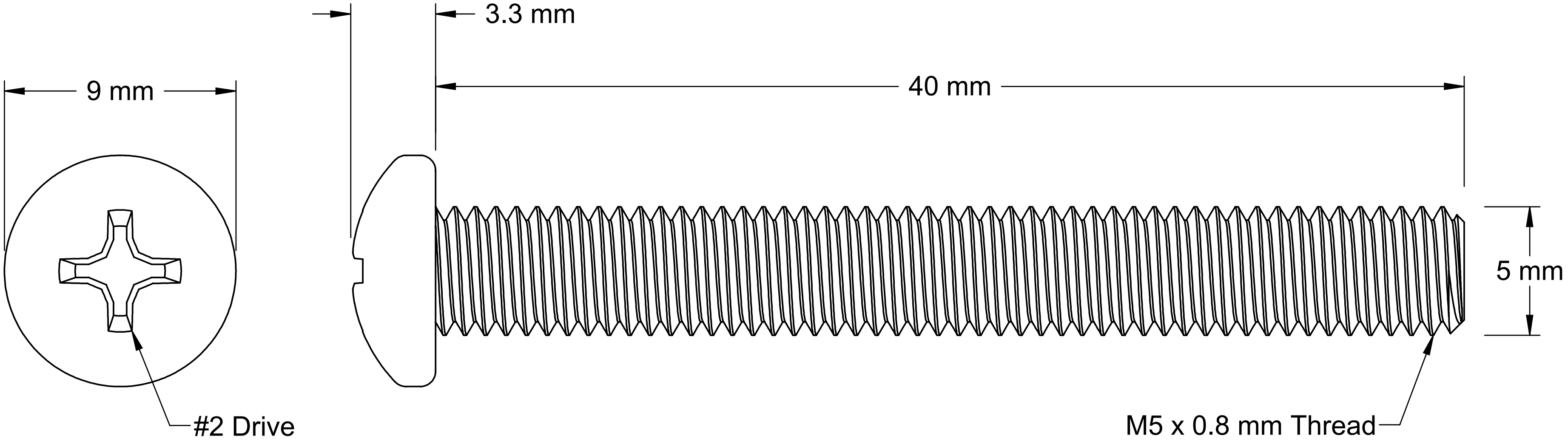
4x∅.18 use 5/32 Drill Bit
Through All

		NAME	DATE
UNLESS OTHERWISE SPECIFIED:	DRAWN		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL .1875 in thick T304 Stainless Steel Plate and one of Rubber	COMMENTS:		

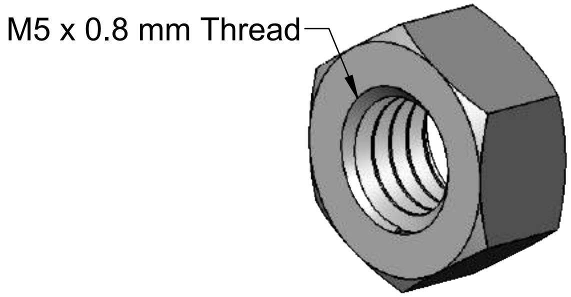
TITLE:
Slave Side Base Plates

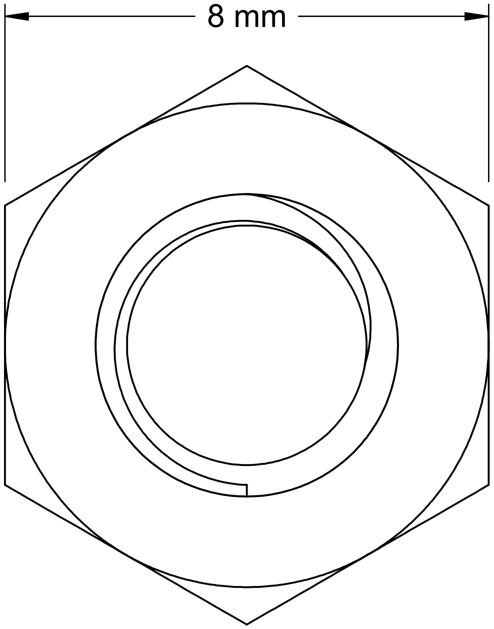
SIZE	DWG. NO.	REV
A	724	1
SCALE: 1:1		SHEET 1 OF 1

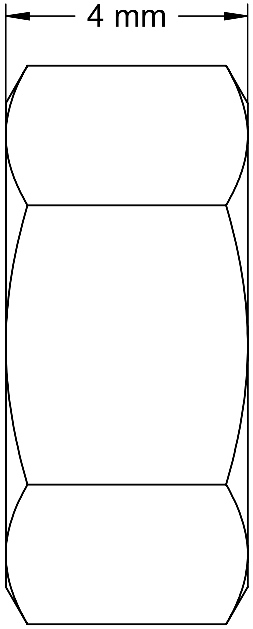




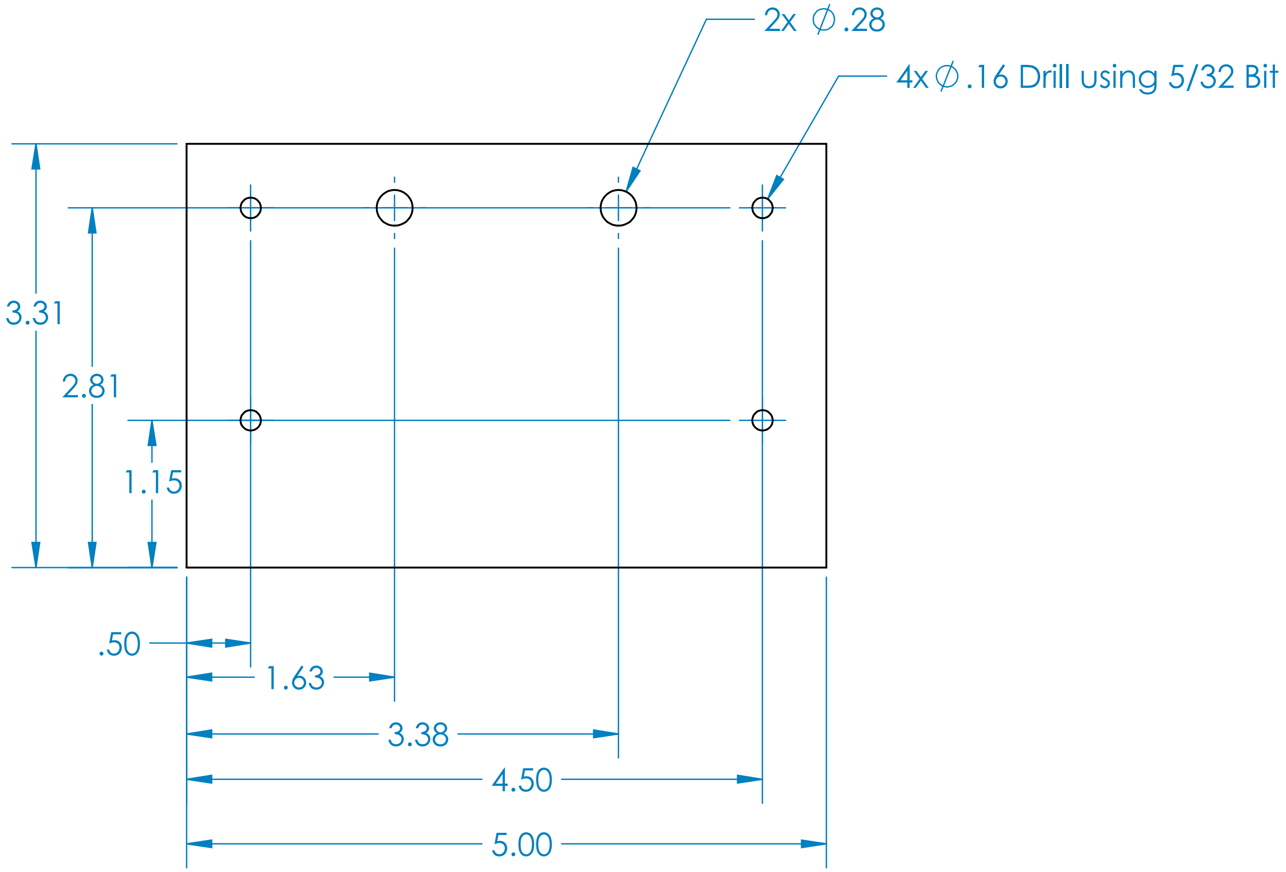
McMASTER-CARR® CAD	PART NUMBER 725
http://www.mcmaster.com © 2012 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Japanese Industrial Standard Pan Head Phillips Machine Screw







