Mars Rover Winter Semester Report

April 14, 2014

Project Sponsor: BYU Department of Mechanical Engineering

Capstone Team 7: University Rover Challenge/BYU M.A.R.S.

BYU M.A.R.S.

By signing below, we approve the submission of this report, and agree that it accurately represents the work the team has accomplished.

Liaison	David Allred		Date 14 Apr 2014
Coach	Rick Giles		Date 4/14/14
Capstone	Dr. Mattson		Date
Instructor	Dr. Sorensen		Date
Team Member	Devin Anderson		Date 4/15/14
Team Member	Drew Anderson		Date 4/15/14
Team Member	Kendal Frogget		Date 4/15/14
Team Member	Clayton Grames		Date 4/15/14
Team Member	Chris Mabey		Date 4/15/14
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Ira A. Fulton College of Engineering and Technology
Brigham Young University

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Executive Summary

The purpose of our project is to design a rover, remotely operated vehicle, capable of taking 1st place at the University Rover Challenge in Hanksville, Utah from 29th-31st May 2014. The intent of this competition is to develop a robotic field assistant to accompany astronauts who travel to Mars. In order to achieve this goal we need to be able to perform set tasks for the competition. The tasks consist of sample return, astronaut assistance, equipment servicing, and terrain traversing. The rover will be judged based on its ability to meet the requirements of each task.

This project is a continuation of efforts made by other BYU students in past years. BYU has had a team enter a rover to the competition every year for the last 7 years. These teams have consisted primarily of volunteers and students receiving individual project credit. The latest rover from the 2013 competition is a culmination of their efforts. This year is the first time a capstone team with significant funding has been involved with the BYU mars rover. The experiences and design work of past teams is being used to help drive the design decisions that will allow this year's rover to complete all the competition tasks.

The contest provides very specific requirements for each required task. The full details of the competition tasks and requirements can be found in Appendix A-3. Consequently, very specific requirements for the rover were created to ensure that the rover would be competitive at the competition. All design decisions have been made to meet those requirements at both the system and subsystem level. Subsystem requirements were developed to better describe the needs of each component. Information and verification checks have been performed against subsequent design decisions to ensure that they meet the requirements.

Design decisions for the rover were driven by the market requirements to ensure the design would be able to accomplish each task in the competition. Failure Mode and Effects Analyses were conducted for each subsystem and potential areas of risk have been mitigated.

All of the mechanical systems have been fabricated and tested individually via remote control to ensure that each mechanical system will be able to accomplish competition tasks. The entire rover has not been tested as a complete system under competition conditions because the electrical and software systems are not in a state to test the entire rover. These systems will be complete before the competition but are not complete at this time.

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Introduction

The purpose of our project is to design a rover capable of taking 1st place at the University Rover Challenge in Hanksville, Utah from the 29-31st May 2014. The intent of this competition is to develop a robotic field assistant to accompany astronauts who travel to Mars. In order to achieve this goal we need to be able to perform set tasks for the competition. The tasks consist of sample return, astronaut assistance, equipment servicing, and terrain traversing. The rover will be judged based on its ability to meet the requirements of each task.

The rover design specifications were derived from the competition tasks defined by the Mars Society. Each task has multiple requirements; these requirements are covered in detail in Appendix A-3.

Summary of task requirements

- Sample Return
  - Select 3-6 sites with potential for signs of life
  - Sample must be collected at a depth of at least 2”
  - Sample must be at least 25 g, but less than 250 g
  - Take high resolution photo of site close up
  - Produce a wide angle panorama image
  - Record GPS coordinates of each site
- Astronaut Assistance
  - Collect objects in field based on GPS coordinates
  - Objects will be up to 5 kg in mass
  - Deploy wireless repeater
- Equipment Servicing
  - Travel 0.5 km
  - Read printed instructions in field
  - Connect pipe fittings
  - Flip switches
  - Push buttons
- Terrain Traversing
  - Traverse soft sand, stony areas and boulder fields
  - Withstand vertical drop in excess of 0.5 m
  - Climb slopes in excess of 60°
  - It will be advantageous to climb vertical terrain
  - Pass through gates 2 m apart based on GPS coordinates
- Presentation
  - Describe rover design and functionality
  - Shall be no longer than 15 minutes

In order to manage our team effectively to create a design that would incorporate all of these requirements, we chose to break up our project into the following systems and subsystems:

Arm

- Links
- Gearboxes and Wrist Servos
- Turret

- End effects

Chassis
- Frame
- Suspension
- Wheels

Communications
- Gimbal and Vision
- Controls and Sensors

The rules and requirements of the competition in May have been laid out by the Mars Society. With the opportunity development already completed, we began with concept development. Currently the rover design is in the final stages of system integration. The rover is mechanically assembled, but the electrical and software systems are incomplete. The rover is functioning under hobby grade electronic controls. The following sections will detail the subsystems, the design decisions, and acceptance testing for each section.

Arm

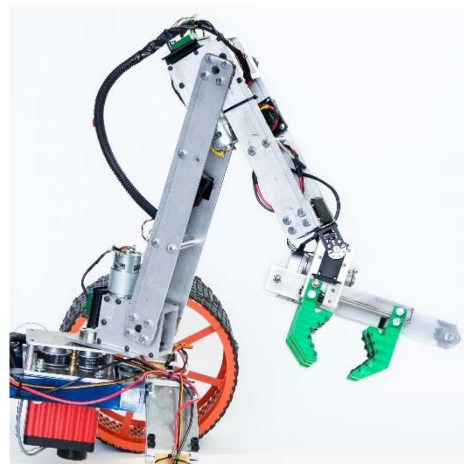
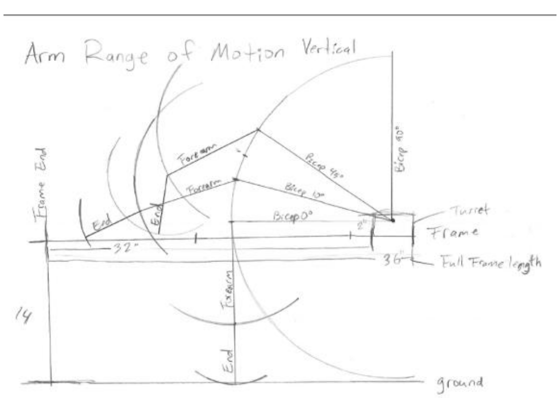


Figure 1: Current Arm configuration

The arm is an integral part of the rover that will be critical in performing three of the tasks. The arm can be bolted between two rails on either the front or the back of the rover. Current setup allows for 120° rotation, which is limited based on the pulse width we are sending using hobby control. The arm is able to reach the full length of the rover, as well as ground-level to 1 meter high. There are two end effects, a claw grip and an auger.

Links

Requirement Information: The arm is required to position the end effects anywhere they need to be moved in order to complete the competition tasks. The overall range of motion is based off of the known minimum requirements; see Figure 2. The information for the payload states that we will have to collect up to 5kg per package. The arm links must also be able to withstand any minor impacts, unforeseen objects, and rough terrain the rover will traverse during the tasks. The constraints on the design were to keep the weight under 10kg with a target of 6kg. The overall arm budget was $2,650.



Design Information: The arm mimics the structure of a human arm, allowing for easier control and a high degree of freedom. The links are aluminum plates measuring a total of 36 inches in length. The overall weight of the links in the current configuration is 3 lbs. The joints act like an elbow and wrist respectively as seen in Figure 1. The elbow is a 1 degree of freedom joint, while the wrist has 2 degrees of freedom. In order to meet the requirements, our design includes a full 360°

rotation with a dead band down the middle of the rover. This allows payloads of interest to be placed onto the rover for transport shown as shown in Figure 2. The dead band is related to the turret itself and only limits the rotation, not the overall reach of the links. We chose T6061 aluminum for its strength-to-weight ratio and failure mode.

The overall frame design uses parallel rails for stiffness in bending and torsion. This allowed gearboxes and servos to mount in between the frame which reduces the size of the arm while retaining the strength. This design also enables the arm to pick up the required 5 kg load while not approaching failure. Since the arm links are vertically aligned, the force will be distributed between both the links. The link lengths were specified based on the reach requirements; the prescribed lengths of 16, 10, and 6 inches for the two arm links and the end effect, respectively. This allows the rover to reach the entire rover frame and all task equipment. Detailed engineering drawings of the arm can be found in Appendix B-1; drawings are labeled AF 0-4 and AF 0-2.

Figure 2: Arm vertical range of motion

Acceptance Test Information: Range of motion of the links has been verified by controlling them remotely through their entire range of motion while under load. A weight of 10kg was used to verify the distribution of load over the links; this ensured that they are strong enough to withstand more than the required safety factor of 2 (see evaluation criteria 3 in the Arm Requirements Matrix. Appendix A-4). An FEA shown in Appendix C-1 Photo 3 confirms the arm design is well within safety limits.

Gearboxes and Wrist Servos

Requirement Information: The arm is required to transport the end effect(s) anywhere they need to be in order to complete the task they were designed for. Designing the system in this way allows the arm to operate as the platform for completing the astronaut assistance, equipment servicing, and sample return tasks. This design includes being able to reach the rover body to store payloads of interest for transport. The motors and effector for astronaut assistance must be able to carry loads of up to 5 kg. The motors must stay within their weight and budget restrictions of under 10 kg and 2,650 dollars for the entire arm.

Design Information: The gearboxes and servos animate the links of the arm. The gearboxes provide the shoulder and elbow motion while the servos provide the two degrees of freedom to the wrist. Research was done to determine if there were suitable, pre-built, items that were on the market for purchase. We found that there are servos that will work for the wrist motions. The servos are made by Dynamixel, and are capable of providing 4 ft-lbs of torque. In researching gearbox options for the shoulder and elbow joints, we determined that nothing commercially available was capable of providing the required torque output of 90 ft-lbs while fitting our space restrictions. This required the design of a custom gearbox with 4 stages. The first 3 stages are a 4:1 reduction, and the last is a 30:1. This design was determined by calculating a load 4 times the required amount being picked up at full extension (See Appendix

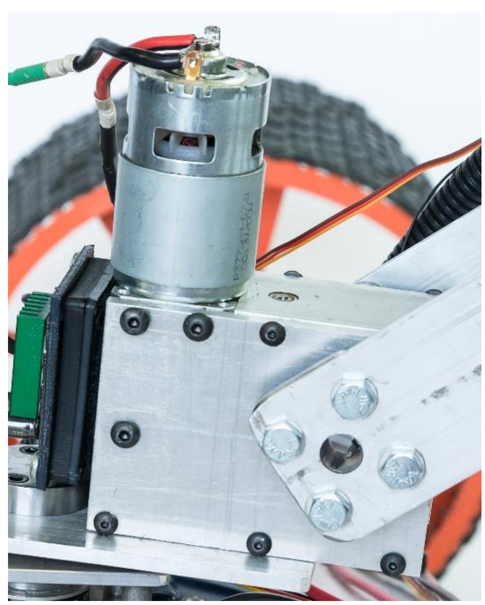


Figure 3: Gearbox

C-1). The gearbox is pictured above in Figure 3; detailed engineering drawings are found in Appendix B-1.

The gearbox features stock parts with custom framework and drive shafts. The use of a worm and gear in the design allows the arm to move and remain in a position without being back driven. A Bane Bots P60 (planetary gearbox) provides an initial reduction of 16:1 before the further reduction by the worm and gear. This gradual reduction helps distribute the forces acting on the different components of the gearbox. Thrust needle bearings resist the side loads produced by the worm as seen in the assembly drawing (AG-0, Appendix B-1).

Further calculations were performed to determine the material and size of the gears. Making these careful considerations avoids shearing teeth off and destroying the box during operation; see calculations in Appendix C-1. The gears are commercial bronze and hardened steel.

Acceptance Test Information: Calculations for the required torque were performed and are included in Appendix C-1. The finalized design of the gearbox provides 60 ft-lb of torque. The arm is able to pick up 10kg at full extension before the worm gear started slipping fulfilling evaluation criteria 3 (Arm Requirements Matrix: Appendix A-4). We have not pinned the worm to the shaft, so we expect it would be able to do twice this when completed. These gearboxes are capable of turning at 90 deg/sec which was tested by our current setup. The speed of the gearboxes was limited by the gearing, which contributed to the high torque capabilities.

Currently, there is approximately 10° of play in both gearboxes. This could be related to gear wear-in, which really is only a major issue when the arms move past vertical. As the gearboxes will not be rotating more than 180 degrees, their control and positioning performance is acceptable.

The servos used for the wrist have been verified by demonstrating basic control with hobby grade electronics. We were able to get the expected range of motion and output torque. During the initial test there was a problem which damaged the encoder in both servos. During testing a wire was severed and the servos became inoperable. They will be repaired under warranty, but the broken servos have delayed testing until the 26th of April.

Turret

Requirements Information: The turret is the main interface between the chassis of the rover and the arm (Figure 4). It is critical for the range of motion of the arm because it provides the rotation in a plane parallel to the ground. The turret must have 360 degrees of rotation to allow the end effects to reach points of interest, which include any objects or equipment in front of the rover and the storage space on the body of the rover. It must be able to support and rotate the arm at full extension when it is under a maximum load of 5 kg. The arm requires great dexterity to perform all of the required tasks. The total weight budget of the arm is 10 kg. This includes any storage compartments added to the rover for the astronaut assistance task or sample

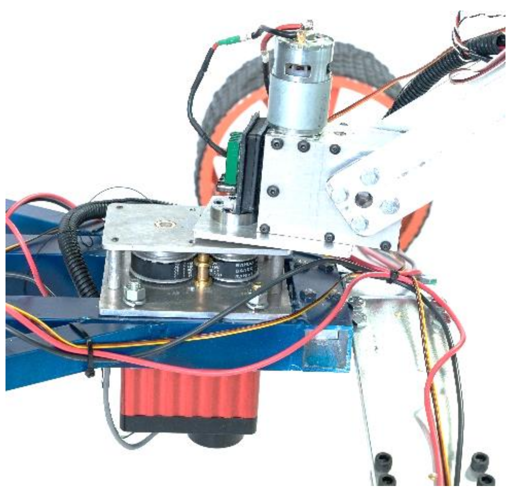


Figure 4: Turret mounted to frame and arm

return. The turret must be designed for minimal weight so that there is room left in the weight budget of the arm for motors and actuators. This will ensure that it will achieve the required dexterity.

Design Information: Turret development is at the end of system integration; minimal changes may be made before the competition to improve performance, but the design is complete and verified. The turret design consists of a pulley case made of two horizontal plates housing timing pulleys that will transfer motion from the servomotor to the main shaft of the turret (See Figure 6). The main shaft of the turret has a hub on one end that bolts to the top plate that interfaces with the gearbox of the shoulder link of the arm. The other end of the main shaft is threaded for a bolt that can be tightened to keep the thrust bearings in compression and adjust preload (Figure 6). This will also prevent the failure seen in previous competitions where the arm fell off the rover, and is especially critical where the arm is pushing the auger into the ground. Two bushings, located at either end of the main shaft, support the shaft in any moment that may be applied during operation. The gearbox mounted to the top plate is offset so the shoulder link can rotate below the plane of the top of the rover (Figure 5). This allows the arm to extend far enough to dig into the ground and collect soil and also to pick up objects placed on the ground. The Torxis i00600 servomotor was reused from previous years. The timing pulleys use a 3:4 gear ratio so that the 270 degree maximum rotation of the servomotor will result in 360 degrees of rotation for the turret. The bottom plate of the turret bolts directly to the rover frame, which will give the entire arm one mechanical connection point. The single connection point allows easy removal from the rover for the terrain traversing task (See drawing package in Appendix B-1).

Figure 5: Arm extension to Ground

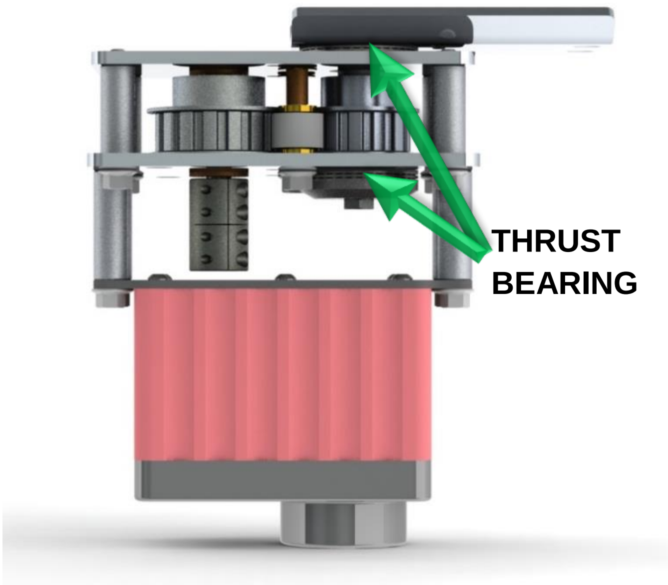


Figure 6: Double bearing system of the turret

Acceptance Test Information*:* The turret design is a more robust version of a previous year's design. It has been redesigned to strengthen its connection to the arm and improve its load capacity. This has been accomplished by using two larger thrust bearings on either end of a threaded shaft that keeps the bearings under preload. Hand calculations were made to verify that the 6.78 N*m the servomotor puts out will be able to move the 13.2 kg*m^2 of inertia that the arm will have under maximum loading conditions; see calculations in Appendix C-1. FEA resulted in a safety factor of six for the main shaft of the turret, which experiences the highest levels of stress [Appendix C-2]. The turret has been successfully tested with a 10 kg load, held by the arm at full extension, which matches the ideal value of arm requirement number 3; see requirements matrix in appendix A-4. This is double the load required by the competition and the maximum load capacity of the arm. The turret is currently only able to turn 120 degrees because of the type of output from the hobby grade controls used for verification. The signal output from the microcontrollers that will be used in the competition will allow a full 360 degrees of rotation with a resolution of 0.72 degrees, in between the ideal and target values for arm requirement 13. The turret is also able to withstand the forces applied by pushing the arm into the ground to drill and collect soil samples of the required size with the auger system. The high forces from drilling hard soil cause noticeable deflection in the top plate of the turret, on the order of 0.5 cm, but there is no plastic deformation. This does not affect performance or the ability to drill, and there is no interference, but the top plate was designed with extra material on the sides that could be bent to increase the stiffness of the plate. This enhancement will be completed before the competition as a precaution against unexpected forces on the turret. While the turret does not directly fulfill any competition requirement or contract performance, it adds a degree of freedom to the arm that allows it to collect soil samples and perform all tasks of equipment servicing and astronaut assistance. The compact design helps the rover remain within the weight requirement of 50 kg, and the simple attachment allows it to be easily removed to reconfigure the rover for other tasks.

End Effects

The end effects connect to the end of the second arm link. The end effects are critical in completing the competition tasks. There are two separate end effects to accomplish the aforementioned three tasks: a claw for astronaut assistance and equipment servicing, and an auger for the sample return task. These attachments are modular so that the arm can be reconfigured between each competition task with the appropriate end effect. Each device integrates with the rest of the arm and is within all weight and cost budgets.

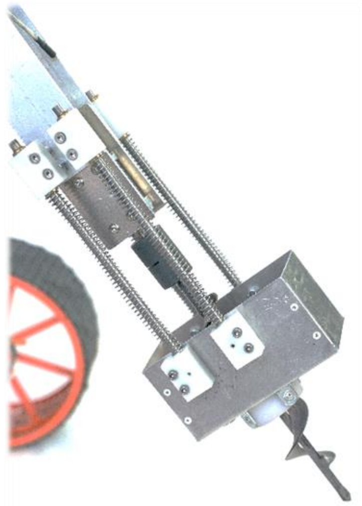


Figure 7: Auger System attached to arm

Sample Return

Requirement Information: The sample return task requires the rover to analyze a soil sample for the potential of life. A sample must be collected from a minimum depth of 5cm beneath the surface of the soil. Up to three GPS locations will be provided as potential collection sites. The sample that is returned must be provided in conjunction with evidence that biomass may exist at the sample location. The sample collected must be between 25 and 250 grams. This may include a single rock, or a soil sample. GPS coordinates for the sample location must be provided as well as a high-resolution photo of the location.

Design Information: This design consists of an auger and motor rigidly attached to the end of the arm. The auger protrudes by 7.5 cm through the bottom of a collection box. When the auger penetrates the ground, it clears away 2 cm more than the required 5 cm of top soil. The collection box then contacts the ground and begins sliding on the steel rods and compressing a series of springs. As the auger penetrates deeper, sliding through a polyethylene sleeve attached to the box, the soil begins to collect in the box. The sleeve protrudes out the bottom of the box to keep topsoil from falling back in the hole, and it extends into the box to keep soil from falling out of the box to the ground. The auger drills to a depth of 7 to 9 cm, with room for adjustment up to another 8 cm. Approximately 75 grams of soil collects in the box. When the auger is pulled out of the hole, the springs decompress and return the collection box to its original position. (See Figure 7 and Appendix B-2, Photo 2).

A 700 mW and 100 mW laser, each 405 nm, will be mounted on the rover chassis and the arm respectively. The chassis laser will be defocused and pointed at the ground with Mylar sheets surrounding it to shade against the sun. The laser reflects light from inorganic matter that appears violet in color. When it passes over organic matter it reflects a bright white light. In the presence of chlorophyll it reflects red light. The camera lens will be covered with a yellow lens than blocks undesirable wavelengths of light. Visual feedback will indicate life-positive areas to dig, and the smaller laser in the arm will be used to verify that the sample collected actually contains bio-matter.

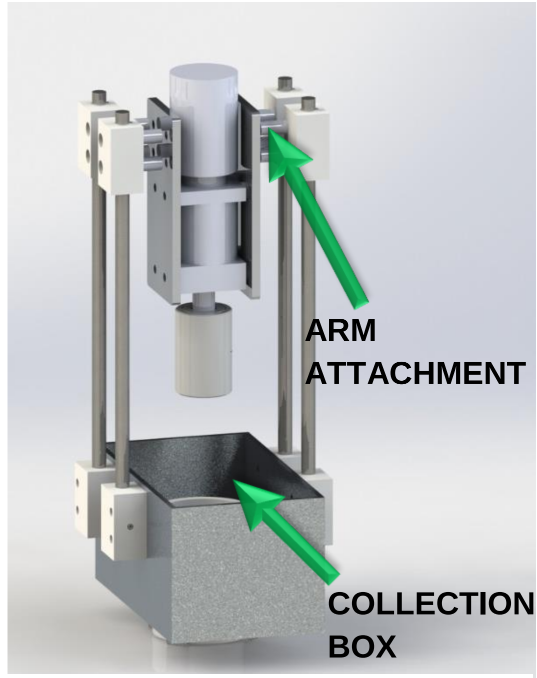


Figure 8: Rendering of Auger Collection System

Acceptance Test Information: The auger design is capable of drilling and collecting many types of soil and ensuring the required sample size and depth. The simplicity of design and one degree of freedom allows straightforward control and consistent, reliable performance. The auger has been tested in loose sand, soft dirt, and hard packed soil and struggled only when it hits a large rock. This does not hinder the performance because the team selects the drilling site and can drill another hole if a rock is encountered. In each test, the auger was able to remove the required 5 cm of top soil before collecting a subsurface sample, fulfilling requirement 10 in the arm matrix, exceeding the ideal (Appendix A-4). Samples collected from 5 different holes averaged 74.9 grams, which is within the range of 25 to 250 grams required by the competition, within the target values of arm requirement 12. The auger hard stops still need to be adjusted to ensure that the soil sample size is consistent each time, but we have verified that it collects samples according to the market requirement. The lasers have been tested and allow clear visual confirmation of the presence of organic matter by white or red reflected light. The auger end effect fulfills the market requirements of identifying signs of life, collecting subsurface soil samples, and returning the appropriate size of sample (See market requirements 9-12, Appendix A-4). This fulfills the contract performance section for sample return.

Equipment Servicing and Astronaut Assistance

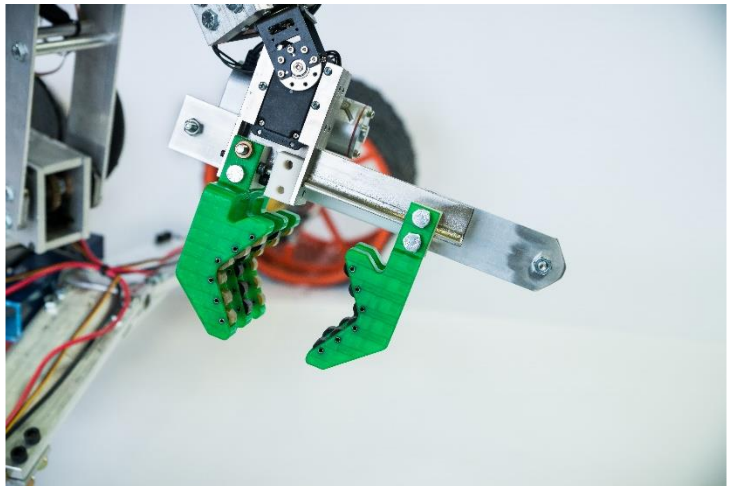


Figure 9: Equipment servicing end effect prototype

Requirement Information: The equipment repair task is one of the more involved and complex tasks that the rover will have to complete. For this task the rover needs to flip switches, turn knobs, push buttons, grasp pipes, and thread or push in pipes as well. The size of the pipe is not clearly specified–only that it will be no larger than 2” in diameter. The exact orientation of the switches, knobs, buttons, or pipes are also unknown variables. The working area was defined to be from 0-0.5m from the ground. In order to develop concepts that would meet these requirements the team developed a unique set of requirements for the task that can be found in Appendix A-4.

The task of astronaut assistance will be one of two options: equipment delivery or wireless signal improvement. Either case requires the rover to pick up packages and deliver them to GPS locations. Both of these options are detailed in the Appendix A-3 3.c.

Design Information: The design is currently in the system integration stage. The design information exists as a set of drawings detailing the geometry, material, and production methods. Additionally, there are hand calculations and finite element analysis ensuring that the design can withstand the stresses required. The end-effect for this task is a clamp type gripper that can grasp objects from 0.5 to 2 inches in diameter. This capability was driven by a release from the Mars Society saying that the hardware the rover would need to manipulate would be PVC pipes and other hardware commonly available at Home Depot or other hardware stores. The V-shape of the jaws provide two points of contact on each side of any roughly cylindrical shape (common tools included). Additionally, the tip of the jaws can grasp flat objects that would not fit entirely within the jaws.

Rubber rollers have composite sleeves to provide a low coefficient of friction on the steel spring pins holding them in place. This allows the pipes to be rotated while being gripped for making threaded connections. The rubber itself provides a high coefficient of friction against the objects being grasped so that they will not slip while being grasped.

The linear motion of the jaw is accomplished with a slider and channel assembly within the grasper, with a linear actuator attached on the side. The T-channel is extruded stainless steel, and the sliders blocks are made of Ultra-High-Molecular-Weight Polyethylene because of its excellent wear properties and light weight. Additionally, the coefficient of friction between steel and polyethylene is 0.2, which means that little of the actuation forces will be lost to heat and wear. The linear actuator attaches to the side of the jaws using aluminum plates for a lightweight, rigid connection. These design features allow the mechanism to grip a variety of pipe sizes. The pipes are rotated into threaded connections using a flat belt driven by a DC motor. CAD drawings of this mechanism can be found in Appendix B-1.

Acceptance Test Information: Verifications were performed by team members not directly involved with the design. These checks on the requirements matrix ensured that it fully reflected all the capabilities that the rover would need to perform the task. Concepts were initially verified by other team members to evaluate their potential to perform the task. Stress analyses and other hand calculations were also checked by other team members before manufacturing was approved.

Verification tests were performed at various stages along the design and production process. The linear actuator was purchased with the expectation that it would provide at least 50 lbs of force. A force test was performed and proved that it can provide up to 75 lbs of force which is much higher than the ideal gripping force initially estimated in the Arm Requirements Matrix (See Appendix A-4). Finite element analysis showed that the jaws could withstand more than a 100 lb force. This exceeds the ideal value for requirement 16 in the Arm Requirements Matrix.

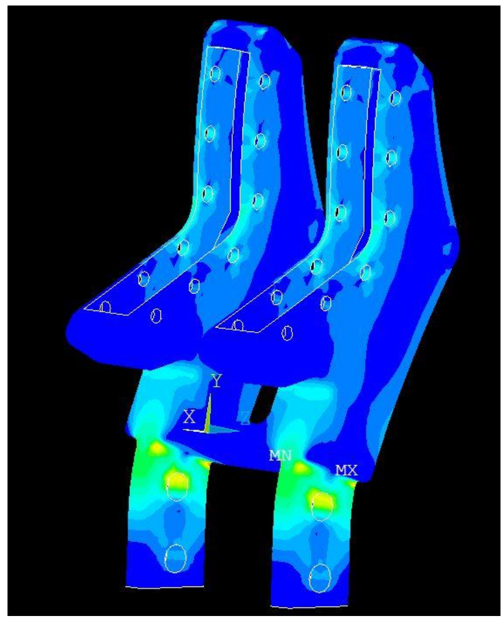


Figure 10: FEA of Grasper

Common pipe fittings, buttons, and knobs were purchased and assembled on a panel that would simulate the setup of the equipment servicing task. The rover arm demonstrated the dexterity, under remote control, to flip switches, push buttons, and manipulate pipes. Due to setbacks in the design stage, including the failure of the prototype gripper being used in testing, verification is still in process. Thus far the design has met expectations and we believe it will be able to complete all requirements by the competition date, but it has not been fully tested and verified.

The broken gripper was made out of 3D printed ABS with a honeycomb infill. The design that was verified with FEA was milled aluminum. The final gripper will be made out of aluminum, but we are investigating simplifications in the geometry to reduce machining time.

Additionally, the arm and end effect was able to fulfill surrogate evaluation criteria 13-17 in the Arm Requirements Matrix (See Appendix A-4). The end effect demonstrates a wrist torque of 5.4 Nm, claw movement resolution of 1 cm, and a grasping strength greater than 100 N. The graspable region is smaller than the target value because of the necessity to be able to pick up smaller diameter pipes that are flat on the ground. As a result, the requirement information was adjusted as the design information developed. These values were achieved under remote control of the arm.

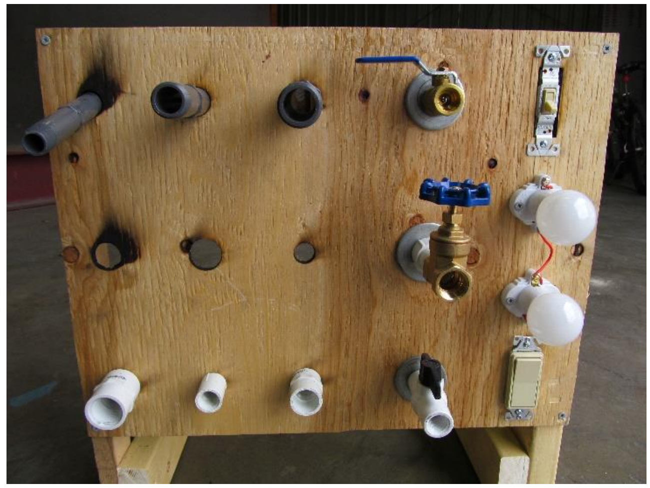


Figure 11: Arm Test Panel

Furthermore, the arm has sufficient reach to cover 100% of the chassis, which fulfills evaluation criteria 2.

Chassis

The chassis provides the frame for the entire rover. It supports the arm, all the communication electronics necessary to operate the rover, and objects that need to be picked up during certain tasks. The chassis also includes the drive and suspension which will move the rover over the obstacles it faces and transport it wherever it needs to go.

The requirements for the chassis are based on the terrain traversing task. This task will require the Rover to climb 60 degree slopes, traverse boulder fields, soft sand, and to go over drops at least a half meter as described in the competition rules in Appendix A-3. The rover chassis will be under the greatest amount of stress during this task; as long as it can complete this task, it will be able to perform its function for the other tasks.

The rover has six wheels to provide better terrain traversing capabilities. The suspension implements rocker joints and compliant links to provide constant contact with the ground reducing stress in the rover frame. The three rocker design is shown in Figure 12. The chassis will be 48 inches square with ground clearance of 12 inches so that it can overcome the terrain described in the competition rules (Appendix A). The size of the chassis fulfills evaluation criteria 15 in the requirements matrix (Appendix A-4). This design, inspired by the rocker-bogie design on NASA's Curiosity rover, showed the greatest potential in initial prototyping. Six wheel designs provide a stable base that can traverse difficult terrain while significantly reducing the likelihood of tipping over.

Figure 12: Three rocker chassis design

The chassis was divided into the frame, the suspension, and wheels. Since the requirements for the competition have been changed for the 2014 year the previous design was not sufficient to meet the requirements; specifically the 60 degree slope climb and the half meter drop. The chassis is currently in the system integration phase and has met or exceeded most market requirements. The following sections detail the design and validation information.

Frame

The frame is the connecting structure between all the major components of the rover. It has a triangular construction with two parallel rails running down the center where the electronics and arm will be mounted. Additionally, the suspension is attached to the ends of the frame with a bearing connection.

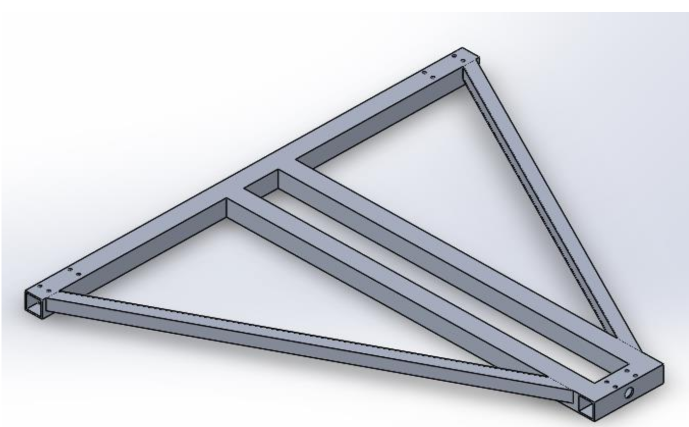


Figure 13: Chassis design

A prototype of the frame was fabricated, tested and found to be adequate. It is close to the end of subsystem integration in the design process. Only minor changes are expected to be made to the final design, before the competition.

Requirement Information: The frame needs to support at least 50kg and still optimally perform all tasks that the rover has been assigned. It needs to withstand a 2500 N force, the highest that it may experience while maneuvering the half meter drops during the terrain traverse challenge. It also needs to take impact from hitting boulders or other terrain obstacles.

Design Information: The box frame from previous years' competitions, required heavy paneling to protect the electronics and was not good for mounting other components. A more skeletal lightweight design is desirable, where components such as the arm are mounted easily and a small box for the electronics replaces the heavy paneling.

A minimal design was first attempted with the three pivot points connected using circular tubing. This was to obtain a quick weight estimate. More members were added for the purpose of mounting components. Eventually, square tubing was chosen so that the frame would be easier to manufacture. The new selection turned out to be stronger in the expected loading directions. Although other designs were considered, the flat frame was the most desirable for mounting the arm and other components. Its low profile allows the arm to collect soil samples from the ground while maintaining a lower center of gravity.

FEA initially revealed that this design would not be strong enough at the joints without increasing the member size and weight. Reinforcement to the joints was necessary. Several concepts were considered, but reinforcement inside the frame members was chosen. This can be seen in Figure 14. Placing the reinforcement inside the tubing conserved space and allowed for a lower center of gravity. This design can withstand the expected 2500N force and does not raise the frame higher than the rocker joints (1 foot above the ground). The final mass of the frame is 4.8kg.

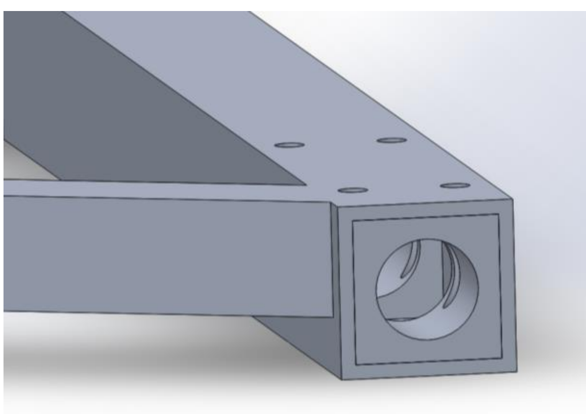


Figure 14: Joint reinforcement

Acceptance Information: Finite element analysis was performed on the final design to show that it could withstand the exaggerated loading we expected. Forces for the analysis were generated from a mathematical model which can be found Appendix C. A safety factor of 1.2 was chosen for this application since the applied force used for the FEA is the most extreme case. This also considers the 20% strength loss due to welding.

After the FEA was performed, a prototype of the frame was built and tested. Testing was completed after it was attached to the suspension. It was loaded with the maximum weight of the rover (50 kg) and taken through terrain similar to that expected during the competition. This terrain included a .5 meter drop and multiple boulders larger than the diameter of the wheel (12 inches). The testing also included dropping the frame on hard rock from the height of the ground clearance. Each of the tests were performed 5 times. These tests fulfill evaluation criteria 20-22 in the Requirements Matrix (Appendix A-4). After testing the frame and joints were examined and no signs of damage or failure were found.

Suspension

The suspension consists of Kevlar leaf springs which can pivot freely about joints connecting to the frame.

Requirements: In the chassis design the suspension links are the only connection between the motors and the chassis frame; the robustness of the suspension is imperative in completing all of the assigned tasks. The design of the suspension will be key in helping the rover navigate uneven terrain, which will be critical for the terrain traversing task.

The mass of the suspension for the previous rover was approximately 5 kg. The mass of the previous rover was above the weight limit, so the new suspension for the six-wheeled design needed to weigh less than the previous suspension. The goal for the new suspension was to have a mass of less than 5 kg and still be able to withstand a 0.5m drop.

Design Information: A rocker suspension system was chosen to better handle the varied terrain the rover would face. This design will allow the suspension links to pivot and keep the wheels in contact with the ground. Fiberglass bushings are used in the rocker joints for their performance under high radial load and low speeds, with minimal wear. The rocker joints were also designed to stop the suspension from pivoting too far. Out in front of the rover the wheels may be need to go up 0.5 meters, achieved by a pivot limit of 60 degrees. The middle set of wheels must be limited to 45 degrees to ensure that they do not rise above the frame. The rear wheels were limited to 45 degrees. The front joints are shown in the figure below.

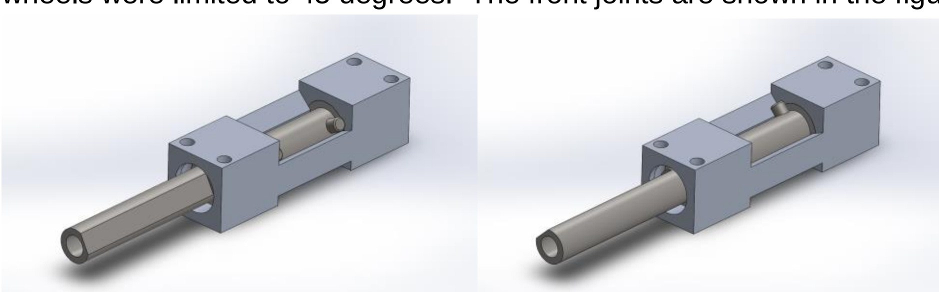


Figure 15: Front Rocker Joints showing full dexterity

A design similar to a leaf spring was selected during concept generation. This results in a part count reduction from the previous year’s rover and significant weight savings. The leaf spring design had been tried in a previous rover without success. The previous attempt produced a suspension that gave more than adequate vertical travel, but it was not sufficiently rigid in torsion. It could not withstand the moment the wheels places on the suspension.

Composites were selected to maximize weight savings. By adjusting the design of our laminate we made a leaf spring that will have vertical compliance and torsional rigidity. Orienting many of the layers at ±45° greatly increased the torsional rigidity.

Kevlar was chosen as the leaf spring material because it is much tougher than glass or carbon fiber. If failure were to occur, Kevlar undergoes a fibril failure instead of a brittle failure like carbon and glass fibers. These attributes of Kevlar make it ideal for the rover because it will be going over varied terrain and the suspension may be subjected to impacts. Kevlar will be lighter than glass fiber, but not as light-weight as carbon fiber.

Acceptance Test Information: Leaf springs were fabricated and tested in a clamp fixture. The layup was then optimized until the leaf spring could withstand the desired force of 50 lbs for the final version. For the shorter leaf springs a layup of 23 layers was used and for the longer leaf springs a layup of 26 layers was used. For information on the specific layup see Appendix B-3. The combined weight for all of the leaf springs is 2.4 lbs (1.1 kg) which contributes to meeting evaluation criteria 1 (Requirements Matrix: Appendix A-4).

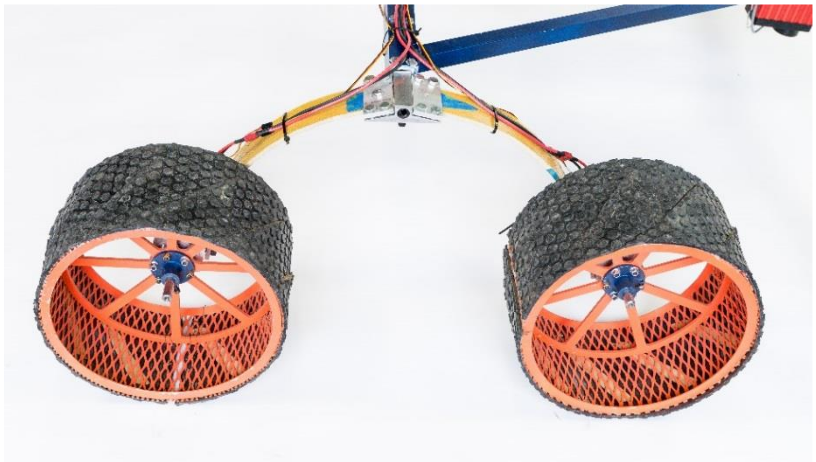


Figure 16: Kevlar leaf spring suspension

In testing earlier versions of the leaf springs on the rover, the longer leaf springs did fail, but the failure that occurred in the system was not catastrophic. If such a failure were to occur in the field the rover would still be able to return to the base station by traveling over more benign terrain. The suspension design was revised to use the longer clamp system and secondary helper springs as seen in Figure 17.

The longer leaf springs for the rear of the rover were initially not strong enough in acceptance testing; the rover sagged 2 inches lower than desired. In order to strengthen the members longer clamps were made to reduce the moment arm and a helper spring was added to reinforce the leaf spring.

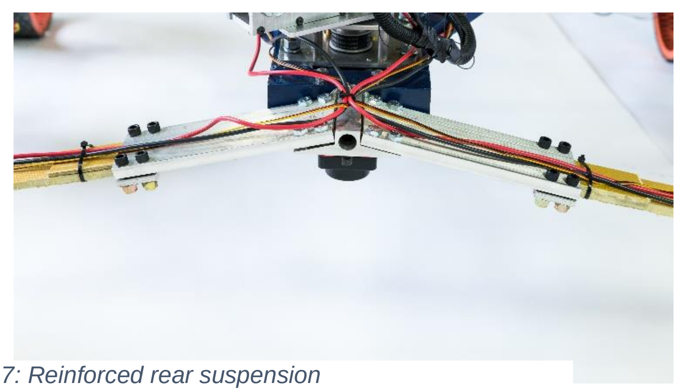


Figure 17: Reinforced rear suspension

The final acceptance testing for the suspension was to drive the rover over terrain that would be similar to what it would encounter in the competition. To accomplish this the rover was taken to Rock Canyon to traverse boulder fields, vertical surfaces, 0.5 m drops and climbing a 60º slope. In testing the rover was able to navigate all of the required terrain surfaces and the suspension articulated well to aid in terrain navigation.

Prototype rocker joints were fabricated and tested over this terrain. The rotation of the rockers was found to be adequate for the terrain. However, a lot more testing will be required to find optimal angles for the rocker limits; this includes driving the rover underweight.

Possible improvements: Although the suspension design is adequate for the requirements a few improvements could be further researched. During testing it was determined that it may be beneficial for the rocker joints to have a spring type resistance to return the rocker to its 0 degree position. This way when a wheel rises off the ground due to one wheel gaining more friction with the ground, the spring resistance will push it back down.

In future iterations the suspension should be made slightly stiffer. The suspension performs well now, but it would benefit from additional stiffness.

Wheels

The wheels and their associated motors are critical components of the rover; the wheels will provide mobility and stability for all required tasks. Well engineered wheels are essential for providing precision control and rover placement for tasks involving the arm and sensors. Most importantly, the wheels will provide traction during the terrain traversing task. They must accomplish all these tasks while remaining within the allotted weight and cost budget. (See Appendix A-1 and A-2)

Requirement Information: The major motivation for designing new wheels is to overcome both the weight and traction limitations of the current wheels. The previous rover utilizes four aftermarket inflated rubber tires that weigh 2.5kg each; these stock wheels do not provide ample traction on loose and steep terrain. Concept development and the market requirements have driven a design with six wheels; see Requirements Matrix in Appendix A-4. This number of wheels gives the rover added stability and traction without excessive weight addition. The most important task for the wheel is the terrain-traversing task; the rover must overcome 60 degree slopes, large boulders, and a .5m-drop. In order to achieve the weight reduction in the drive, a new design was necessary that would reduce the mass to 1.5 kg per wheel.

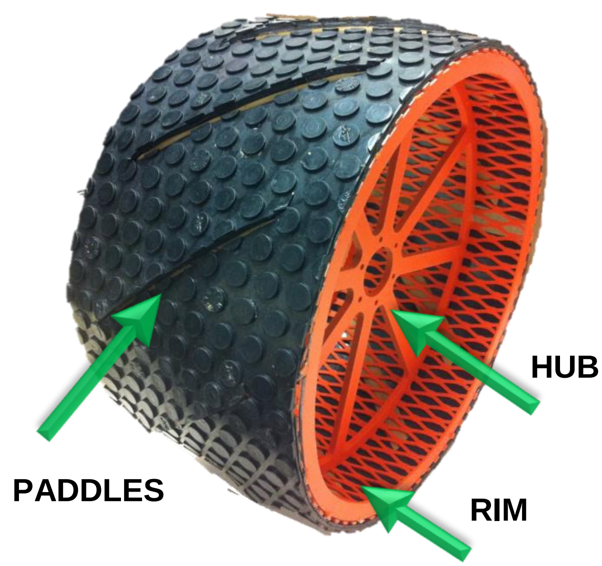


Figure 18: Final Wheel Design

Concurrent research of existing aftermarket wheels has confirmed our decision to produce our own wheels. No commercially available wheels exist that meet our requirements. To make the six wheel design viable, our wheels must provide more traction than the existing models. They must also have a combined weight equal to or less than the current wheel set at 10 kg and provide sufficient strength to take impact and static loads. Also, the final design must remain within our budget; see Contract in Appendix A-1.

Design Information: Subsystem engineering was finalized early winter semester; system integration and verification tests took place mid-semester. The design was then verified and a functioning set of wheels produced. The wheels were completed in time to test the entire chassis during its verification phase.

From the requirements matrix created for the drive system, major design criteria for the wheels were selected. The 12in diameter of the 2013 wheels was maintained while increasing the width to 6in. This will allow the rover to traverse the .5m drop and have a contact area force less than 300 N/m to provide traction in loose soil and on steep, loose slopes while not increasing the original contact angle.

C4 Stealth Rubber was selected for our wheel tread. Stealth Rubber is made for rock climbing and other high traction shoes. It has a very high coefficient of friction (.65) while maintaining great strength and damping. We have sourced the rubber with a pre-molded tread pattern that comes in relatively thin sheets. The specific rubber we chose is 2mm thick with a 2.5x6mm dot pattern. The rubber sheets have slits at 45 degree angles with cork inserts that raise these portions; this effectively creates the paddle design seen in Figure 15.

The decision was made to move forward with a rigid aluminum wheel instead of a compliant plastic wheel. A prototyped plastic wheel presented several manufacturing challenges that made continued effort on that front unreasonable**.** High strength plastics do not weld together well nor are they bonded well with adhesives. Although a compliant wheel was desirable, we can still meet our compliance goals with the Kevlar suspension.