McMASTER-CARR® CAD	PART NUMBER	726
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric Hex Nut	



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL

.024in thick
cold rolled steel

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

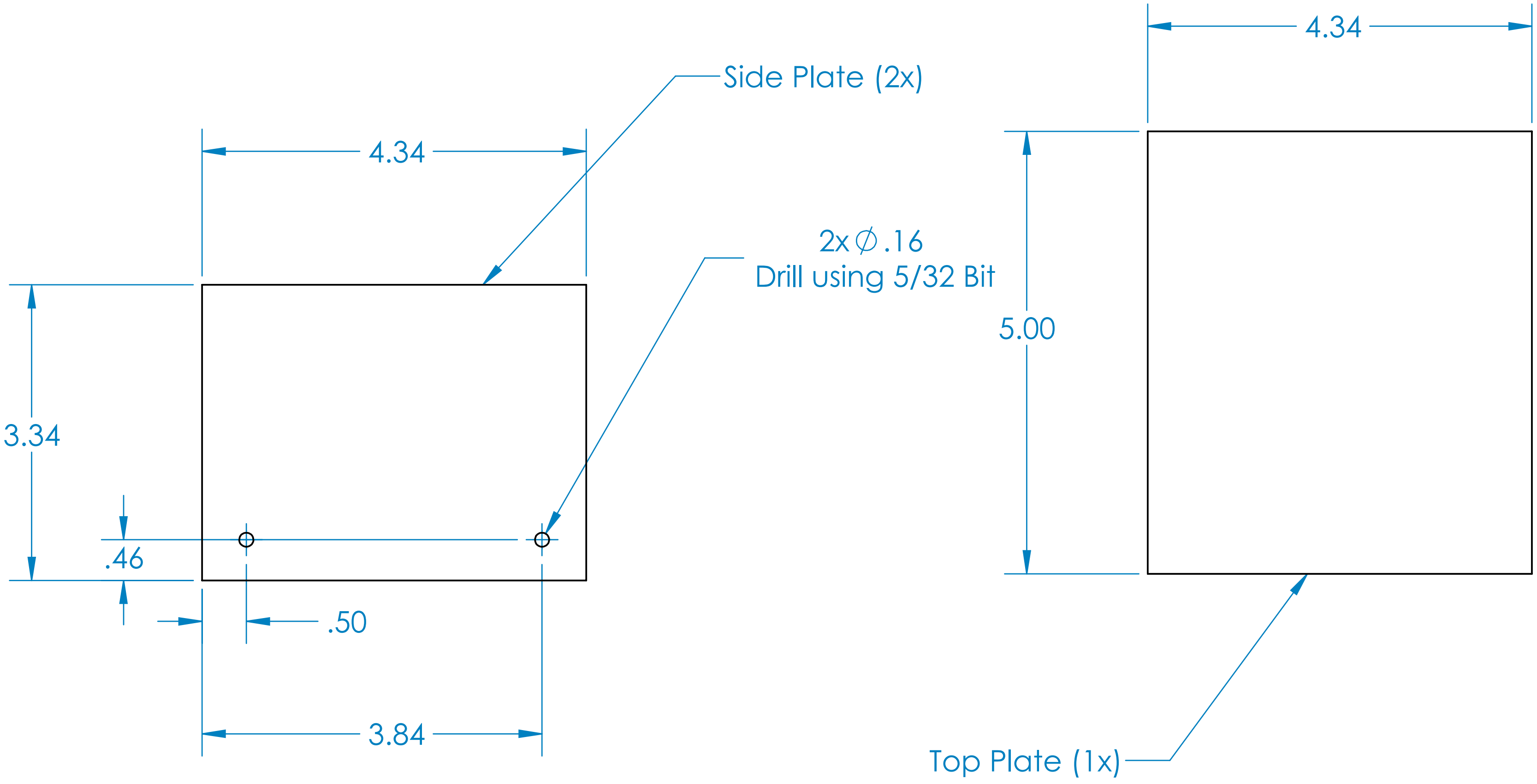
COMMENTS:

TITLE:

BACK COVER FOR SLAVE
PULLEY HOUSING

SIZE	DWG. NO.	REV
A	727	1

SCALE: 2:3
SHEET 1 OF 1

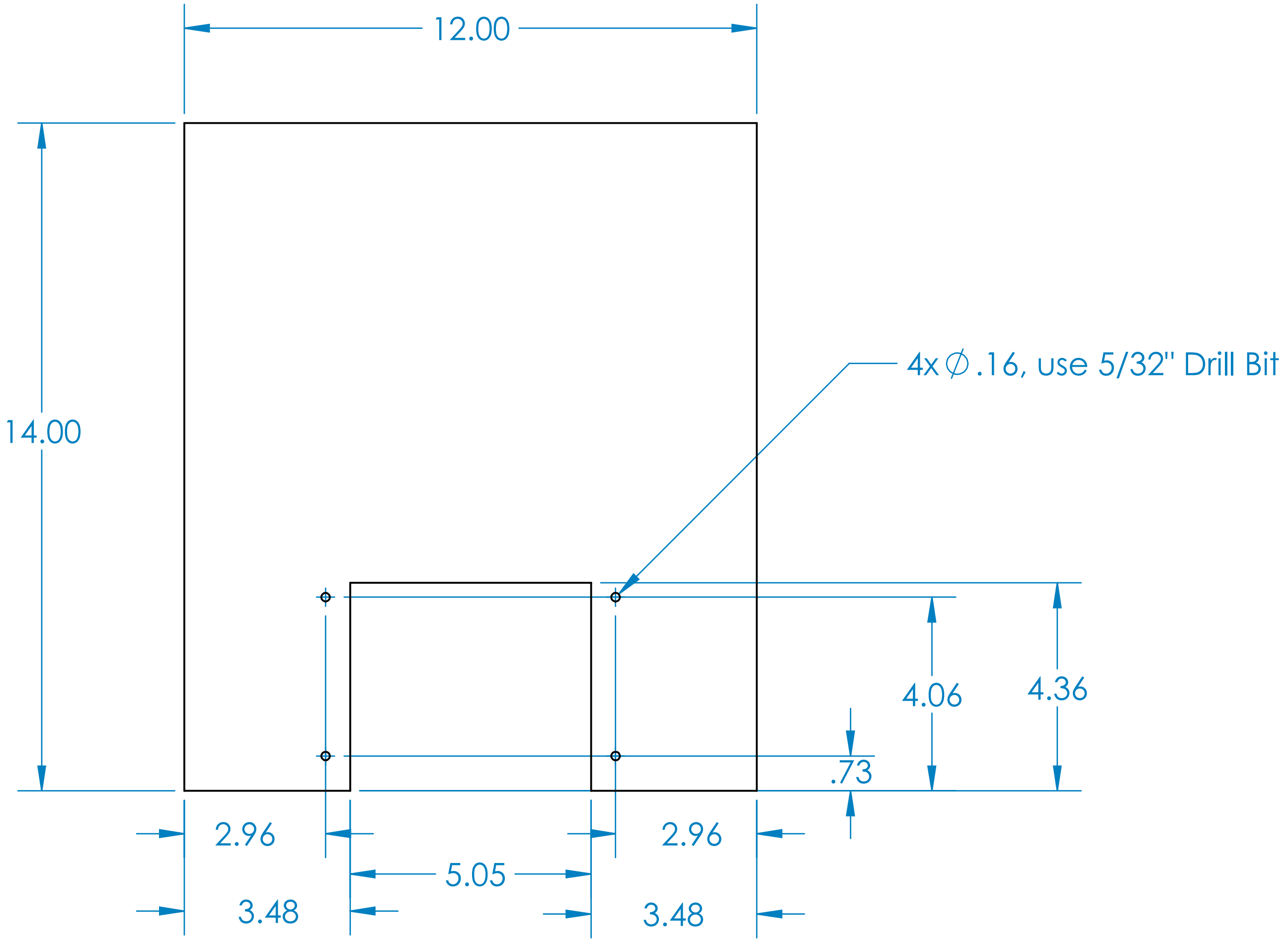


UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL .024in thick cold rolled steel	COMMENTS:		

TITLE:

Side and Top Casings for
Pulley Housing

SIZE	DWG. NO.	REV
A	728	1
SCALE: 2:3		SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL

.024in thick
cold rolled steel

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

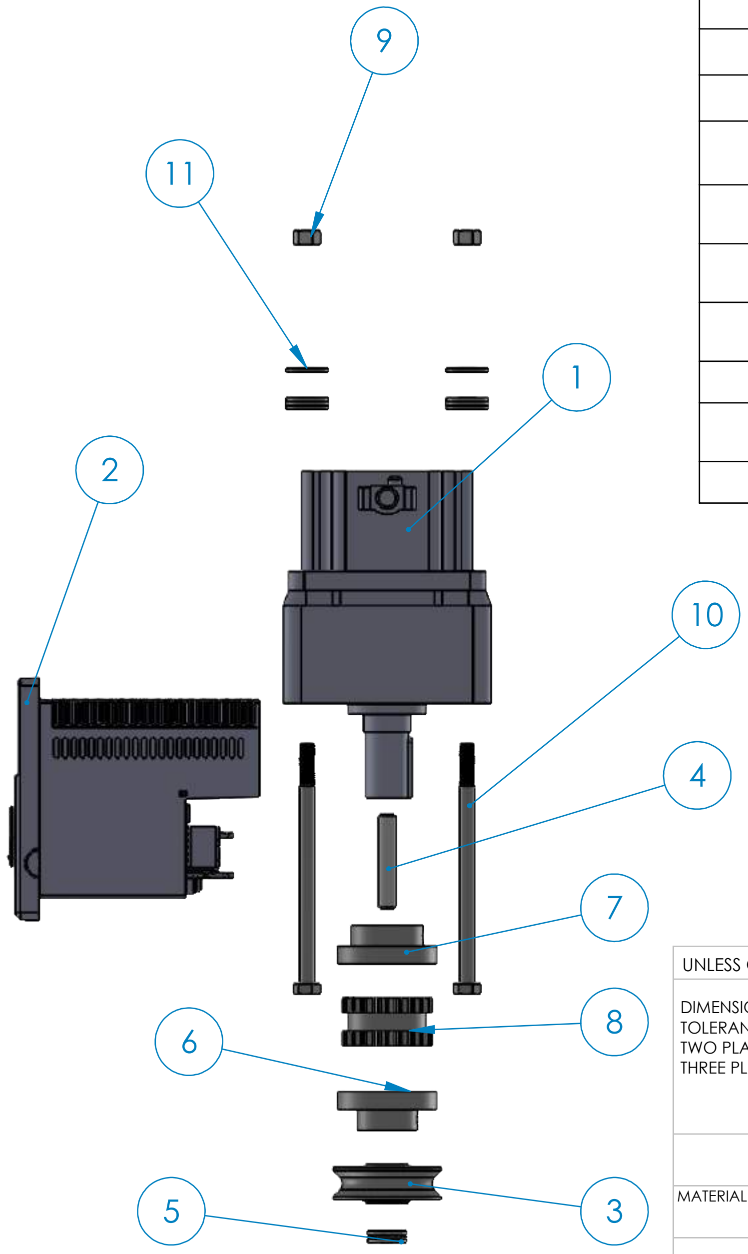
COMMENTS:

TITLE:

Base Extension for Pulley Housing

SIZE **A**
DWG. NO. 729
REV 1
SCALE: 2:3
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	Motor	Translation Motor	Various	1
2	Driver	Translation Driver	Various	1
3	3524T14	Pulley	Steel	1
4	1346K11	Pulley Shaft	Steel	1
5	6655K15	Thrust Ball Bearing	Plastic	1
6	6507K411	3/8" Shaft Conversion	Steel	1
7	6507K415	7/8" Shaft Conversion	Steel	1
8	6507K69	Shaft Conversion Center	Rubber	1
9	95036A035	5/16 - 24 Nut	Steel	4
10	91257A445	5/16 - 24 5inch Bolt	Steel	4
11	91860A030	5/16 Washer	Steel	16



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

MATERIAL
VARIOUS

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

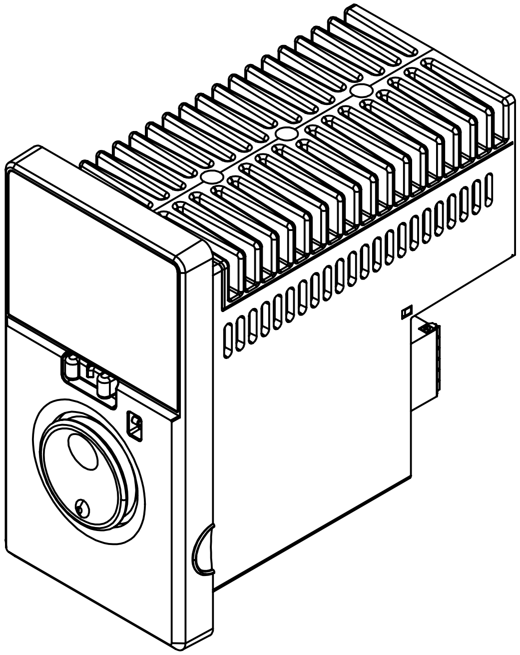
COMMENTS:

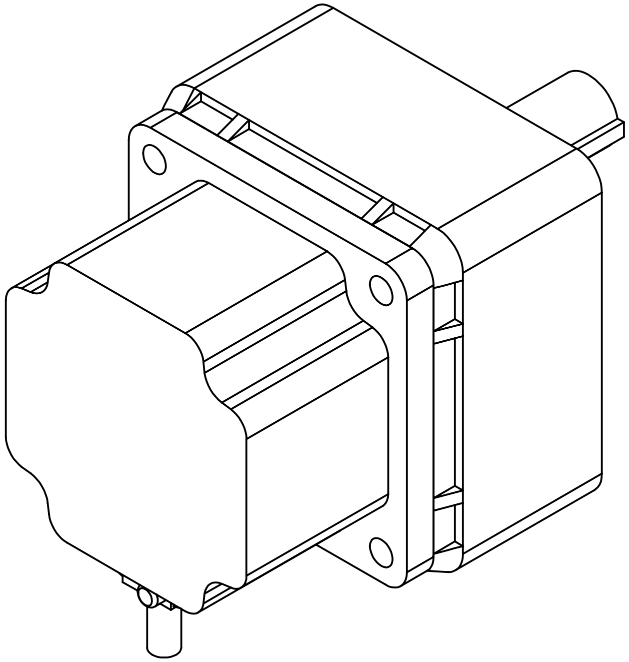
TITLE:

Motor Pulley Subassembly

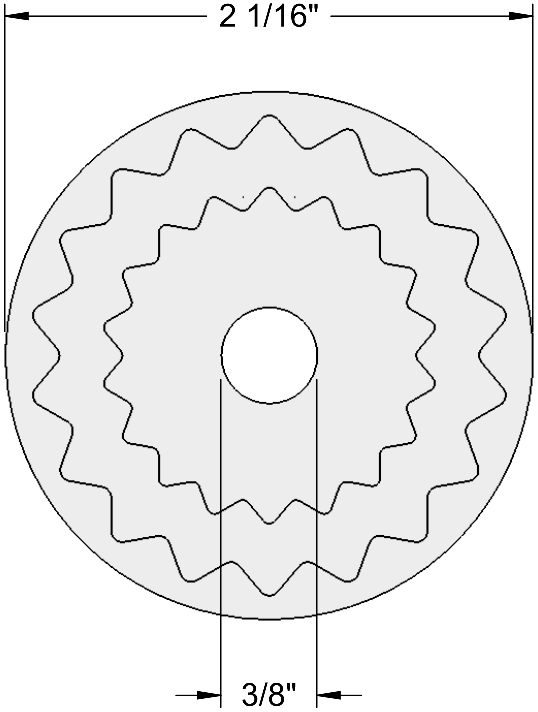
SIZE	DWG. NO.	REV
A	730	1

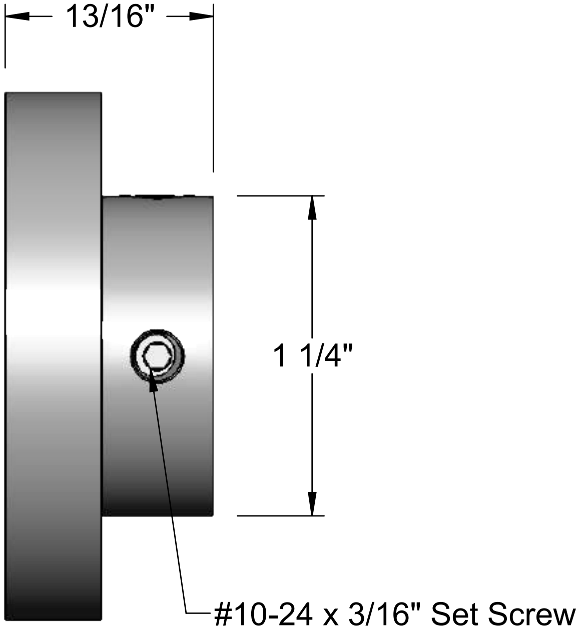
SCALE: 1:1 SHEET 1 OF 1





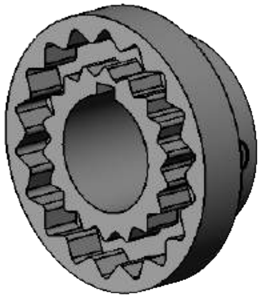
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			
	CHECKED			TITLE: Oriental Motor and Driver
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL	COMMENTS:			SIZE A
Various				DWG. NO. 731
				REV 1
				SCALE: 1:1
				SHEET 1 OF 1

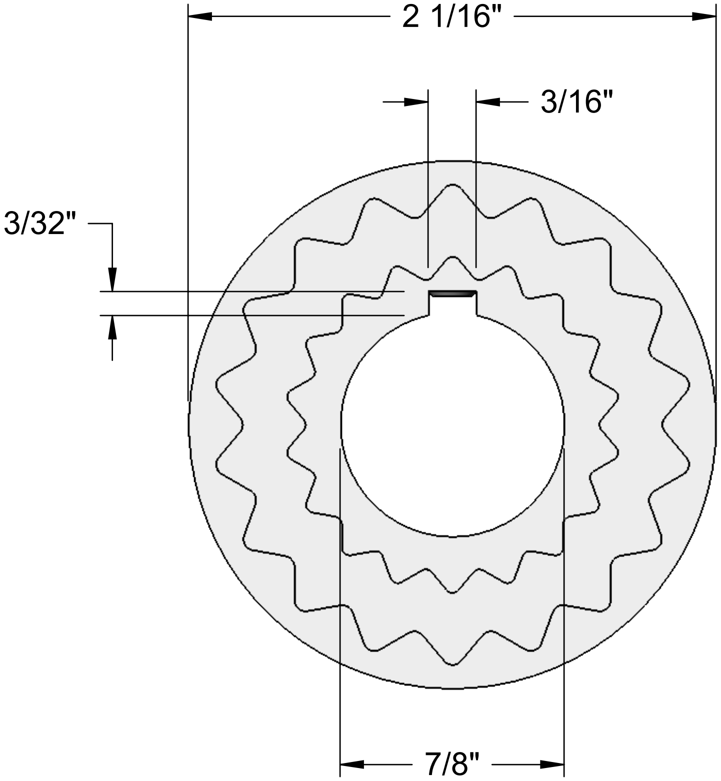


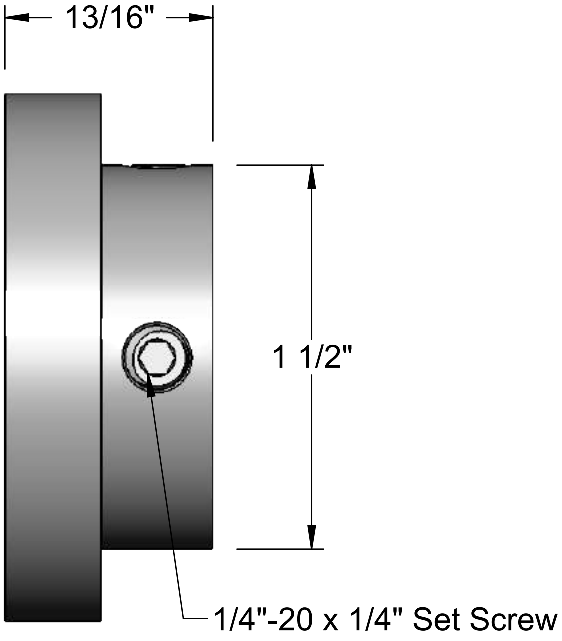


Complete Coupling (Two Hubs and One Rubber Center) Overall Length 2"

McMASTER-CARR® CAD	PART NUMBER 732
http://www.mcmaster.com © 2013 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Coupling Hub for Heavy Duty Replaceable-Center Flexible Shaft Coupling

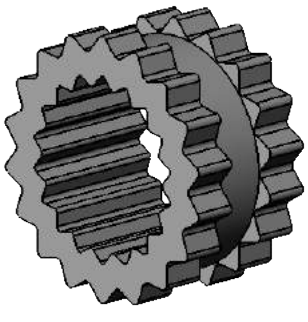


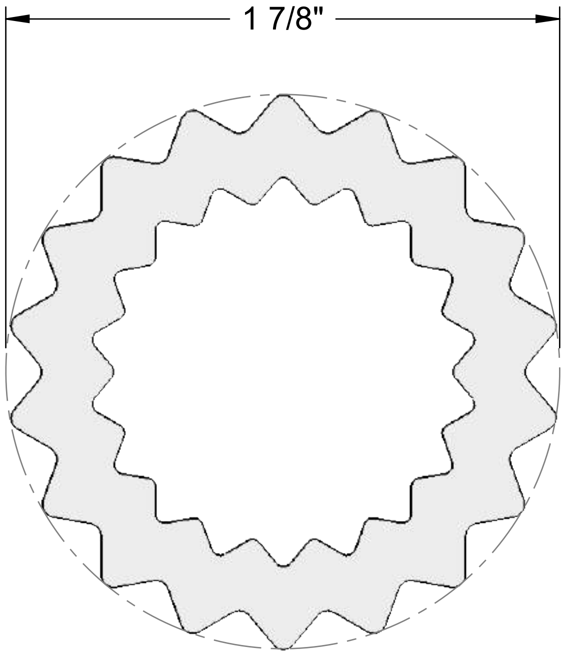


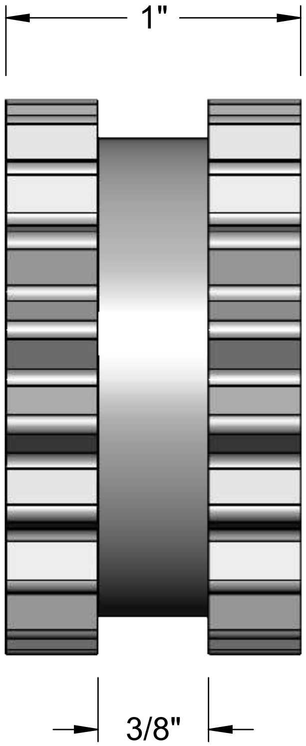


Complete Coupling (Two Hubs and One Rubber Center) Overall Length 2"

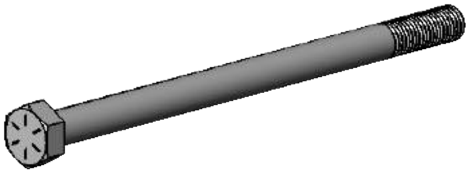
McMASTER-CARR CAD	PART NUMBER **733**
http://www.mcmaster.com 	Coupling Hub for Heavy Duty Replaceable-Center Flexible Shaft Coupling