With weight and impact load requirements in mind (see Drive requirement matrix in Appendix A-4) the aluminum wheel was designed using CAD and hand calculated stress controls. The design is a spoked hub with an expanded aluminum rim; it has 12 x 0.5 x 1/8 inch aluminum hoops on the outer edges of the rim that effectively increases the hoop and radial strength of the wheel. The stealth rubber was then bonded with contact cement and stitched together with Dyneema thread, a process that created a chemical and mechanical bond with the rim. The design met our weight goal of 1.5kg. Engineering drawings are found in Appendix B-1, labeled W; the hand calculations of wheel stresses are found in Appendix C-1.

Acceptance Information: Our acceptance tests of fall semester had validated the basic design of our wheel; these test also showed us areas where improvement was needed: strength in the middle section of the wheel and needing better traction in loose soil. We added an inner hoop to the hub and developed a paddle design to overcome these limitations. In early March, we completed a set of wheels to begin system testing. We conducted our tests based on the market requirements (the assigned competition tasks) and the performance of last year's rover; see

Drive requirement matrix in Appendix A-4. Most of the tests were performed up Rock Canyon on terrain that met or exceeded the market requirements. The wheels performed the tasks well, exceeding the requirements on hard surfaces (See achieved values for evaluation criteria 20-22: Appendix A-4). In every comparison test performed, the new rover outperformed last year's design. A detailed report of the validation tests is given under Chassis Verification which follows this section. Additionally, the wheels were painted a bright orange color to match our logo and fulfill evaluation criteria 16 (Requirements Matrix: Appendix A-4).

Possible improvements: Although the wheels have performed all the prescribed tests remaining functional, wear on the wheel frames is accumulating. The outer reinforcement hoops, being thin and exposed, are gathering dents and slight bends. This wear could eventually lead to failure of the wheel edge. Increasing the thickness of these hoops from 1/8 in. to 3/16 in. would significantly increase the wheel's resistance to this wear. We are confident, however, that the current wheels will remain functional throughout this year's competition and into next year's testing.

Chassis Verification and Testing

In verification testing, the chassis performed well in terrain traversing tasks. The rover was able to traverse boulder fields with an average boulder size of 10-12 inches. This size of boulder is larger than what appears in the competition location. It can climb slopes of 50° and go down 60° slopes. Being able to climb 50° slopes achieves 83% of the target value in the requirements matrix. The rover can climb a vertical wall 14 inches high, thus satisfying the requirement to climb vertical surfaces (evaluation criteria 14: Appendix A-4). It can traverse loose sandy terrain; it does not sink into the sand and the pressure the rover puts on the sandy terrain is 6 kPa, which is far better than the target value of 95 kPa. The rover was able to fully complete all of the terrain traversing requirements in the contract, requirements matrix, and competition guidelines with the exception of climbing a 60º slope; the rover can climb up to a 50° slope.

The rover chassis meets the physical requirements as set forth in the requirements matrix. The chassis' total weight is 24 kg which is less than the target value of 25 kg. Each wheel meets the targeted weight of 1.5 kg, diameter of 0.304 m, and friction coefficient on hard surfaces of 0.65. The wheels can take impact loads from 0.5 m drops and boulder impacts at driving speed. The frame has an average ground clearance of 13 inches, 1 inch greater than the targeted value. The rover has a top speed of 7 mph, exceeding the desired value of 5 mph enabling the rover to travel the required distances of 2km within 60 minutes.

Communications

The communication package provides the life-link between the base station operators and the rover. This system is the way our team will control the rover through the various tasks as well as receive vital telemetry regarding the status of the rover. The communications package includes vision, control and sensor information data transfer.

Gimbal and Vision

Because of the remote nature of the University Rover Challenge the vision system is essential to the navigation of the rover. The gimbal and vision system will allow the operator at the base station to view the current location of the rover and to see where it should go. Currently, the gimbal/vision system is in the system integration phase.

Requirement Information: All 4 tasks require remote, non-line of sight operations. This includes driving the rover over varying terrain and manipulating various objects found in the field. This requires the operator to have visual orientation of the rover and sensors. The vision system must provide a view of the path the rover will traverse and detailed enough views of objects so they can be grasped and manipulated.

Design Information: A gimbaled camera system was chosen as the best way to accomplish the requirements. The gimbal allows us to point a high resolution camera to any portion of the rover and its' path. The gimbal will provide ideal vision of the arm and the objects its manipulating. This design calls for a gimbal with 180 degrees of azimuth and 60 degrees of elevation control. The driving motors will provide ample torque to move the mass of the camera. The cameras themselves will be network cameras that support MJPEG or H.264 encoding, depending on the latency requirements for the application.

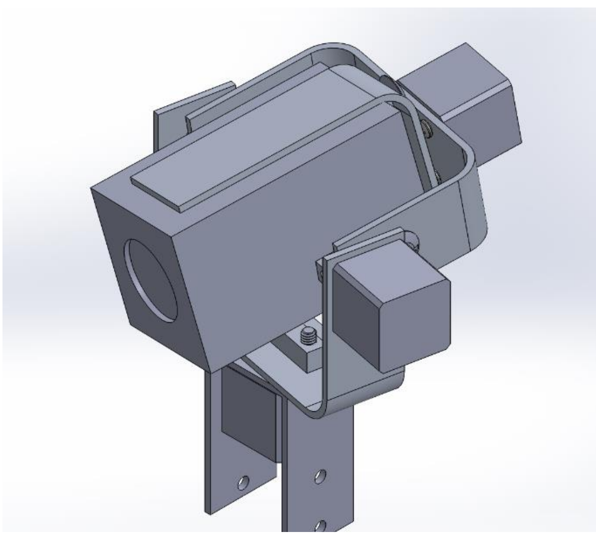


Figure 19: CAD Model of Camera Gimbal

The gimbal frame was built from aluminum sheet metal. The three axes of the camera go through the center of gravity, so that the motors will not have to hold the camera in place when it is stationary. This helps prevent drift in the motors when the rover goes over terrain that shakes the gimbal. Brass washers were chosen for the joints over bearings, because they are cheaper and will likely perform better in the dust environment of the competition. Testing of the joints is discussed below.

The gimbal is mounted on a 3ft single pole. A base plate which matches the hole pattern of the turret plate is used to hold the pole in place. This is so the mast can be moved in the place of the arm during the terrain traverse task. From this position, it is easier to view rough terrain. To strengthen the pole and conserve weight, the pole will be supported by Kevlar tension lines secured to parts of the rover (see Figure 20).

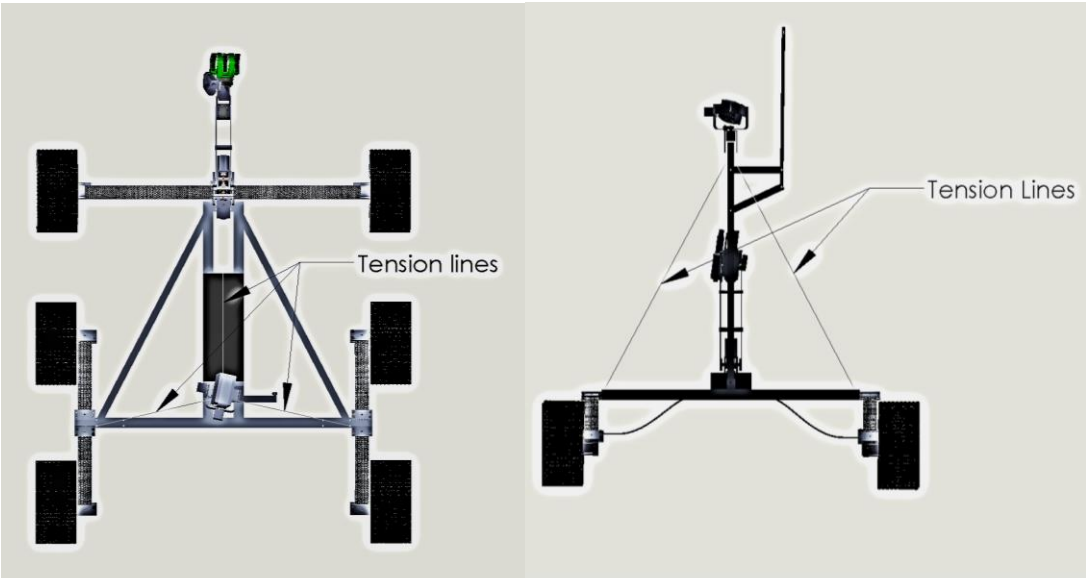


Figure 20: Rover with tension guide lines supporting gimbal mast

Acceptance Test Information: Gimbal control tests with stepper motors have been run with custom firmware. A design review was performed on the gimbal control Printed Circuit Board (PCB). The design was subsequently revised to improve its robustness.

The frame was tested separately by vibrating it at 2hz with an amplitude of 2cm which is what is expected to be the average frequency of the rover as it travels. During this test the camera held still enough for the motors to hold it in position. Dust was also sprinkled on the joints to see if there was too much friction added for the motors to handle; no significant change was measured, meeting market requirement 17 (Appendix A-4). This is adequate to provide a clear image while driving during the competition.

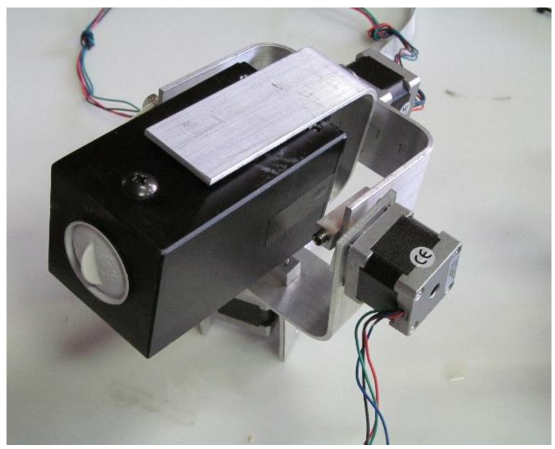


Figure 21: Fabricated gimbal

Remote Operation Verification: All competition tasks require the rover to be remotely operated, completely controlled via sensors such as cameras and GPS. During chassis verification, we integrated a small wireless camera and GPS unit into the rover; both signals were then wirelessly transmitted back to a base station TV. This simulated the competition environment of operation. We verified the rover's ability to be controlled via camera by driving out of line-of-sight and large distances away from the operator (400m), identifying objects, and traversing obstacles such as boulder fields and drops. This fully satisfies our contractual and competition requirements of camera operation as seen in Appendix A-4.

To validate GPS usability, we replicated the competition task of astronaut assistance. A team member placed himself in the field as an astronaut surrogate; he relayed his GPS coordinates and those of a “package” back to the operator via cellphone. The operator, via camera and GPS feed, was able to locate the location of the package and then continue to the astronaut's location. These tests were accomplished in less than 20 minutes. These validation tests fully satisfy the requirements of GPS control and package delivery in the required time-frame.

Controls and Sensors

The controls are the methods we will use to operate the rover drive, arm and vision gimbal. This includes the communications boards, the sensors that reside on each subsystem, and the controls programming. This is the nervous system of our rover that electronically connects all the subsystems. The diagram that gives the high level overview of how the system has been designed can be seen in Appendix C-4 Photo 5.

Requirement Information: All tasks require remote operation up to 1km away from the base station which may be obstructed with hills. The communications boards must operate within a 900 MHz or 2.4 GHz frequency using bands of less than 20 MHz using antennas that have a solid Radio Frequency (RF) link to the rover at all times. The control boards must provide all motor, gimbal and arm control and sensor ports. The controls system needs to read in all sensor data as well as write all control signals.

Design Information: To accomplish remote communications, aftermarket 700 mW, 2.4 Ghz transceivers were selected. Dual polarization 15 dB, 120 degree sector antennas will be used for the command station. The onboard antennas will be 8 dB Omni antennas. These antennas will be mounted on the same mast as the gimbal to conserve weight. A two foot fiber glass extension to the mast was chosen to hold the antenna. This is can be seen in Figure 20.

It was decided to design a custom controller boards that will interface between the transceiver and the rover sensors/ actuators for greater flexibility and control. This custom board will provide the specified number of sensor/ actuator ports as well as data manipulation and distribution for all controls. In addition to the main control board a number of simple control boards will be designed to control the various subsystems of the rover. No aftermarket boards exist that will be as robust, light, small and low cost as a custom board can be. The control program that will reside on this board is being written in C.

All of the controller boards have CAD models, drawings, and have been printed. The electronics team has populated the master controller board and two periphery boards, the gimbal controller and motor control. These boards are being used concurrently with programming to create the overall control system. Serial communication, I2C, has been established between the boards as well as preliminary controls for PWM. The last major piece to be completed is the control algorithms and serial communication with the arm servos.

Acceptance Test Information: Our verification tests at this point have included bench-top board power-up and processor boot-up. We have been able to load and execute code that runs serial communication thus validating our read and write capabilities. These hardware tests have also validated our ability to produce our own custom boards. Our 2.4 GHz antennas have been installed and tested; we are able to send and receive wireless telemetry validating our wireless link. The antennas operate within the 20Mhz band requirement and at our required 2.4GHz frequency.

Although many of the subsystems have been validated independently, system integration with the chassis and arm must take place to finalize the controls. This requires the control system algorithms to be completed and tuned, all motor control boards populated, and all components wired into the rover chassis. We are confident this will be completed by the competition deadline; the electronics team has agreed to set weekly mile-stones that allows for complete system testing prior to the competition.

Future Recommendations: Future teams should be aided more by electrical engineers in the form of senior projects and other support from the Electrical Engineering Dept. The lack of man-power has significantly impacted the electrical system's timeline. Future teams could also benefit from heavy recruitment from EE volunteers early on in each semester.

Conclusions and Recommendations

Currently, the rover is in the system integration phase. We are able to operate all mechanical systems remotely; these systems are being tested regularly for in preparation for validation and competition. The electronics package is in the final stages of subsystem engineering; the electronics will be integrated into the rover for complete system testing in the next several weeks.

A major focus of this year's team in the coming months will be testing and practice. Now that the rover is operational, we must become proficient at control and telemetry interpretation. Much of the competition relies on user skills, not just mechanical functionality. This year's team also recommends that future teams' compliment of electrical engineering students be increased drastically; a major component of this competition relies on electronic control systems and communication protocols.

Appendix A: Requirements Information

A-1 Development Budget

Rover Budget			
	Budget	Spent	Funds Remaining
Arm	$2,650.00	$2,500.43	$149.57
Gimbal	$450.00	$224.53	$225.47
Chassis	$4,750.00	$2,402.30	$2,347.70
Comms	$3,750.00	$3,120.5	$629.50
Misc. Expenses	$150.00	$00.00	$150.00
Rover Total	$11,750.00	$8,247.76	$3,502.24
Travel	$1,950	0	$1950
Total	$13,700.00	$8,247.76	$5452.24

Capstone Financial Summary

Financial Summary By Team

Monday, April 14, 2014
11:05:06 AM

Team	Date	Vendor	Description	Expense Amount	Sponsoring Company	Credit Amount
7	8/28/2013		Initial budget		BYU Mechanical Engineering	$1,500.00
7	10/2/2013	BYU Bookstore	tape and a ream of paper	$7.88		
7	10/3/2013	Tindie.com	breakout board	$30.00		
7	10/3/2013	DigiKey	PSoL 4 Pioneer Kit	$57.90		
7	10/3/2013	Amazon Marketplace	Zieis 400lb capcity digital scale platform	$99.97		
7	10/3/2013	Amazon	Ubiquiti Rocket M2 Basestation	$169.98		
7	10/10/2013	Amazon Marketplace	Pololu	$38.85		
7	10/10/2013	Amazon Marketplace	120 degree sector antenna	$149.95		
7	10/11/2013	StepperOnline	NEMA 14 Bipolar Stepper	$53.75		
7	10/14/2013	Robotshop	500 Key Hub	$67.32		
7	10/14/2013	McMaster-Carr	White Delrin	$79.94		
7	10/14/2013	Amazon	Castle creations mamba max	$105.66		
7	10/15/2013	Home Depot	PVC adapter, threaded Tee, Elbow, pipe section	$9.86		
7	10/16/2013	BYU Bookstore	Postage to ship package	$5.85		
7	10/21/2013		additional prototype & travel funding from sponsor		BYU Mechanical Engineering	$12,200.00
7	10/23/2013	MetalsDepot.com	aluminum expanded metal, aluminum plate	$60.32		
7	10/23/2013	Five Ten	Stealth Rubber Sheet	$149.00		
7	10/30/2013	Soller Composites	Resin pump, 10 yards of kevlar material	$253.88		
7	10/31/2013	BYU Bookstore	packaging and postage	$4.86		
7	11/8/2013	BYU Precision Machining Lab	Aluminum	$10.00		

Some expenses may not be on the report yet, including packages that have not been received, on-campus charges that have not been billed yet, etc

Page 1 of 4

Team	Date	Vendor	Description	Expense Amount	Sponsoring Company	Credit Amount
7	11/13/2013	McMaster-Carr	bronze lub. Sleeves, thrust roller bearing, shaft coupling	$53.07		
7	11/13/2013	SDP-Si	aluminum timing pulleys, timing belt	$56.70		
7	11/14/2013	Amazon	passive DC connector, video encoder, antenna	$250.47		
7	11/15/2013	BYU Precision Machining Lab	Aluminum	$2.40		
7	11/18/2013	BYU Precision Machining Lab	Aluminum sheet	$2.00		
7	11/18/2013	New Egg	lewis tools roto driller	$18.99		
7	11/18/2013	McMaster-Carr	Polyethylene Tube	$19.00		
7	11/18/2013	McMaster-Carr	Bronze Sleeve Bushing shafts	$26.76		
7	11/19/2013	BaneBots.com	mounting kit, Gearbox motor block, RS775 Motor	$56.75		
7	11/26/2013	BYU Projects Lab	Fasteners	$1.10		
7	12/5/2013	DigiKey	Capacitors	$15.53		
7	12/5/2013	DigiKey	Capacitors and connectors	$19.23		
7	12/5/2013	Adafruit.com	Board edge mounting kit	$22.04		
7	12/5/2013	Hobby King	Vibration dampener ball	$29.05		
7	12/5/2013	Component Distributors Inc	Motion sensors	$49.36		
7	12/5/2013	Hobby King	Battery charger and power supply	$207.02		
7	12/5/2013	Hobby King	Nano-tech lipo pack	$453.04		
7	12/5/2013	DigiKey	Capacitors, resisters, connectors, plugs	$649.62		
7	12/6/2013	Mars Society	Team registration	$250.00		
7	1/7/2014	SDP-Si	Gears, bores and right hand worm	$342.95		
7	1/10/2014	Trossen Robotics	Dynamixel robics	$599.80		
7	1/13/2014	McMaster-Carr	Bushings, rods, pins, bolts and nuts	$117.10		

Some expenses may not be on the report yet, including packages that have not been received, on-campus charges that have not been billed yet, etc

Team	Date	Vendor	Description	Expense Amount	Sponsoring Company	Credit Amount
7	1/14/2014	Neutronics	Rotor, hall sensor, stator and neumotor	$449.00		
7	1/16/2014	MetalsDepot.com	Aluminum	$83.01		
7	1/23/2014	Home Depot	MDF and wood glue-Christopher Mabey	$40.45		
7	1/23/2014	McMaster-Carr	bearings, washers, & polyethylene sheet	$57.34		
7	1/30/2014	BYU CAEDM	Printing Services	$2.10		
7	1/30/2014	BYU Water Jet Cutter	cutting wheels for Mars Rover	$52.50		
7	1/31/2014	Trossen Robotics	Hinge frame set	$33.89		
7	2/13/2014	Adafruit.com	blank SMT storage book	$20.73		
7	2/13/2014	Amazon	rack organizer, tweezer set, and router	$84.57		
7	2/15/2014	McMaster-Carr	T-bar, carbon fiber & rubber tubes, dowel & spring pins,	$141.32		
7	2/19/2014	McMaster-Carr	Returned dowel pin	($25.12)		
7	2/19/2014	Progressive Automations Inc.	mini linear actuator	$129.62		
7	2/20/2014	BYU Bookstore	shipping return back to McMaster	$5.60		
7	2/20/2014	Soller Composites	resin qt. med hardener pt.	$64.98		
7	2/20/2014	Amazon	mamba max brushless ESC	$217.16		
7	2/21/2014	McMaster-Carr	band saw blade	$20.10		
7	2/24/2014	McMaster-Carr	dowel pin	$26.58		
7	2/24/2014	McMaster-Carr	Rubber	$31.57		
7	2/26/2014	BYU Bookstore	sharpie marker & masking tape	$5.82		
7	2/26/2014	OSHpark.com	Neil H: motor driver & arm, master, & battery controllers	$98.35		
7	2/26/2014	DigiKey	Capacitors, resistors, connectors, mosfets, blades, motor driver	$233.99		
7	2/27/2014	Spark Fun	Potentiometer, actuator	$98.48		

Some expenses may not be on the report yet, including packages that have not been received, on-campus charges that have not been billed yet, etc

Team	Date	Vendor	Description	Expense Amount	Sponsoring Company	Credit Amount
7	3/10/2014	McMaster-Carr	screws, nuts, steel spring	$47.74		
7	3/14/2014	McMaster-Carr	steel brackets, spring pins	$14.07		
7	3/14/2014	McMaster-Carr	coupling, spring, retaining ring, spacer, shim, PTFE tube	$67.12		
7	3/17/2014	Amazon	marine wire	$37.95		
7	3/17/2014	Amazon	Connectors, mamba max pro	$455.30		
7	3/19/2014	McMaster-Carr	Washers, screws	$44.04		
7	3/24/2014	BYU Precision Machining Lab	Aluminum plate	$2.00		
7	3/25/2014	Amazon	Roto driller	$15.49		
7	3/27/2014	AutoZone	Matt T: heat shrink tube, black wire ties	$11.37		
7	3/27/2014	Fastenal	Devin A: nuts & bolts	$86.66		
7	3/29/2014	McMaster-Carr	Spacers	$15.19		
7	4/8/2014	Trossen Robotics	Dynamixel robotics	$623.50		
7	4/10/2014	BYU Bookstore	Packaging/shipping	$12.38		
			Total Expenses:	$7,901.80	Total Credits:	$13,700.00

Budget Remaining or (Balance Due): $5,798.20

Some expenses may not be on the report yet, including packages that have not been received, on-campus charges that have not been billed yet, etc

A-2 Development Milestones

Date	Milestone
September 27th	Sub-teams, budget, weight, Schedule done
Oct 4th	Contract draft (capstone) • Preliminary prototypes for all subsystems – Rover 1 (cardboard/wood/pvc models) • Subsystem specs/interfacing
Oct 11th	Contract of deliverables (capstone) for customer completed and submitted
November 1st	Concept Finalized and verified for all subsystems – Rover 2 (Higher fidelity models of individual subsystems. Works-like or looks-like)
November 26th	Completed CAD models, Drawings – Rover 3 (metal and plastic rover. Possibly drivable) • Purchase parts, outsource fabrication (Precision Machining Lab)
December 12th	Fall semester reports/presentation completed (capstone)
January 6th	Begin Fabricating final design • Iterative testing of parts begins • Test systems designed and ready for use
April 15th	Reports finished and written up
May 20th	Rover fully assembled and tested
May 29th	Competition – Rover 6

A-3 Competition Requirements

University Rover Challenge 2014 – Requirements and Guidelines

Any issues not covered by these published rule sets will be addressed on a case-by-case basis by the University Rover Challenge (URC) Director. Please consult the Questions and Answers (Q&A) portion of the URC web site (http://urc.marssociety.org/home) for updates. All matters addressed in the Q&A are applicable to the requirements and guidelines.

1. Competition Overview 1.a. The 2014 University Rover Challenge will be held May 29th – 31st, 2014 at the Mars Society's Mars Desert Research Station (MDRS) near Hanksville, Utah.

1.b. The rover shall be a stand-alone, off-the-grid, mobile platform. No tethers will be allowed during its operation for connection to external sources. 1.b.i. A single connected platform must leave the designated start gate and return to this location (except when otherwise indicated). In the open field, the primary platform may deploy any number of smaller sub-platforms, so long as the combined master/slave sub-platforms meet all additional requirements published.
1.b.ii. Any airborne vehicles must meet any and all FAA (United States Federal Aviation Authority) guidelines that apply to operating unmanned aircraft in a remote area. It will be the responsibility of each team to research any such FAA requirements and provide documentation to the judges prior to April 25, 2014.

1.c. Teams will operate their rovers from designated command and control stations. These stations will be metal trailer units (such as the back of a small moving truck) or tents with tarp walls restricting visibility of the course (to be provided). Alternatively teams may operate from inside their own vehicles if they elect to do so provided they also bring covers to block the view from the vehicle. In addition the Mars Desert Research Station Habitat (Hab) may be used for one of the control stations. Basic power (120V, 60Hz), tables, and chairs will be provided. All of the competition events will be held in full daylight.

1.d. There is no restriction on the number of team members or operators allowed, as long as all operators remain in the designated operators' area. Nobody may follow alongside the rover for the purpose of providing feedback to the operators. Members of the judging team, media, and non-operator team members may follow a rover at the judges' discretion. Team members following the rover may participate as runners in accordance with Section 2.h, or activate an emergency kill switch (in the event of an emergency), but may not otherwise participate in that task.

1.e. The GPS standard shall be the WGS 84 datum. Teams shall adhere to this standard. Coordinates will be provided in latitude/longitude format (degrees/minutes).

1.f. The MDRS field site is located in the desert of southern Utah. As such, the site will have a full spectrum of sloped terrain from flat to vertical. Teams should be prepared for any ground conditions that would appear at MDRS (please consult the MDRS web site – http://mdrs.marssociety.org/ – for field reports, images, and other resources). Except for when noted in this document, the objective sites shall be reachable by paths of no greater than a 15° slope. The rover shall also be capable of withstanding such an environment in the early summer, including airborne dust and temperatures that can easily reach 100°F. Although it is improbable, rovers shall be able to withstand extremely light rain. Rovers will not be expected to compete in heavy rain or thunderstorms.

1.g. URC activities of any sort, including teams practicing, may only be conducted on state managed lands. All land managed by the Bureau of Land Management (BLM) may not be used during URC. This map highlights the two areas at MDRS that are state managed, and available for use. Please ask URC staff if you are uncertain where these boundaries are.

1.h. Teams must provide a video of their rover operating by April 25th 2014 either directly to the judges or via social media. Operations should include the rover moving under remote control at least 10 feet forwards and backwards and turning 90°. If rovers do not have this minimal capability one month before the competition the judges will strongly advise against travelling out to Utah.

2. Rover Guidelines 2.a. Rovers shall utilize power and propulsion systems that are applicable to operations on Mars. Air-breathing systems (such as internal combustion engines and certain fuel cells) are permissible, but must be implemented as fixed-supply systems. No power or propulsion system may ingest ambient air for the purpose of combustion or other chemical reaction that yields energy. Teams implementing such systems are required to understand and follow all applicable safety regulations at their university. Teams are required to document their adherence with these safety regulations during the design phase, and submit this documentation to the URC Director prior to implementation. The URC Director further reserves the right to ban any system deemed unsafe from competition.

2.b. The maximum allowable mass of the rover when deployed for any competition event is 50 kg. This mass does not include any other hardware used to prepare or maintain the rover, any spare power sources not being used, or any additional rover configuration components not on-board for the particular competition event. 2.b.i. For each event in which the rover is overweight, the team shall be assessed a penalty of 10 points, plus 1 additional point per kilogram over 50.
2.b.ii. Rovers over 75 kg in any given configuration must be cleared with the URC Director by email prior to April 25, 2014 to be eligible to compete.
2.b.iii. The combined mass of spare power sources and additional rover configuration components shall not exceed 20 kg.
2.b.iv. There will be no weight limit imposed on command and control team equipment, base communications equipment or maintenance tools.
2.b.v. If a gas-consuming engine is used, the rover shall weigh-in with all tanks full.

2.c. Wireless communication methods used by teams shall adhere to all applicable FCC (United States Federal Communications Commission) standards and regulations. The 900 MHz and 2.4 GHz are further regulated in their use at URC as described in section 2.d.
Other bands are not further regulated. Teams must submit details regarding any wireless communication devices being implemented and operator licenses (when applicable) to the URC Director no later than April 25, 2014. Teams must notify the URC Director immediately of any changes after this date. Teams may be required to power down communications equipment at the event sites while not competing, so as not to interfere with other teams. 2.c.i. Communications equipment must not rely on the team's ability to watch and track the rover first hand. Equipment may be directionally steered if kept

inside the command and control tent. Any communications equipment outside of the tent shall be stationary. The stationary requirement does not impose mechanical rigidity, just a rigid, stable base. An automated azimuth-finding antenna is permissible, as long as it is safe and stable. Electrically steered antennas are also permissible, as long as they are operated within FCC regulations (as applicable).
2.c.ii. Teams may have a member visually track the rover and rotate/steer communications equipment placed outside of the tent. This person may not communicate with the rest of the team inside the tent, and will result in a penalty of 10 points per event utilized.
2.c.iii. Antenna bases must be located within 5 meters of the team's command and control tent, and shall adhere to all applicable regulations. Any such antenna must be documented as part of the communications documentation deadline. Any ropes or wires used for stability purposes only may be anchored within 10 meters of the command and control tent. The exception to this is the use of the MDRS Hab where antennae may be located up to 20m away from the Hab to avoid underground pipe and cables. Teams should bring at least 20m of antenna cable to be to deal with this scenario.
2.c.iv. Lighter-than-air devices are not allowed for communications at URC.

2.d. Teams must notify the organizers of the communications standards they will be using, including frequency bands and channels, by April 25, 2014. The URC restrictions on the 900 MHz and 2.4GHz bands are as follows: 2.d.i. 900 MHz frequency band (902-928 MHz): Teams shall not use frequency bandwidths greater than 8 MHz. Teams must also be able to operate exclusively within one of the following three sub-bands: "900-Low" (902-910 MHz), "900-Mid" (911-919 MHz), and "900-High" (920-928 MHz). The competition schedule will notify teams which sub-band may be used for each task, and teams must be able to shift to another sub-band if required. There is no limit on the number of 900 MHz channels a team uses, so long as they are all within the designated sub-band.
2.d.ii. 2.4 GHz frequency band (2.400-2.4835 GHz): Teams shall use center frequencies that correspond to channels 1-11 of the IEEE (Institute of Electrical and Electronics Engineers) 802.11 standard for 2.4 GHz. Teams shall not use frequency bandwidths greater than 22 MHz. The competition schedule will notify teams which channels may be used for each task. Teams shall be limited to using no more than three channels in the 2.4 GHz band.

There will be spectrum monitoring on-site to ensure that teams are not interfering with channels outside those allotted. Teams should anticipate being within signal range of one other team operating on a different 900 MHz sub-band and different 2.4GHz channels and be able to operate their rover under these conditions. Teams must also be able to deconflict communications as specified above (the URC Director will mediate as necessary). Beyond this requirement a 0.8 km minimum separation between competition areas will be guaranteed, which will include large terrain barriers, and event scheduling will avoid communication interference to the greatest extent possible.
2.e. The rover is not required to be autonomous. However, it shall be operated remotely by a team which will not be able to view the rover on the site or the site itself directly. The rover may be commanded by the team using a wireless link, with information needed for guiding the rover acquired by the rover's own on-board systems and transmitted to the team wirelessly. There shall be no time delay in communications, as the URC is based on the assumption that the rovers in question are telerobots, being operated by astronauts on or orbiting Mars. Refer to rule 2.h regarding the impacts of a loss of communications.

2.f. If the rover carries a deployable airborne vehicle, that is not a lighter-than-air system, in addition to conforming to rules 1.b.i and 1.b.ii it must also simulate a vehicle that could fly on Mars. While the ground level air density on Mars is much lower than on Earth the gravity is lower too. In order to simulate these effects on Earth the vehicle shall carry a dead weight equal to the weight of the battery(s) used. For example if the airborne vehicle is powered by a battery that weighs 50g it must carry a dead weight of 50g. Teams shall provide the dead weight(s) and may distribute it (them) as they see fit provided that the dead weight and battery(s) are removable from the vehicle so they can be weighed. A dead weight shall not provide power, add structural or aerodynamic support, perform computation or sensing, or otherwise add functional utility to the system.

2.g. Lighter-than-air vehicles are not allowed at URC since lighter-than-air vehicles on Mars are only practical for heavy lift applications.

2.h. If a rover suffers a critical problem during a task that requires direct team intervention (including a loss of communication that requires the team to move the rover to reestablish communications), that intervention shall be subject to the following: 2.h.i. The team may designate any number of members (herein referred to as “runners”) who may retrieve the rover, and return it to the blind side of the command and control station (such that the other members may work on the rover without being able to view the task site).
2.h.ii. Runners shall not communicate any details about the task site to the rest of the team (judges will monitor conversation), however are permitted to take part in the diagnostic process.
2.h.iii. After completing work on the rover, the runners may relocate the rover to any position within the start gate area.
2.h.iv. The runners shall not be permitted to participate in the command and control of the rover, or analysis of any data, after this point for the current event. Runners will still be permitted to retrieve the rover in future interventions, although only at the direction of the eligible command and control team.
2.h.v. Teams will be penalized 10 points for every intervention. The task clock will continue to run during interventions.

3. Competition Tasks 3.a. The rover shall be judged in the four competition tasks outlined below in 3.b to 3.e, in addition to the presentation task outlined in 3.f. The five tasks will be independent events. 3.a.i. For the four competition events, the rover is not required to be in the same configuration. Teams will have at least 2 ½ hours to reconfigure, adjust and repair their rovers in between competition events, and will not have to compete in more than 2 such events in a single day.
3.a.ii. Each event, including the presentation task, shall be worth 100 points, for a total of 500 points. The minimum points awarded for a single event is zero, even if the penalties are greater than the points earned.
3.a.iii. From the time teams are given access to their command and control tent, they shall be able to set up all necessary systems, including all communications systems, and be ready to compete in no more than 25 minutes. Teams shall be able to fully disassemble all equipment in no more than 15 minutes at the end of the event.

3.b. Sample Return Task:

Teams will be given a field briefing by judges to discuss the task site. Teams controlling their rovers shall then select multiple (3-6) sites of potential biological interest within a 0.5km radius of the start gate. Based upon investigation of the selected sites, teams shall then collect and return a single sub-surface sample from the site they determine to have the greatest likelihood of containing photosynthetic bacteria such as cyanobacteria/blue-green algae, other bacterial colonies such as are associated with desert varnish, as well as other nonbacterial extremophiles such as lichen. The sample must be collected from just below the topsoil at 5cm (2”) depth or deeper. The mass of this sample must be at least 25 grams, but no greater than 250 grams, and may consist of a single rock, or a soil sample. The primary indicator of the extremophiles of interest is reflected light in the visible spectra.
In addition to visual observation teams must select and an in-situ science capability of their choice that the rover will perform in the field on the sample collected. Teams must explain the value of that capability, why they chose it, and the trade-offs made. Rovers shall return the collected sample to the team's command and control tent by the end of the time allotted.
Teams shall document each site investigated according to the following procedure:
3.b.i. At a given site, the team must take a close up, high-resolution picture with some indication of scale (scale can be indicated post-capture).
3.b.ii. Produce a wide-angle panorama showing the full context of the site and immediate surrounding area. The panorama must indicate cardinal directions, and have some indication of scale.
3.b.iii. Teams must also record the GPS coordinates of each site, to include elevation and accuracy range. Thorough documentation is especially crucial for the sample that is returned.

Teams will be given 30-60 minutes to collect data and the sample with the rover (exact amount of time to be announced on-site), after which they will be given a similar amount of time (not necessarily equal to the on-course time) to prepare data for a field briefing to the judges (which will last 15 minutes, to include questions from the judges). In the field briefing to judges, teams will be required to describe and analyze their data for all sites investigated, and provide a justification for returning the sample that was selected. The score for this task will be based on the following, equally weighted, components: 1) thoroughness of the investigation of sites; 2) quality and applicability of the analysis of the field science; 3) quality of the sample returned; and 4) quality and applicability of the analysis of the sample returned.

3.c. Astronaut Assistance Task:

Teams shall be required to collect multiple objects left in the field and deliver/deploy them to multiple locations throughout the field. The location and description of the equipment will be given in GPS coordinates to within 3m. There will be two distinct types of deployment as described below.
3.c.i. The equipment will include small lightweight hand tools (e.g. a hammer) and supply containers up to 5kg in mass. Items will include visual markings to help distinguish them. Teams will be provided with instructions to deliver specific pieces of equipment to specific astronauts throughout the field. The astronauts will be identifiable by simulated space suits, and approximate GPS coordinates (to within 25m) will also be given for the astronauts. A successful delivery is defined by placing the appropriate equipment on the ground within 1m of the appropriate astronaut.

3.c.ii. A single wireless repeater box that is required to service an unattended sensor deployed in the field out of line of sight communications with the control station. Teams will be provided with a “black box” receiver and signal monitor in the control station. Teams shall deploy the repeater in the field such that the communications path between the unattended sensor and command station receiver is successfully completed. The receiver shall provide confirmation of connectivity between the receiver and repeater, as well as between the repeater and unattended sensor. Teams will only be provided with 75m accurate GPS coordinates for the sensor, and will need to scan for the sensor’s signal using the repeater and receiver feedback. Teams are not required to actually locate the exact sensor position.

All items to be picked up by the rover in this task will have stable graspable features no greater than 5cm in width or diameter. Containers and the repeater box shall be no larger than 40cm x 40cm x 40cm, with a mass no greater than 5kg. Rovers may pick up multiple items at a time, and are also permitted to make multiple trips to retrieve additional objects.

As many as half of the objects or astronauts will be intentionally located out of line-of-sight communication with the control station. A maximum time limit between 30 and 60 minutes, and approximate GPS coordinates (as previously described) for the equipment, unattended sensor, and the astronauts will be provided to teams. All equipment, astronauts and the unattended sensor will be located within a 1.0 km radius of the start gate. Line of sight communication with the start gate will only be guaranteed for 50% of the course. The equipment and the astronauts will be accessible via relatively benign terrain. Scores will be based on the number of objects delivered to the correct astronaut, signal quality between the unattended sensor and receiver, and the time taken. The rover is not required to return to the start gate at the end of this task.

3.d. Equipment Servicing Task:

Rovers shall be required to perform several dexterous operations on a mock-up equipment system. The rover shall have to travel up to 0.5km across relatively flat terrain (negligible slope) to reach the equipment. Teams and their rover shall then have to read directions, printed on a panel, describing the sequence of tasks to be performed. This year the equipment servicing task will involve performing maintenance on a series of pipes, hoses and valves and switching on a compressor to inflate an inflatable structure. Tasks may include connecting pipes into fittings, turning valves, screwing on connections, pushing buttons, and reading pressure gauges.

Teams will only be required to manipulate one end of a pipe or hose to make connections that a human could do with one hand so that a single robotic arm should be sufficient to perform the task. Pipes will include PVC plumbing pipes less than 2” in diameter either rigid or flexible with push in or threaded screw connections. Flow valves may have knob or handle actuation.

Fittings, valves, or gauges will be between 0.2 and 0.5m above the ground and may be mounted horizontally or vertically. Loose parts that need to be connected will be located within the general workspace but may be lying on the ground or leaning against equipment. All text on the panel shall be printed in the equivalent of Times New Roman 18 point font in black ink against a white background.

Teams will receive points for every sub-task completed successfully, but will be partially penalized for subtasks completed out of order. Sub-task point weights will be consistent with the level of difficulty (i.e. making screw connections will have the largest weight, pushing buttons the smallest weight).

3.e. Terrain Traversing Task:

Rovers shall be required to traverse a variety of difficult terrains as part of an engineering field test of the ruggedness and route-finding ability of the rovers. Terrain may include soft sandy areas, rough stony areas, rock and boulder fields, vertical drops potentially in excess of 0.5m, and steep slopes in excess of 60°. There is no limit placed on the slopes or size of drops or boulders that may be encountered. It will be advantageous to be able to climb or descend near vertical faces but will not be required. Rovers will be required to pass through a set of target gates not more than 1km from the start gate. Gates will consist of 2 white PVC pipes no less than 10cm in diameter, standing vertically from the ground to a height of 1-2 meters, and spaced at least 2m apart, and will be numbered or lettered so they can be distinguished from each other. Teams will be given GPS coordinates of the gates and may walk the terrain course ahead of time. In some areas teams may be asked to follow marked routes to the gates, and in others they may be required to pick their own route. Teams may deviate from marked routes if their rover cannot overcome a specific obstacle but will suffer a penalty. Teams will have a maximum time of between 30 and 60 minutes on course and do not have to return to the start gate. Teams will be scored on the number of gates they pass through, any deviations from marked routes, and the time taken.
3.f. Presentation Task:

Teams shall prepare and deliver a presentation to the URC judges describing their team, rover design and functionality. The length of the presentation (not including questions) shall be no longer than 15 minutes. Judges may ask follow-on questions as warranted after this time. Scoring for this section will be assessed on the following equally weighted categories:
- Team structure, organization, and management
- Core rover design and presented functionality (rover need not function for presentation)
- Suitability of rover design to competition tasks
- Response to follow-on questions
- Overall quality of presentation

4. Team Management 4.a. Teams shall be required to track all finances as related to this project, and submit a final expense record no later than May 23, 2014 (if necessary, teams may submit an updated record – hard or soft copy – on the first day of the URC event – May 29, 2014). Teams shall be penalized 25 points per day if they are late in submitting the expense report, and will be disqualified for not submitting their expense report by the end of the URC event.

4.a.i. The maximum allowable cash budget to be spent on the project is $15,000 US, which shall include money spent on parts and components for the rover, rover modules, rover power sources, rover communications equipment, and base station communications equipment (only that equipment used to communicate with the rover). The budget limit shall not apply to command and control equipment not included above (i.e. base station computers and monitors), tools, volunteer labor time, or travel expenses.
4.a.ii. Teams may acquire in-kind donations of equipment. Such donations will count towards the cash budget at its documented value. Corporate sponsorship is encouraged.
4.a.iii. Teams may be required to submit receipts as proof of budget upon request (donations must be documented by the donor).

4.a.iv. Any parts and/or components purchased in previous years and/or leveraged from previous rovers or projects for this year's rover shall be valued at purchased prices unless teams elect to document the current newly purchased value of all components.
4.a.v. Teams have the option of using either the as-bought prices or may apply depreciation rules to 50% of their re-used components. If teams apply depreciation rules they must determine the current prices of all components. The idea is that teams not close to the maximum limit do not need to spend a lot of time here looking up current prices. However teams close to the maximum budget and re-using a lot of components may gain some benefit from depreciation rules if they are willing to go to the effort of finding current prices for everything, some of which like computers may be cheaper but others like raw materials and machining labor may have increased. For information regarding depreciation, teams may consult the U.S. Internal Revenue Service's website.
4.a.vi. If used equipment is purchased commercially the as-bought price may be used. If used equipment is donated to the team and no used market exists for a component then the cost of a new component must be used. Depreciation rules may then be applied if desired according to rule 4.a.v.
4.a.vii. International teams have an allowable budget equivalent to $15,000 US based on the most advantageous documented currency conversion rate between August 1, 2013 and May 29, 2014.

4.b. There shall be one division of competition open to both graduate and undergraduate students. Teams are permitted to include secondary school (high school) students. A single university may field multiple rovers and multiple teams, however there may be no overlap between team members and leaders, budget, donated equipment, or purchased equipment.

4.c. Teams are encouraged to work with advisors. However, advisors are expected to limit their involvement to academic level advising only. It is incumbent upon the student team leaders to ensure that their respective teams uphold the integrity of this competition. Nontechnical team management duties, including tracking finances, fall within the duties of the students.