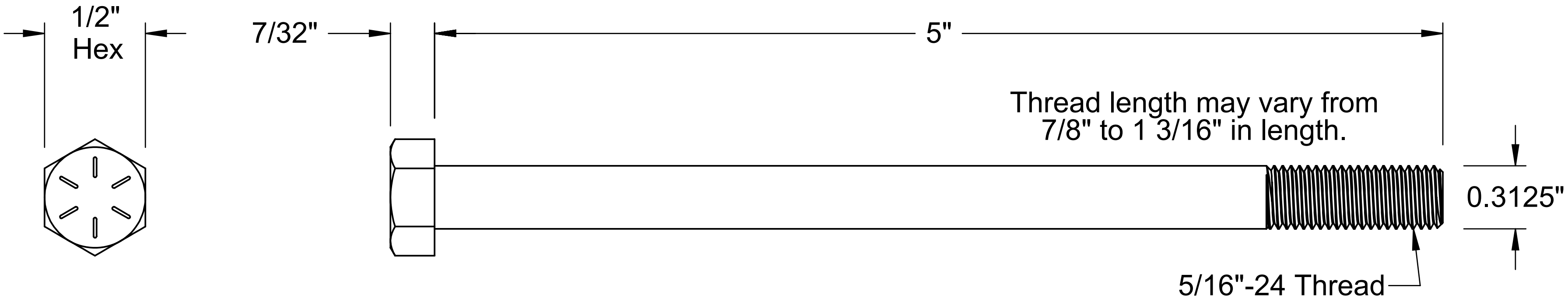






McMASTER-CARR® CAD	PART NUMBER 734
http://www.mcmaster.com © 2013 McMaster-Carr Supply Company	Rubber Center for Heavy Duty Replaceable-Center Flexible Shaft Coupling
Information in this drawing is provided for reference only.	