A-4 Requirements Matrices

Product: BYU Mars Rover 2014

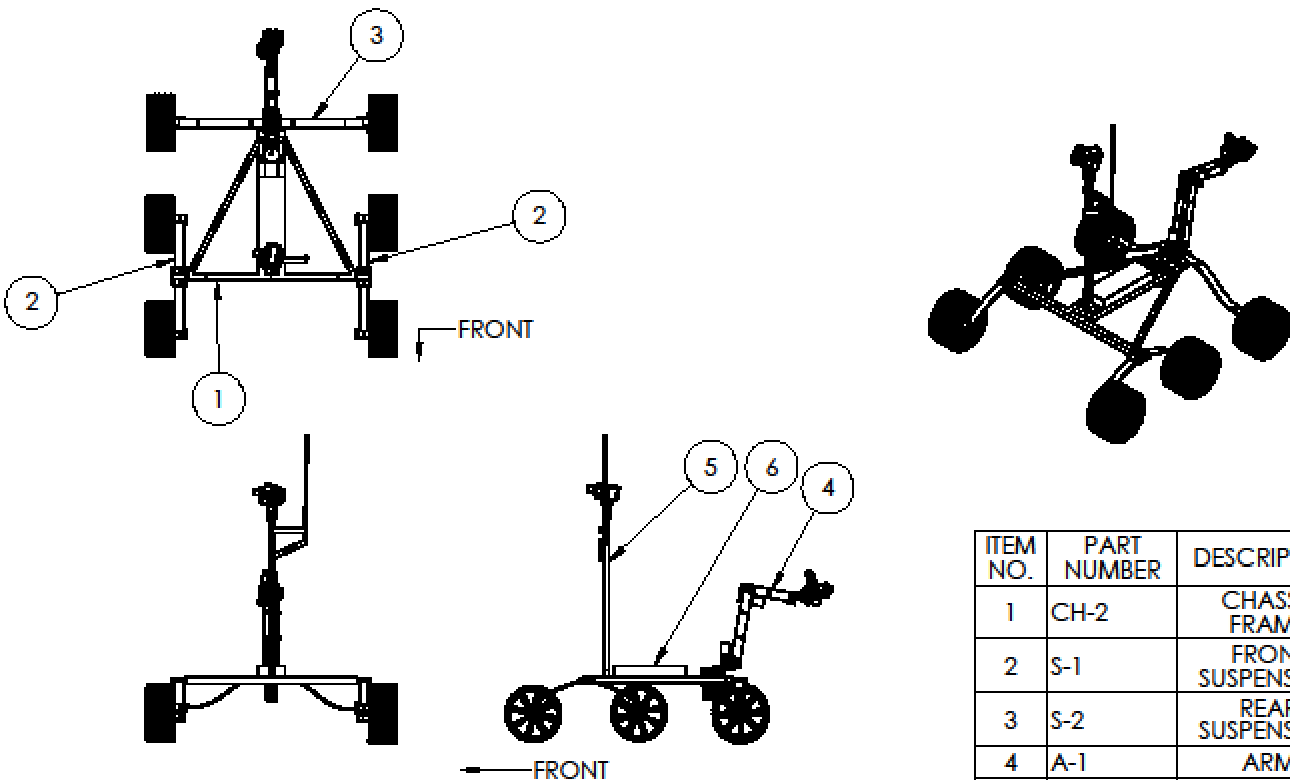
#	Market Requirement	Surrogate Evaluation Criterion	Any configuration weights less than 50 Kg	Spare parts less than 20 Kg	Total out of poket cost to remain under 15000	Obtain a sample between 25-250g	Dig deeper than 5 cm below surface	Camera capable of wide angle capture	Complies to FCC rules	Greater than 1 KM communcation out of site	Can pick up at least 5 Kg	Graspable reagion 5cm width/diameter	Live gps capable	Resolution capable of reading 18pt Times new roman font	Grip and spin and push and flip items	Traverse vertical terrain	Wheel base less than 2M	Sexy rover	Interchangable connection points	Less than 25 min command post setup	Battery life longer than 60 minutes worst case	Traverse boulder	Soft sand	60Deg slope	Operate in 100 deg heat
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Weights less than 50 kg		X	X																					
2	Cost less than $15000, actual costs less than $13000				X																				
3	Collect sample deeper than 2 inches from surface					X	X																		
4	Take picture of sample							X																	
5	Panoramic photo		X	X				X																	
6	Return data from sites							X	X	X															
7	Pick up, carry and drop items to a location										X	X													
8	Locate and record gps infromation												X												
9	Read written instructions							X						X											
10	Manipulate buttons, switches, thread pipes		X	X							X	X			X										
11	Travel over soft sand, rough stone, 60% grade up/down, and							X								X									
12	Fit through a 2M wide space																X								
13	Looks attrative-requirement?																	X							
14	Modular configuration		X	X															X						
15	Easy setup of command post																			X					
16	Long battery life		X	X																	X				
17	Operate in desert conditions																					X	X	X	X
18	No line of sight communication		X	X					X																
		Unit of measureme	Kg	Kg	$	grams	cm	Degrees view	Y/N	KM	Kg	cm	Y/N	Font size	Y/N	Verticle height (m)	m	Y\N	#of Connections	min	min	Dia of Boulder (m)	KPa of rover on sand	Degrees	Deg C
		Marginal	50	20	15000	25	5	100	Y	1	5	5	Y	18	Y	0.1	2	Y	10	25	60	0.15	100	60	37
		Ideal	40	10	15000	100	10	170	Y	2	10	0-5	Y	6	Y	1	2	Y	1	10	240	0.5	120	90	49
		Target	45	15	15000	50	7.5	150	Y	1.5	8	41279	Y	12	Y	0.2	1.3	Y	5	15	120	0.3	95	60	40
		Achieved																							

Product: Rover Arm			Surrogate Evaluation Criterion	Reach from 0-.5 m	Area of rover bed reachable by arm	Ammount of weight the arm can pick up	Arm integrates with chassis	arm and any attachment are within weight limits	dust resistant	water resistant	static resistant	heat resistant	depth of dirt removable	downward/lateral force applied	Weight of sample collected	resolution of arm turret	resolution of attachment positioning	torque of attachment	gripping strength of attachment	size of grippable region
#	Category	Market Requirement	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	size of grip
1	General Arm	Has appropriate reach		X																
2		Place objects on and pickup from Rover			X														X	X
3		Support the weight of payload				X													X	
4		Integrates with chassis					X													
5		Within weight limits						X												
6		Operable in desert conditions							X	X	X	X								
7	Astronaut Assistance	Place repeater in appropriate location		X	X	X										X	X			
8		Pick up and deliver packages/tools		X	X	X										X	X		X	X
9	Sample Return	Analyze sample		X																
10		Remove top layer of dirt/rock											X	X						
11		Collect science sample											X		X	X	X			
12		Transport sample			X															
13	Equipment Maintenance	Push buttons		X												X	X	X		
14		Flip switches		X												X	X	X		
15		Turn knobs		X												X	X			X
16		Manipulate pipes		X										X		X	X	X		X
17		Read instructions		X												X	X			
		Market desired values	Unit of Measurement	m	%	kg	Y/N	kg	Y/N	Y/N	Y/N	Deg C	cm	N	kg	Deg	cm	N*m	N	cm2
			Marginal	0.4	50	5	Y	10				32	2	10	0.02	3	5	5	15	1
			Ideal	0.5	100	10	Y	6				43	5	25	0.25	0.5	0.5	15	25	6
		Product performance	Target	0.4	80	5	Y	7	Y	Y	Y	43	4	20	0.2	1	2.5	10	20	4
			Achieved	1	100	10	Y	6	Y	Y	Y	32	8	133	0.074	0.72	1	5.4	100	2

Appendix B: Design Information

B-1 Drawing Package

Drawing package will begin on next page



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	CH-2	CHASSIS FRAME	1
2	S-1	FRONT SUSPENSION	2
3	S-2	REAR SUSPENSION	1
4	A-1	ARM	1
5	G-6	COMMS MAST	1
6	COMMS	ELECTRONICS	1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S. MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:
ROVER FULL ASSY

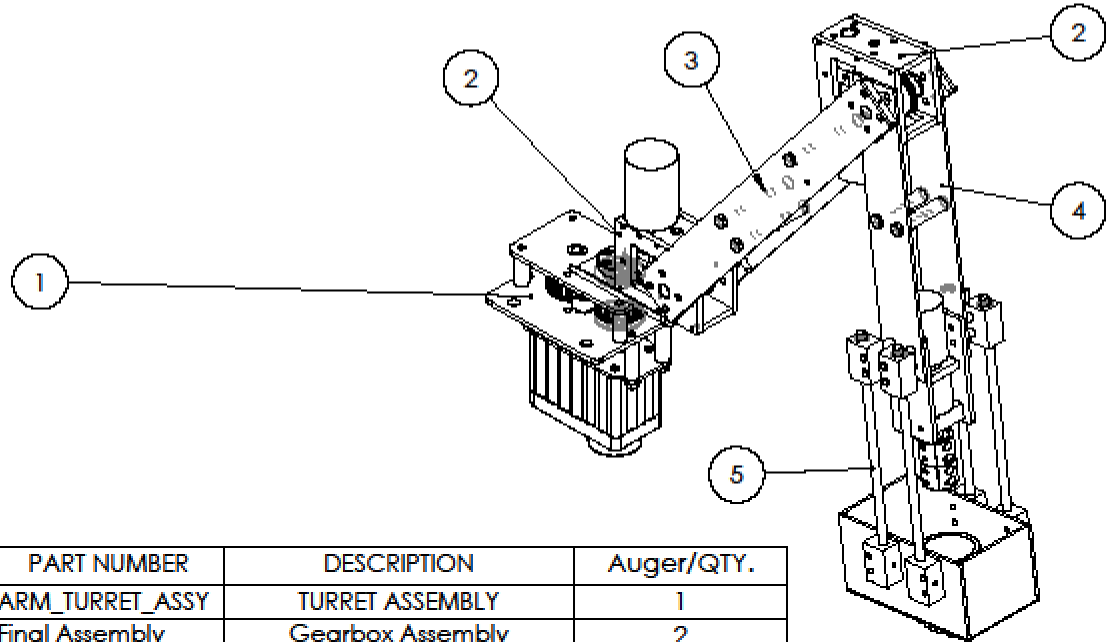
TITLE:
MARS ROVER

SIZE	DWG. NO.	REV
A	1	1

SCALE: 1:32 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	Auger/QTY.
1	ARM_TURRET_ASSY	TURRET ASSEMBLY	1
2	Final Assembly	Gearbox Assembly	2
3	Bicept Assembly	Bicep Assembly	1
4	Forearm Assembly	Forearm Assembly	1
5	Auger Assembly	AUGER ASSEMBLY	1

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DWA	4-15-2014
CHECKED	DHA	4-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.
Mars Applied Robotic Systems

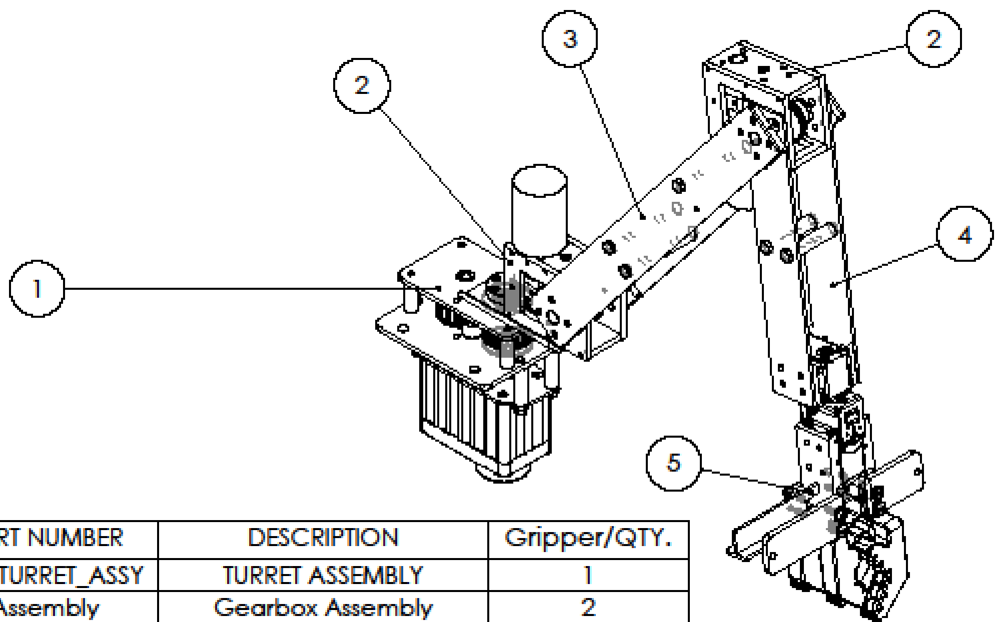
DESCRIPTION: Arm Assembly

TITLE: Arm Assembly

SIZE	DWG. NO.	REV
A	A0	1

SCALE: 1:10 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	Gripper/QTY.
1	ARM_TURRET_ASSY	TURRET ASSEMBLY	1
2	Final Assembly	Gearbox Assembly	2
3	Bicept Assembly	Bicep Assembly	1
4	Forearm Assembly	Forearm Assembly	1
5	Winter Assembly Gripper		1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DWA	4-15-2014
CHECKED	DHA	4-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

NEXT ASSY | USED ON

APPLICATION

BYU M.A.R.S.

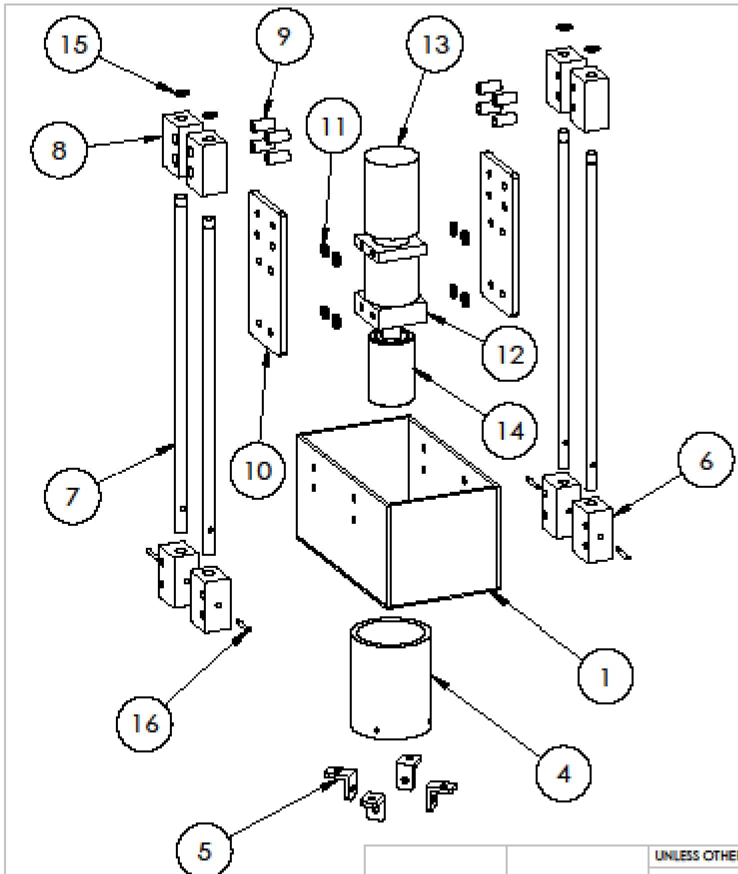
DESCRIPTION: Arm Assembly

TITLE: Arm Assembly Gripper

SIZE A | DWG. NO. A1 | REV 1

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

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	BOX	COLLECTION BOX	1
4	4Tube	AUGER SLEEVE	1
5	1556A24	SLEEVE MOUNT BRACKET	4
6	base bracket-3	BOX GUIDE BLOCK	4
7	Rod	GUIDE ROD	4
8	base bracket-TL	ARM GUIDE BLOCK	4
9	92510A319	BLOCK SPACER	8
10	motor plate	MOTOR PLATE	2
11	3088A464	MOTOR SHIMS	8
12	Gearbox	BANEBOTS P60 64:1	1
13	Motor	BANEBOTS RS550	1
14	3084K31	SHAFT COUPLER	1
15	98410A650	RETENTION RINGS	4
16	98296A853	SLOTTED PIN	4

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
VARIOUS
FINISH
N/A
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DEVIN	4/15/14
CHECKED	DREW	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

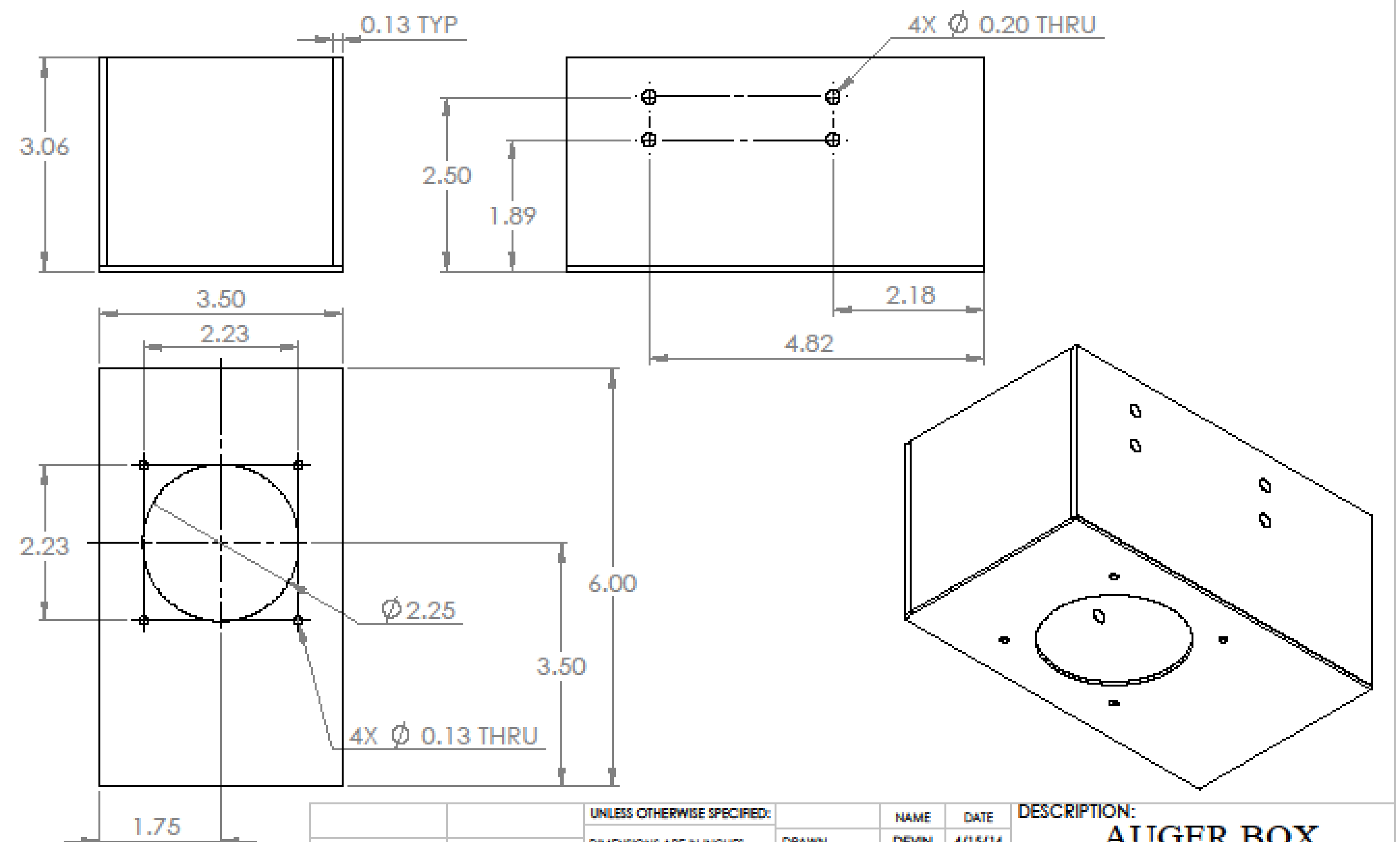
BYU M.A.R.S.

DESCRIPTION:
AUGER ASSEMBLY
TITLE:
ARM AUGER TURRET ASSEMBLY

SIZE	DWG. NO.	REV
A	AA0	A

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DEVIN	4/15/14
	CHECKED	DREW	4/15/14
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.		
MATERIAL AL 6061			
FINISH N/A			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

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BYU M.A.R.S.

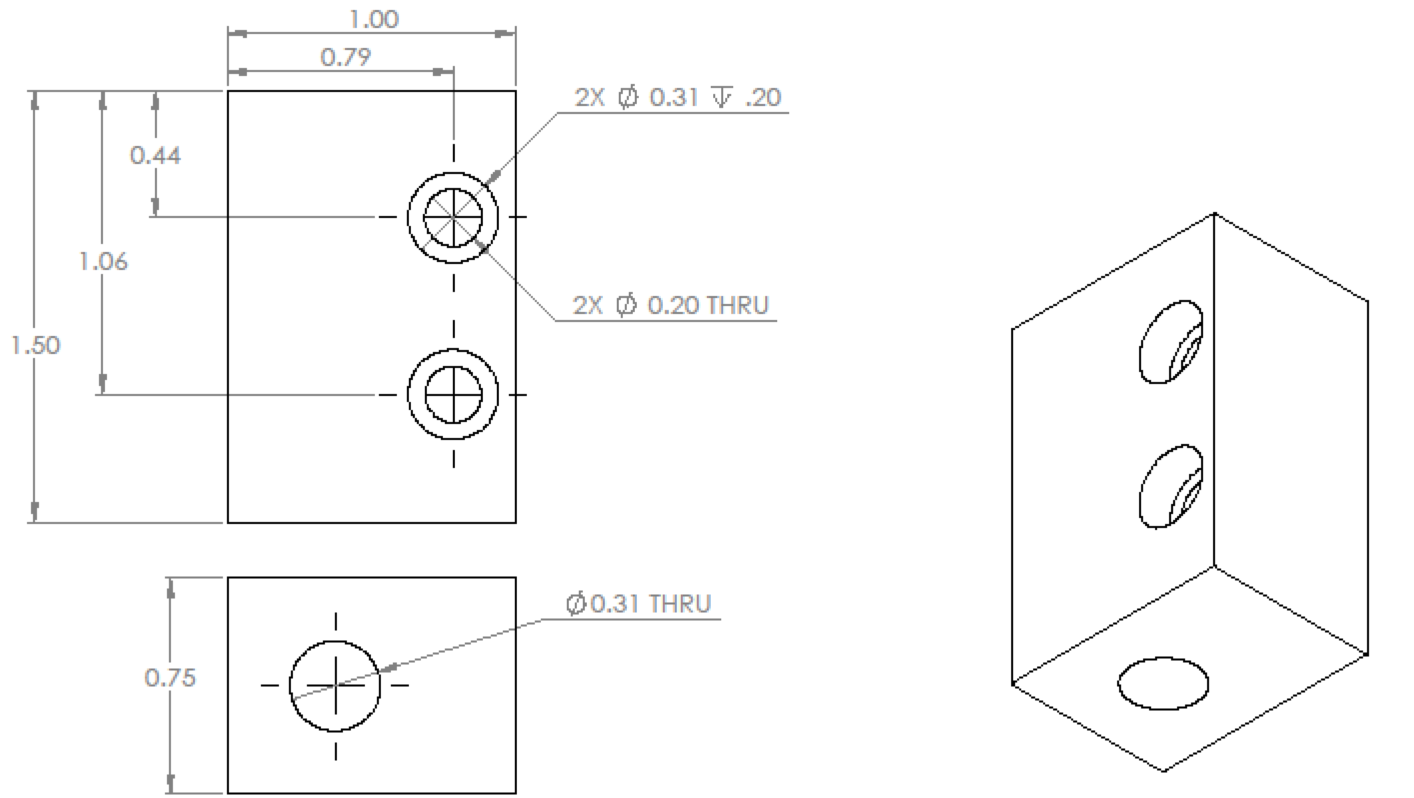
DESCRIPTION: AUGER BOX

TITLE: ARM AUGER AUGER BOX

SIZE	DWG. NO.	REV
A	AA1	A

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1

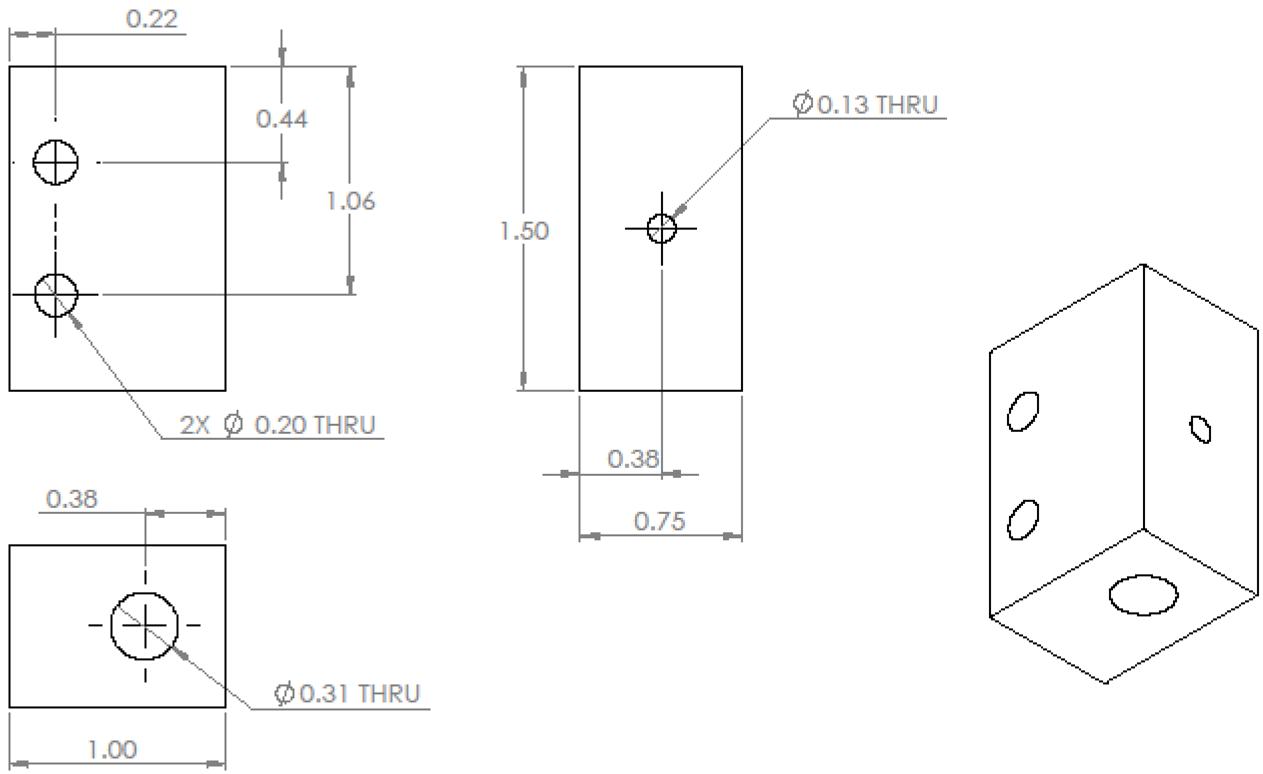


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION: ARM GUIDE BLOCK		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DEVIN	4/15/14	TITLE:		
	CHECKED	DREW	4/15/14	ARM AUGER ARM GUIDE BLOCK		
	ENG APPR.					
	MFG APPR.					
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.					
MATERIAL UHMW PE	BYU M.A.R.S.			SIZE A	DWG. NO. AA2	REV A
FINISH N/A						
DO NOT SCALE DRAWING				SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

5 4 3 2 1



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APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
UHMW PE

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DEVIN	4/15/14
CHECKED	DREW	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

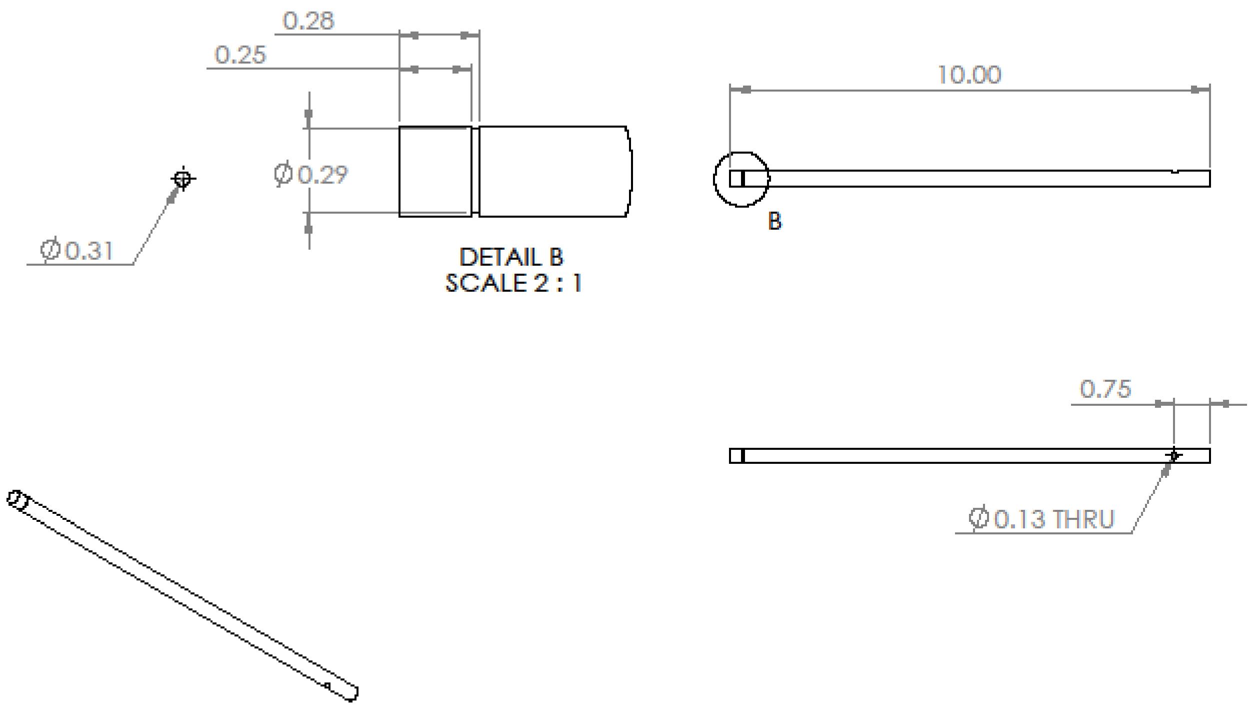
DESCRIPTION:
BOX GUIDE BLOCK

TITLE:
ARM AUGER
BOX GUIDE BLOCK

SIZE	DWG. NO.	REV
A	AA3	A

SCALE: 3:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
MILD STEEL
FINISH
POLISHED
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DEVIN	4/15/14
CHECKED	DREW	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

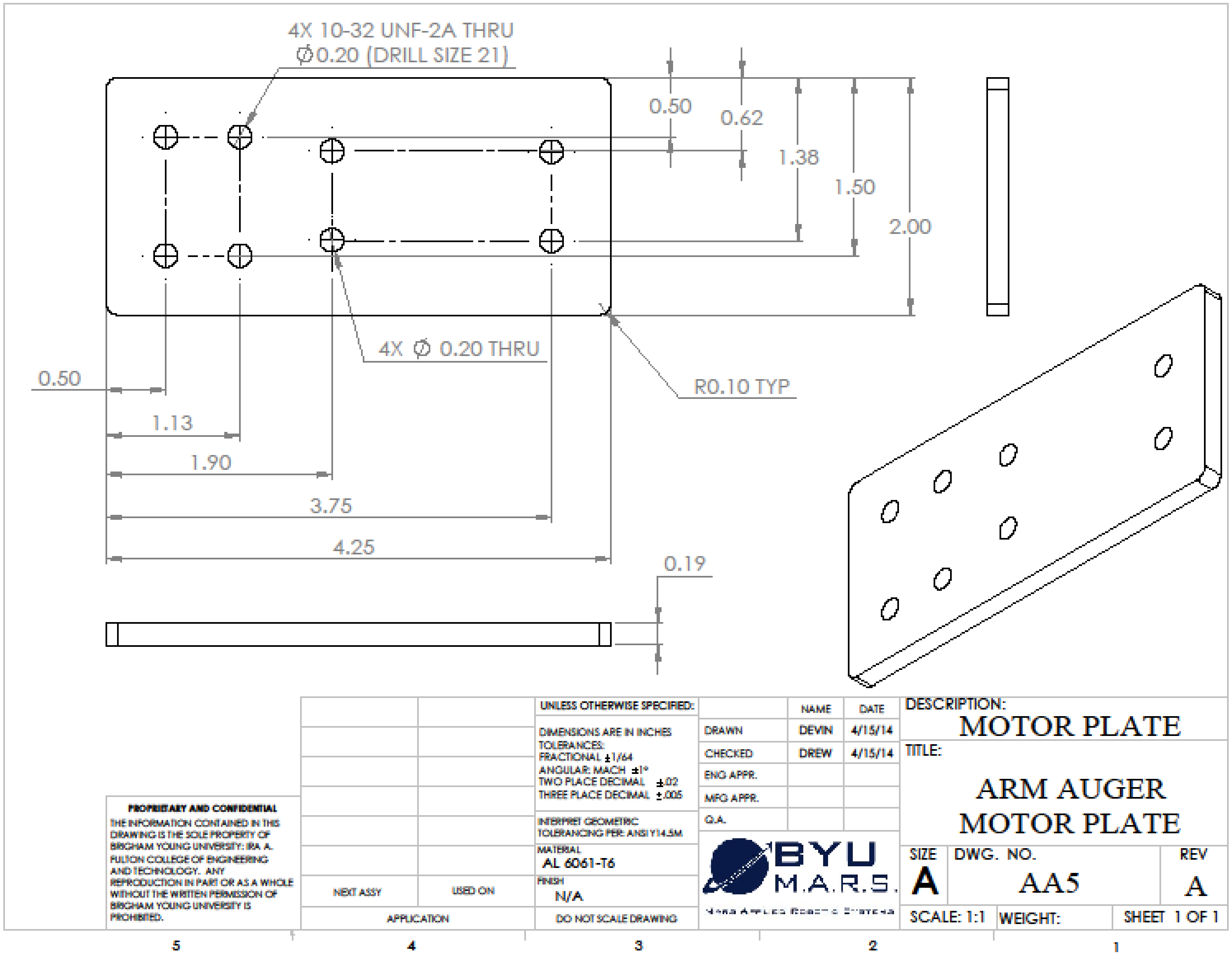
DESCRIPTION:
GUIDE ROD

TITLE:
ARM AUGER GUIDE ROD

SIZE	DWG. NO.	REV
A	AA4	A

SCALE: 1:3 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



4X 10-32 UNF-2A THRU
∅0.20 (DRILL SIZE 21)
0.50
0.62
1.38
1.50
2.00
4X ∅ 0.20 THRU
R0.10 TYP
0.50
1.13
1.90
3.75
4.25
0.19
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
AL 6061-T6
FINISH
N/A
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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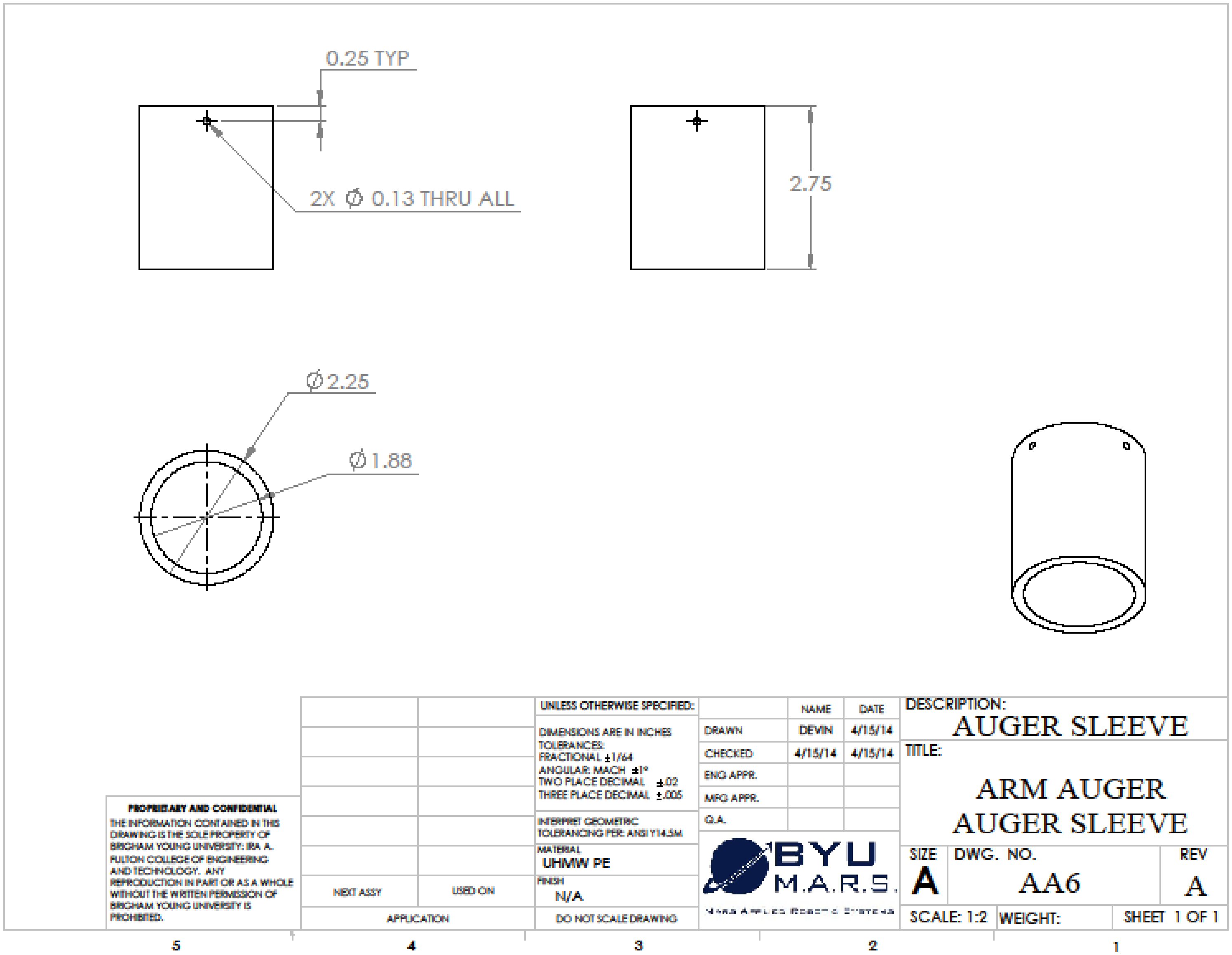
NAME
DATE
DRAWN
DEVIN
4/15/14
CHECKED
DREW
4/15/14
ENG APPR.
MFG APPR.
Q.A.
BYU
M.A.R.S.
DESCRIPTION:
MOTOR PLATE
TITLE:
ARM AUGER MOTOR PLATE
SIZE
A
DWG. NO.
AA5
REV
A
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



0.25 TYP
2X Ø 0.13 THRU ALL
2.75
Ø2.25
Ø1.88
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
UHMW PE
FINISH
N/A
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
DEVIN
4/15/14
CHECKED
4/15/14
4/15/14
ENG APPR.
MFG APPR.
Q.A.
DESCRIPTION:
AUGER SLEEVE
TITLE:
ARM AUGER
AUGER SLEEVE
SIZE
A
DWG. NO.
AA6
REV
A
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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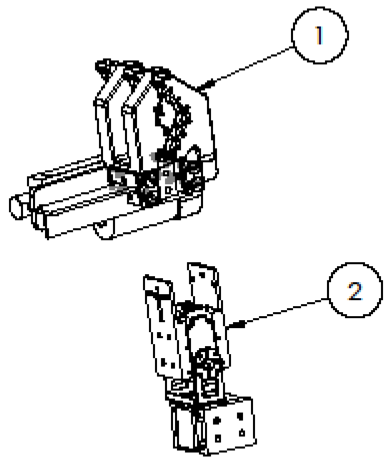
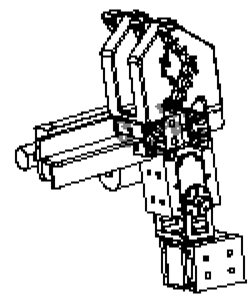
BYU
M.A.R.S.
5
4
3
2
1





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	V_C Clamp	V GRIP	1
2	Assem1	WRIST	1

	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
VARIOUS

FINISH
N/A

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

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BYU M.A.R.S.

DESCRIPTION:

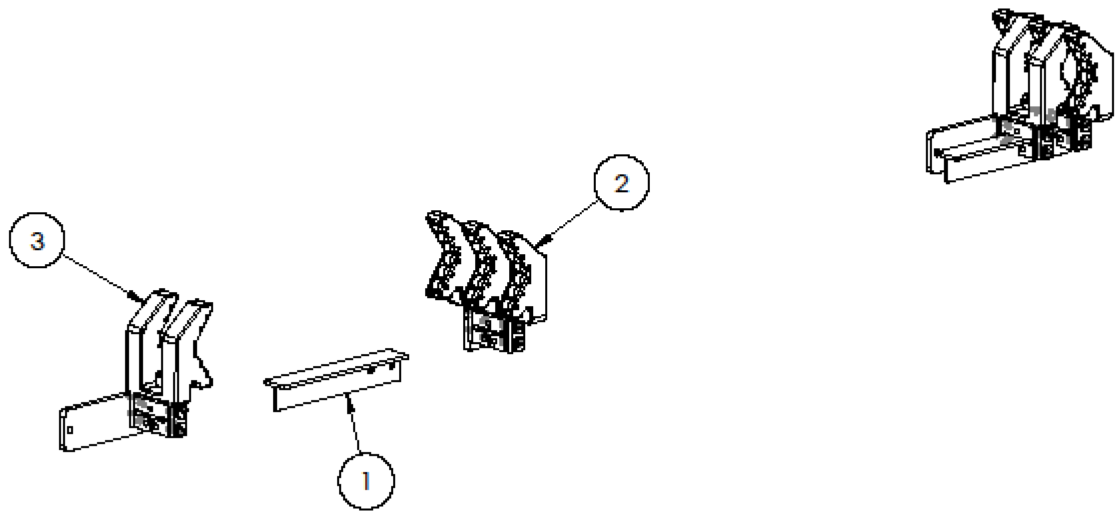
TITLE:

V GRIP WITH WRIST

SIZE A | DWG. NO. AC0 | REV A

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

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	V_t_channel	T CHANNEL	1
2	V_Static Jaws	JAWS STATIONARY	1
3	V_Dynamic Jaws	JAWS SLIDING	1

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
VARIOUS
FINISH
N/A
DO NOT SCALE DRAWING

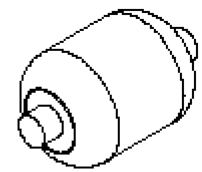
	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

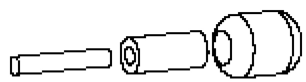
BYU M.A.R.S.
Mars Applied Robotic Systems

DESCRIPTION:
TITLE:
V GRIP
ASSY

SIZE A | DWG. NO. AC1 | REV A
SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	rod	SPRING PIN	1
2	PE sleeve	SLEEVE	1
3	PU roller	ROLLER	1

PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
VARIOUS

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION:

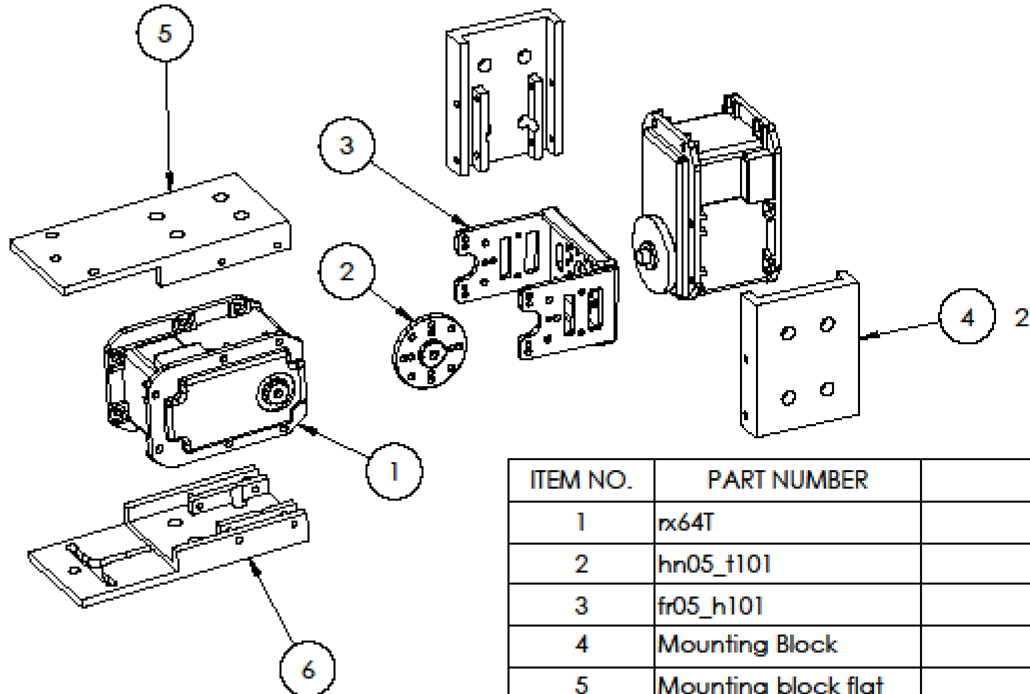
TITLE:

ROLLER ASSY

SIZE	DWG. NO.	REV
A	AC2	A

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	rx64T	WRIST SERVO	2
2	hn05_t101	DISK	1
3	fr05_h101	CONNECTOR	1
4	Mounting Block	ARM MOUNT	2
5	Mounting block flat	GRIP MOUNT	1
6	Mounting block flat	GRIP MOUNT SLOT	1

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
VARIOUS
FINISH
N/A
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

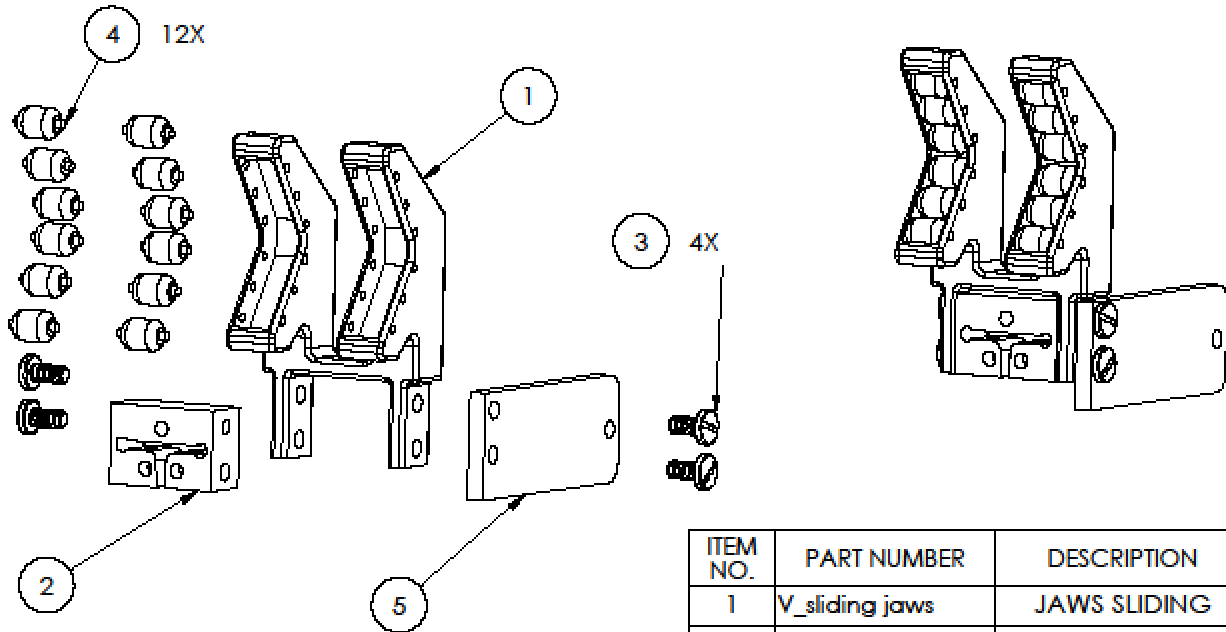
DESCRIPTION:

TITLE:

WRIST

SIZE	DWG. NO.	REV
A	AC3	A
SCALE: 1:5	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	V_sliding jaws	JAWS SLIDING	1
2	full_t_slot	SLIDER	1
3	91792A537	SCREW	4
4	rod	ROLLER ASSY	12
5	actuator mount sliding	ACTUATOR MOUNT SLIDING	1

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
VARIOUS

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION:

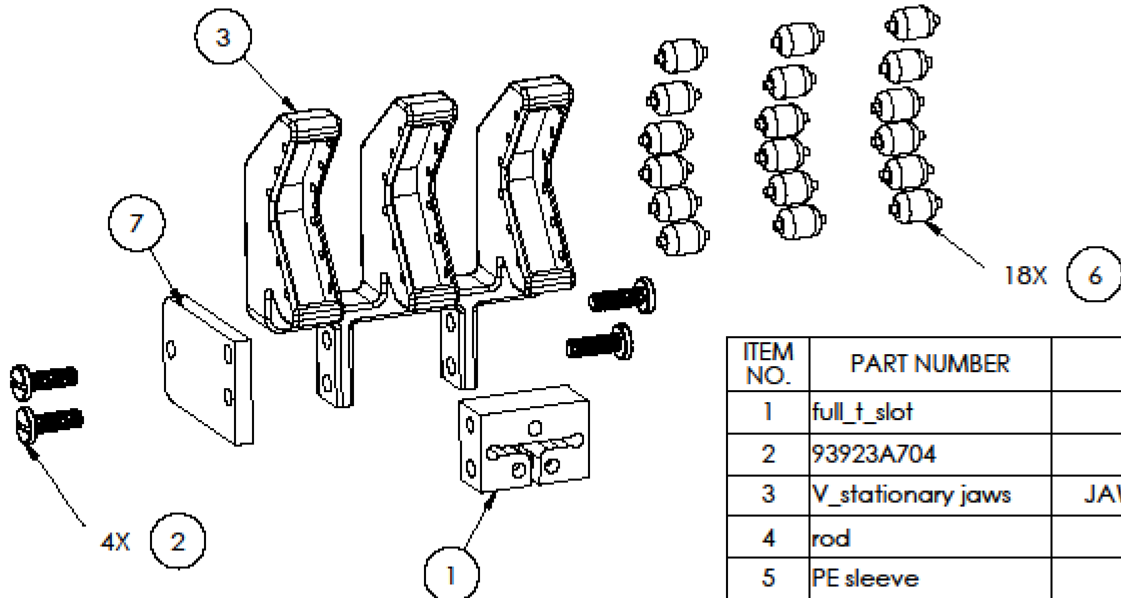
TITLE:

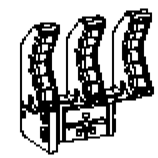
JAWS SLIDING

SIZE	DWG. NO.	REV
A	AC4	A

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

5 4 3 2 1





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	full_t_slot	SLIDER	1
2	93923A704	SCREW	4
3	V_stationary jaws	JAWS STATIONARY	1
4	rod	SPRING PIN	18
5	PE sleeve	SLEEVE	18
6	PU roller	ROLLER	18
7	actuator mount stationary	ACTUATOR MOUNT STATIONARY	1

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
VARIOUS
FINISH
N/A
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.
NASA APPLIED ROBOTIC SYSTEMS

DESCRIPTION:

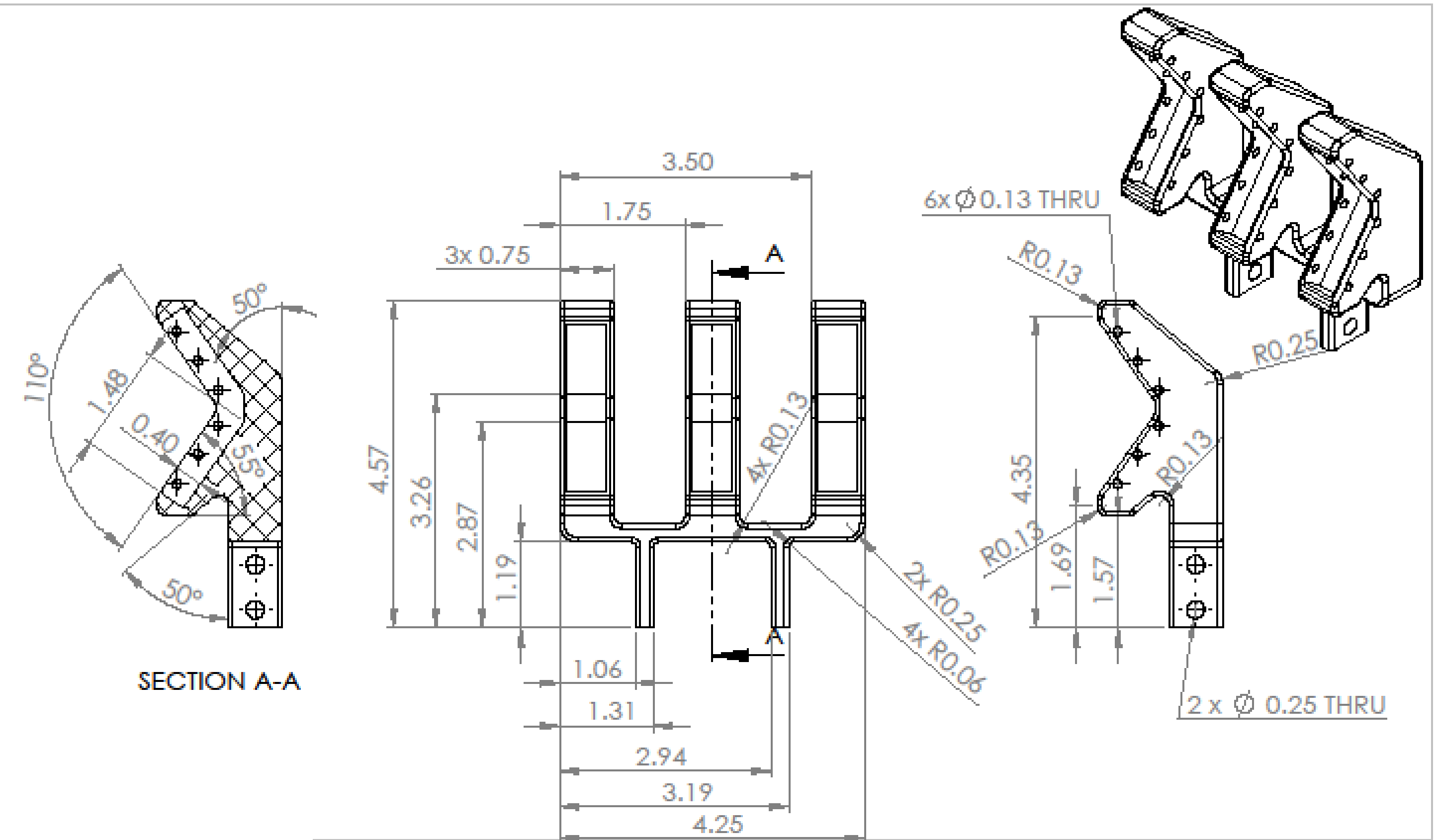
TITLE:

STATIC JAWS

SIZE A | DWG. NO. AC5 | REV A

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

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

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TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL: ABS

FINISH: N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION:

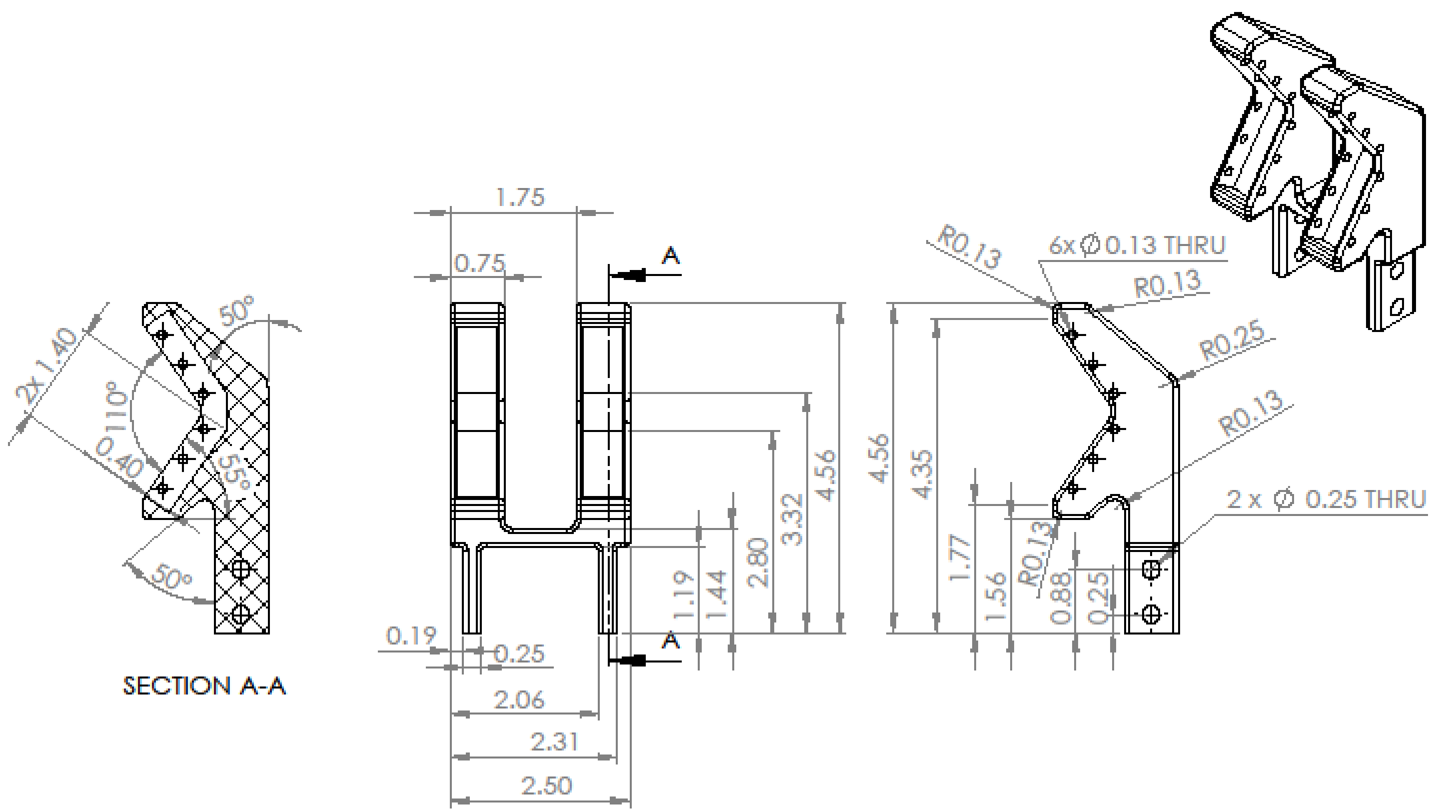
TITLE:

JAW STATIONARY

SIZE	DWG. NO.	REV
A	AC6	A

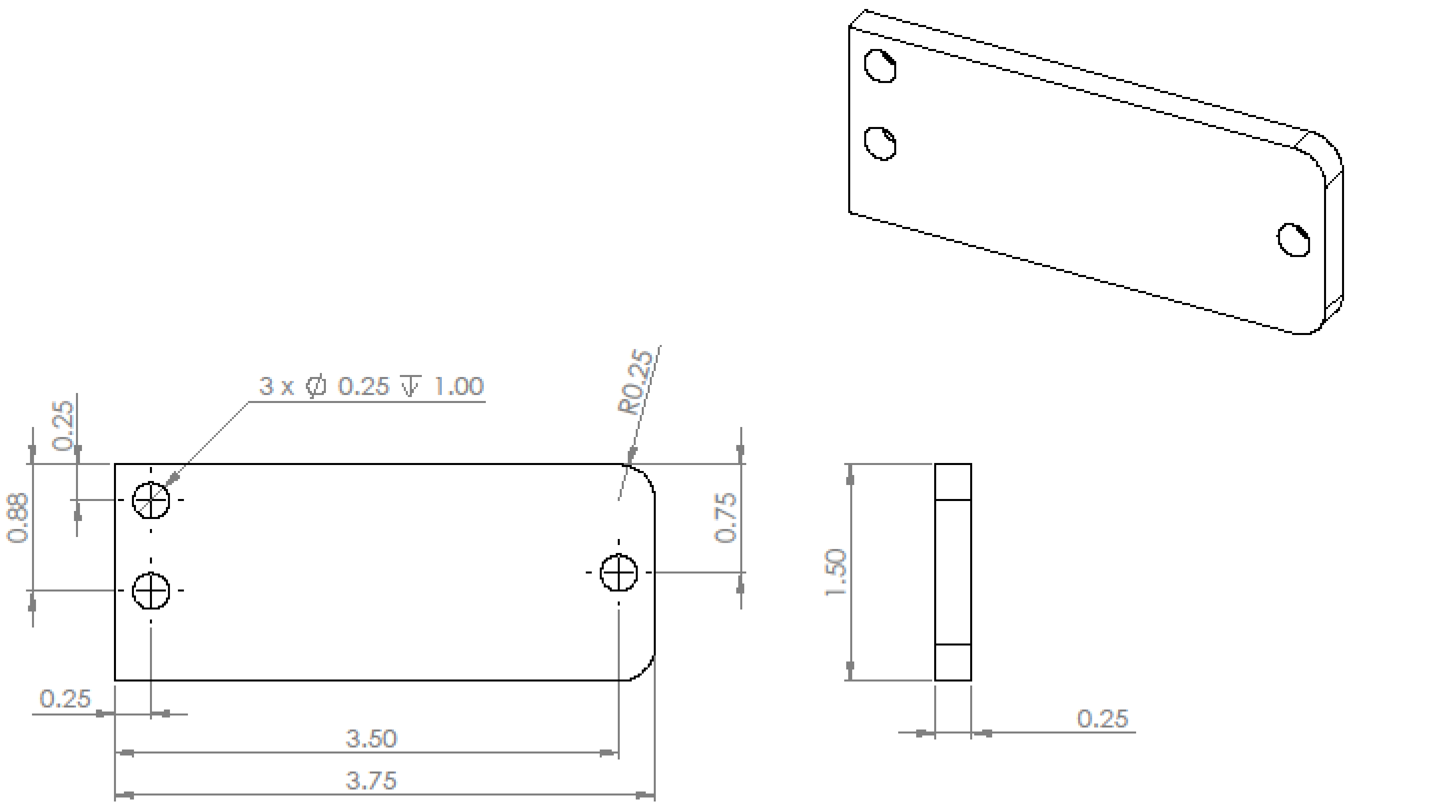
SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION:
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	C GRAMES	4/15/14	TITLE:
			CHECKED	DEVIN	4/15/14	JAW SLIDING
			ENG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	MFG APPR.			
		MATERIAL ABS	Q.A.			SIZE A
NEXT ASSY	USED ON	FINISH N/A	BYU M.A.R.S.			DWG. NO. AC7
APPLICATION		DO NOT SCALE DRAWING				REV A
						SCALE: 1:2 / WEIGHT: / SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
AL 6061

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

NEXT ASSY	USED ON
APPLICATION	

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BYU M.A.R.S.

DESCRIPTION:

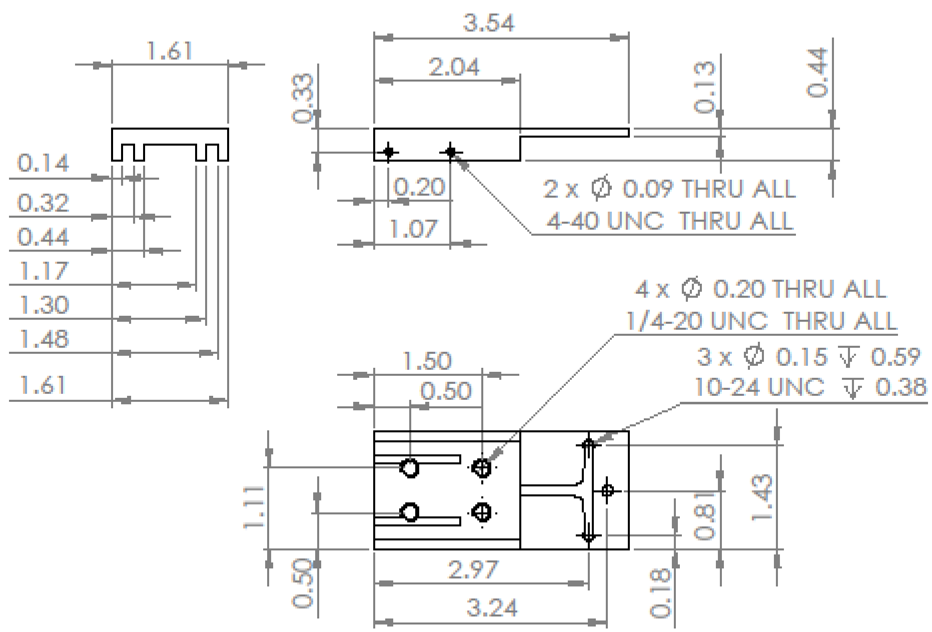
TITLE:

ACTUATOR MOUNT SLIDING

SIZE	DWG. NO.	REV
A	AC8	A

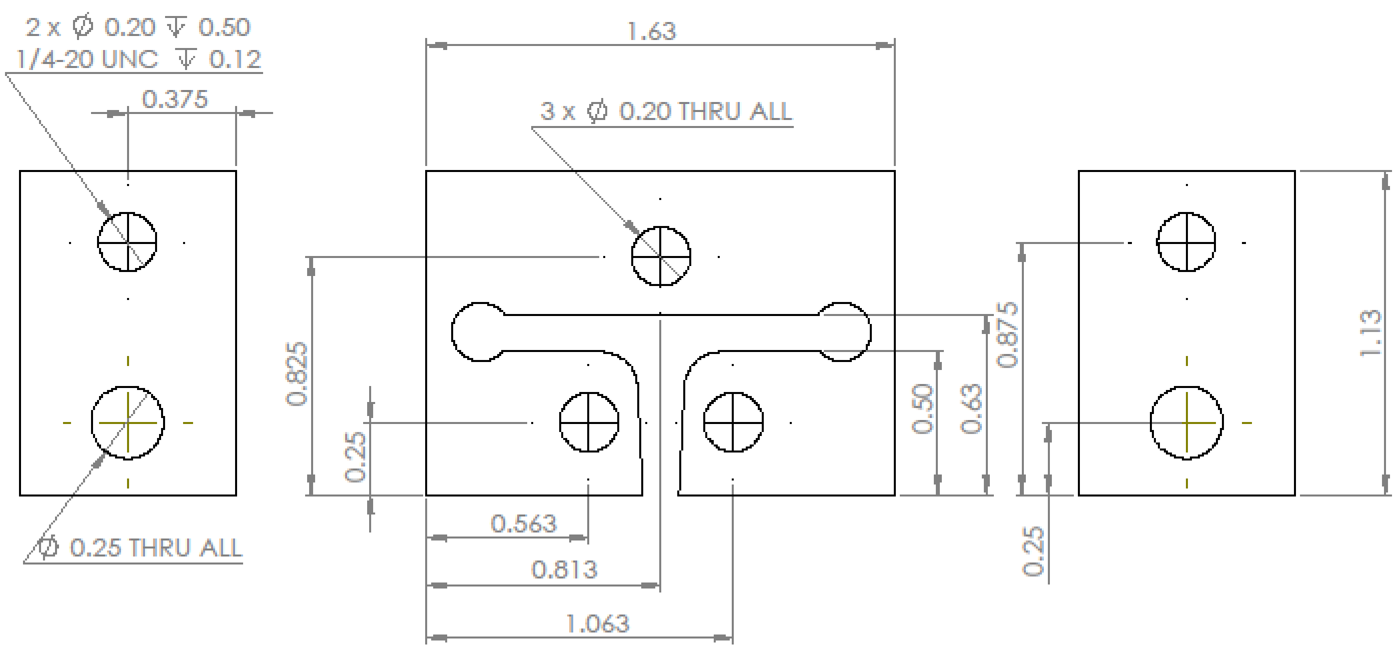
SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION: Servo Block
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	C GRAMES	4/15/14	TITLE: Servo Mount Block
			CHECKED	DEVIN	4/15/14	
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.			
		MATERIAL 6160-T Aluminum	BYU M.A.R.S.			SIZE A · DWG. NO. AC9 · REV A
	NEXT ASSY / USED ON	FINISH None				
	APPLICATION	DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL: HIGH TEMP UHMW PE
FINISH: N/A
DO NOT SCALE DRAWING

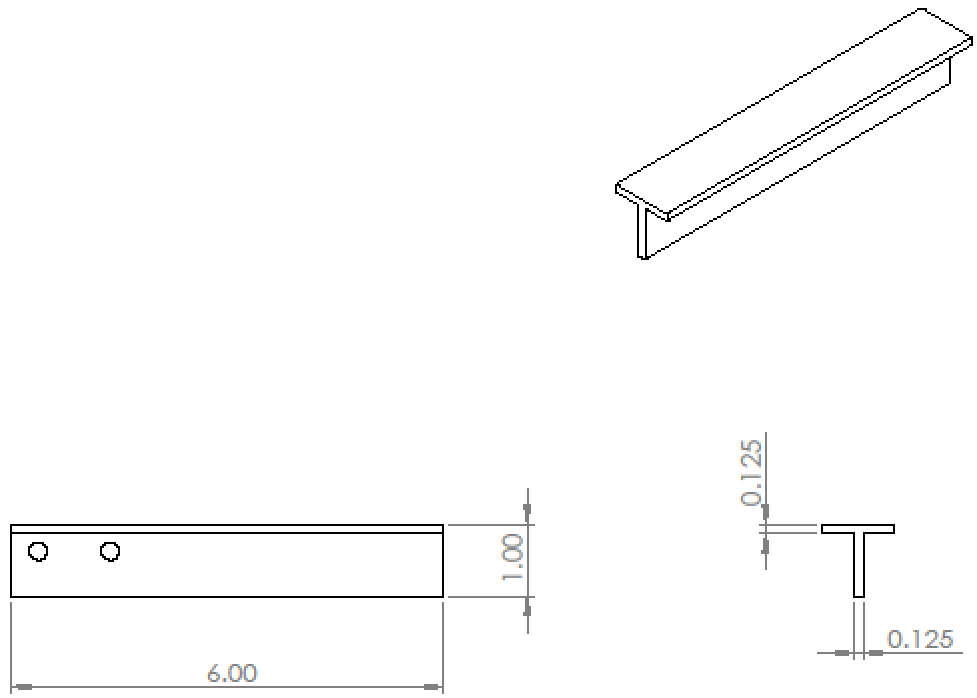
	NAME	DATE
DRAWN	C GRAMES	4/15/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.
NASA APPLIED ROBOTIC SYSTEMS

DESCRIPTION: Slider for V-grip
TITLE: V T Slot

SIZE	DWG. NO.	REV
A	AC10	A
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

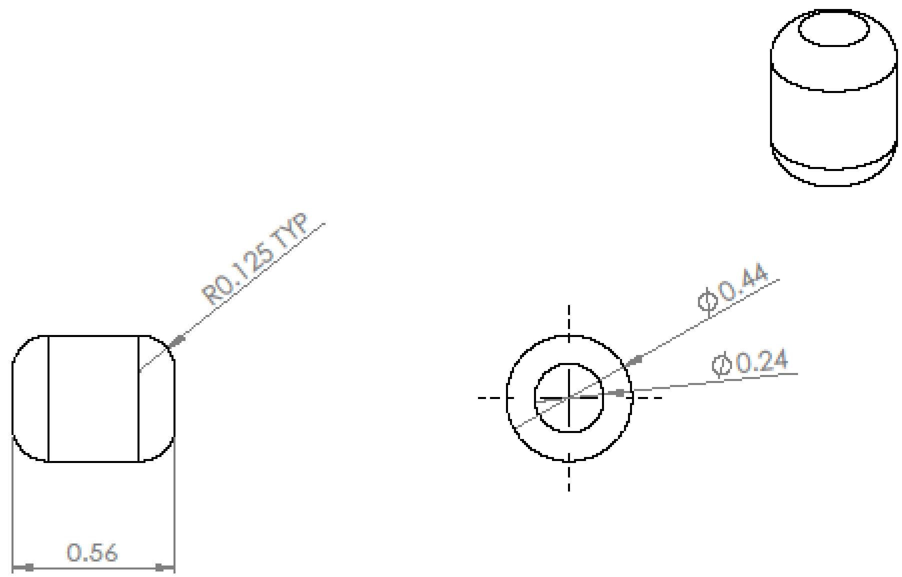
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION: T CHANNEL
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	C GRAMES	2/19/14	TITLE: V T CHANNEL
	CHECKED	DEVIN	4/15/14	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.			
MATERIAL 304 STAINLESS	BYU M.A.R.S.			SIZE A — DWG. NO. AC11 — REV A
FINISH POLISHED				
DO NOT SCALE DRAWING				SCALE: 1:2 — WEIGHT: — SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
PVC TUBE SHORE A65

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	CGRAMES	2/21/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

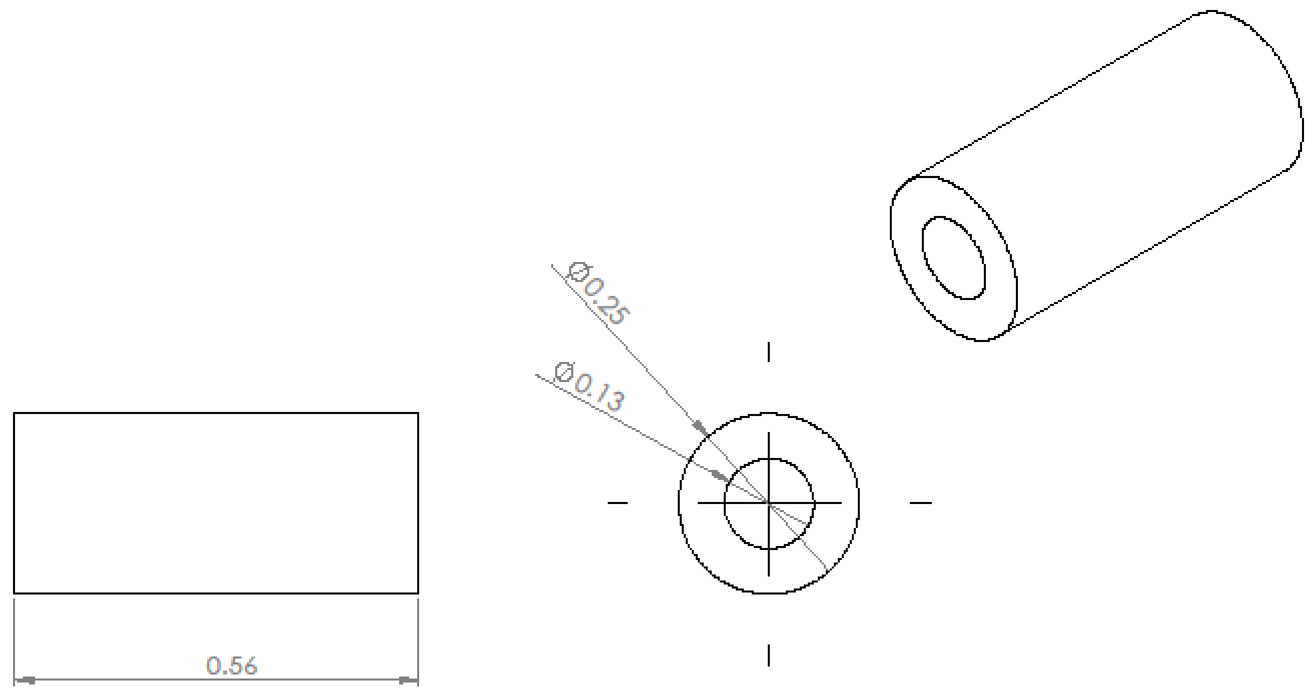
DESCRIPTION:

TITLE:

Roller

SIZE	DWG. NO.	REV
A	AC13	A
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
CF

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	C GRAMES	2/21/14
CHECKED	DEVIN	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION:

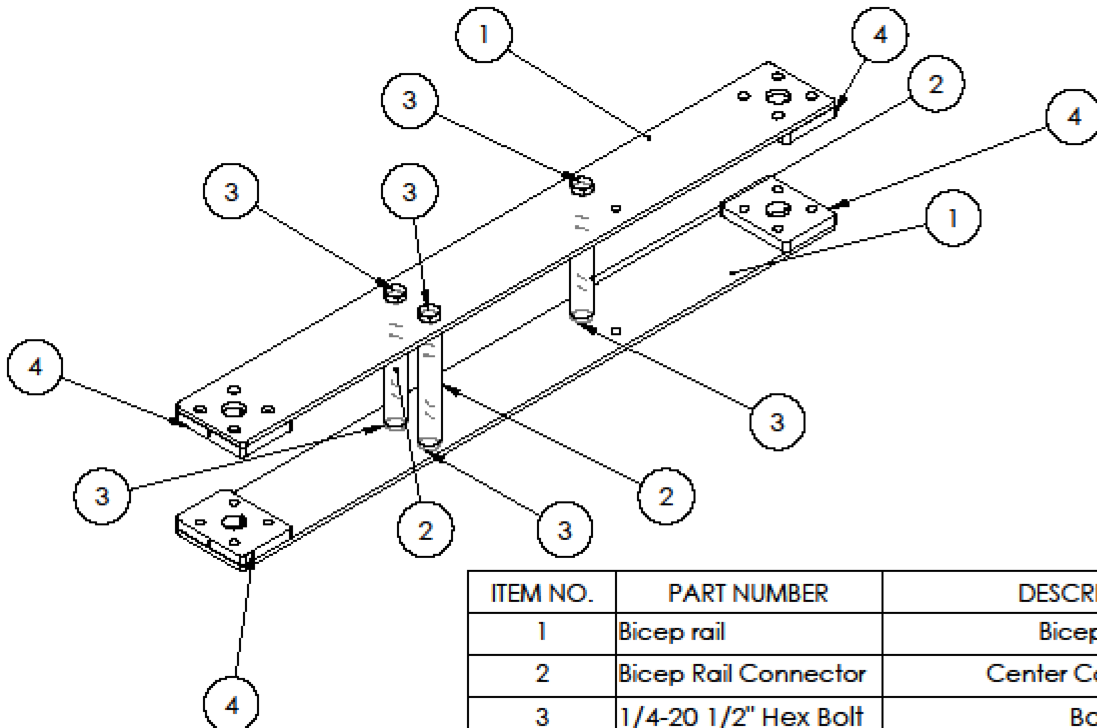
TITLE:

Roller Sleeve

SIZE	DWG. NO.	REV
A	AC14	A

SCALE: 5:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Bicep rail	Bicep link	2
2	Bicep Rail Connector	Center Connector	3
3	1/4-20 1/2" Hex Bolt	Bolt	6
4	Cap peice 3	Bicep Cap Interface	4

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DWA	4-12-2014
	CHECKED	DHA	4-15-2014
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.		
MATERIAL			
FINISH			
DO NOT SCALE DRAWING			

DESCRIPTION:
Bicep Assembly

TITLE:
Bicep Assembly

BYU M.A.R.S.

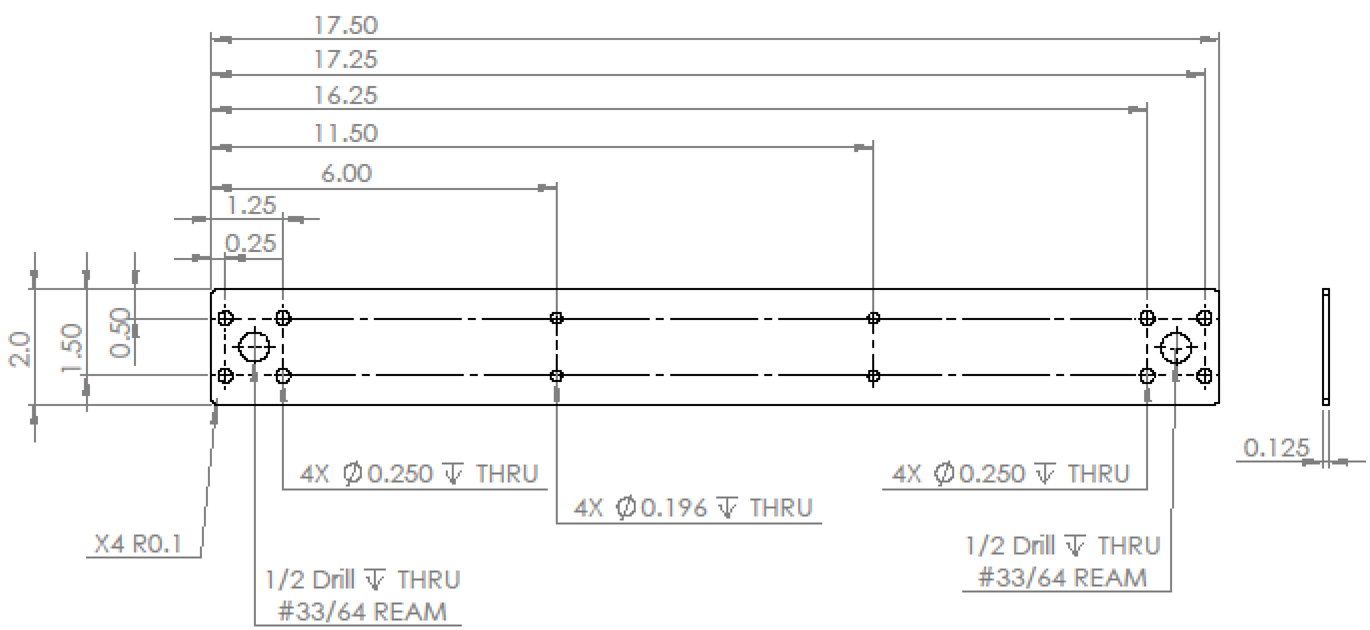
SIZE	DWG. NO.	REV
A	AB0	1

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

NEXT ASSY | USED ON
APPLICATION

5 4 3 2 1

2X for the full arm bicep



	NAME	DATE
DRAWN	DWA	2-6-2014
CHECKED	DHA	2-10-2014
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
AL 6061-T

FINISH
None

DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

DESCRIPTION: Bicep link

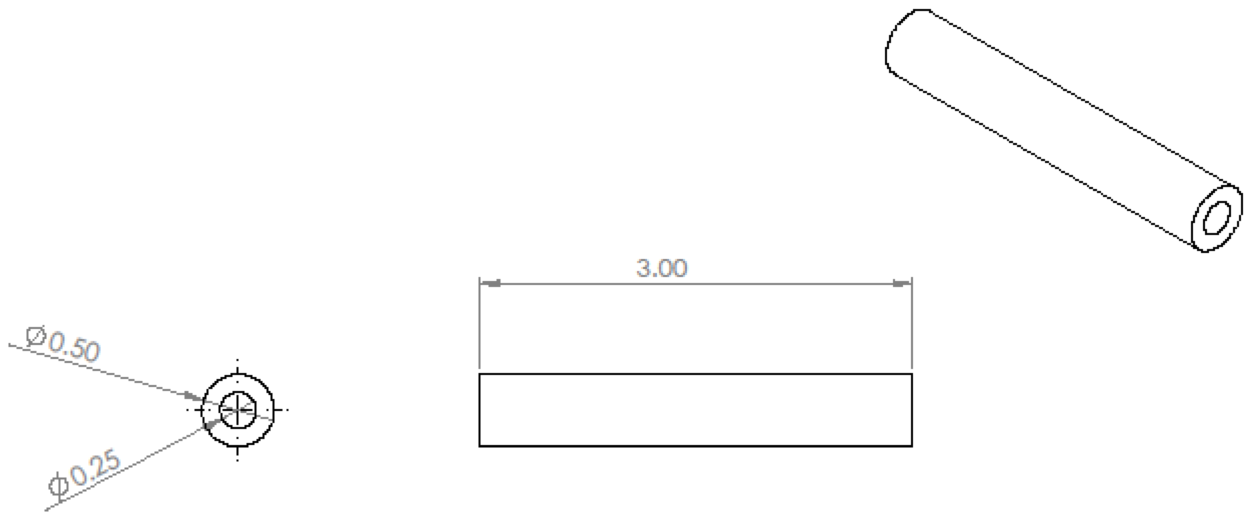
TITLE: Bicep Rail

BYU M.A.R.S.

SIZE A | DWG. NO. AB1 | REV 1

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

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DWA	2-14-2013
	CHECKED	DHA	4-15-2014
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.		
MATERIAL AL 6061-T6			
FINISH None			
DO NOT SCALE DRAWING			

DESCRIPTION: Center Connector

TITLE: Bicep Rail Connector

SIZE	DWG. NO.	REV
A	AB2	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

BYU M.A.R.S.

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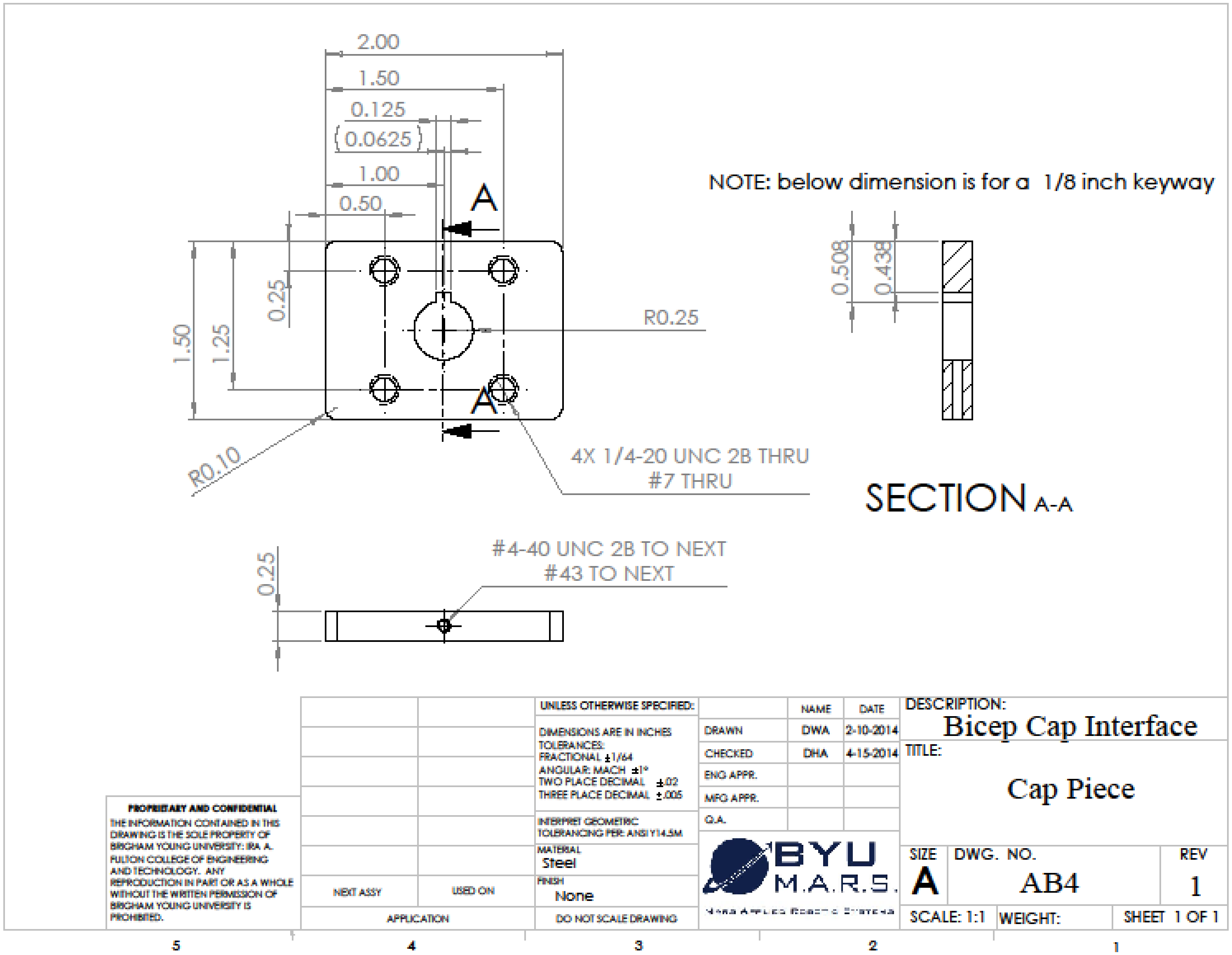
5 4 3 2 1


2.00
1.50
0.125
(0.0625)
1.00
0.50
A
NOTE: below dimension is for a 1/8 inch keyway
0.25
1.50
1.25
R0.25
0.508
0.438
R0.10
4X 1/4-20 UNC 2B THRU
#7 THRU
SECTION A-A
#4-40 UNC 2B TO NEXT
#43 TO NEXT
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
Steel
FINISH
None
DO NOT SCALE DRAWING
NAME
DATE
DRAWN DWA 2-10-2014
CHECKED DHA 4-15-2014
ENG APPR.
MFG APPR.
Q.A.
BYU M.A.R.S.
DESCRIPTION:
Bicep Cap Interface
TITLE:
Cap Piece
SIZE A
DWG. NO. AB4
REV 1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
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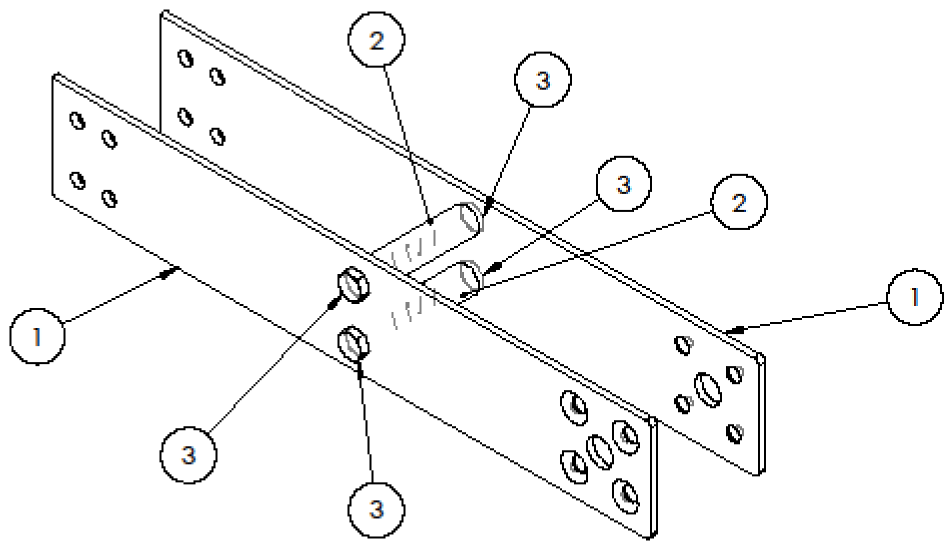
5
4
3
2
1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Forearm rail	Forearm Rail	2
2	Forearm Rail Connector	Forearm connector	2
3	1/4-20 1/2" Hex Bolt	Bolt	4



	NAME	DATE
DRAWN	DWA	4-12-2014
CHECKED	DHA	4-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

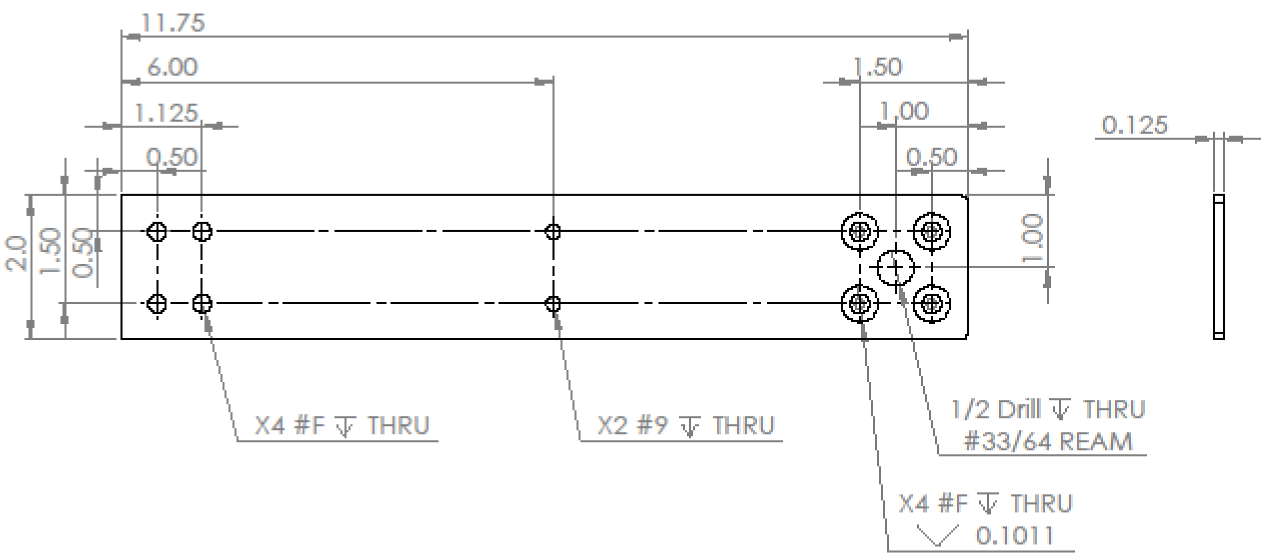
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

BYU M.A.R.S.

DESCRIPTION: Forearm Assembly
TITLE: Forearm Assembly
SIZE A | DWG. NO. AF0 | REV 1
SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
AL 6061-T6
FINISH
None
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DWA	2-14-2014
CHECKED	DHA	2-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

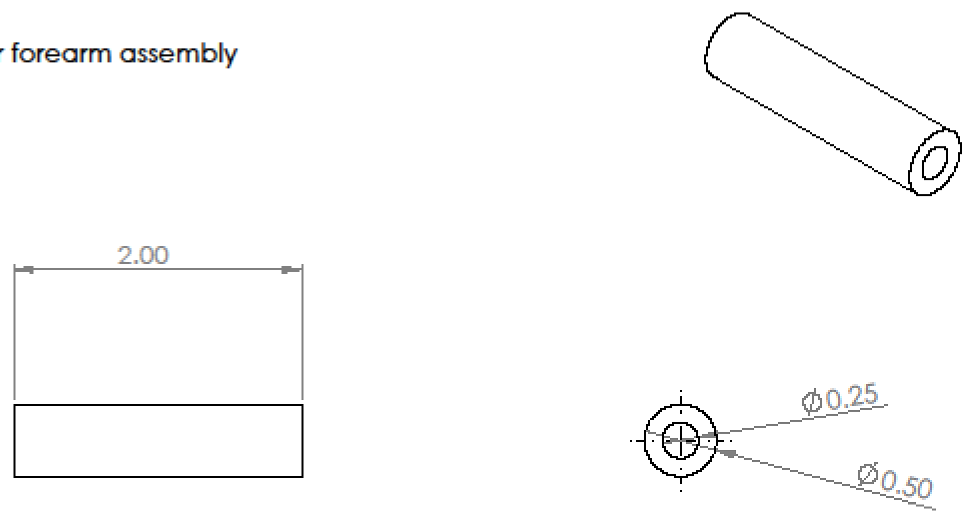
DESCRIPTION: Forearm Rail
TITLE: Forearm Rail

SIZE	DWG. NO.	REV
A	AF1	1

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1

X2 For forearm assembly



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL AL 6061-T6
FINISH None
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DWA	2-18-2014
CHECKED	DHA	2-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

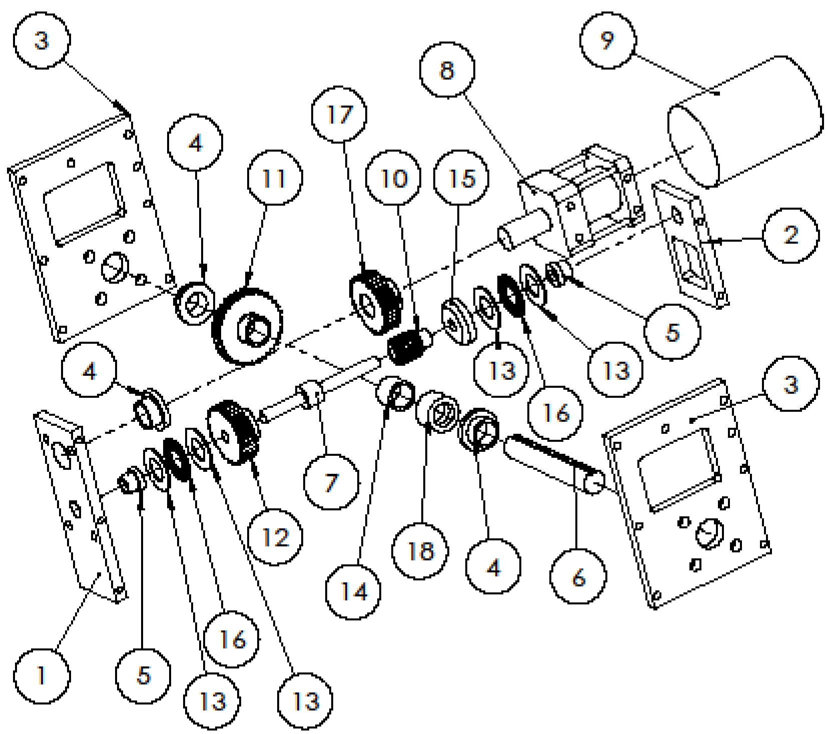
BYU M.A.R.S.

DESCRIPTION: Forearm connector

TITLE: Foreamr Rail Connector

SIZE	DWG. NO.	REV
A	AF2	1
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Front Plate Vertical Alignment	Mount for turning shafts	1
2	Vertical Back plate	Plate under Motor	1
3	Vertical Side Plate	Sides for gearbox	2
4	1-2 and 5-8 bushing 6338K419		3
5	1-4 and 1-2 bushing	Connection for Shaft	2
6	1-2 inch Output Shaft	Output Shaft	1
7	WormShaft	Turning shaft of gearbox	1
8	P60		1
9	RS775 Mock Motor		1
10	Worm a_1c55-n24		1
11	Worm Gear 1 1-2 Dia a_1b_6-n24036		1
12	Spur 1-4 Bore s10c6z-032h040		1
13	5909K44	Stock Part - Trust Washer	4
14	1-2 inch 1-2 inch spacer Worm Gear	Spacer for Worm Gear	1
15	Worm Shaft back spacer	Spacer and Reducer	1
16	5909K31		2
17	Spur 1-2 Bore s10c9z-032h040		1
18	1-2 inch Sleve Worm Gear	Load Transfer	1

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
FINISH
DO NOT SCALE DRAWING

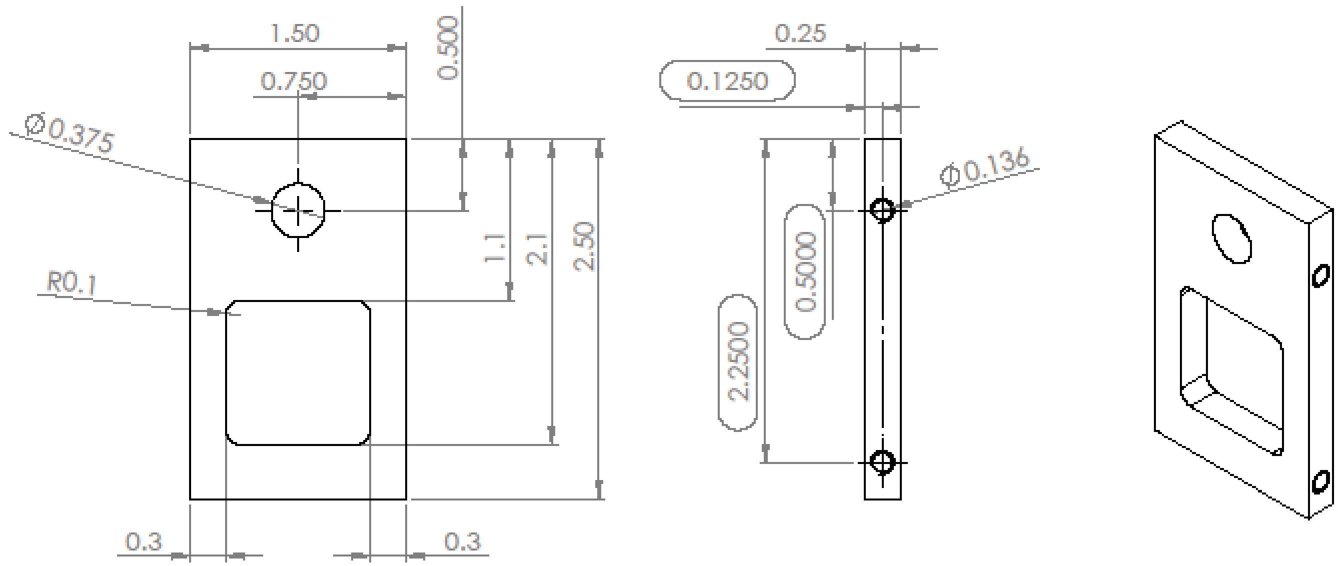
	NAME	DATE
DRAWN	DWA	2-3-2014
CHECKED	DHA	2-3-2014
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION: Gearbox Assembly
TITLE: Exploded Assembly

SIZE A | DWG. NO. AG0 | REV
SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



Note: Tollerance for 4 Decimal places should be to 0.0005, as close as possible

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
6061-T Aluminum
FINISH
Smooth
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DA	12-9-2013
CHECKED	DHA	4-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

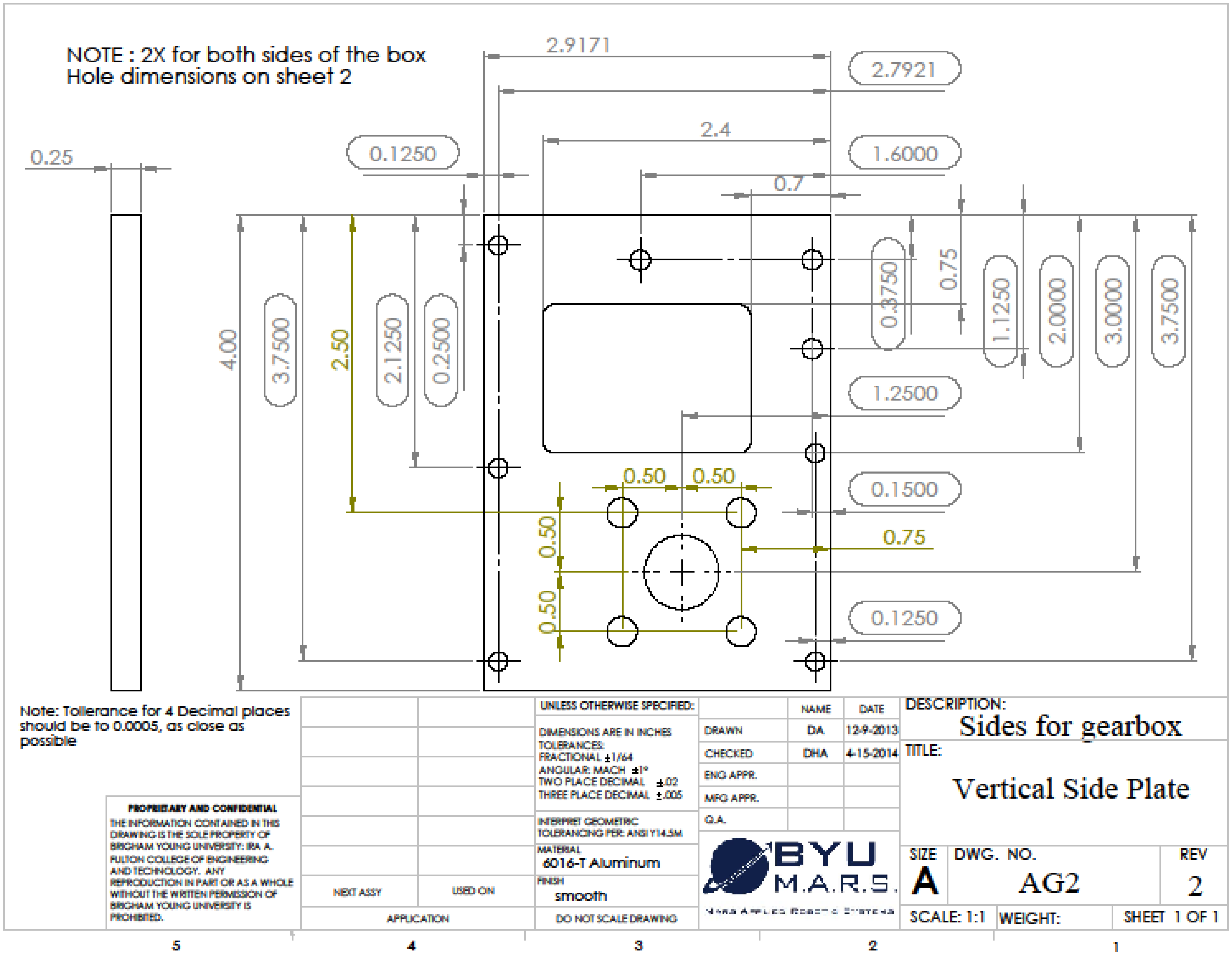
BYU M.A.R.S.

DESCRIPTION:
Plate under Motor
TITLE:
Vertical Back Plate

SIZE	DWG. NO.	REV
A	AG1	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1


NOTE : 2X for both sides of the box
Hole dimensions on sheet 2
2.9171
2.7921
2.4
1.6000
0.7
0.1250
0.25
4.00
3.7500
2.50
2.1250
0.2500
0.3750
0.75
1.1250
2.0000
3.0000
3.7500
1.2500
0.50
0.50
0.50
0.50
0.1500
0.75
0.1250
Note: Tollerance for 4 Decimal places should be to 0.0005, as close as possible
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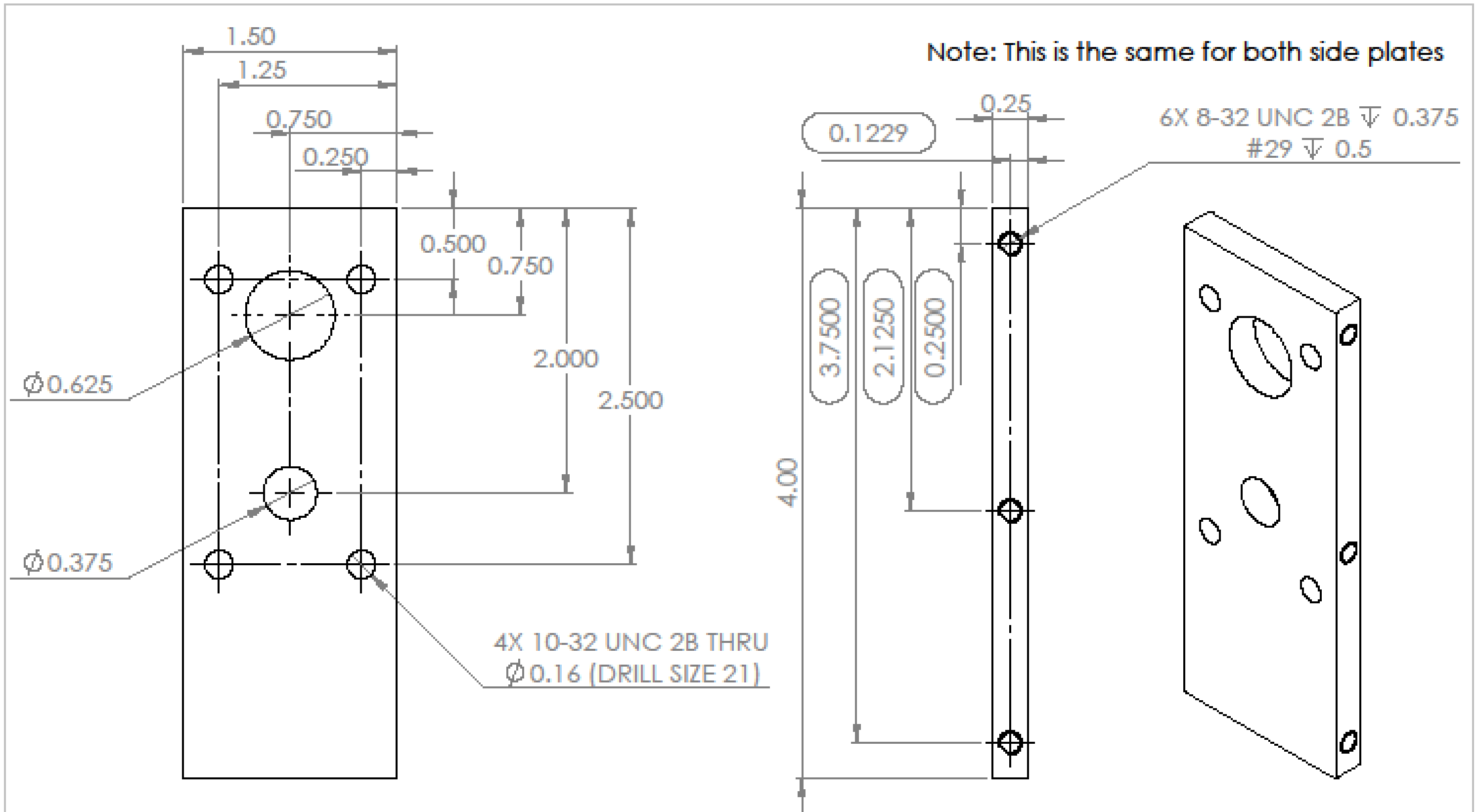
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
6016-T Aluminum
FINISH
smooth
DO NOT SCALE DRAWING
NAME
DATE
DRAWN DA 12-9-2013
CHECKED DHA 4-15-2014
ENG APPR.
MFG APPR.
Q.A.
BYU M.A.R.S.
DESCRIPTION:
Sides for gearbox
TITLE:
Vertical Side Plate
SIZE A
DWG. NO. AG2
REV 2
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Note: Tollerance for 4 Decimal places should be to 0.0005, as close as possible

UNLESS OTHERWISE SPECIFIED:	NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005		
DRAWN	DA	12-9-2013
CHECKED	DA	12-9-2013
ENG APPR.		
MFG APPR.		
Q.A.		
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M		
MATERIAL: 6061-T Aluminum		
FINISH: Smooth		
DO NOT SCALE DRAWING		

NEXT ASSY	USED ON
APPLICATION	

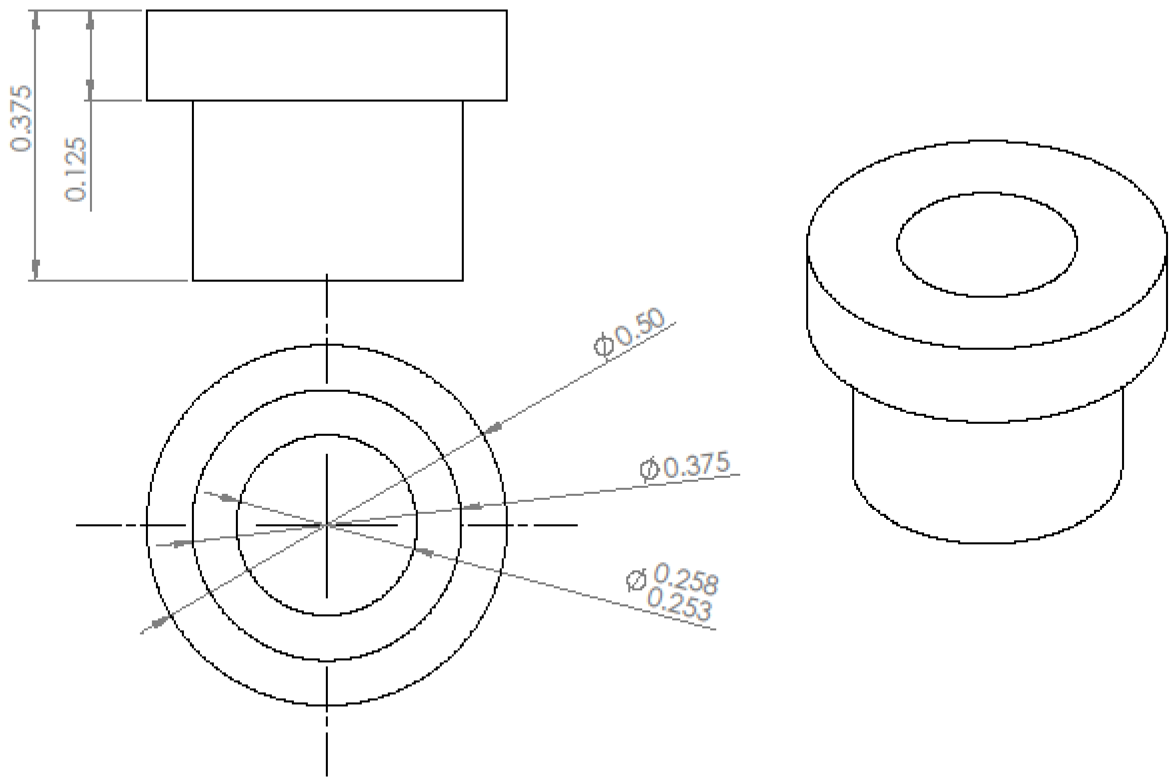
BYU M.A.R.S.

DESCRIPTION: Mount for turning shafts

TITLE: Front Plate Vertical

SIZE	DWG. NO.	REV
A	AG3	1
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

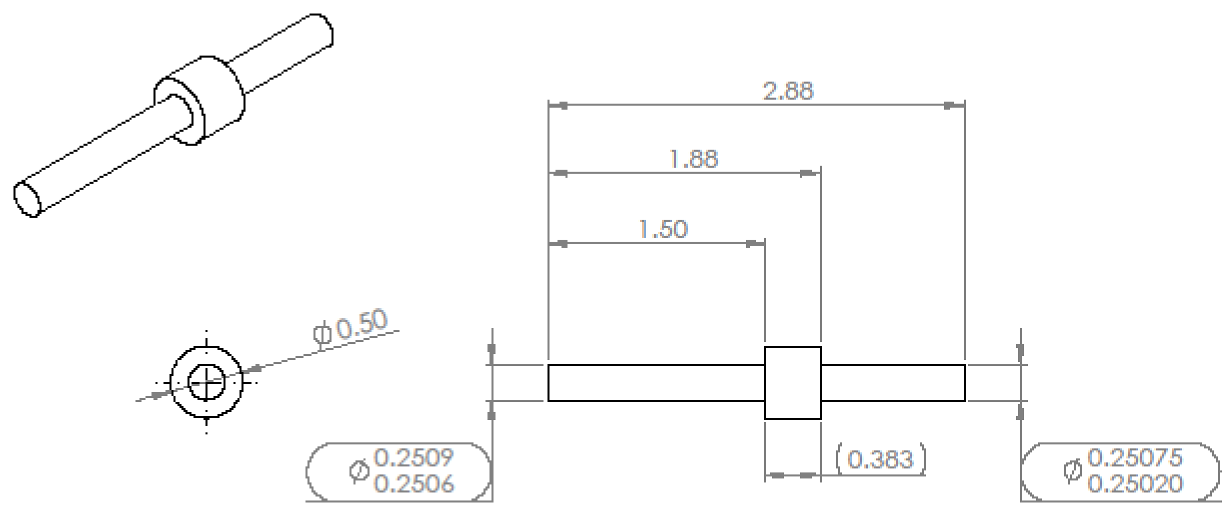
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION: Connection for Shaft
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DA	12-9-2013	TITLE:
	CHECKED	DA	12-9-2013	1/4 and 1/2 Bushing
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.			
MATERIAL Oil Filled Bronze	BYU M.A.R.S.			SIZE A — DWG. NO. AG4 — REV 1
FINISH Rough				
DO NOT SCALE DRAWING				SCALE: 5:1 — WEIGHT: — SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

5 4 3 2 1



Note: Tolerance for 4 Decimal places should be to 0.0005, as close as possible

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
4140 Steel

FINISH
Sanded

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DWA	12-9-2013
CHECKED	DHA	1-14-2014
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

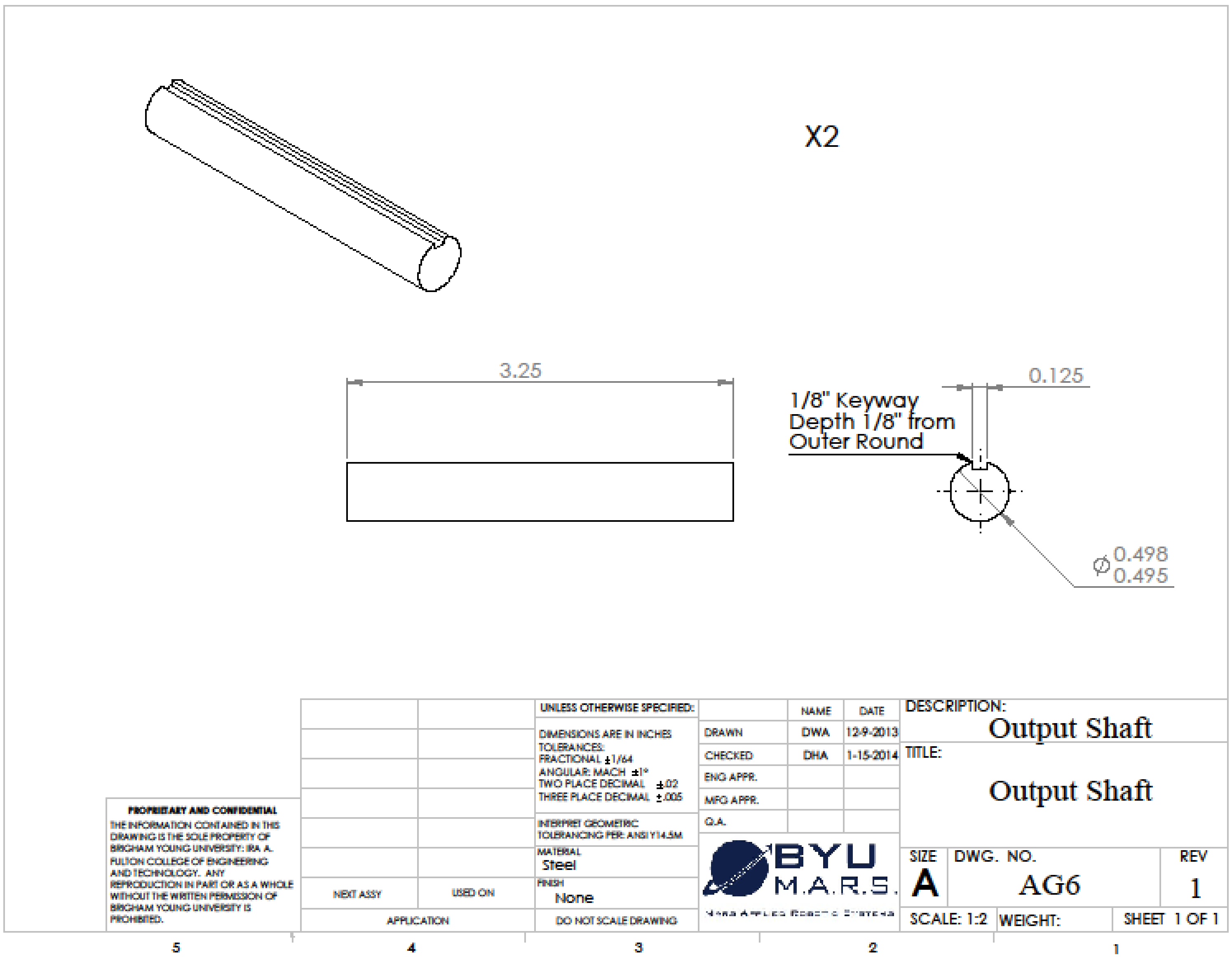
DESCRIPTION:
Turning shaft of gearbox

TITLE:
Worm Shaft

SIZE	DWG. NO.	REV
A	AG5	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1


X2
3.25
0.125
1/8" Keyway
Depth 1/8" from
Outer Round
Ø 0.498
0.495
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC
TOLERANCING PER: ANSI Y14.5M
MATERIAL
Steel
FINISH
None
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN DWA 12-9-2013
CHECKED DHA 1-15-2014
ENG APPR.
MFG APPR.
Q.A.
BYU
M.A.R.S.
DESCRIPTION:
Output Shaft
TITLE:
Output Shaft
SIZE
A
DWG. NO.
AG6
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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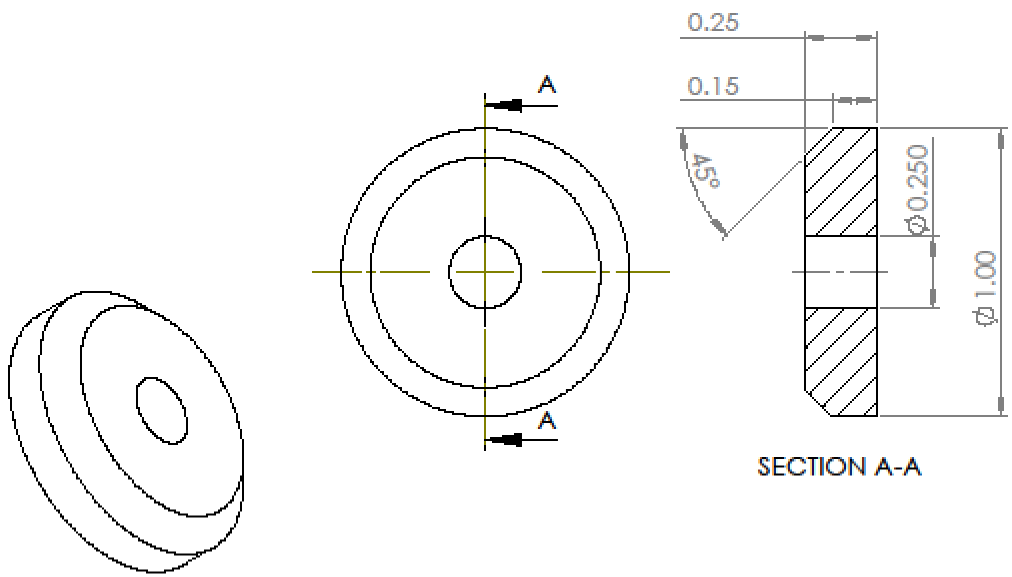
5
4
3
2
1



Note: Tollerance for 4 Decimal places should be to 0.0005, as close as possible

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL: 4140 Steel

FINISH: Rough

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DA	12-9-2013
CHECKED	DHA	4-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

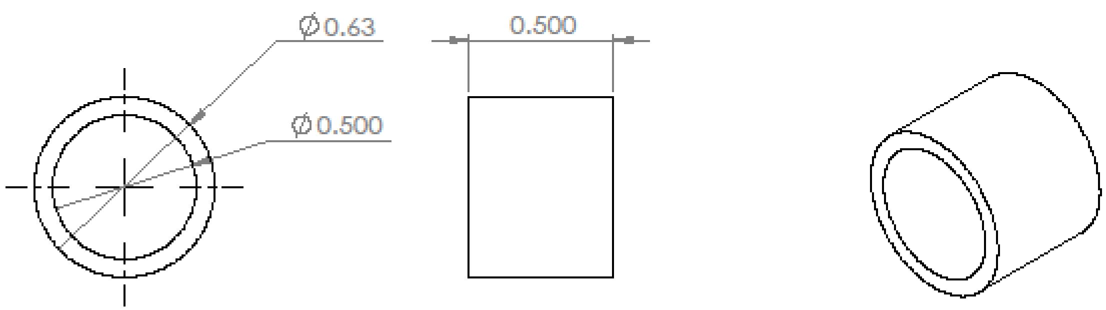
DESCRIPTION: Spacer and Reducer

TITLE: Worm Shaft back Spacer

SIZE	DWG. NO.	REV
A	AG7	1

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
4140 Steel Rod

FINISH
Rough

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DA	12-9-2013
CHECKED	DA	1-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

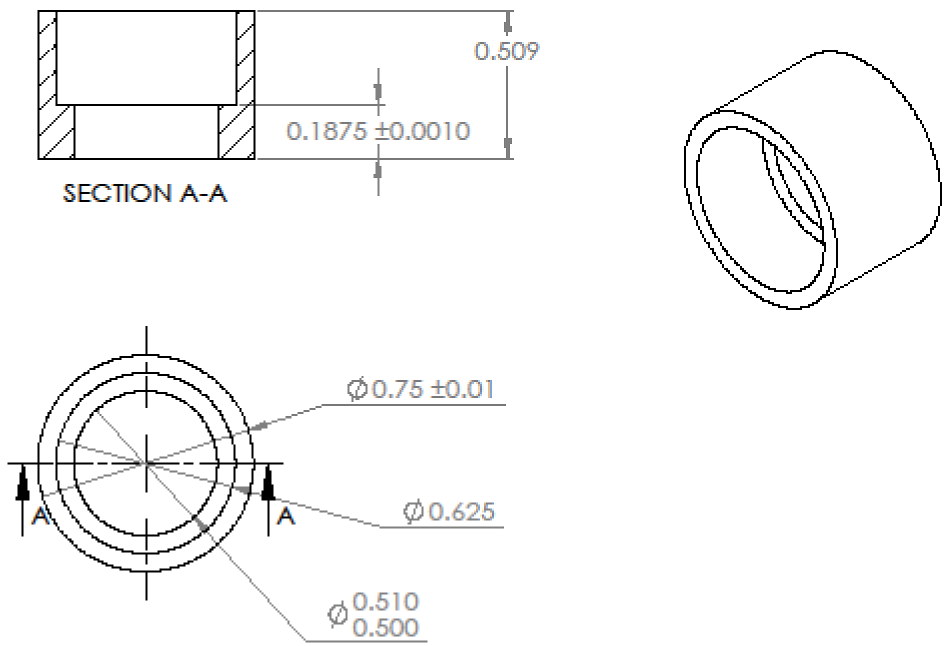
DESCRIPTION:
Spacer for Worm Gear

TITLE:
1/2 inch Spacer Worm

SIZE	DWG. NO.	REV
A	AG8	1

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
4140 Steel

FINISH
Ground

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DWA	12-9-2013
CHECKED	DHA	1-15-2014
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

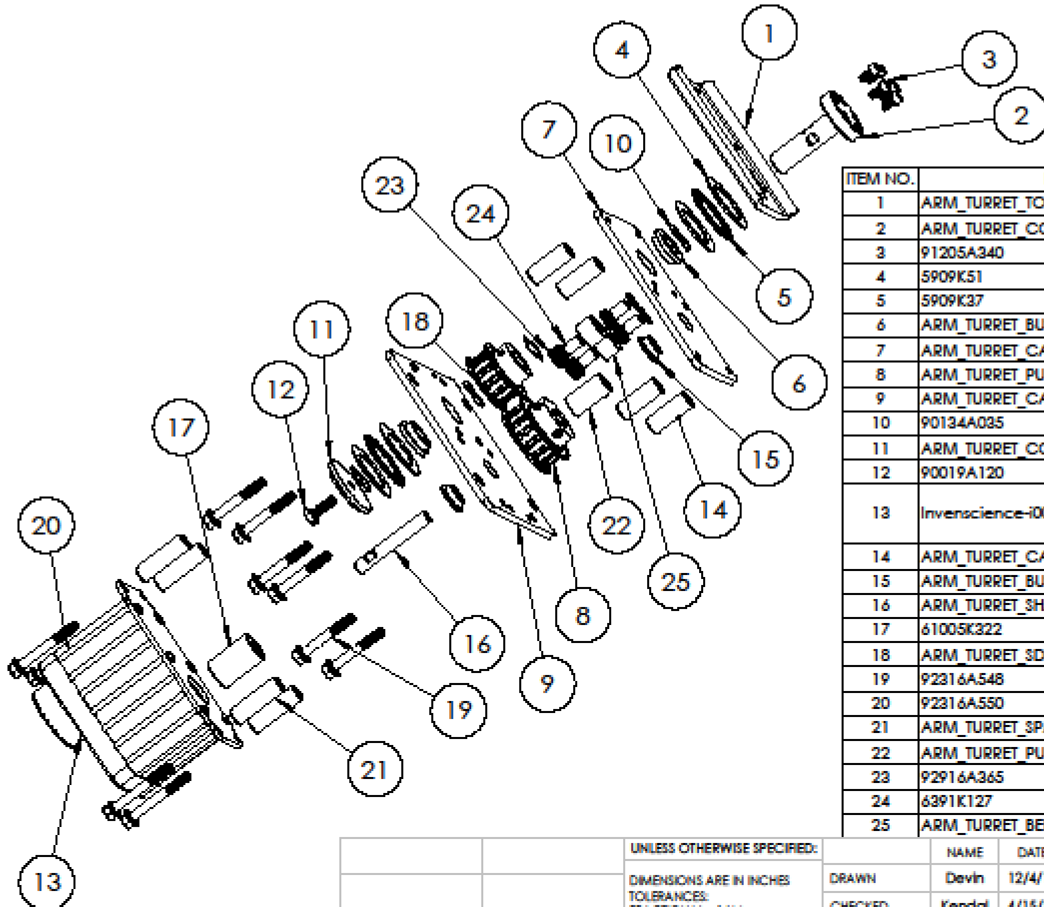
DESCRIPTION: Load Transfer

TITLE: 1/2 inch Sleve Worm Gear

SIZE	DWG. NO.	REV
A	AG9	1

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	ARM_TURRET_TOP-PLATE	TURRET PLATE	1
2	ARM_TURRET_COMPRESSION-SHAFT	TURRET SHAFT	1
3	91205A340	5/16-18 BOLT	5
4	5909K51	BEARING RACE	4
5	5909K37	THRUST BEARING	2
6	ARM_TURRET_BUSHING-MCMASTER-6338K427	BUSHING	2
7	ARM_TURRET_CASE-TOP	TURET PLATE	1
8	ARM_TURRET_PULLEYSDP-SI_6A-4-16DF05020	TIMING PULLEY	1
9	ARM_TURRET_CASE-BOTTOM	TURRET PLATE	1
10	90134A035	WASHER	4
11	ARM_TURRET_COMPRESSION-SHAFT-WASHER	TURRET WASHER	1
12	90019A120	1/4-20 BOLT	1
13	Invenscience-i00600	RC PWM controlled rotary servo	1
14	ARM_TURRET_CASE-SPACER	TURRET SPACER	4
15	ARM_TURRET_BUSHING-MCMASTER-6338K461	BUSHING	2
16	ARM_TURRET_SHAFT-EXTENSION	TURRET SHAFT	1
17	61005K322	SHAFT COUPLER	1
18	ARM_TURRET_SDP-SI_A-6A-413DF05012	TIMING PULLEY	1
19	92316A548	1/4-20 BOLT	6
20	92316A550	1/4-20 BOLT	4
21	ARM_TURRET_SPACER-SERVOMOTOR	TURRET SPACER	4
22	ARM_TURRET_PULLEY-INSERT	PULLEY INSERT	1
23	92916A365	BRASS WASHER	16
24	6391K127	OILITE BUSHING	4
25	ARM_TURRET_BELT-ROLLER	TENSION ROLLER	2

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
VARIOUS

FINISH
VARIOUS

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Devin	12/4/13
CHECKED	Kendal	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

NEXT ASSY | USED ON

APPLICATION

BYU M.A.R.S.

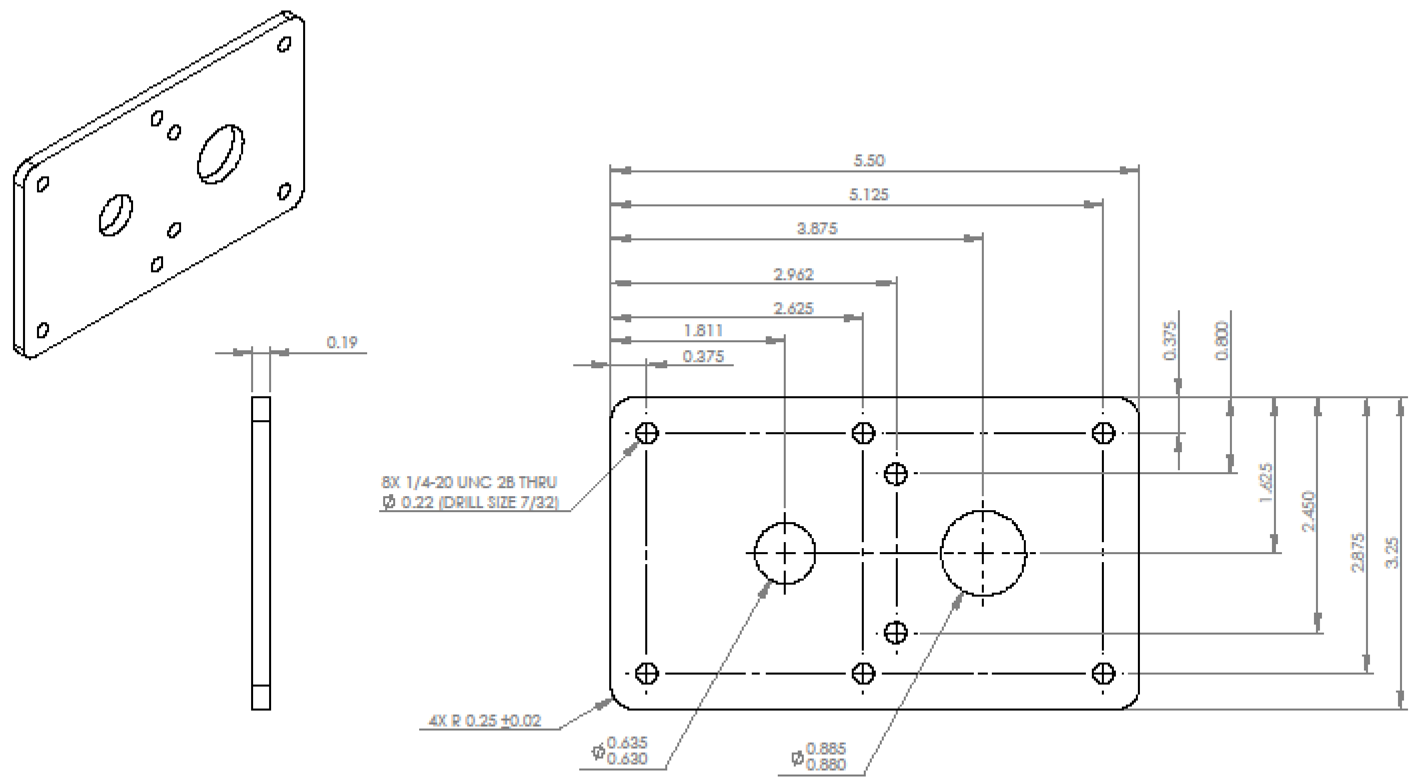
DESCRIPTION:
TURRET ASSEMBLY

TITLE:
ARM TURRET ASSEMBLY

SIZE	DWG. NO.	REV
A	AT0	B

SCALE: 1:3 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
6061 Al

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DHA	11/04/13
CHECKED	DREW	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

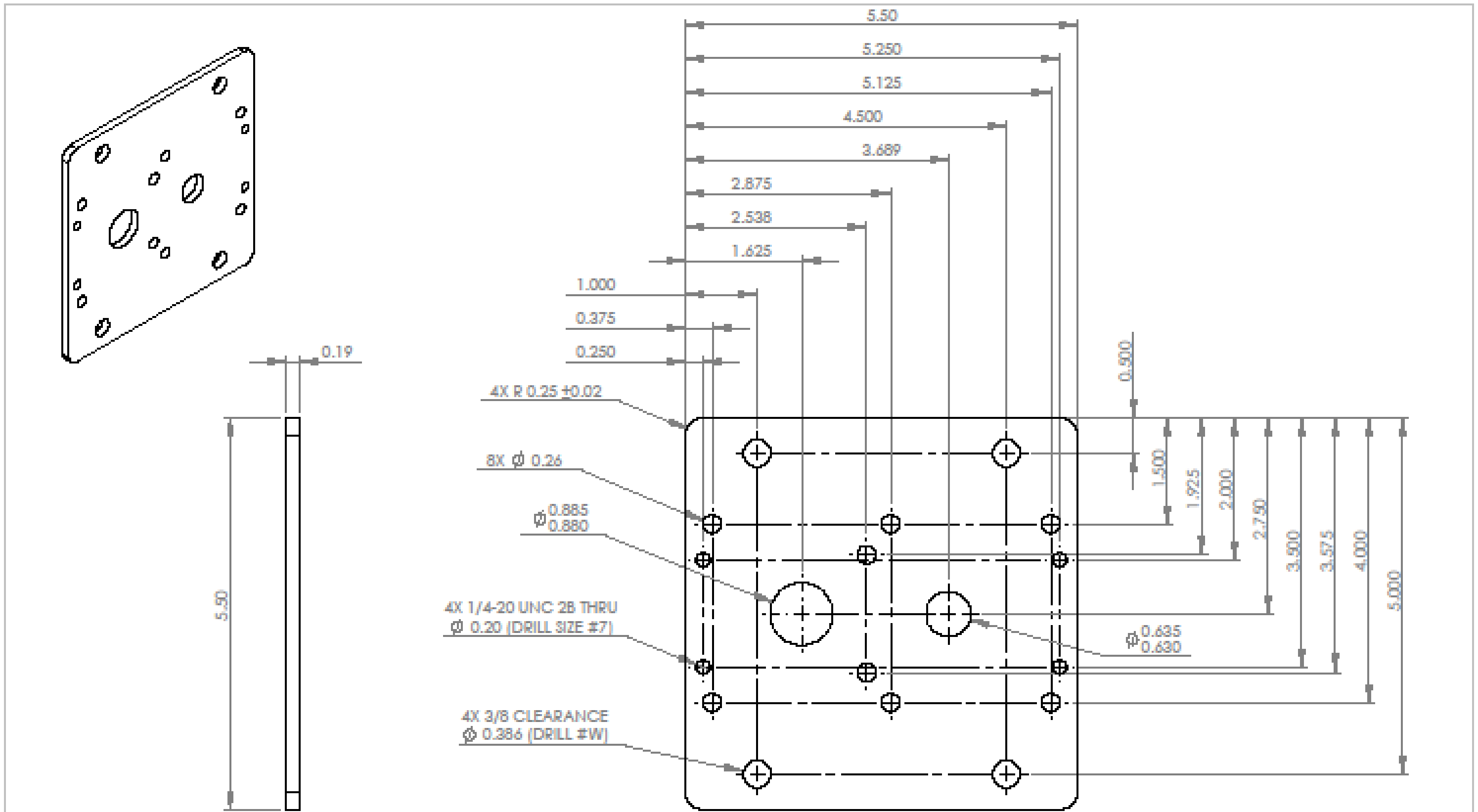
DESCRIPTION:
TURET PLATE

TITLE:
ARM TURRET
TOP CASE PLATE

SIZE	DWG. NO.	REV
A	AT1	B

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

5 4 3 2 1

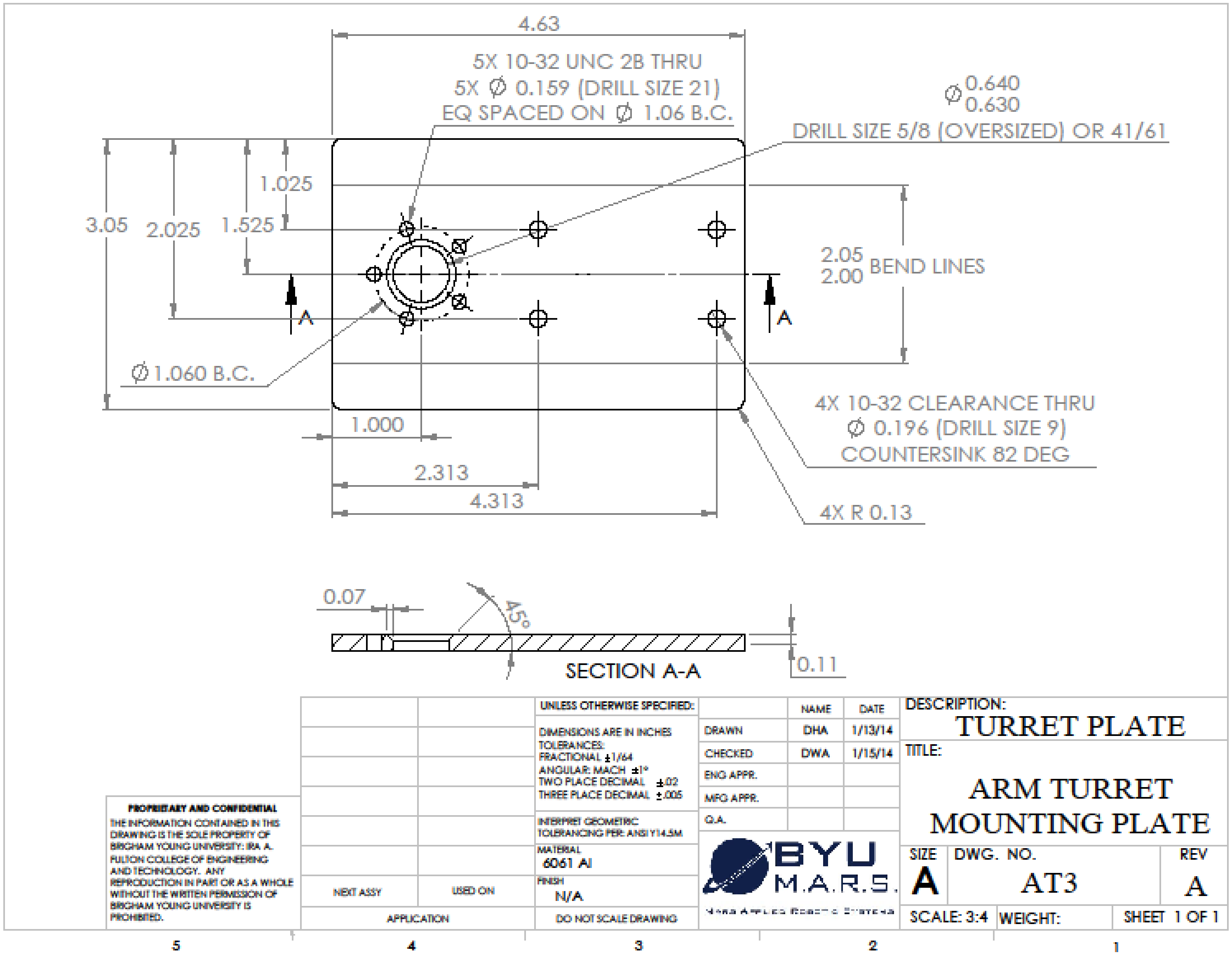


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION: TURRET PLATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DHA	11/05/13	TITLE:	
	CHECKED	KENDAL	4/15/14	ARM TURRET BOTTOM CASE PLATE	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.				
MATERIAL ALUMINUM	BYU M.A.R.S.			SIZE A / DWG. NO. AT2	REV E
FINISH N/A					
DO NOT SCALE DRAWING				SCALE: 1:2 / WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

5 4 3 2 1


4.63
5X 10-32 UNC 2B THRU
5X Ø 0.159 (DRILL SIZE 21)
EQ SPACED ON Ø 1.06 B.C.
Ø 0.640 0.630
DRILL SIZE 5/8 (OVERSIZED) OR 41/61
1.025
3.05
2.025
1.525
2.05 2.00 BEND LINES
A
A
Ø1.060 B.C.
1.000
2.313
4.313
4X 10-32 CLEARANCE THRU
Ø 0.196 (DRILL SIZE 9)
COUNTERSINK 82 DEG
4X R 0.13
0.07
45°
0.11
SECTION A-A
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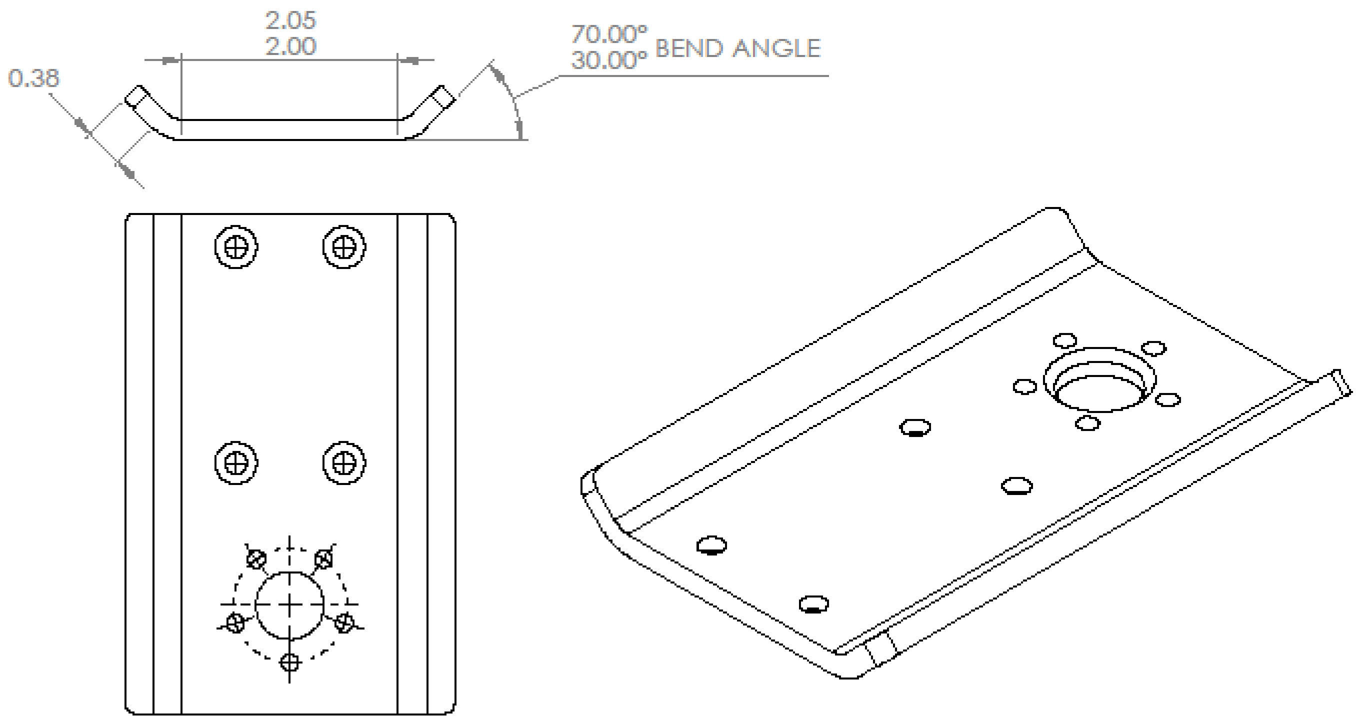
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
6061 Al
FINISH
N/A
DO NOT SCALE DRAWING
NAME
DATE
DRAWN DHA 1/13/14
CHECKED DWA 1/15/14
ENG APPR.
MFG APPR.
Q.A.
BYU
M.A.R.S.
DESCRIPTION:
TURRET PLATE
TITLE:
ARM TURRET MOUNTING PLATE
SIZE A
DWG. NO. AT3
REV A
SCALE: 3:4
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
6061 Al

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DHA	1/13/14
CHECKED	DWA	1/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.
Mars Applied Robotic Systems