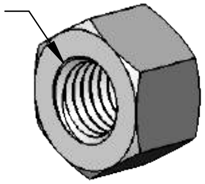


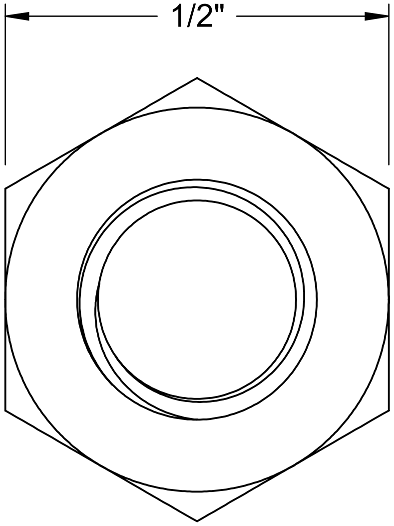
McMASTER-CARR® CAD

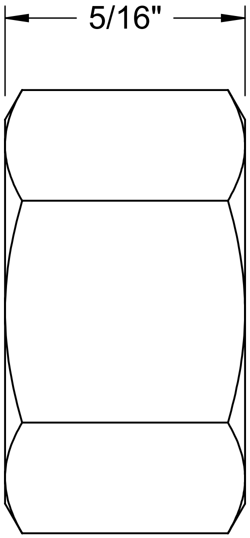
PART NUMBER **735**

http://www.mcmaster.com

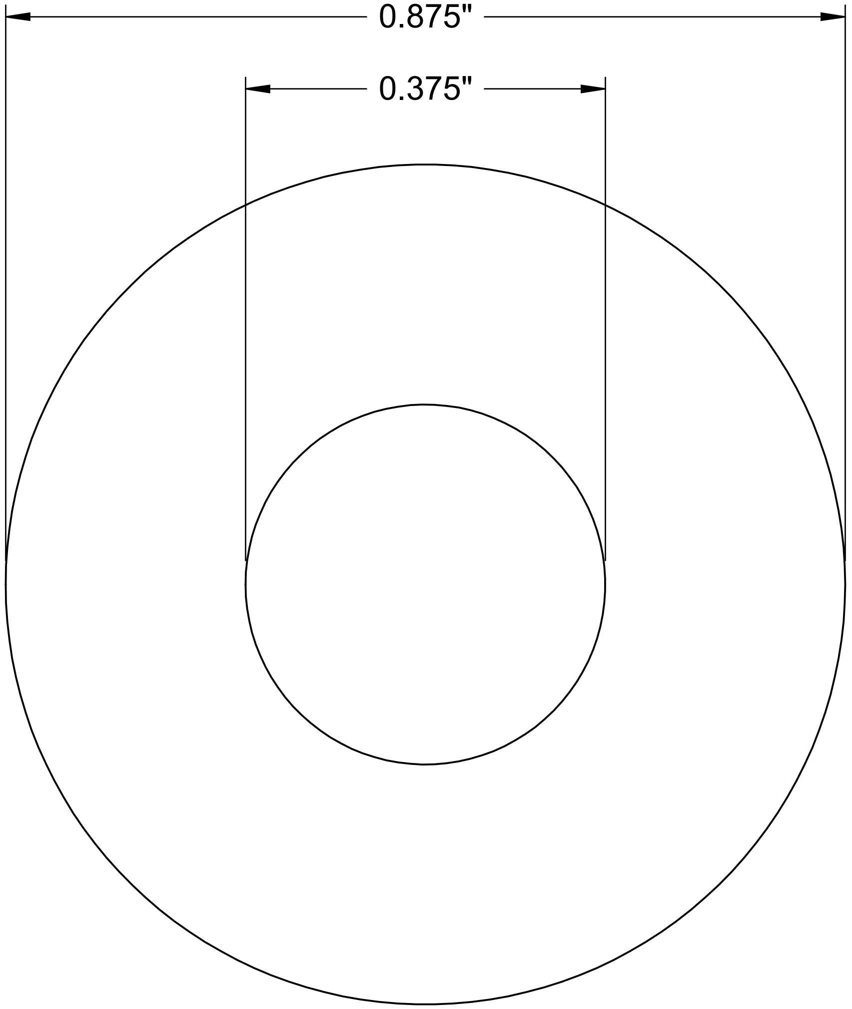
High-Strength Steel
Cap Screw-Grade 8

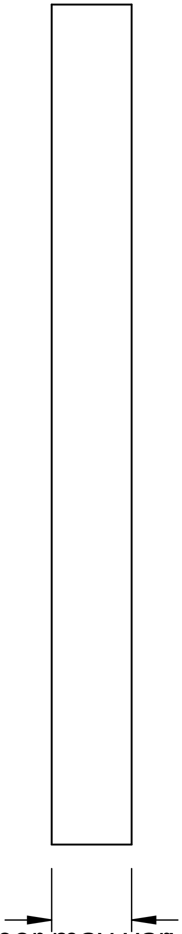


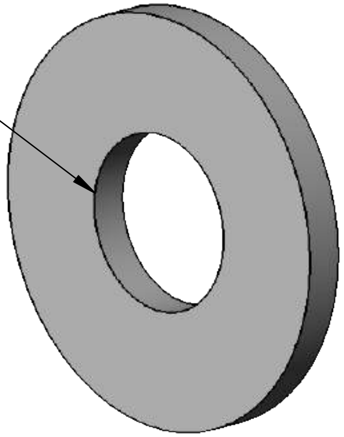




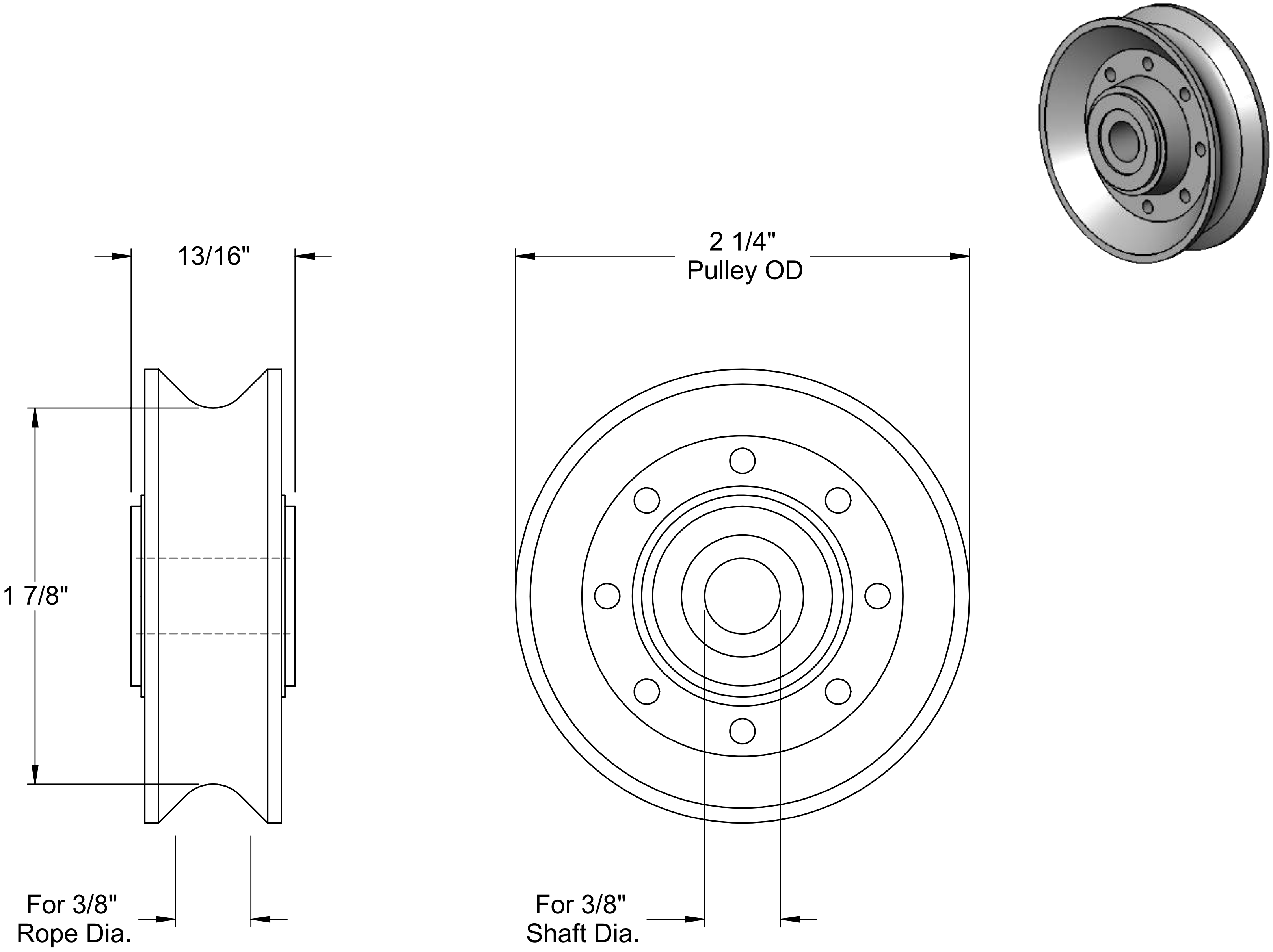
McMASTER-CARR® CAD	PART NUMBER	736
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Hex Nut	




Washer may vary from
0.073" to 0.083" in thickness.


For 5/16"
Screw Size

McMASTER-CARR® CAD	PART NUMBER 737
http://www.mcmaster.com 	General Purpose Washer