DESCRIPTION:
TURRET PLATE

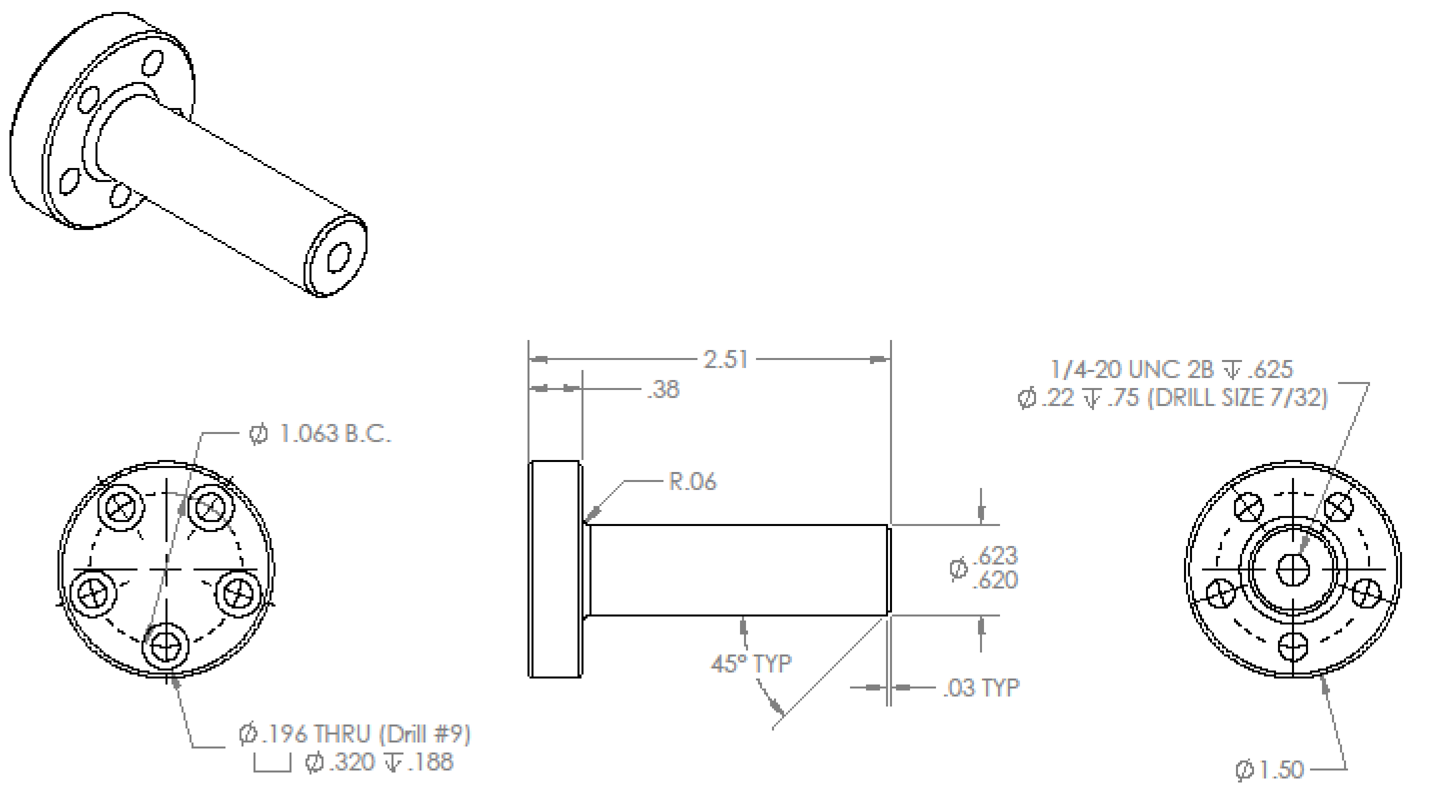
TITLE:
ARM TURRET MOUNTING PLATE

SIZE	DWG. NO.	REV
A	AT3	A

SCALE: 3:4 WEIGHT: SHEET 1 OF 2

NEXT ASSY	USED ON
APPLICATION	

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
4140 STEEL

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DHA	11/06/13
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

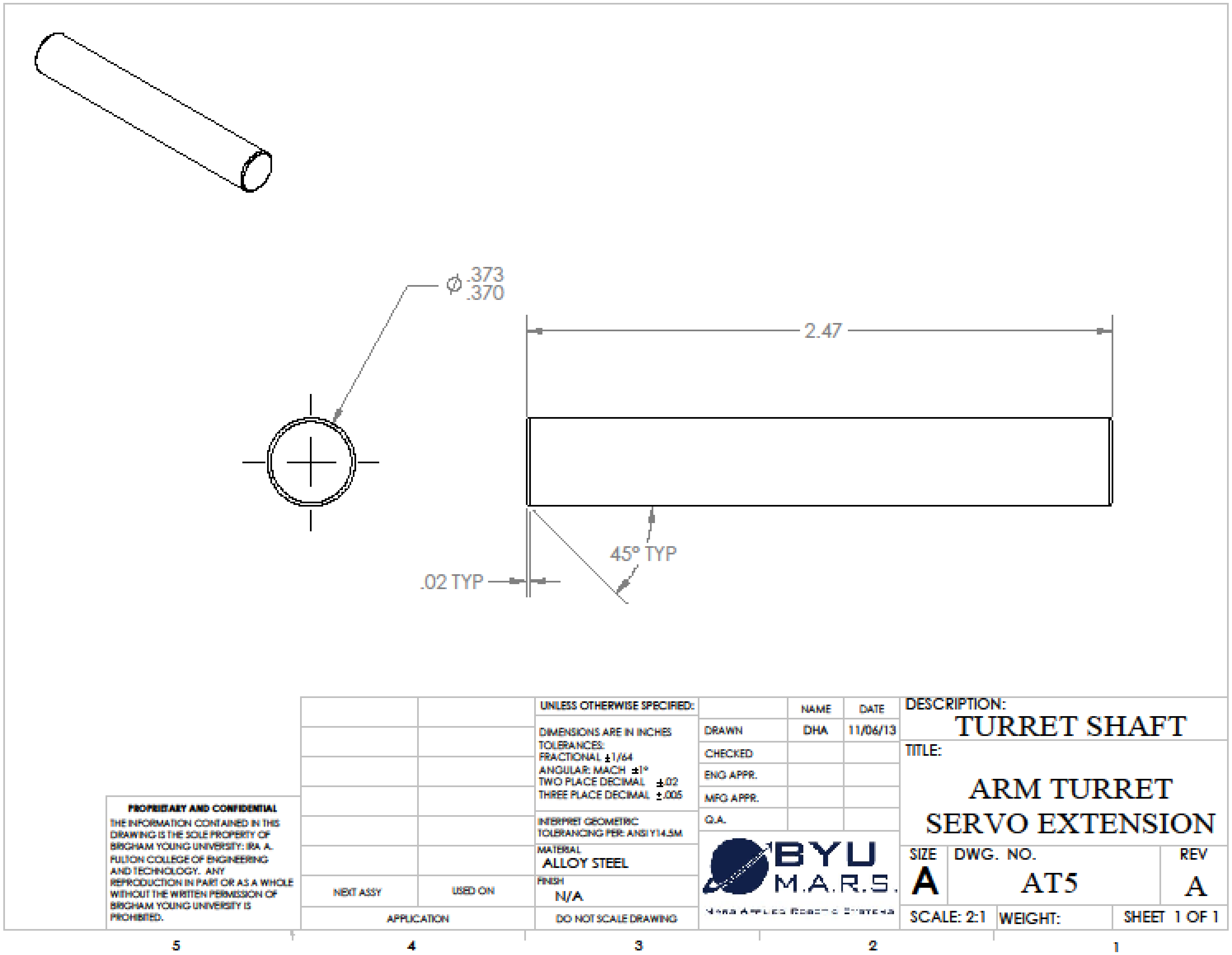
DESCRIPTION:
TURRET SHAFT

TITLE:
ARM TURRET COMPRESSION SHAFT

SIZE	DWG. NO.	REV
A	AT4	A

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



∅ .373
.370
2.47
45° TYP
.02 TYP
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
ALLOY STEEL
FINISH
N/A
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
DHA
11/06/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
BYU M.A.R.S.
DESCRIPTION:
TURRET SHAFT
TITLE:
ARM TURRET SERVO EXTENSION
SIZE
A
DWG. NO.
AT5
REV
A
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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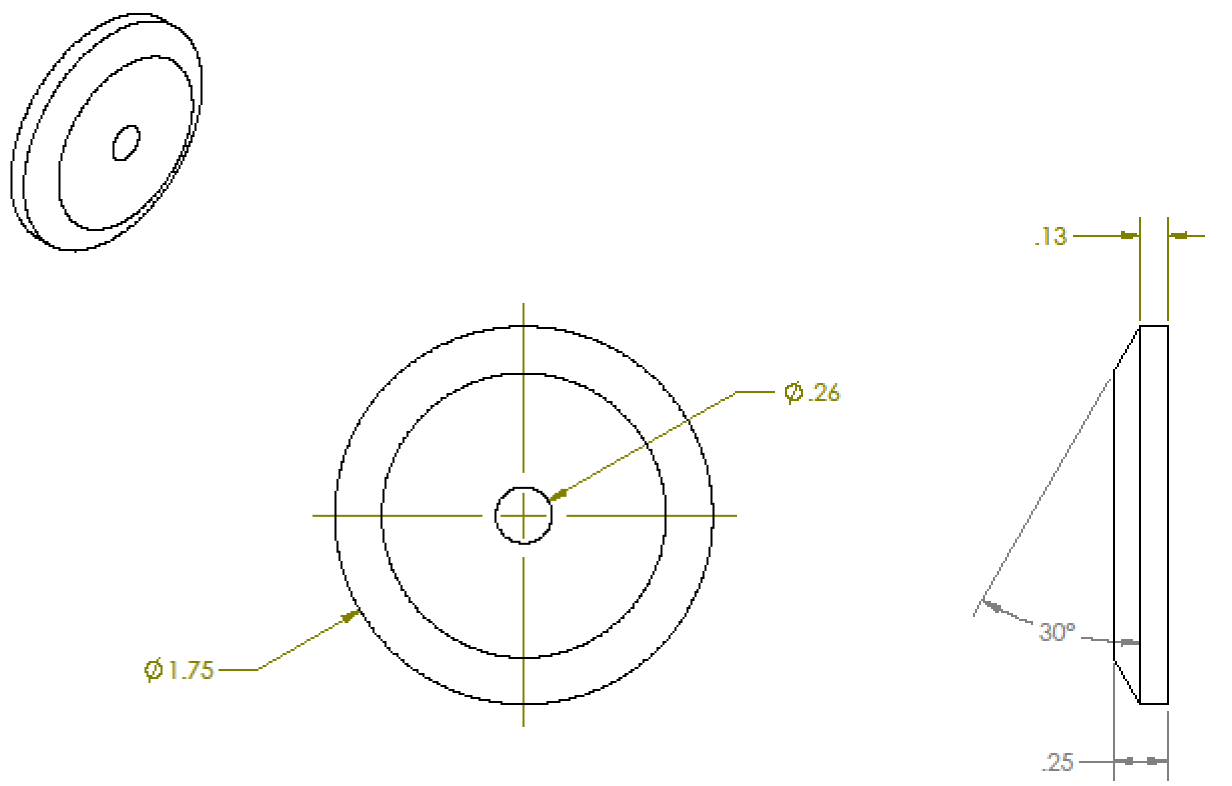
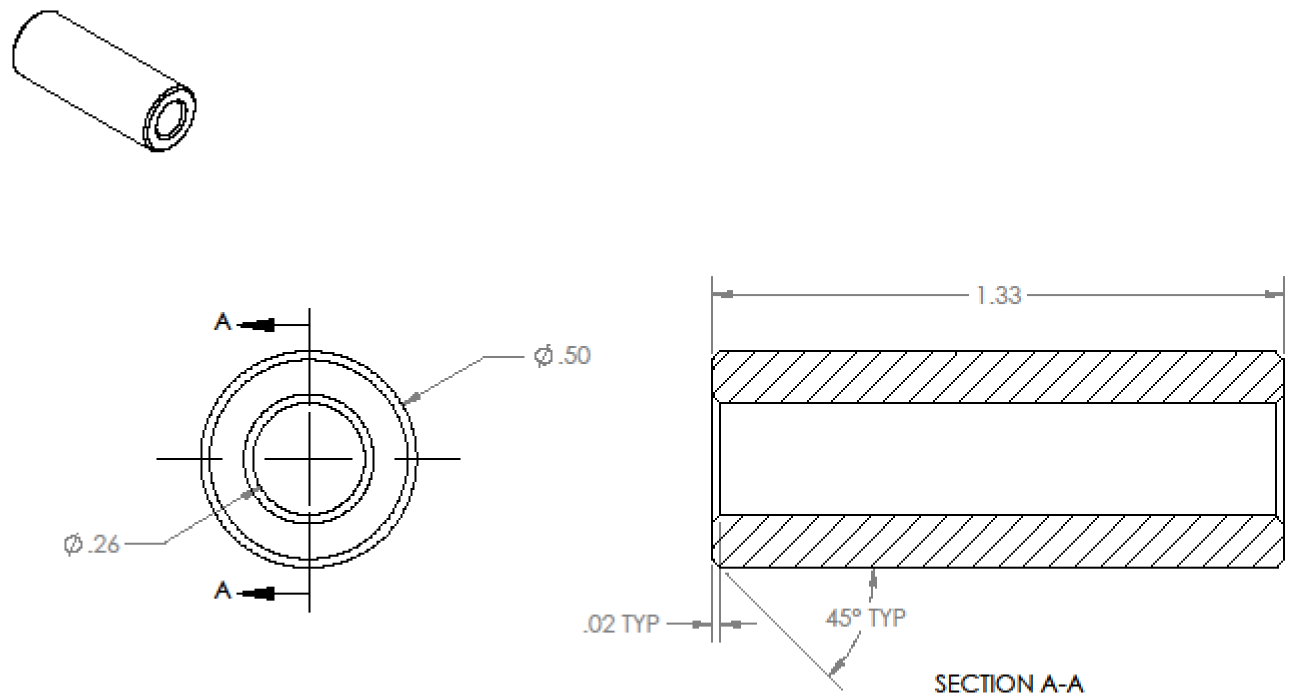
5
4
3
2
1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION: TURRET WASHER
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DHA	11/06/13	TITLE:
			CHECKED	DREW	4/15/14	ARM TURRET COMPRSN WASHER
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.			
		MATERIAL ALLOY STEEL	BYU M.A.R.S.			SIZE A · DWG. NO. AT6 · REV B
NEXT ASSY	USED ON	FINISH N/A				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 3:2 · WEIGHT: · SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL: ALUMINUM

FINISH: N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DHA	11/06/13
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

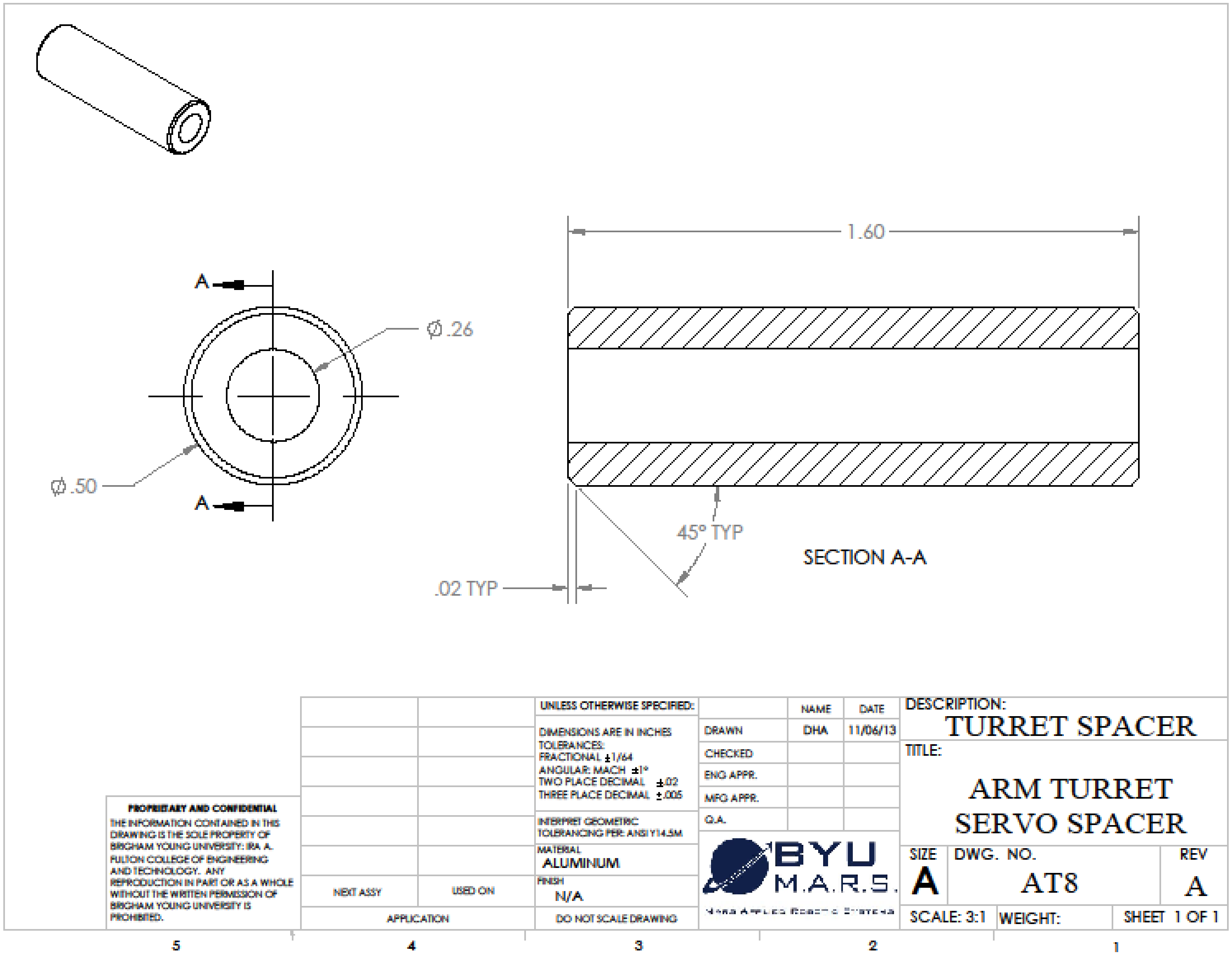
DESCRIPTION: TURRET SPACER

TITLE: ARM TURRET CASE SPACER

SIZE	DWG. NO.	REV
A	AT7	A

SCALE: 3:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1


A
A
Ø .26
Ø .50
1.60
45° TYP
.02 TYP
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
ALUMINUM
FINISH
N/A
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
DHA
11/06/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
BYU
M.A.R.S.
DESCRIPTION:
TURRET SPACER
TITLE:
ARM TURRET SERVO SPACER
SIZE
A
DWG. NO.
AT8
REV
A
SCALE: 3:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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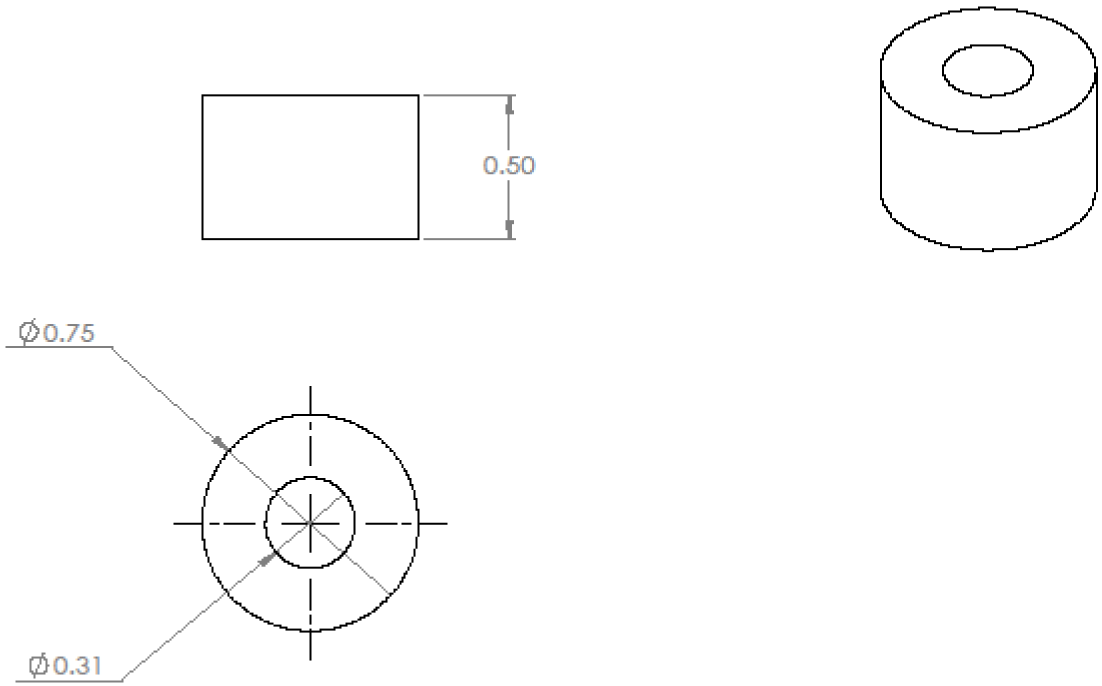
5
4
3
2
1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION: TENSION ROLLER	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	DHA	4/15/14	TITLE:	
	CHECKED	DREW	4/15/14	ARM TURRET TENSION ROLLER	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.				
MATERIAL NYLON	BYU M.A.R.S.			SIZE A	DWG. NO. AT9 — REV A
FINISH N/A					
DO NOT SCALE DRAWING				SCALE: 2:1 — WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

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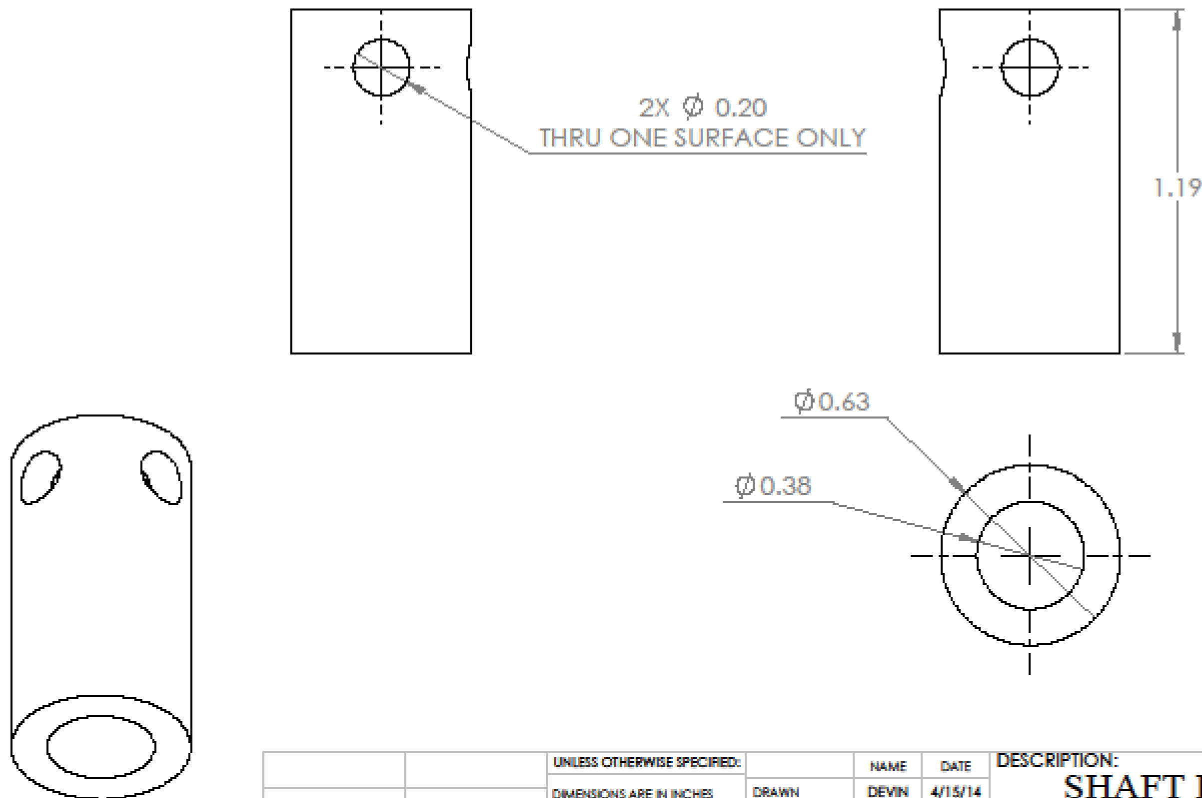
5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
6061 AL
FINISH
N/A
DO NOT SCALE DRAWING

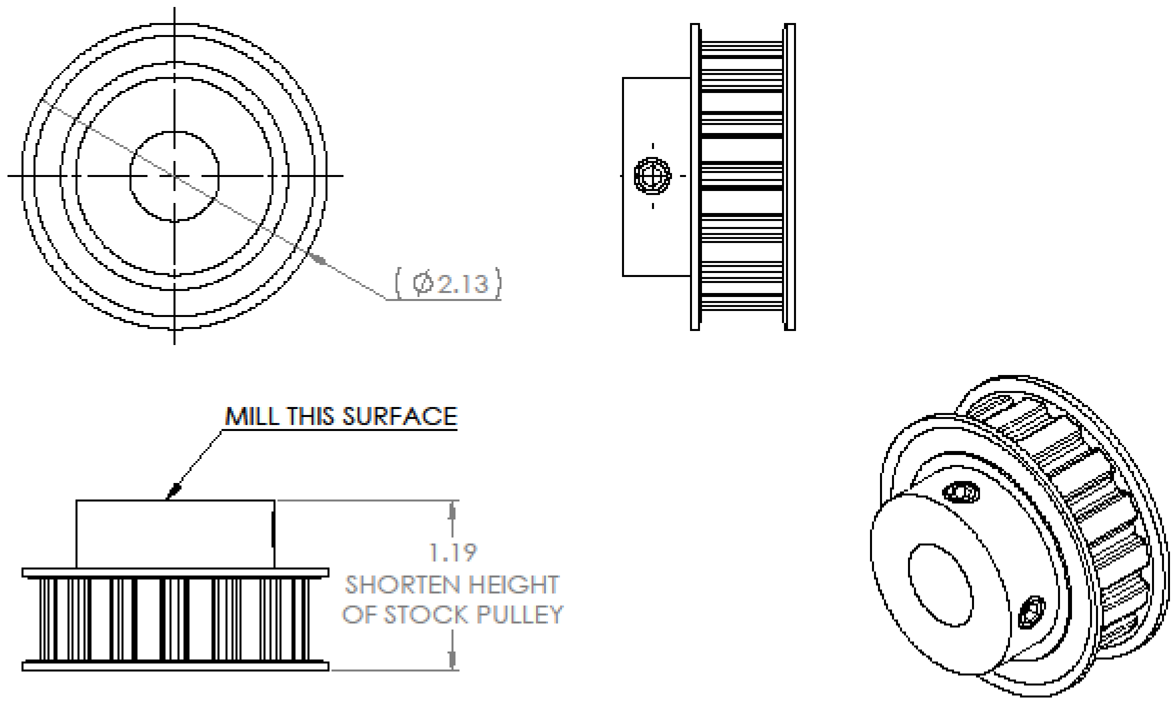
	NAME	DATE
DRAWN	DEVIN	4/15/14
CHECKED	DREW	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION:
SHAFT INSERT
TITLE:
ARM TURRET
SHAFT INSERT

SIZE	DWG. NO.	REV
A	AT10	A
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
AL

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DEVIN	4/15/14
CHECKED	DREW	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

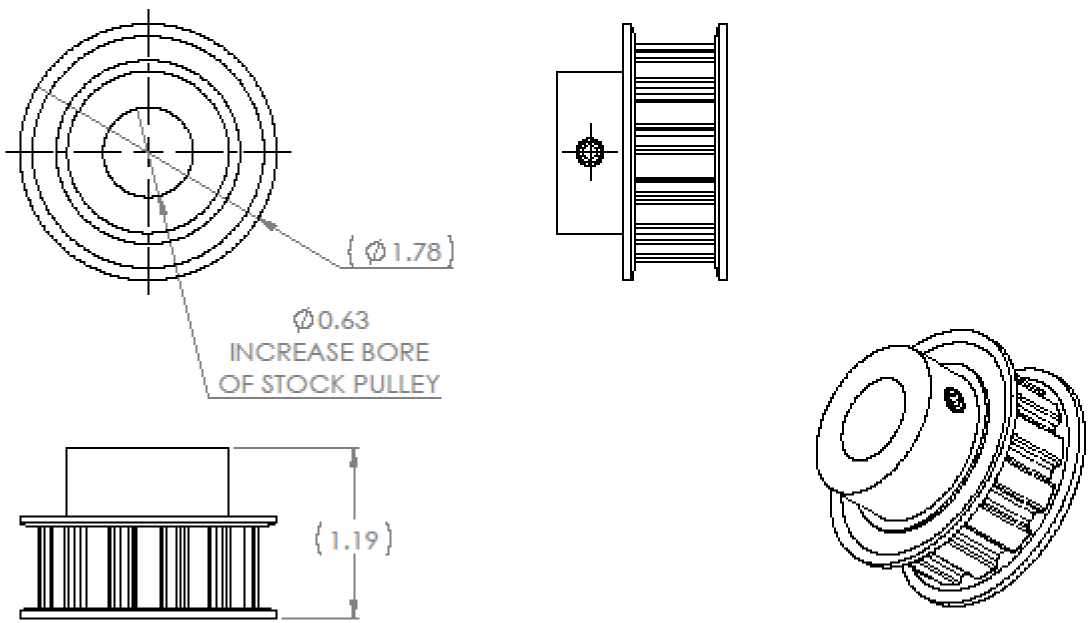
DESCRIPTION:
TIMING PULLEY

TITLE:
ARM TURRET
LARGE TIMING PULLEY

SIZE	DWG. NO.	REV
A	AT11	A

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
AL

FINISH
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DEVIN	4/15/14
CHECKED	DREW	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

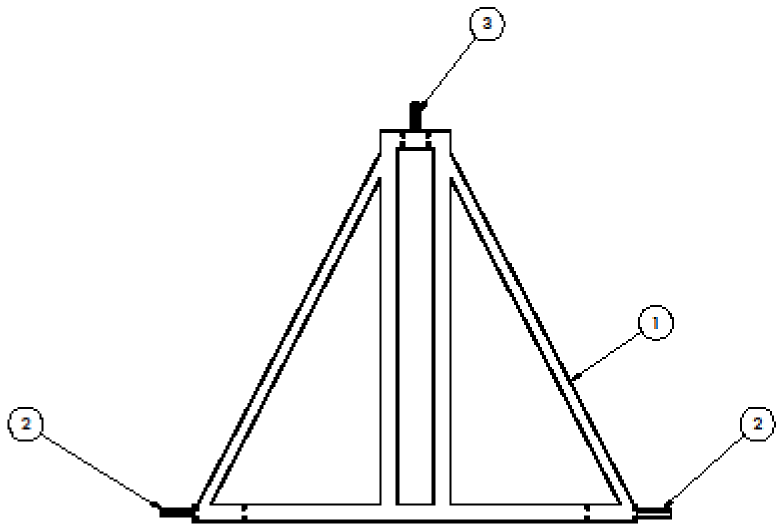
DESCRIPTION:
TIMING PULLEY

TITLE:
ARM TURRET
SMALL TIMING PULLEY

SIZE	DWG. NO.	REV
A	AT12	A

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1

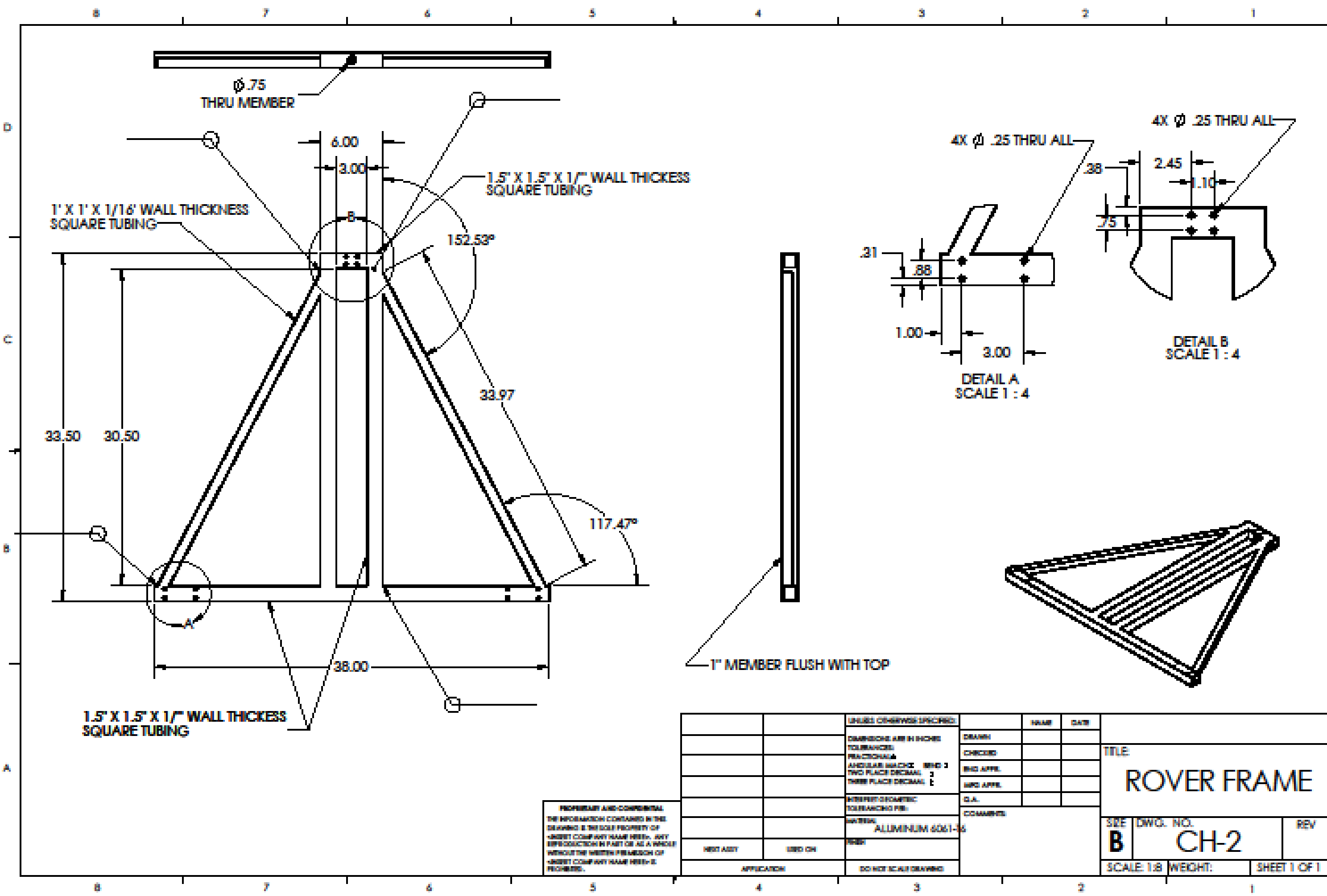


ITEM NO.	PART NUMBER	DESCRIPTION	Exploded/QTY.
1	CH-2	ROVER FRAME	1
2	CH-4	FRONT JOINT ASSY	2
3	CH-3	REAR JOINT ASSY	1

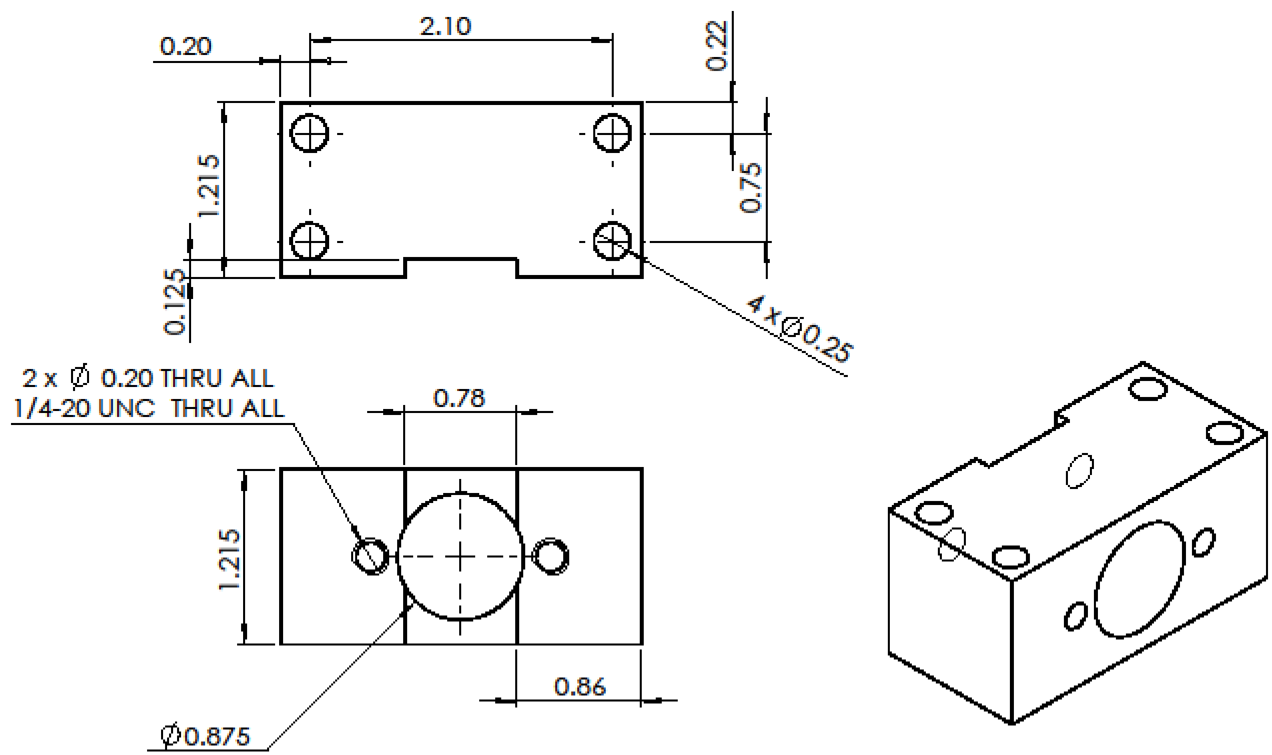
TITLE:
CHASSIS ASSY

SIZE B DWG. NO. CH-1 REV 2

SCALE: 1:12 WEIGHT: SHEET 1 OF 1



ϕ.75
THRU MEMBER
6.00
3.00
1' X 1' X 1/16' WALL THICKNESS
SQUARE TUBING
1.5" X 1.5" X 1/" WALL THICKESS
SQUARE TUBING
152.53°
33.97
33.50
30.50
117.47°
38.00
1.5" X 1.5" X 1/" WALL THICKESS
SQUARE TUBING
1" MEMBER FLUSH WITH TOP
4X ϕ .25 THRU ALL
.31
.88
1.00
3.00
DETAIL A
SCALE 1 : 4
4X ϕ .25 THRU ALL
.38
2.45
1.10
.75
DETAIL B
SCALE 1 : 4
TITLE:
ROVER FRAME
SIZE
B
DWG. NO.
CH-2
REV
SCALE: 1:8
WEIGHT:
SHEET 1 OF 1
MATERIAL
ALUMINUM 6061-T6
DO NOT SCALE DRAWING
APPLICATION
NEXT ASSY
USED ON
PROPRIETARY AND CONFIDENTIAL



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
ALUMINUM 6061

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:

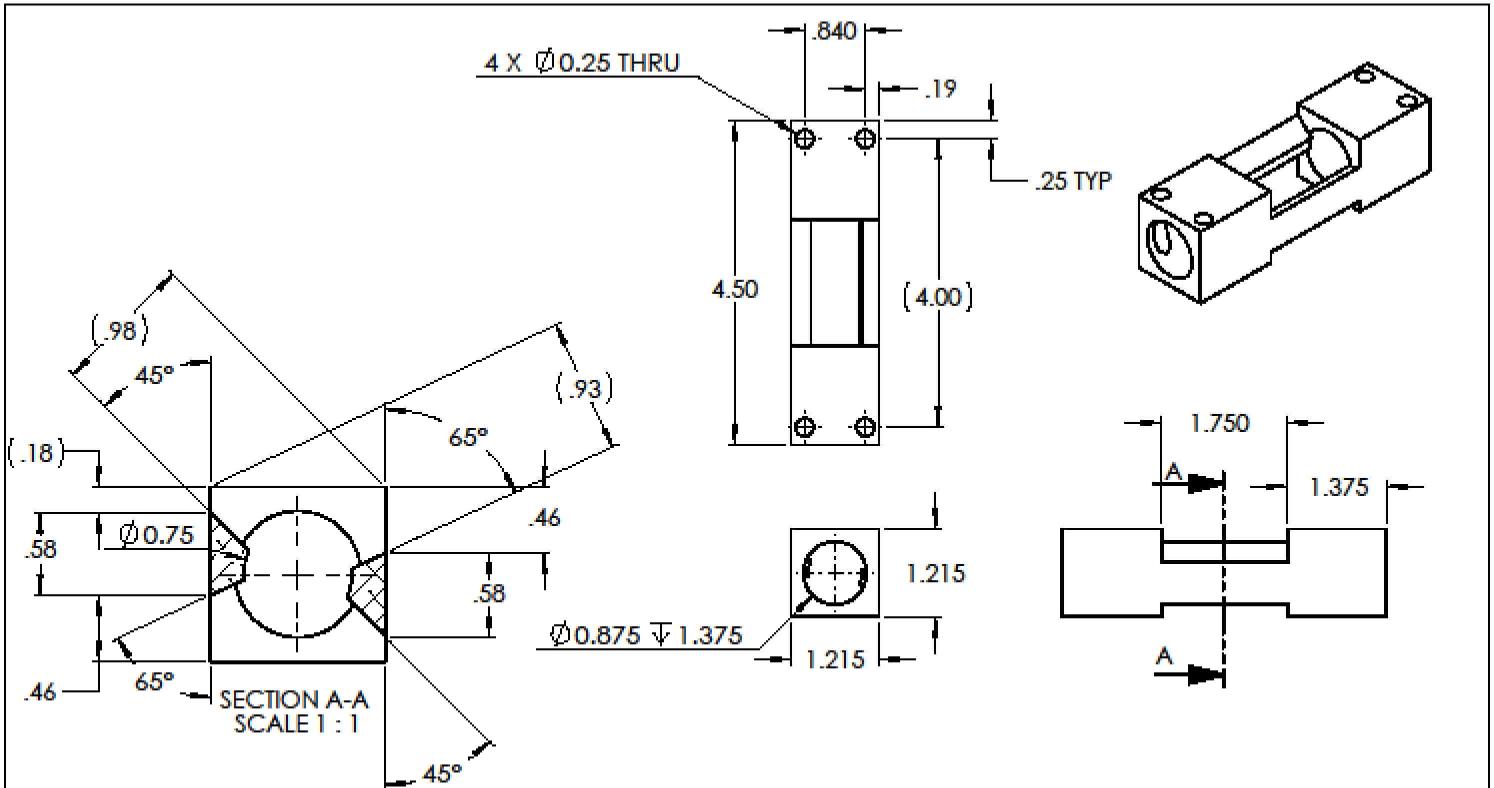
TITLE:

REAR BEARING HOUSING

SIZE	DWG. NO.	REV
A	CH-4	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
Aluminum
FINISH
DO NOT SCALE DRAWING

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

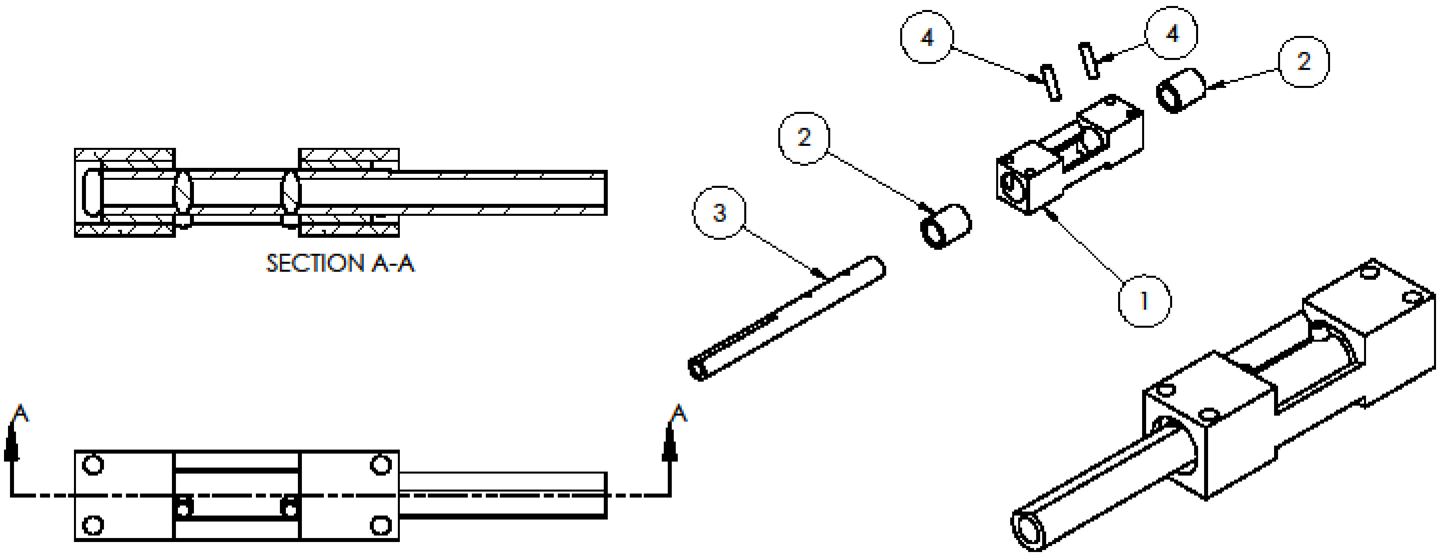
BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:
BEARING HOUSING
TITLE:
BEARING HOUSING

SIZE	DWG. NO.	REV
A	CH-5	1

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

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	CH-5	BEARING HOUSING	1
2	Fiberglass Sleeve Bearings	FIBERGLASS SLEEVE BUSHING .625" ID X .75"	2
3	CH-8	SHAFT	1
4	18-8 SST Dowel pin	18-8 SST DOWEL PIN .25" DIA X 1"	2

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.

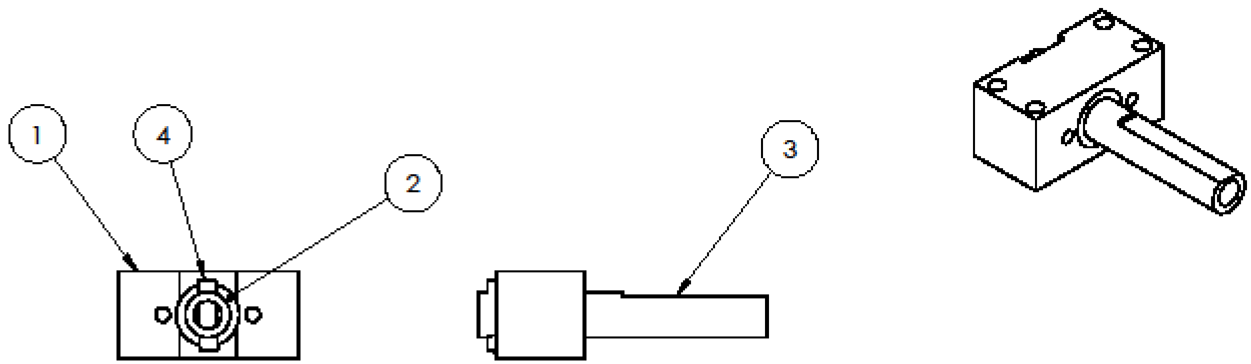
DESCRIPTION: FRONT JOINT ASSY

TITLE: Joint Assy

SIZE	DWG. NO.	REV
A	CH-6	1

SCALE: 1:2 | WEIGHT: 0.69 | SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	CH-3	REAR BEARING HOUSTING	1
2	Fiberglass Sleeve Bearings	FIBERGLASS SLEEVE BUSHING .625" ID X .75"	1
3	CH-8	SHAFT	1
4	18-8 SST Dowel pin	18-8 SST DOWEL PIN .25" DIA X 1"	1

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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.