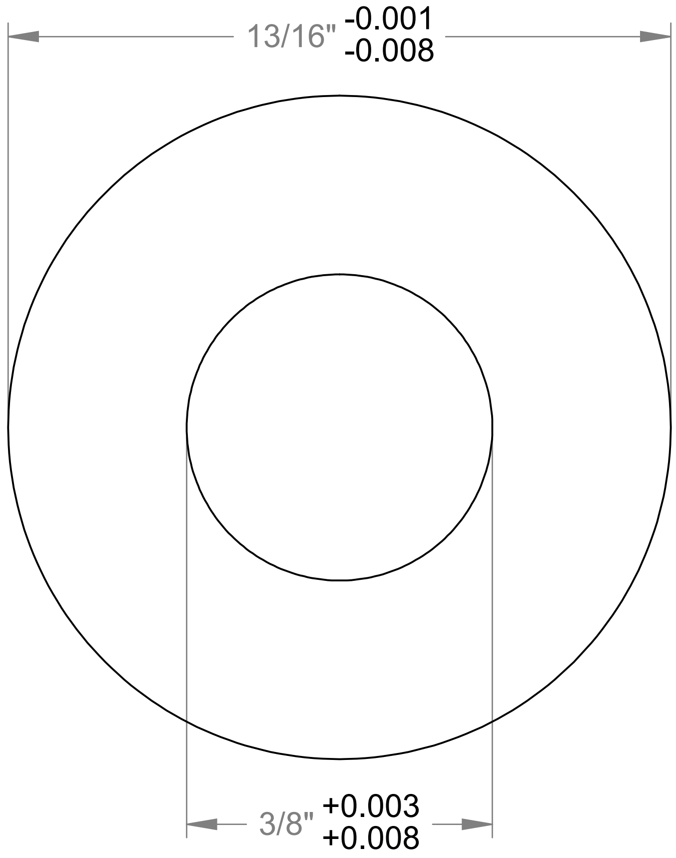


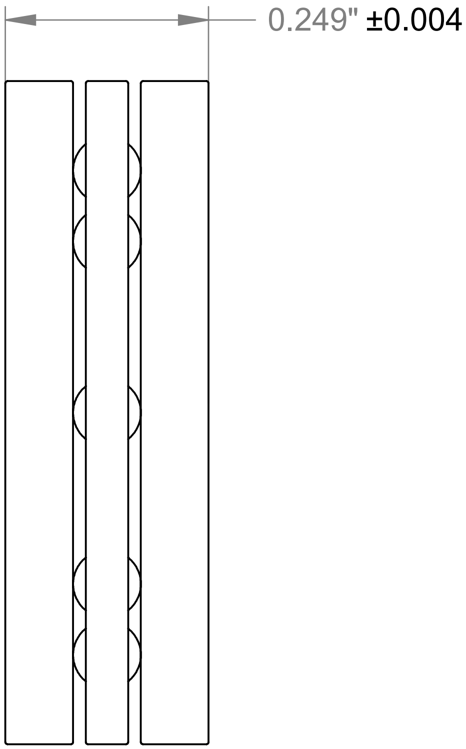
McMASTER-CARR® CAD

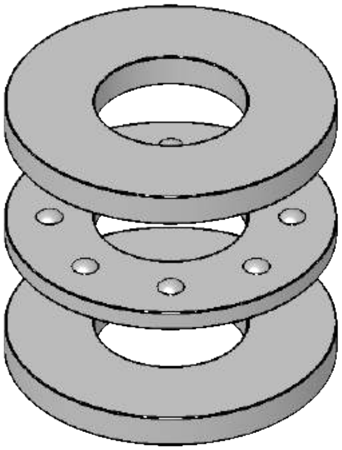
PART NUMBER **738**

http://www.mcmaster.com

Pulley for 3/8"
Fibrous Rope







McMASTER-CARR® CAD

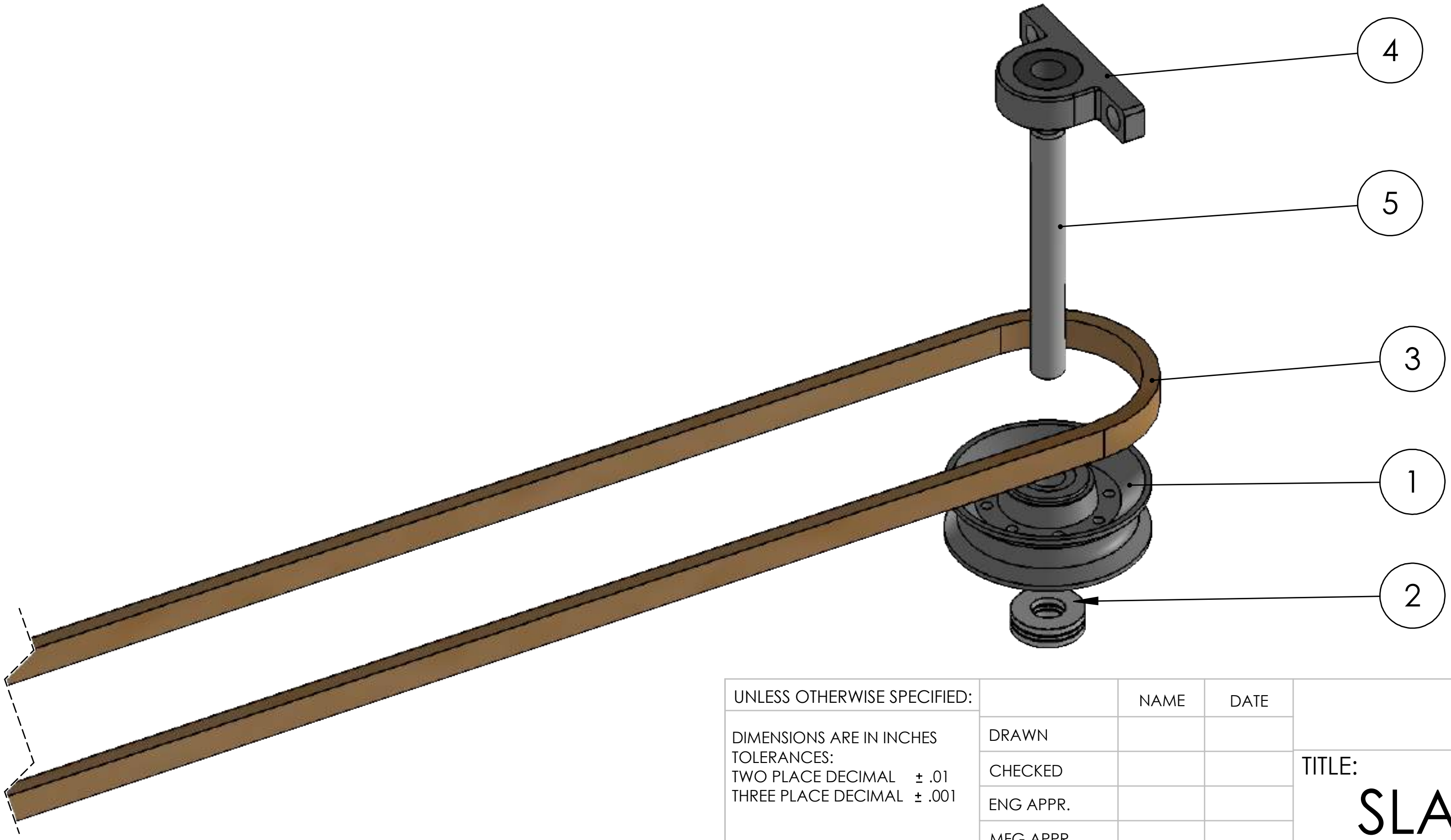
http://www.mcmaster.com

PART NUMBER 739

Plastic Thrust Ball Bearing Plastic
Thrust Ball Bearing Steel Washers,
for 3/8" Shaft Diameter, 13/16" OD

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	3524T14	Pulley	Steel	1
2	6655K15	Thrust Ball Bearing	Plastic / Steel	1
3	Rope	Manila Rope	Manila	1
4	5912K3	Mounted Ball Bearing	Steel	1
5	1346K11	Shaft	Steel	1

B B



A A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .001

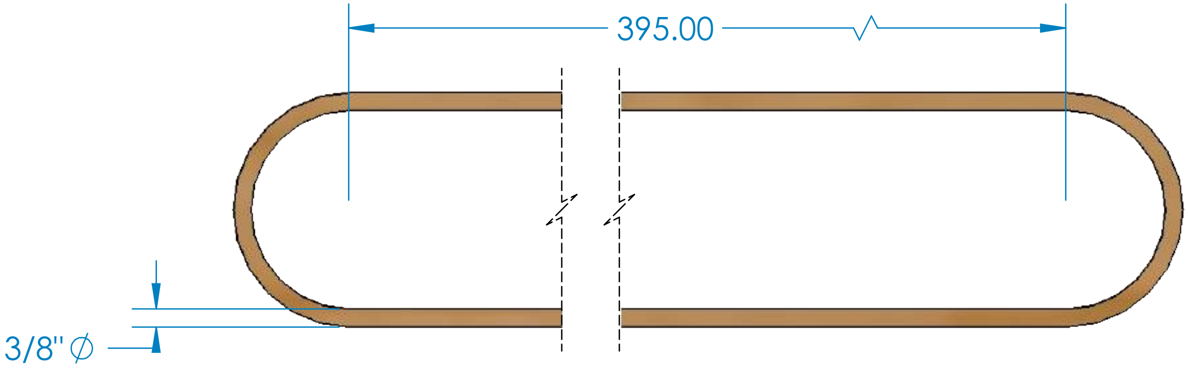
MATERIAL
VARIOUS

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

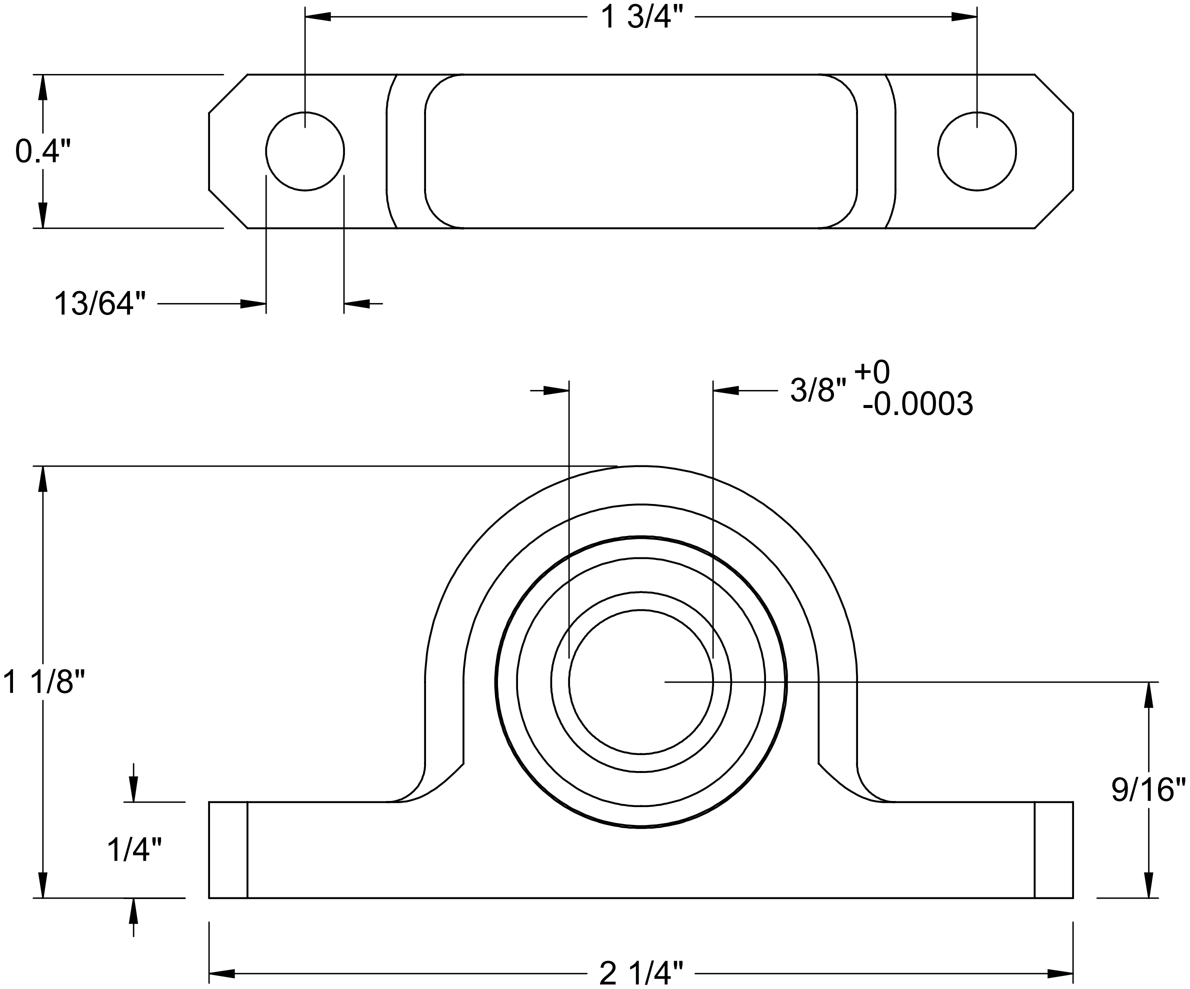
COMMENTS:

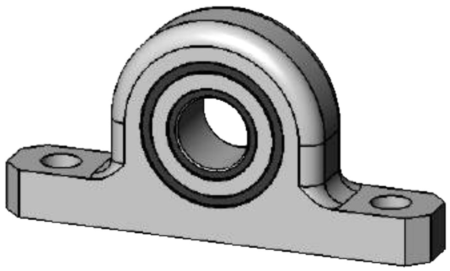
TITLE:
SLAVE PULLEY
ASSEMBLY

SIZE A
DWG. NO. 740
REV 1
SCALE: 1:2
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .001	DRAWN			TITLE: 3/8" DIAMETER MANILA ROPE
	CHECKED			
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL MANILA ROPE	COMMENTS:			SIZE A · DWG. NO. 741 · REV 1
				SCALE: 1:2 · SHEET 1 OF 1





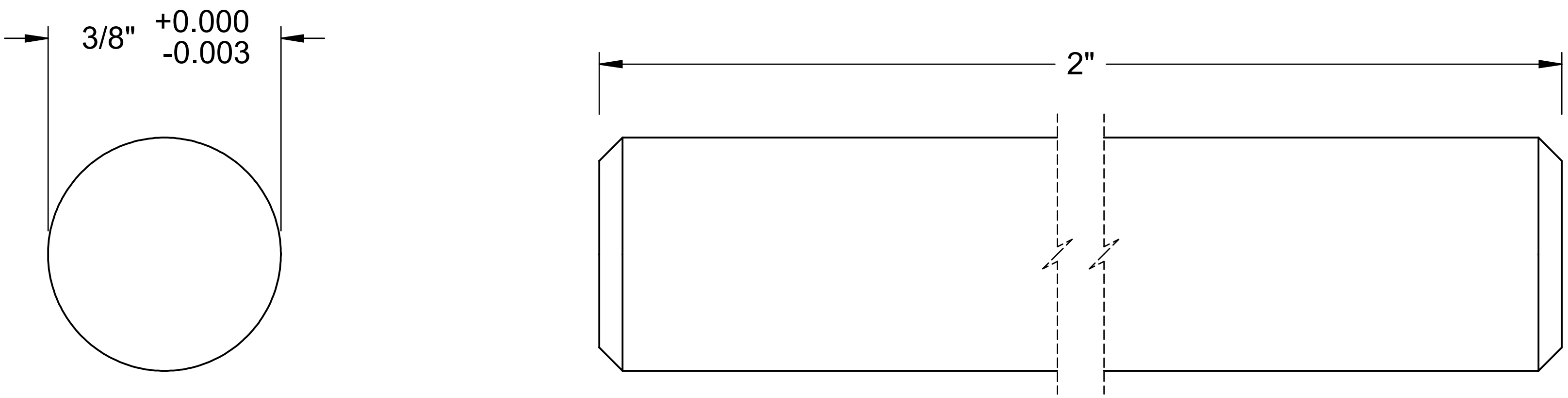
McMASTER-CARR CAD

http://www.mcmaster.com

PART NUMBER **742**

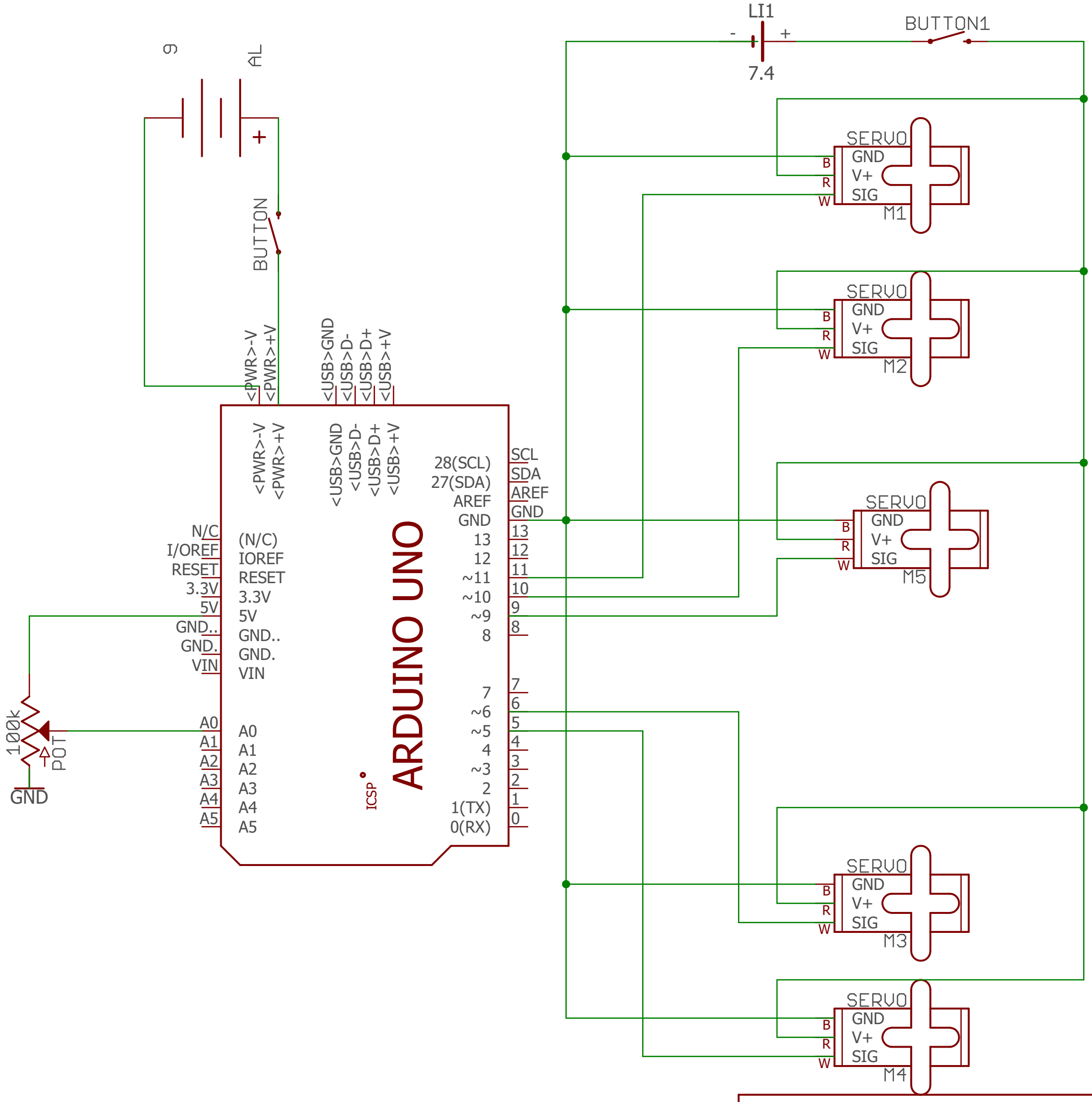
Aluminum Base-Mounted
Stainless Steel Ball Bearing

2" LENGTH USED IN MOTOR AND PULLEY SUBASSEMBLY
3.25" LENGTH USED IN SLAVE PULLEY SUBASSEMBLY



Straightness Tolerance is 0.012" per Foot

McMASTER-CARR® CAD	PART NUMBER	743
http://www.mcmaster.com © 2012 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Drive Shaft	



TITLE: Motor&Controls_Schematic

Design by: **800**

REV:

Date: 6/5/2017 7:44 PM

Sheet: 1/1

6/5/2017 7:46 PM C:\Users\Tim\Documents\eagle\Senior Project Articulation\Motor&Controls_Schematic.sch (Sheet: 1/1)