MARS APPLIED ROBOTIC SYSTEMS

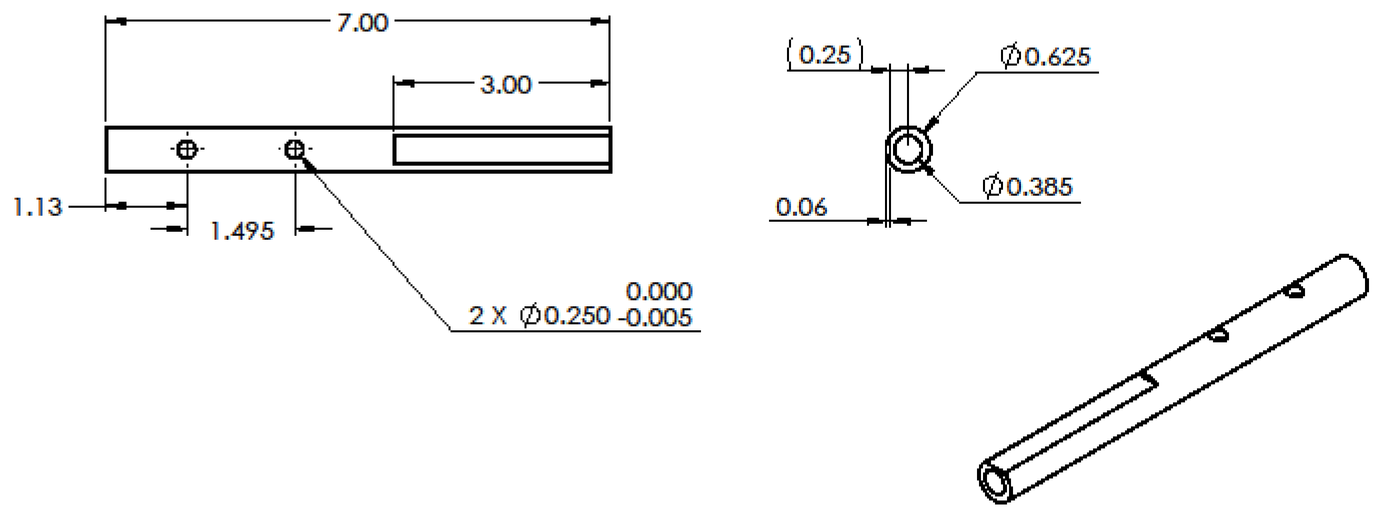
DESCRIPTION:
REAR JOINT ASSY

TITLE:
REAR JOINT ASSY

SIZE	DWG. NO.	REV
A	CH-7	1

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

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	K. Frogget	
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.		
MATERIAL 1018 STEEL	BYU M.A.R.S.		
FINISH	MARS APPLIED ROBOTIC SYSTEMS		
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

DESCRIPTION:

TITLE:

JOINT SHAFT

SIZE	DWG. NO.	REV
A	CH-8	1
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

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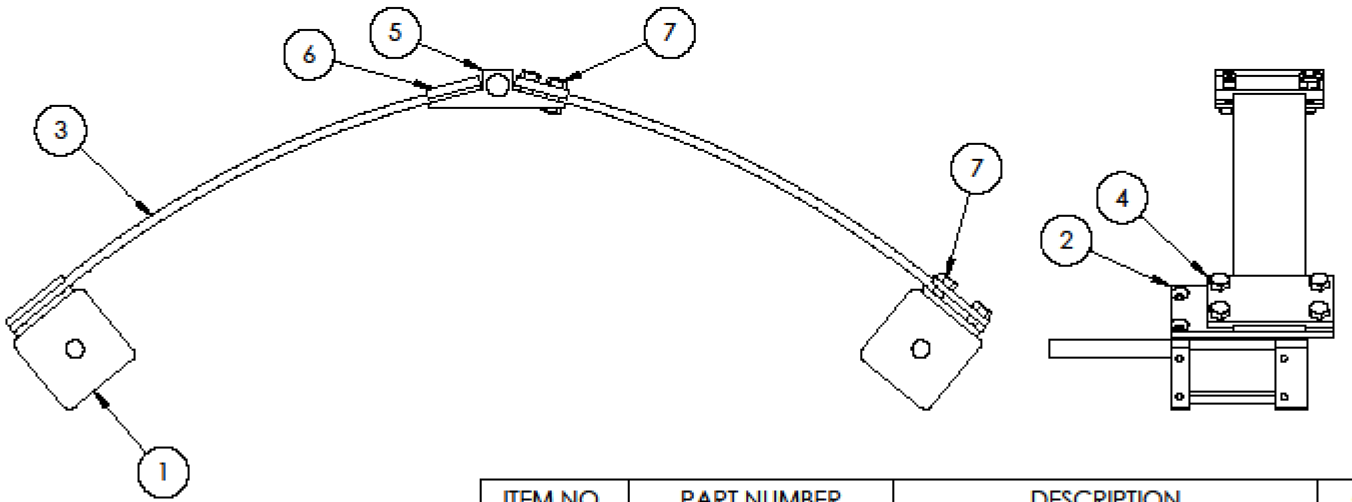
5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P80A_48to1		2
2	MotorPlate		2
3	KevlarSuspension		2
4	Motor Mount, top plate		2
5	Rocker joint housing		1
6	Joint mounting plate		2
7	92240A303		8

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KF	12/1/13
CHECKED	CM	12/9/13
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

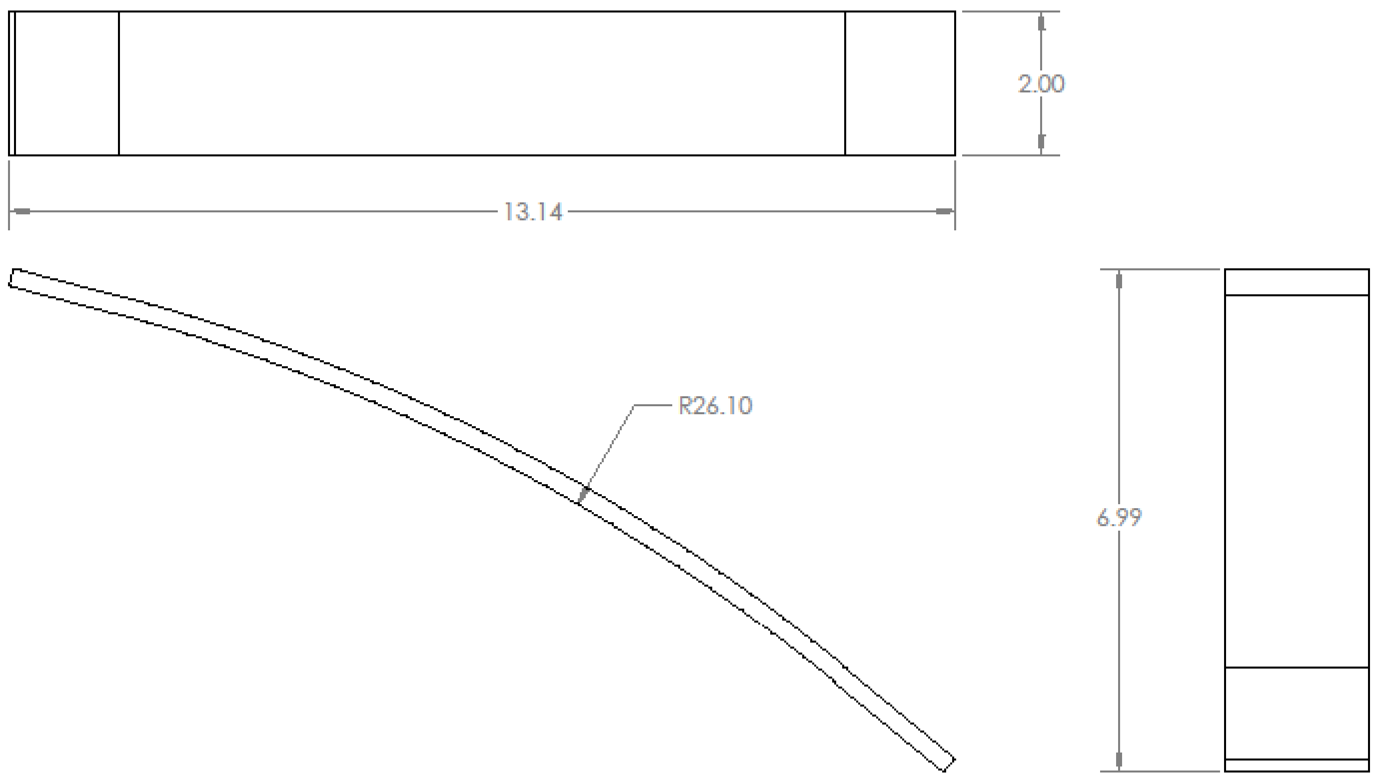
DESCRIPTION:

TITLE:

Suspension Assembly

SIZE	DWG. NO.	REV
A	S-1	1
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
Kevlar 49

FINISH
Epoxy

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	CM	12/3/13
CHECKED	MTT	12/3/13
ENG APPR.	MTT	12/3/13
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION: Structural Member

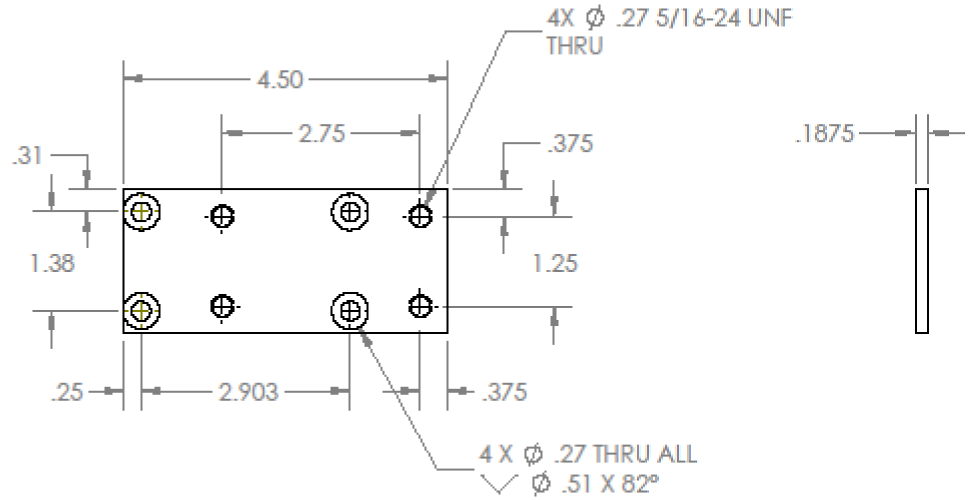
TITLE:

Suspension Link

SIZE	DWG. NO.	REV
A	S-2	2.1

SCALE 1:2 | WEIGHT: 0.41 lb | SHEET 1 OF 1

5 4 3 2 1

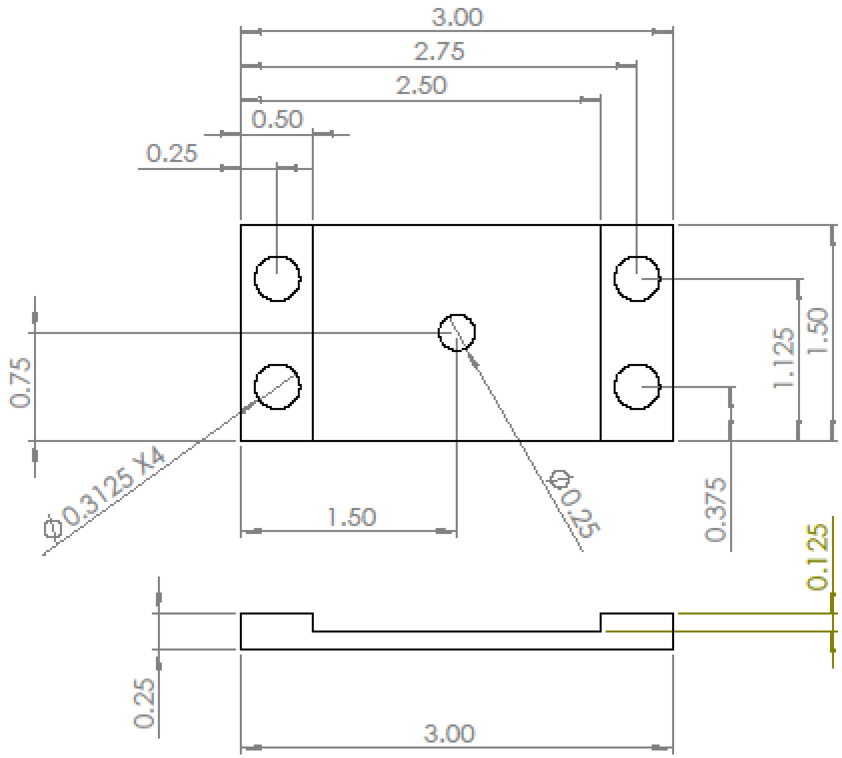


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	DESCRIPTION:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	KF	12/1/13	TITLE:	
	CHECKED	CM	12/9/13	MOTOR PLATE	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.				
MATERIAL ALUMINUM 6061	BYU M.A.R.S.			SIZE A	DWG. NO. S-3 / REV 1
FINISH					
DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

5 4 3 2 1



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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.

DESCRIPTION:

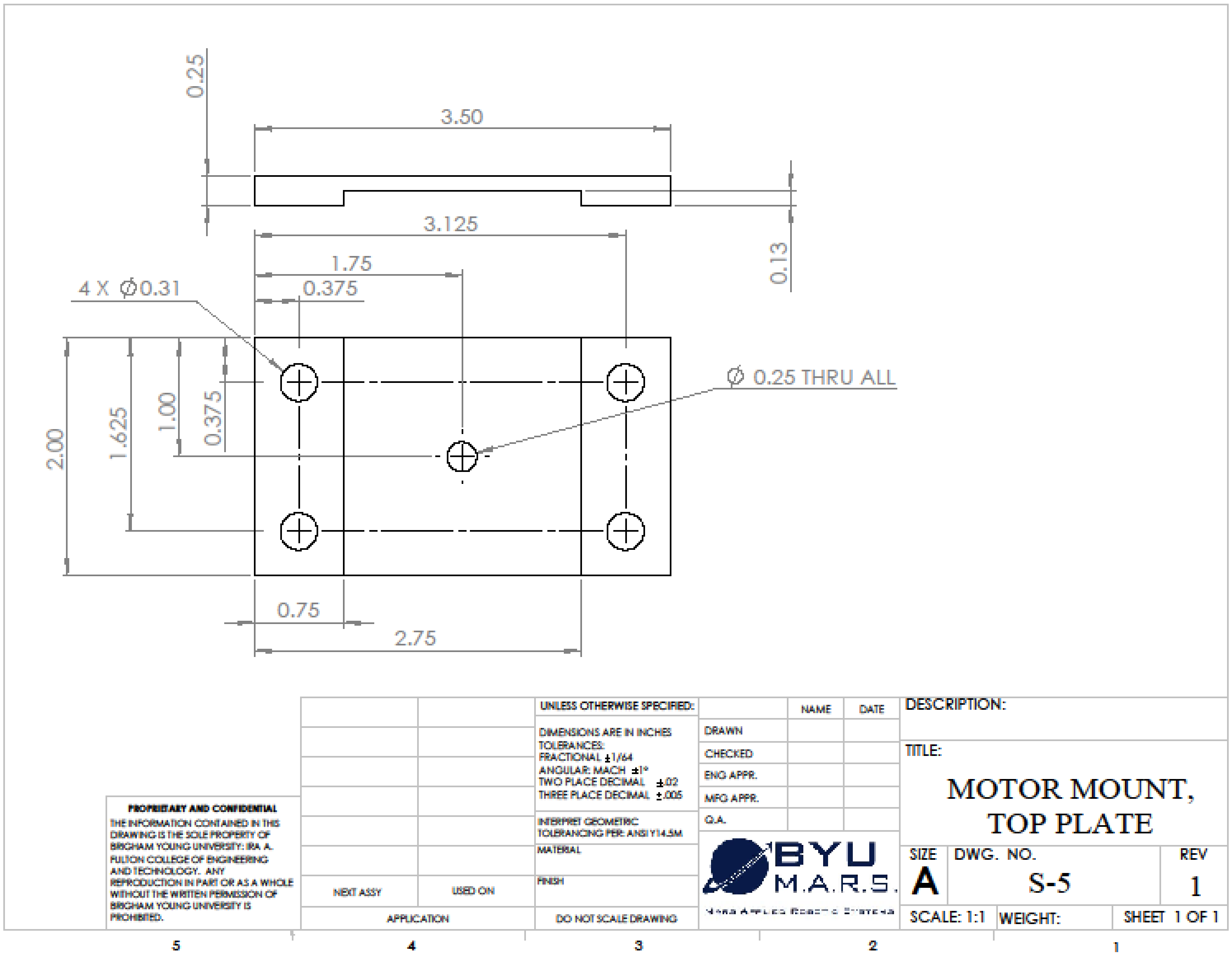
TITLE:

JOINT MOUNTING PLATE

SIZE	DWG. NO.	REV
A	S-4	1

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1


0.25
3.50
3.125
0.13
1.75
0.375
4 X ∅0.31
∅ 0.25 THRU ALL
2.00
1.625
1.00
0.375
0.75
2.75
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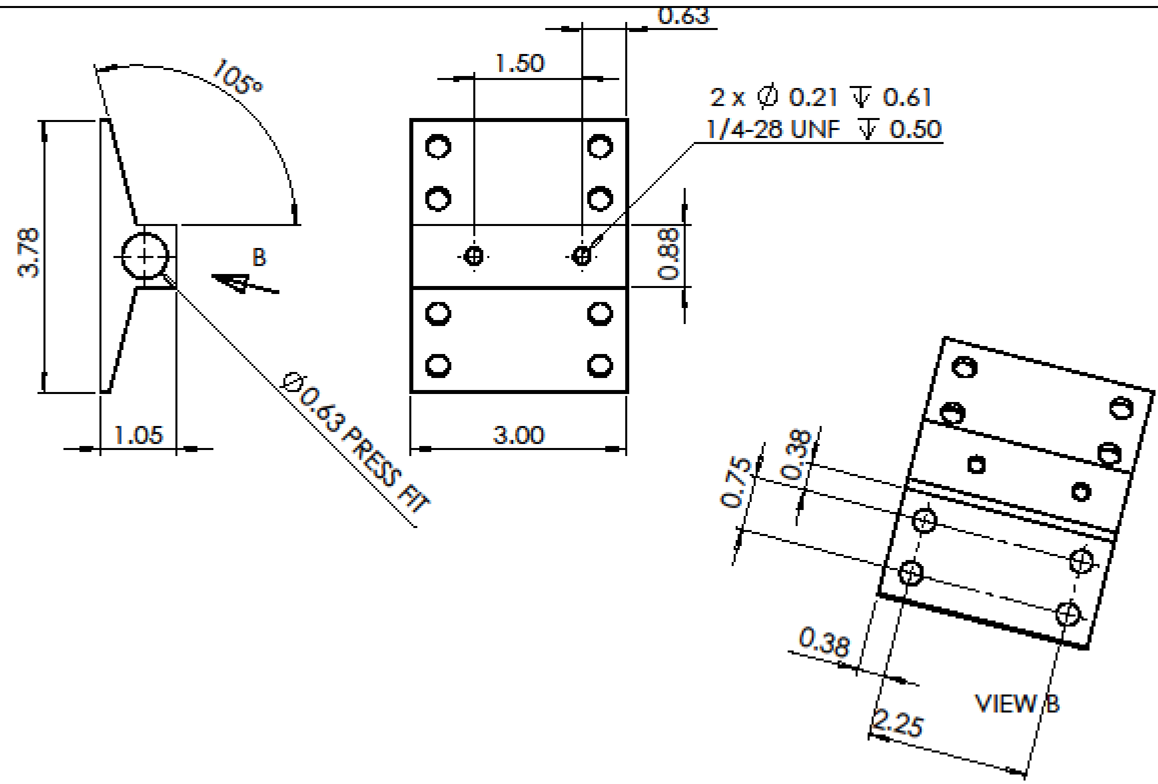
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
BYU M.A.R.S.
DESCRIPTION:
TITLE:
MOTOR MOUNT, TOP PLATE
SIZE A
DWG. NO. S-5
REV 1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:

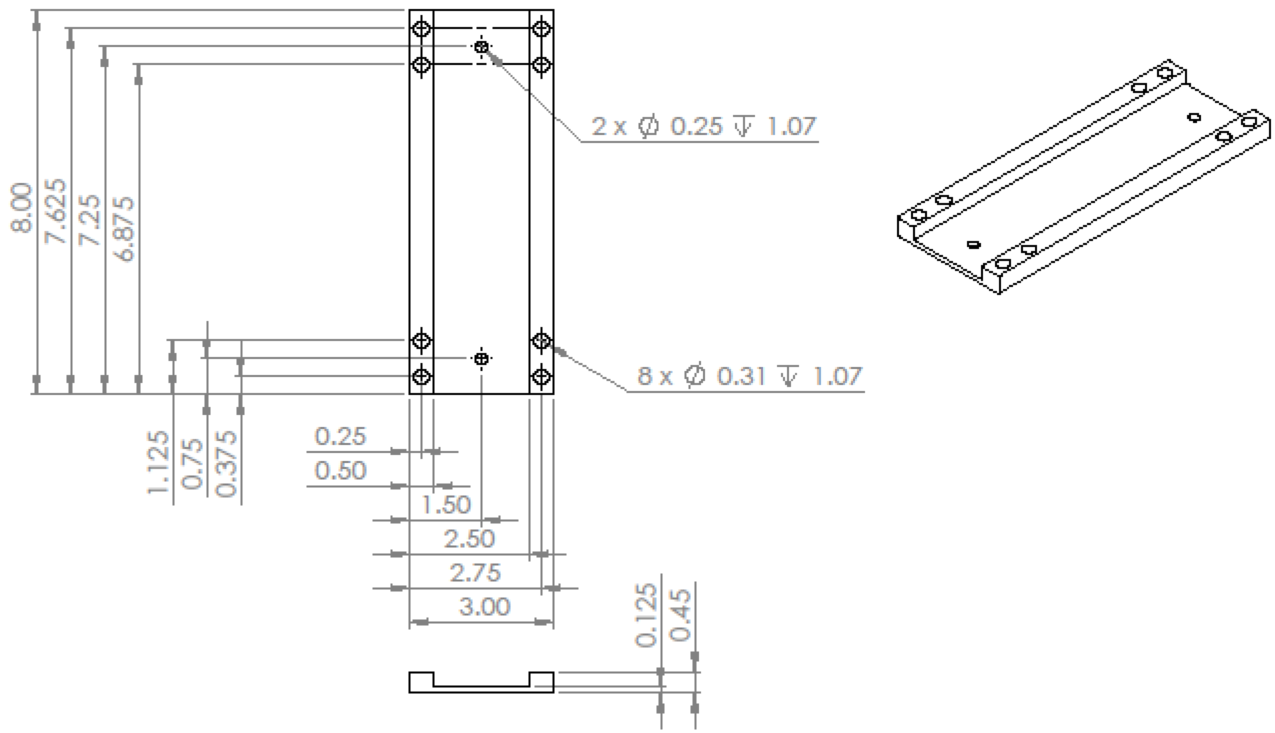
TITLE:

JOINT HOUSING

SIZE	DWG. NO.	REV
A	S-6	1

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.

DESCRIPTION:

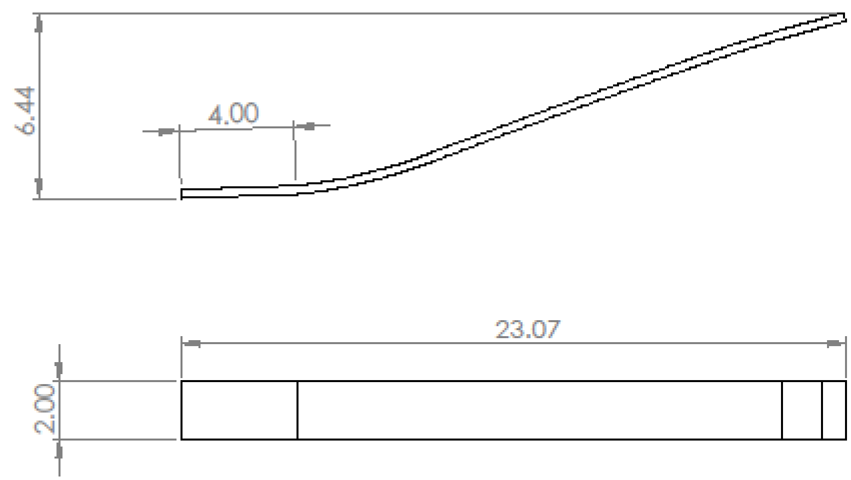
TITLE:

LONG SUSPENSION SUPPORT CLAMP

SIZE A | DWG. NO. S7 | REV

SCALE: 1:3 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	CSM	4/15/14
CHECKED	MT	4/15/14
ENG APPR.		
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION:

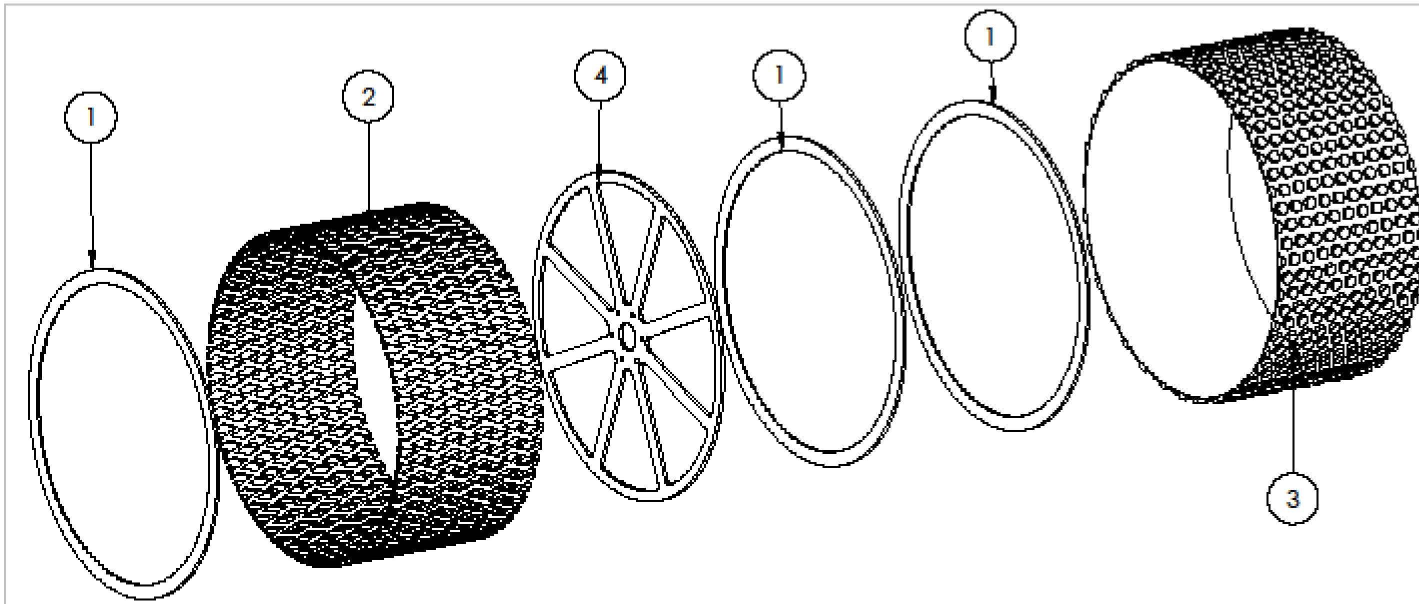
TITLE:

LONG SUSPENSION LINK

SIZE	DWG. NO.	REV
A	S8	

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	W-1	Reinforcing Hoop	3
2	W-2	Expanded Aluminum Rim	1
3	W-3	Rubber Tread	1
4	W-4	Wheel Hub	1

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NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
6061 T-6 Aluminum
FINISH
Polished
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MTT	11/20/13
CHECKED	CM	11/21/13
ENG APPR.	MTT	11/21/13
MFG APPR.		
Q.A.		

BYU M.A.R.S.

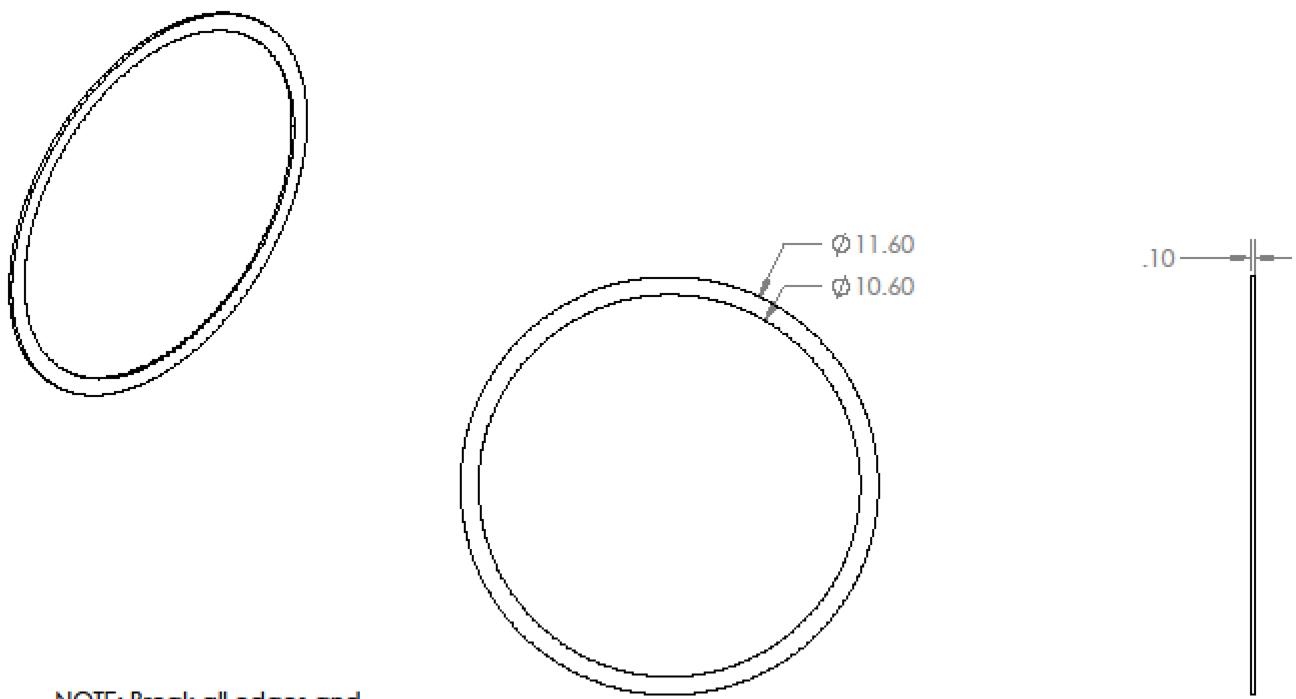
DESCRIPTION: Assembly

TITLE:
Wheel Assembly

SIZE A | DWG. NO. W-0 | REV 2.1

SCALE: 1:5 | WEIGHT: 0.41 lb | SHEET 1 OF 1

5 4 3 2 1



NOTE: Break all edges and prep. outside diameter for welding

FRONT

SIDE

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/64 ANGULAR: MACH ±1° TWO PLACE DECIMAL ±.02 THREE PLACE DECIMAL ±.005	DRAWN	MTT	11/20/13
	CHECKED	CM	11/21/13
	ENG APPR.	MTT	11/21/13
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M	Q.A.		
MATERIAL 6061 T-6 Aluminum			
FINISH Polished			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

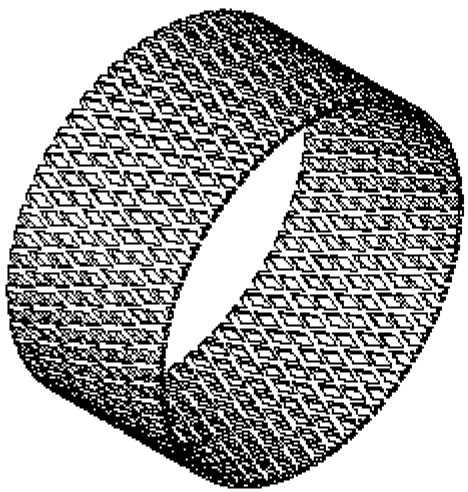
BYU M.A.R.S.

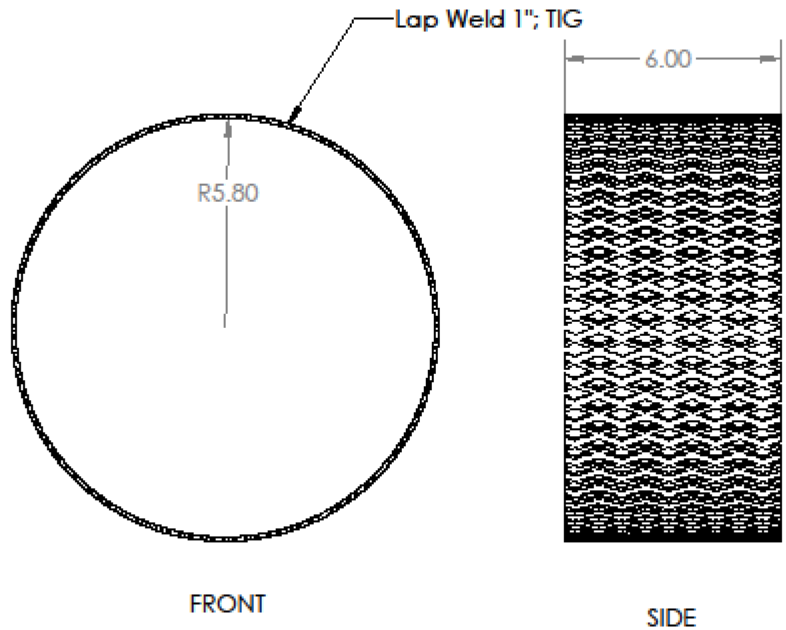
DESCRIPTION: Structural Member

TITLE: **Wheel Hoop**

SIZE	DWG. NO.	REV
A	W-1	2.1
SCALE: 1:4	WEIGHT: .06lb	SHEET 1 OF 1

5 4 3 2 1





NOTE: .081" expanded aluminum sheet; 1"x.5" holes. Cut on stomp shear and use wheel form to form radius. Insert hub before welding.

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL: 3003 H14 Aluminum

FINISH: As Recieved

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MTT	11/20/13
CHECKED	CM	11/21/13
ENG APPR.	MTT	11/21/13
MFG APPR.		
Q.A.		

BYU M.A.R.S.

DESCRIPTION: Structural Member

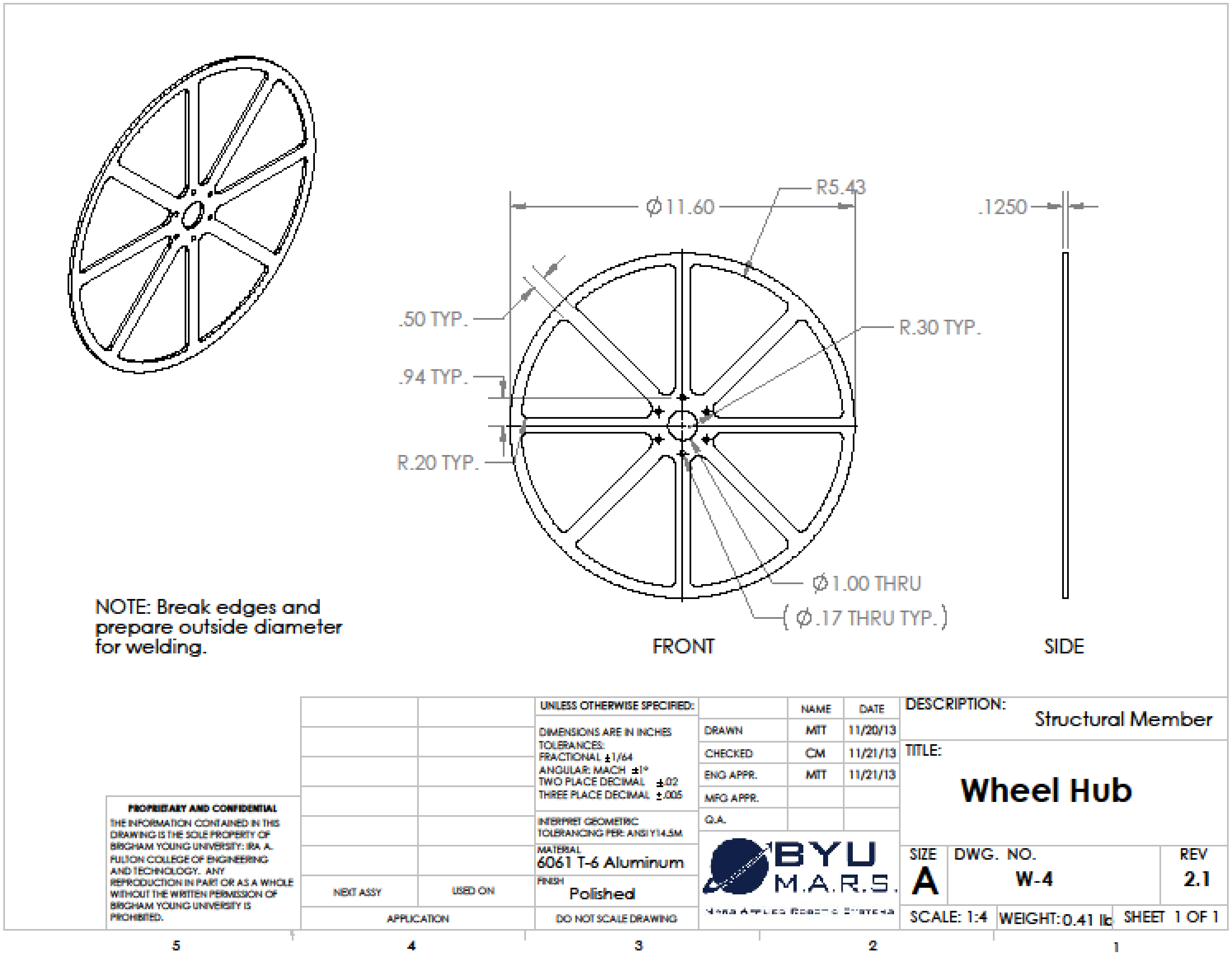
TITLE:

Wheel Rim

SIZE	DWG. NO.	REV
A	W-2	2.1

SCALE: 1:4 | WEIGHT: 1 lb | SHEET 1 OF 1

5 4 3 2 1


Ø11.60
R5.43
.1250
.50 TYP.
R.30 TYP.
.94 TYP.
R.20 TYP.
Ø1.00 THRU
Ø.17 THRU TYP.
NOTE: Break edges and prepare outside diameter for welding.
FRONT
SIDE
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
6061 T-6 Aluminum
FINISH
Polished
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN MTT 11/20/13
CHECKED CM 11/21/13
ENG APPR. MTT 11/21/13
MFG APPR.
Q.A.
DESCRIPTION:
Structural Member
TITLE:
Wheel Hub
BYU M.A.R.S.
SIZE A
DWG. NO. W-4
REV 2.1
SCALE: 1:4
WEIGHT: 0.41 lb
SHEET 1 OF 1
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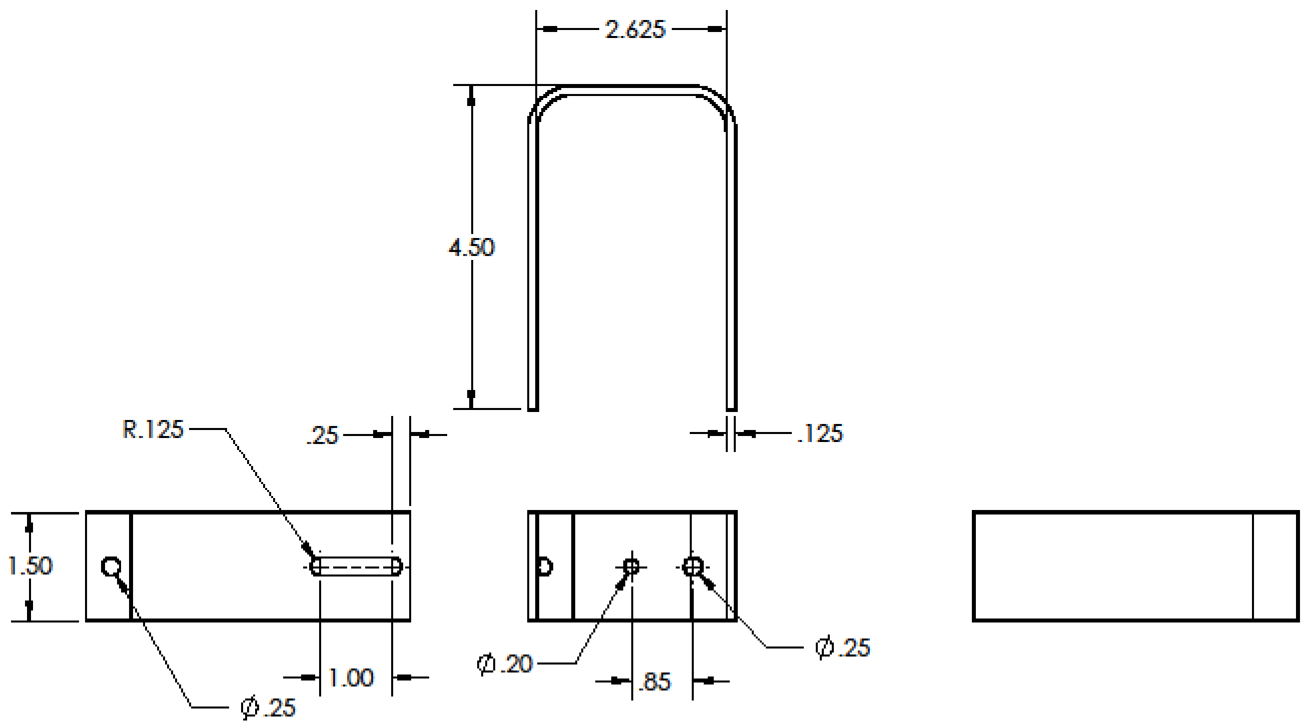
5
4
3
2
1



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NEXT ASSY	USED ON
APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

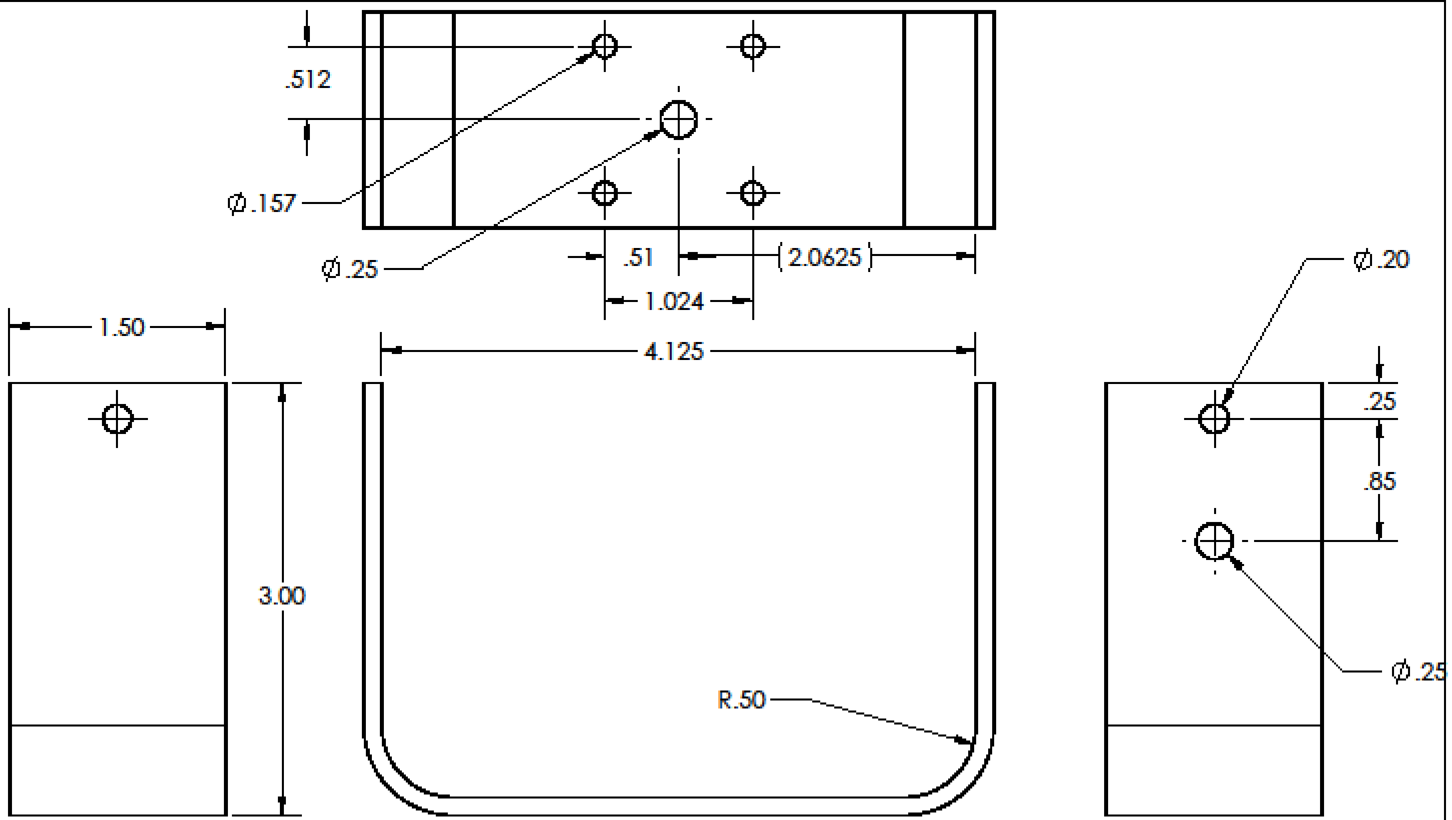
DESCRIPTION:
ROLL AXIS BRACKET

TITLE:
FIRST AXIS BRACKET

SIZE	DWG. NO.	REV
A	G1	1

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

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING

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

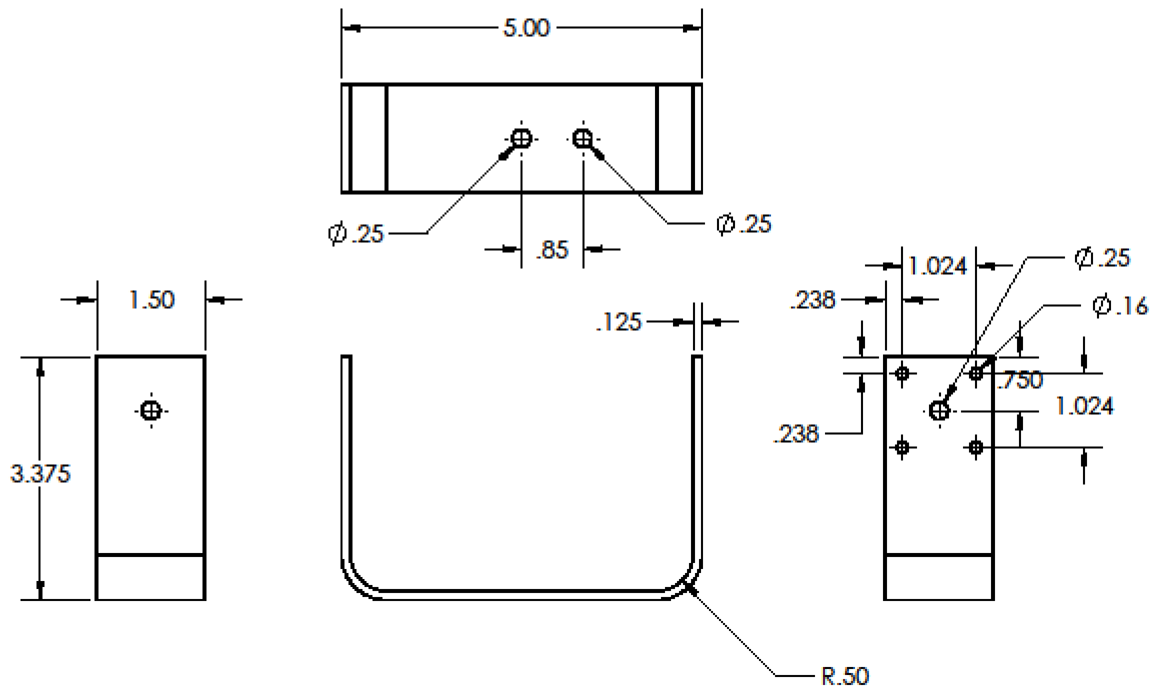
BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:
PITCH AXIS BRACKET
TITLE:
SECOND AXIS BRACKET

SIZE	DWG. NO.	REV
A	G2	1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING

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

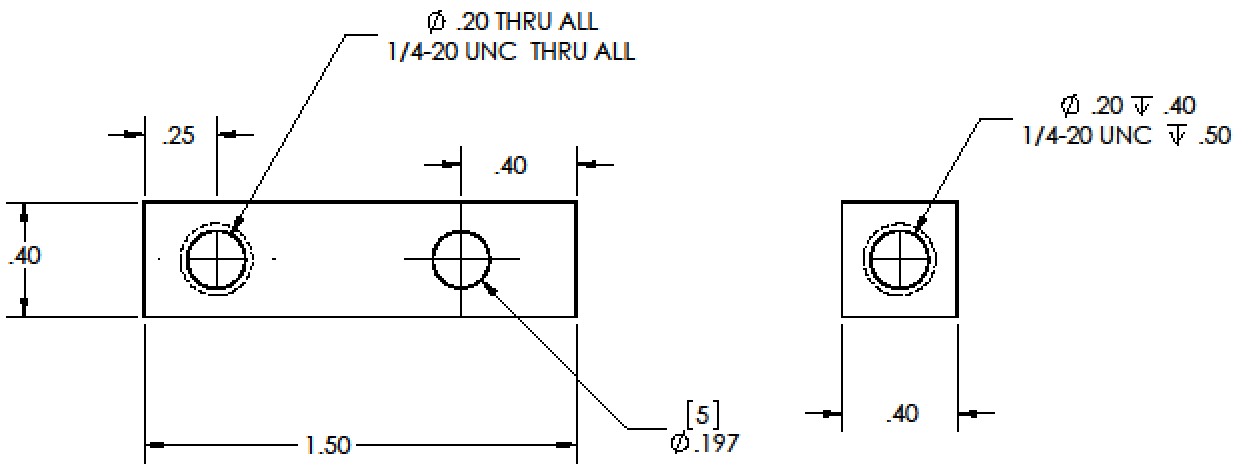
BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:
VERTICAL AXIS
TITLE:
THIRD AXIS BRACKET

SIZE	DWG. NO.	REV
A	G3	1

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

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

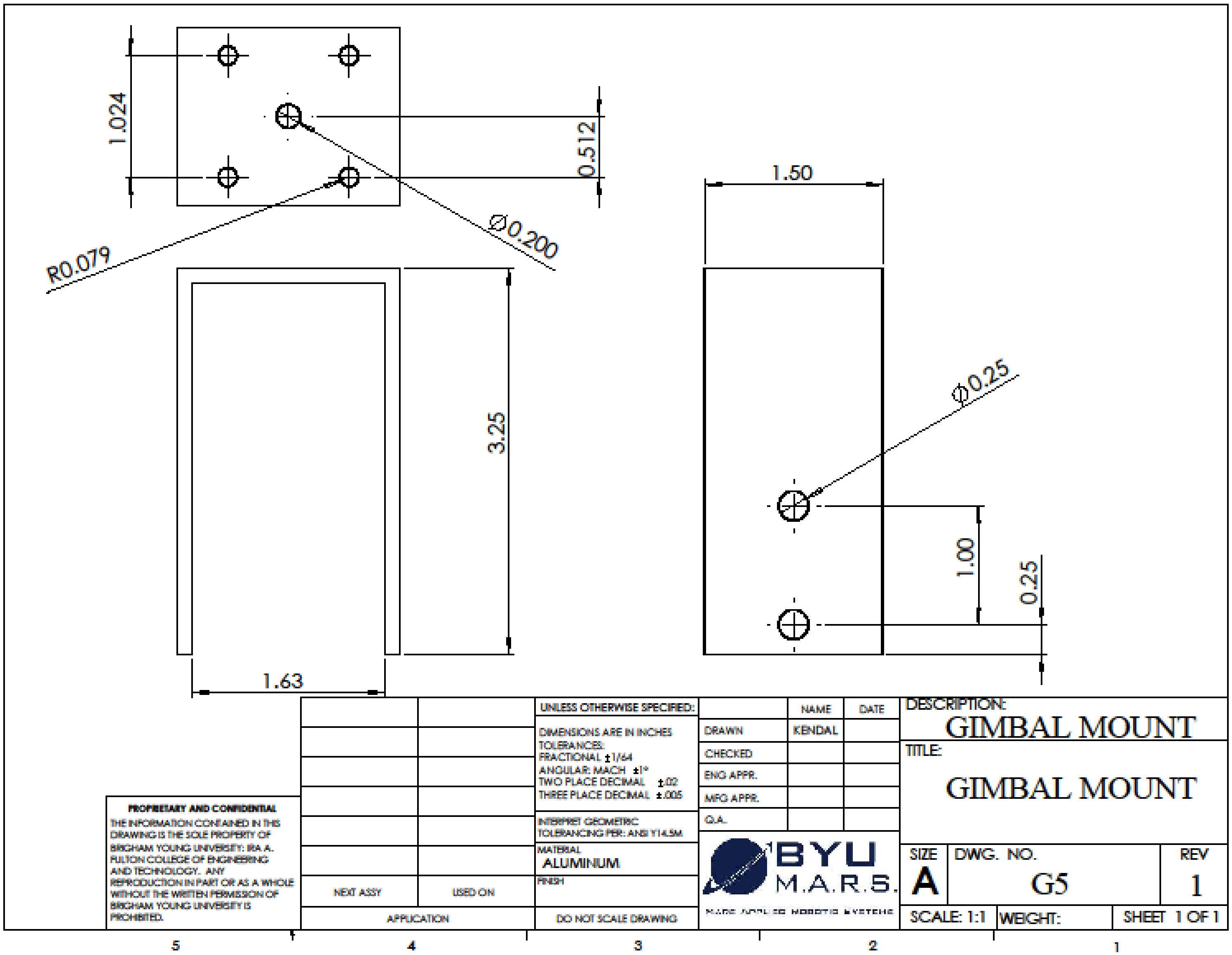
DESCRIPTION:
MOTOR SHAFT BRACKET

TITLE:
MOTOR SHAFT BRACKET

SIZE	DWG. NO.	REV
A	G4	1

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

5 4 3 2 1


1.024
0.512
Ø0.200
R0.079
1.50
Ø0.25
3.25
1.00
0.25
1.63
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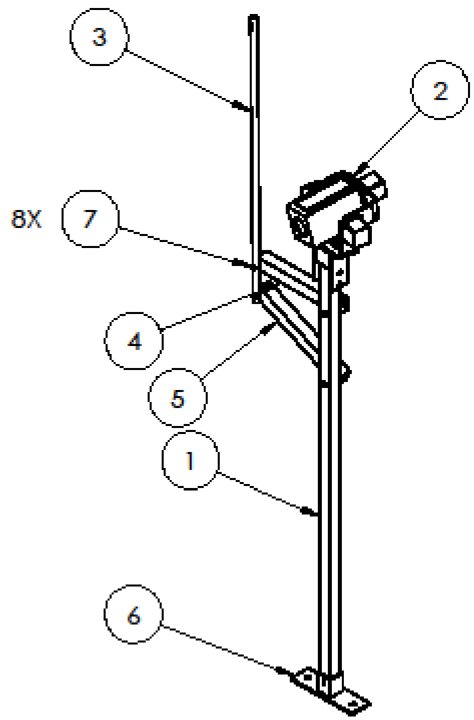
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
KENDAL
CHECKED
ENG APPR.
MFG APPR.
Q.A.
BYU
M.A.R.S.
DESCRIPTION:
GIMBAL MOUNT
TITLE:
GIMBAL MOUNT
SIZE
A
DWG. NO.
G5
REV
1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	G-9	COMMS MAST	1
2	G-7	GIMBAL ASSY	1
3	AntennaMast	FIBERGLASS ANTENNA MAST	1
4	AntennaMastBracket	ANTENNA BRACKET	1
5	AntennaMastBracket	ANTENNA BRACKET 2	1
6	G-8	COMMS BASE PLATE	1
7	90116A207	1/4-20 X 2" LONG BOLT	8

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.

MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:

MAST ASSY

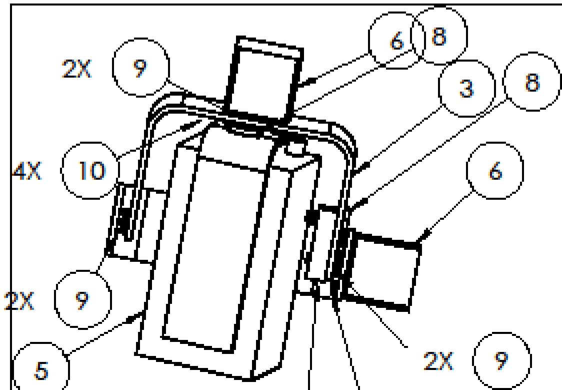
TITLE:

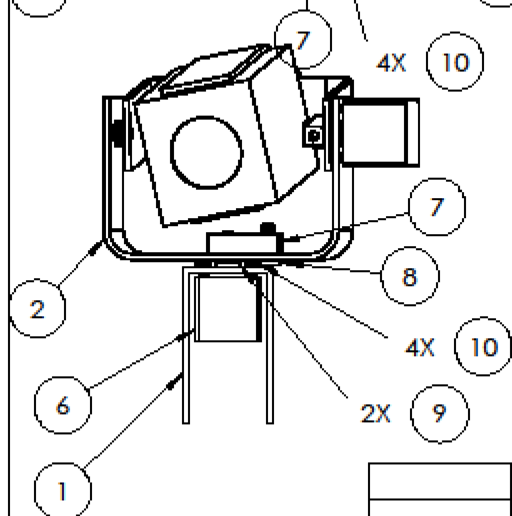
MAST ASSY

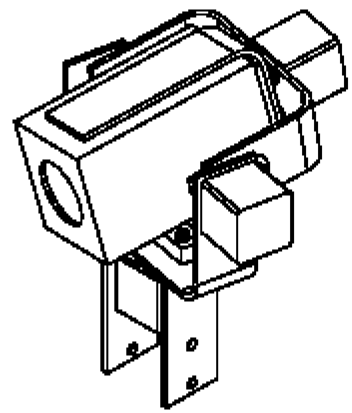
SIZE A | DWG. NO. G6 | REV 1

SCALE: 1:20 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1







ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Gimbal_mounting_Bracket	GIMBAL MOUNT	1
2	Z-axis bracket	VERTICAL AXIS	1
3	second_Axis	PITCH AXIS BRACKET	1
4	first_Axis	ROLL AXIS BRACKET	1
5	Camera		1
6	Stepper_Motor_14HS13-0804S		3
7	Motor_Shaft_Bracket	MOTOR SHAFT BRACKET	3
8	90015A410		3
9	95395A210		8
10	90116A207		12

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M
MATERIAL
FINISH
DO NOT SCALE DRAWING

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

BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

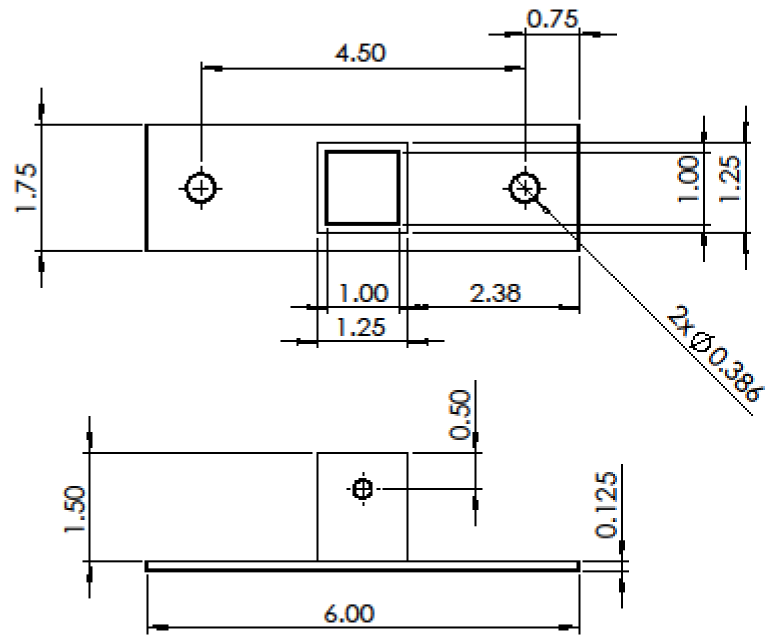
DESCRIPTION: GIMBAL ASSY

TITLE: GIMBAL ASSY

SIZE	DWG. NO.	REV
A	G7	1

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
ANGULAR: MACH ±1°
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

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

BYU M.A.R.S.
MARS APPLIED ROBOTIC SYSTEMS

DESCRIPTION:
COMMS BASE PLATE

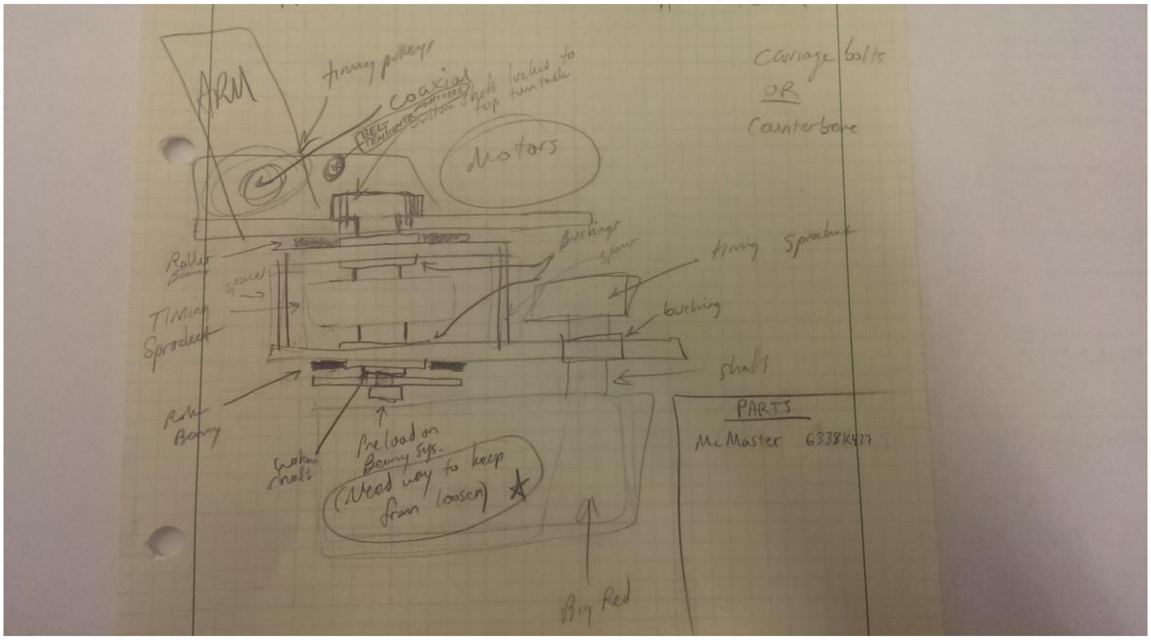
TITLE:
COMMS MAST BASE PLATE

SIZE	DWG. NO.	REV
A	G-8	1

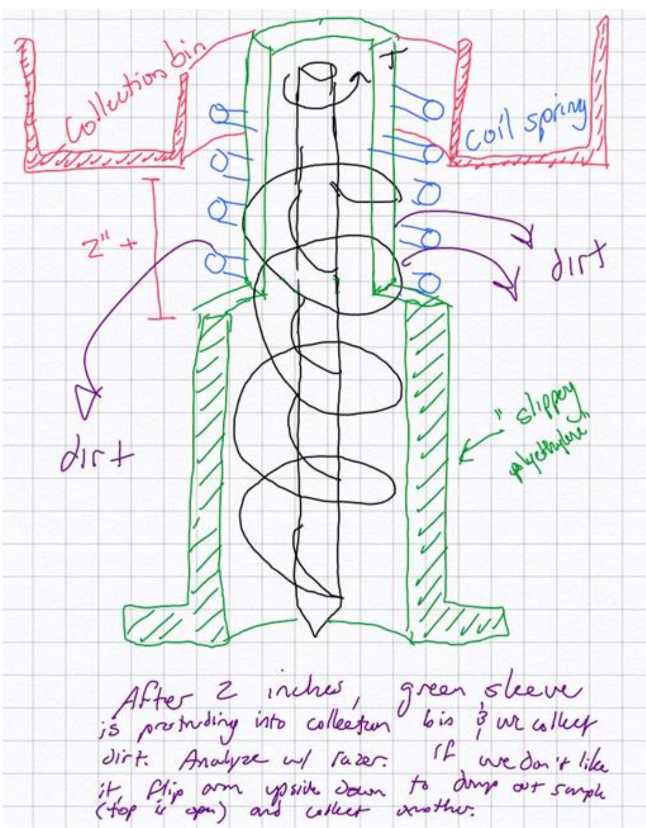
SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1

B-2 Prototypes



Concept drawing of turret (include?)



Concept drawing of auger

Several of the arm prototypes

B-3 Other

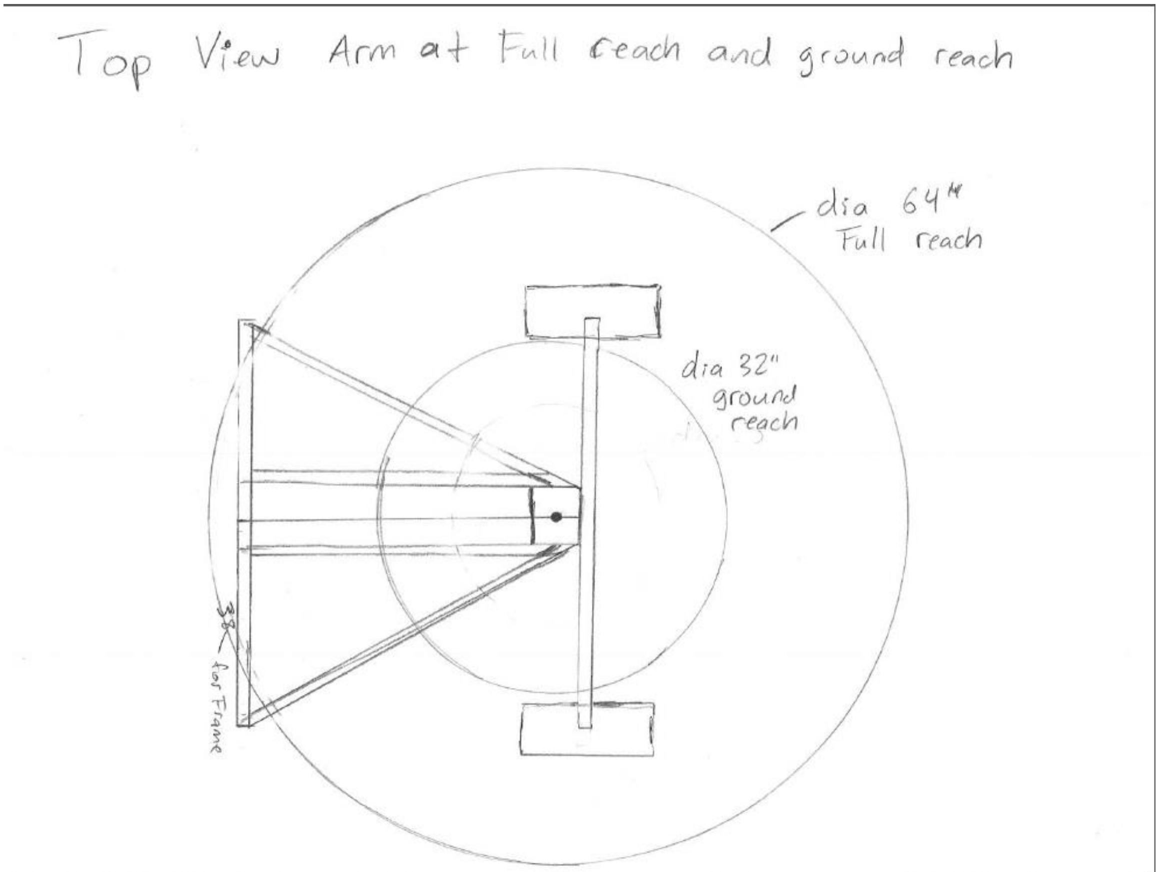
Suspension Lay-up

The Kevlar fabric used was a Kevlar 49 weave and the resin was Adtech 820 epoxy. This was fabricated using a wet lay-up process with vacuum bagging. Dimensions for the suspension links can be found in the engineering drawing in Appendix A Drawing S-2 .

Layer	Orientation
1	±45°
2	0°/90°
3	0°/90°
4	±45°
5	0°/90°
6	±45°
7	0°/90°
8	±45°
9	±45°
10	0°/90°
11	±45°
12	0°/90°
13	±45°
14	0°/90°
15	±45°
16	0°/90°
17	±45°
18	0°/90°
19	±45°
20	0°/90°
21	0°/90°
22	±45°

Rear Suspension Lay Up

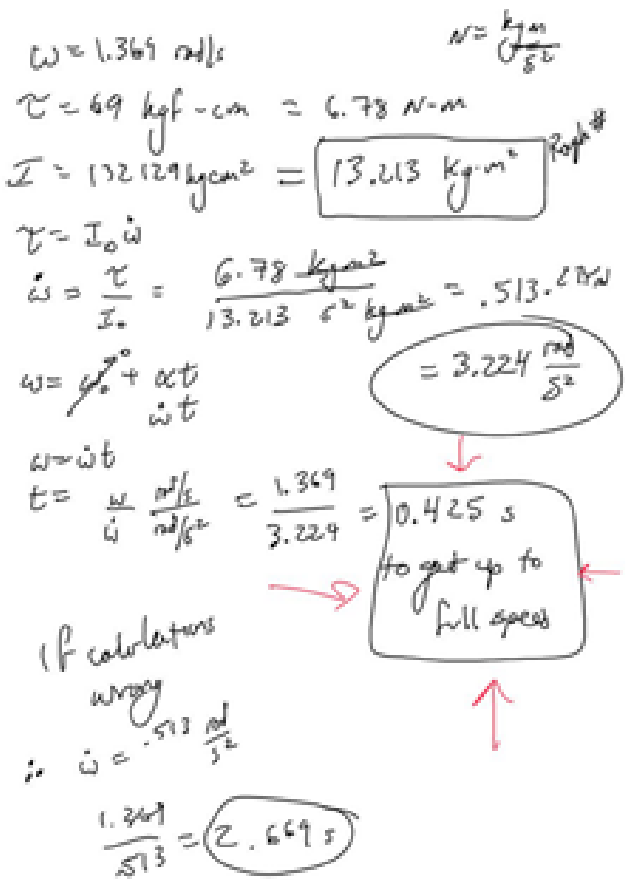
Layer	Orientation
1	±45°
2	0°/90°
3	0°/90°
4	±45°
5	0°/90°
6	±45°
7	0°/90°
8	±45°
9	0°/90°
10	±45°
11	0°/90°
12	±45°
13	0°/90°
14	±45°
15	0°/90°
16	±45°
17	0°/90°
18	±45°
19	0°/90°
20	±45°
21	0°/90°
22	±45°
23	±45°
24	0°/90°
25	0°/90°
26	±45°



Arm reach diagram top view

Appendix C: Acceptance Testing

C-1 Hand Calculations



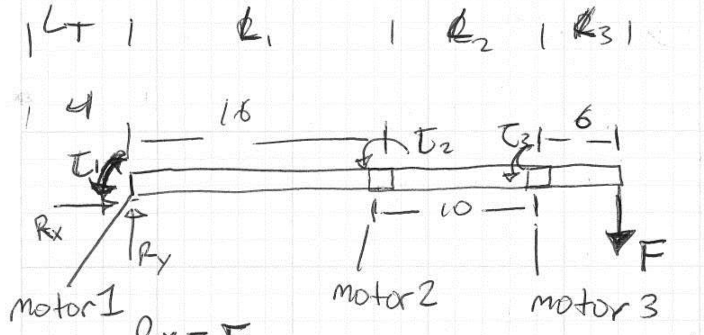
Hand calculations for turret motor. *Used the given motor specifications and simplified estimate of arm moment of inertia to determine acceleration of the servomotor under worst possible loading conditions.*

Required Output	80	ft lb
Applied Voltage	12	V

Cost		Kv	Stall Current	Stall torque out		Gear Ratio	P60	Output Torque	output speed p60	Remaining Gear ratio	final output speed		Adjust Gear Ratio	Adjusted	Resulting End Torque
$7.50	rs550	rpm/V	Amp	oz in	ft lb			ft lb	rpm		rpm	s/90 deg		s/90 Deg	ft lb
	Bane Bots	1608	85	68.85	0.3586	267.7124354	16:1	5.737499633	1206	16.73202721	72.07733914	0.208109791	80	0.995024876	458.9999706
							64:1	22.94999853	301.5	4.183006804	72.07733914	0.208109791	20	0.995024876	458.9999706
$12.75	rs775	rpm/V	Amp	oz in	ft lb			ft lb	rpm		rpm	s/90 deg		s/90 Deg	ft lb
	Bane Bots	608	30	61.1	0.3182	301.6693946	16:1	5.091666663	456	18.85433716	24.18541665	0.620208459	30	0.986842105	152.7499999
							64:1	20.36666665	114	4.713584291	24.18541665	0.620208459	8	1.052631579	162.9333332
$28.16	turnigy sk3	rpm/V	Amp	oz in	ft lb			ft lb	rpm		rpm	s/90 deg		s/90 Deg	ft lb
		530	46		0.7043	136.3016957	16:1	11.26911879	397.5	8.518855981	46.66119499	0.321466263	25	0.943396226	281.7279697
							64:1	45.07647516	99.375	2.129713995	46.66119499	0.321466263	7	1.056603774	315.5353261
		rpm/V	Amp	oz in	ft lb			ft lb	rpm		rpm	s/90 deg		s/90 Deg	ft lb
$28.00	First CIM	443	133	343.27	1.7879	53.6953453	16:1	28.6058315	185.8362341	3.355959081	55.375	0.270880361	12	0.968594746	343.269978
							64:1	114.423326	46.45905853	0.83898977	55.375	0.270880361	3	0.968594746	343.269978

Arm Gearbox Motor Comparison

10 PROJECT RECORD



$R_y = F$

Not considering arm weight or motors

$\tau_1 = F(\ell_1 + \ell_2 + \ell_3)$ 29.46667

$= 353.6$ in lb

$\tau_2 = 176.8$ in lb - 14.733 ft lb

11.05 lbs → 5 kg

$\tau_3 = 66.3$ in lb

$\tau_T = 397.8$ in lb

Arm torque balancing

$\frac{16 \cdot 1466.4 \text{ in.lb}}{\pi(.3357)}$ $\boxed{141.62 \text{ kpsi}}$

$SF = \frac{S_y}{\sigma_{max}}$ $\tau = \frac{Tc}{J} = \frac{\frac{TD}{2}}{\frac{\pi D^4}{32}}$

$\frac{(16)(122.2 \text{ ft.lb})}{\pi(.03125)^3}$ $\frac{32TD}{2\pi D^4} = \boxed{\frac{16T}{\pi D^3}}$

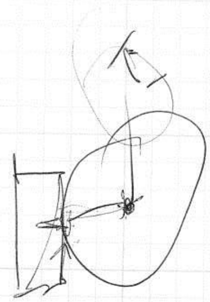
Gear shaft shear force calculation

$$\tau = \frac{V}{A} = \frac{FL}{R}$$

R = Dia Pitch

Moment = FL

$$\frac{FL}{R} = V$$



$$\tau = \frac{FL}{t\,w\,N}$$

length

number of teeth

width

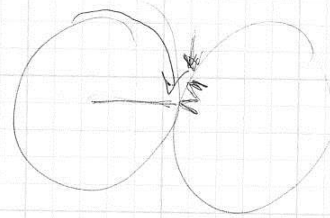
thickness

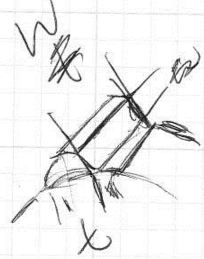
N = 4

L =

T = 152.75 ft lb

F =





Gear box hand calculations

Suspension calculaitons:

This model simulates the rover dropping from some height h and landing on only two wheels. Two wheels are used, because the rocker bogie design does not allow for less than two wheels to be in contact with the ground.

$h := .5m$

$g = 9.807\frac{m}{s^2}$

$Mwheel := 1.5kg$

$Mrover := 50kg - 2Mwheel$

$E := Mrover \cdot g \cdot h = 230.456J$

Work done by one suspension arm: Wsuspension. All weight is distributed between two wheels:

$Wsuspension := \frac{E}{2} = 115.228J$

Max displacement of the wheel: x

$x := .2m$

Verticle force per unit distance: k

$k := 2\frac{Wsuspension}{x^2} = 5.761 \times 10^3 \frac{kg}{s^2}$ (Newtons per meter)

Max force on chassis joint

$Fjoint := 2k \cdot x = 2.305 \times 10^3 N$

Acceleration on components:

$a := \frac{Fjoint}{2Mrover} = 24.517\frac{m}{s^2}$

Suspension Calculations

This model simulates the force felt by the wheel impacting a rock or some hard object, if all the velocity of the wheel is transfered upwards.

Maximum speed of the motor:

$Vmax := 2\frac{m}{s}$

$Ewheel := Mwheel \cdot \frac{Vmax^2}{2} = 3\,J$

$Wsuspension2 := Ewheel$

$x2 := \sqrt{2 \cdot \frac{Wsuspension2}{k}} = 0.032\,m$

$Fwheel := k \cdot x2 + \frac{Mrover \cdot g}{6} = 262.745\,N$

Impact forces

Climb a vertical wall

Motor output torque = 1.49 n·m

Gear ratio 48:1

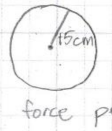
Ideal Torque output per wheel = $(1.49)(48)$

$= 71.04$ N·m

Actual torque estimate / wheel = $71.04\,(0.8)$

$= 56.83$ N·m

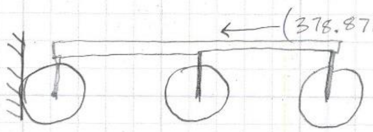
wheel



Thrust force per wheel = $56.83 / (.15)$

$= 378.87$ N

Friction coefficient = .65



Possible friction force = $(378.87)(4)(.65)$

$= 985.05$ N

Friction force required = $(25)(9.8)$

$= 245$ N

Safety factor = $\frac{985}{245}$

$= 4.02$

Thrust force needed per wheel = $(12.5)(9.8)$

$= 122.5$ N

Safety Factor = $\frac{378}{122}$

$= 3.1$

Vertical Friction Climb Calculations

NOV 18, 2013 — ALUMINUM HUB STRESS RESULTS — MT

KNOWN: $Y_S = 35{,}000$ PSI

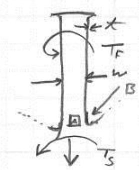
$T_F = 20$ lb/in

$T_S = 6.6$ lb/in

$P = 50$ lb

$A_c = .0937\ in^2$

$C = .375$



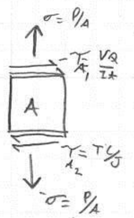
MAX STRESS IN HUB

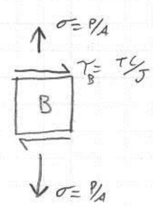
ASSUME:
- HALF ROVER WEIGHT ON ONE SPOKE
- MAX TORSION LOADS
-

PRELIMINARY

$J = (.999)(.75)(.0937)^3$

$= 6.16 \times 10^{-4}$ (1)





$\sigma = P/A = 50/.0937$

$= 533.6$ PSI (2)

$\tau_{A_1} = \frac{VQ}{It} = \frac{3}{2}\frac{V}{A} = \frac{3(6.6)}{2(.0937)}$

$= 211$ PSI (3)

$\tau_{A_2} = Tc/J = \frac{20(.0625)}{6.16 \times 10^{-4}}$

$= 2030$ PSI (4)

$\tau_B = Tc/J = \frac{20(.375)}{(.999)(.0625)(.0937)^3}$

$= 12{,}175.3$ PSI (5)

VON MISES

ELEMENT A

$\sigma_A' = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_x\sigma_y + 3\tau_{xy}^2}$

$= \sqrt{(533.6)^2 + 3(211+2030)^2}$

$= 3881.9$ PSI

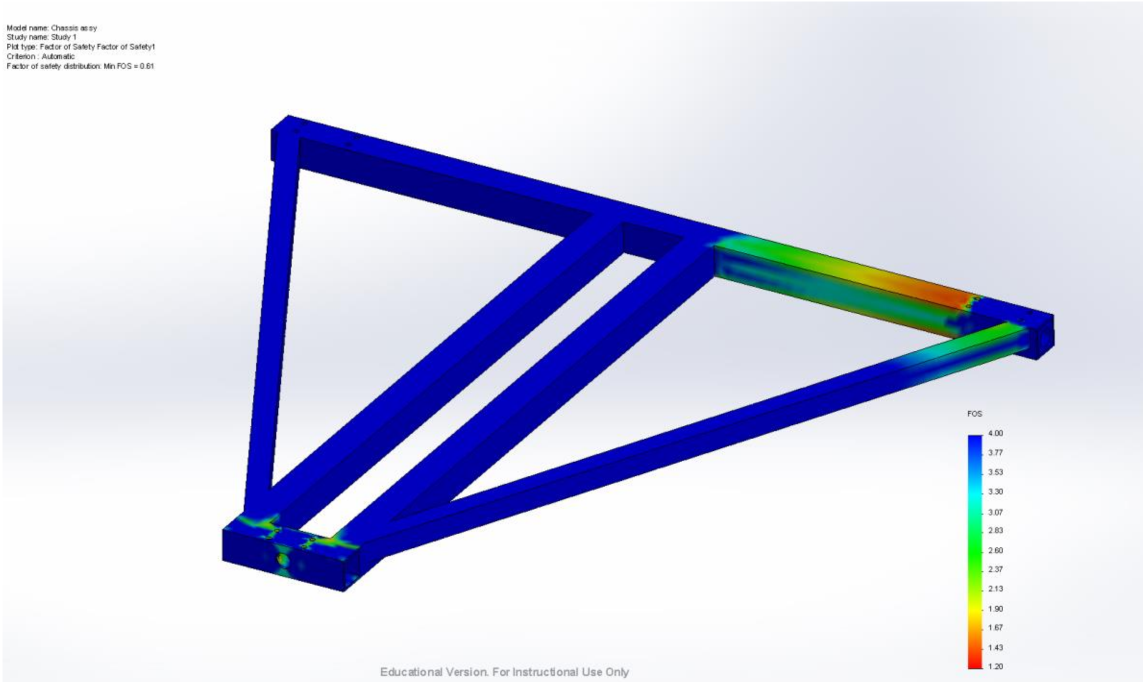
$\sigma_B' = \sqrt{(533.6)^2 + 3(12{,}175.3)^2}$

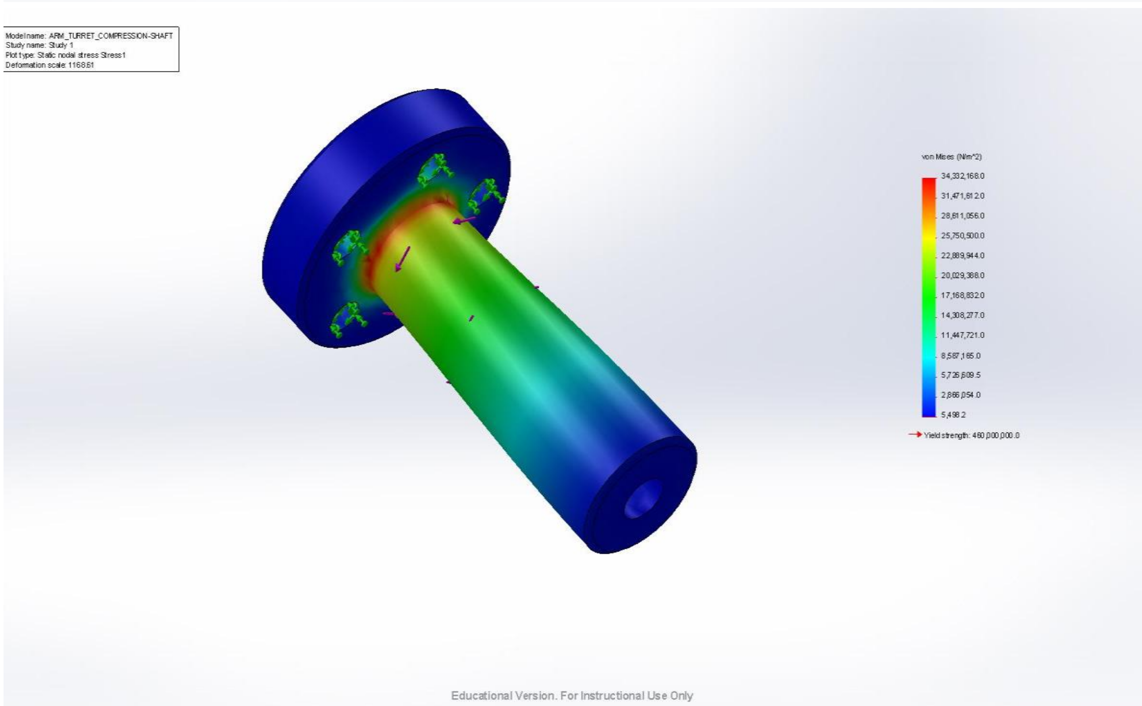
$= 21{,}095$ PSI

$n = \frac{S_y}{\sigma'} = 35{,}000/21{,}095 = \underline{1.659}$

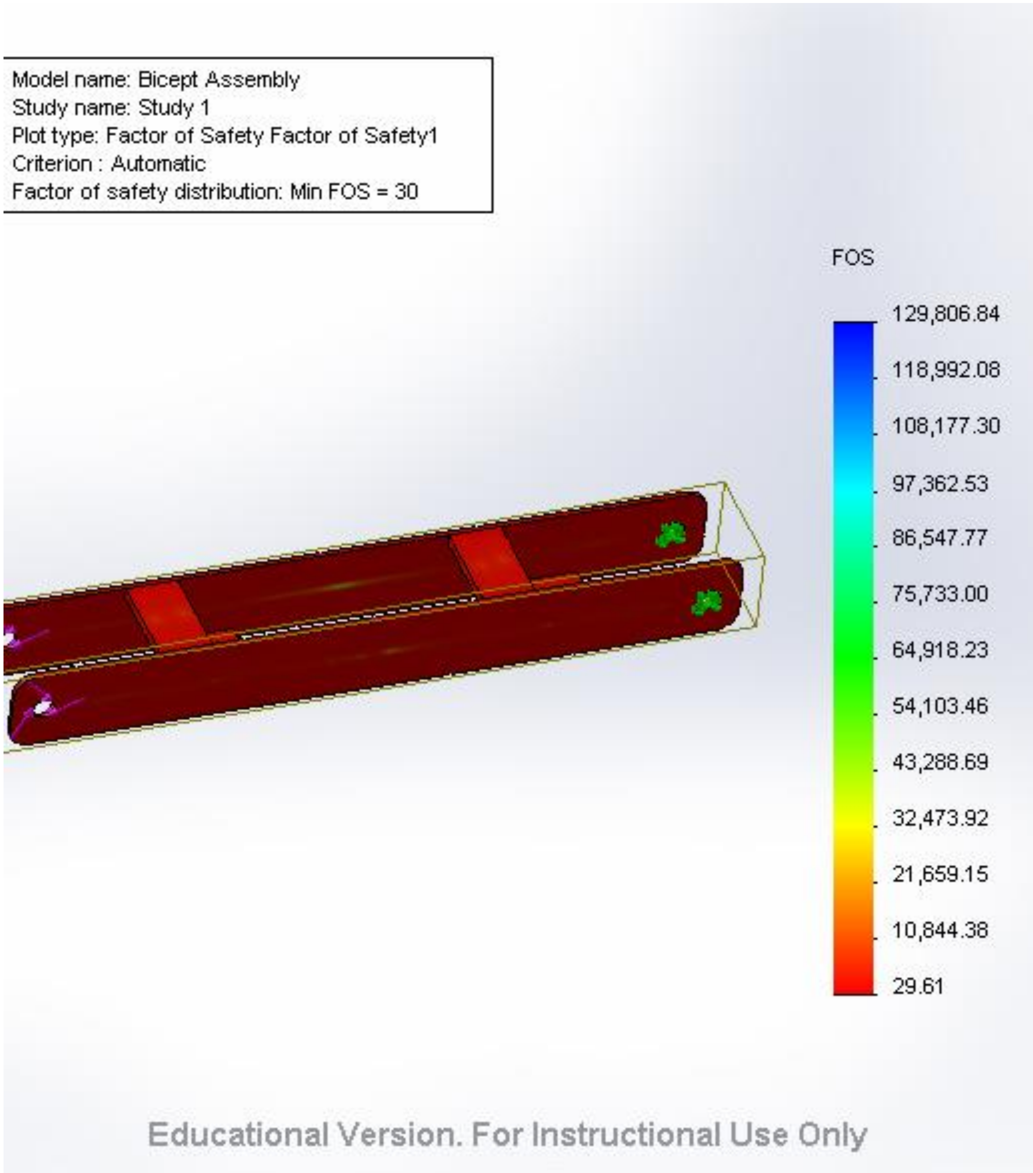
Wheel Stress Hand Calculations

C-2 FEA





Turret output shaft



Bicep links factor of safety

C-3 FMEA

Failure Modes and Effects Analysis

Prepared By: Drew Anderson, Devin Anderson, Clayton Grames

For product/subsystem: Rover Arm

Date: 10-24-2013

Component	Functional purpose of component	Failure Mode	Failure Effect	Failure Cause	Current Situation				Assigned Action	Improved Situation			
					S	L	D	RPN		S	L	D	RPN
Frame	support loads	structural failure	arm breaks	bending	8	2	8	128	Stress Analysis SF				
				shearing	9	1	10	90					
				brittle fracture	9	3	10	270	Control system practice				
				bolts shear	9	1	10	90					
	extend to target	limited range of motion	cannot reach the target	hard stops	5	2	4	40	Visual inspection				
				poor lubrication	4	1	2	8					
				interference due to frame	5	1	1	5					
	pivot	siezing of the joint	Can't pivot	cold welding	7	1	10	70					
				uneven loading	4	3	4	48					
Motors/Gearbox	move linkages to desired locations	slipping of gears	arm incapable of lifting loads	tolerance issues	7	1	3	21					
				Overloading	9	1	10	90					
		shearing of gears	fatigue	cyclic overloading	9	2	5	90					
		motor burns out	total incapacitance	overloading	9	1	10	90					
	provide necessary torque	wrong motor/gearbox	cannot complete tasks	design stage error	9	1	1	9					
Turret	rotate the arm	seizing of the joint	pre compressive load is too much	binding	8	4	8	256	Apply preload with torque wrench				
			doesn't move	tolerances	7	2	4	56					
				Sand in bearing	6	3	5	90					
				poor lubrication	6	3	5	90					
		comes apart	arm falls off	bolt failure	9	2	5	90	analyze tension on bolt				
	support overall arm and load	comes apart	center shaft fails	stress failure	9	1	7	63					
		bearings fail	tensile load on bearings	Small Pre compressive load	6	2	6	72					
		Belt breaks	arm rotates freely	tension is too high	9	3	4	108					
		Belt slips	inefficient rotation	tolerances	7	2	4	56	Belt Tensioner				

Failure Modes and Effects Analysis

Prepared By: Chris Mabey & Matt Titensor

Drive System

Component	Functional purpose	Failure Mode	Failure Effect	Failure Cause	Current Situation				Assigned Action	Improved Situation				
					S	L	D	RPN		S	L	D	RPN	
Wheel Rim	Support Rover	Weld breaks	Wheels out of round	Weld not strong enough	4	4	5	80	N/A					
		Rim cracks and fails	Wheels out of round	Material not strong enough	4	2	7	56	N/A					
	Provide Traction	Rubber delaminates	Loss of traction	Bond between rubber and rim not strong enough	6		5	0	N/A					
Hub	Transfer Load and power from rover to rim	Weld breaks	Rim comes free from rover	Weld not strong enough	8	5	6	240	Reinforce connections between hub and rim	8	2	6	96	
		Plastic breaks free from metal hub	Lose drive in one wheel	Bolt failure in hub connection	7	2	4	56	N/A					
Motor	Drive one wheel	Overcurrent/ Over Heat	Wheel locks up	Stuck Wheel	7	3	4	84	N/A					
Motor	Drive one wheel	Loss of Signal	Wheel locks up	ESC Failure	7	3	8	168	Reinforce Signal and Power lines to ESC	7	2	8	112	
Gearbox	Drive one wheel	Stripped Gear	Wheel locks up	Over Loaded Gearbox	7	3	4	84	N/A					

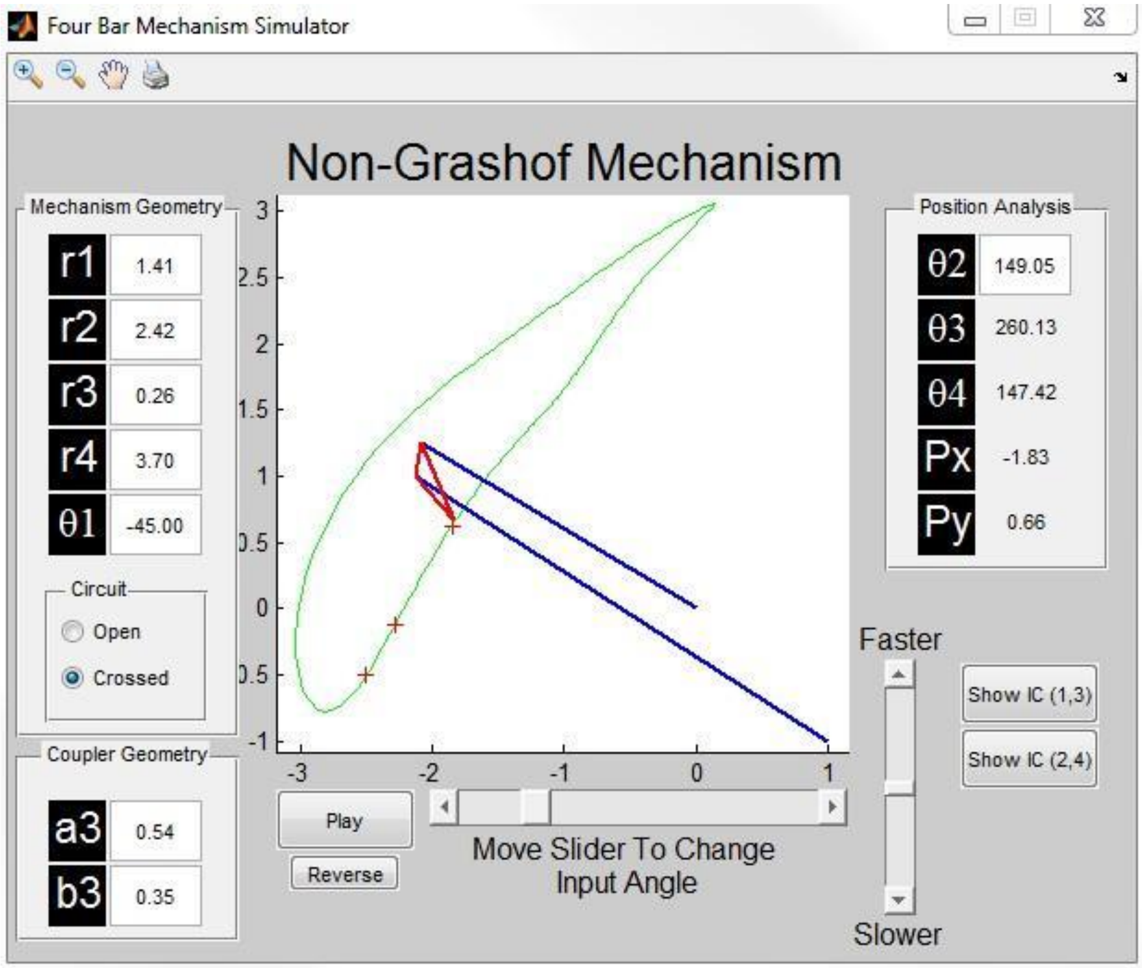
FMEA Table

Failure Modes and Effects Analysis — Prepared By: Kendal Frogget

For product/subsystem: Chassis — Date: 10/18/2013

Component	Functional purpose of component	Failure Mode	Failure Effect	Failure Cause	Current Situation				Assigned Action	Improved Situation			
					S	L	D	RPN		S	L	D	RPN
Frame	Bear load of all components	Bends or breaks	Rover can no longer function	High impact load, weak material	9	7	8	504	Develop chassis design to withstand high impact load	9	2	8	144
Rocker Joints	Articulate suspension to keep chassis displacement low	Seizes	Can disrupt shock absorption	Debris enters component. Heat.	7	1	8	56	no action	-	-	-	56
		Falls off	Disables rover	Bad connection	9	1	8	72	no action	-	-	-	72
Suspension arms	Absorbs impact loads	Breaks	disables rover	Weak Material. High impact load	9	3	8	216	Develop stronger suspension design	9	2	8	144

C-4 Other



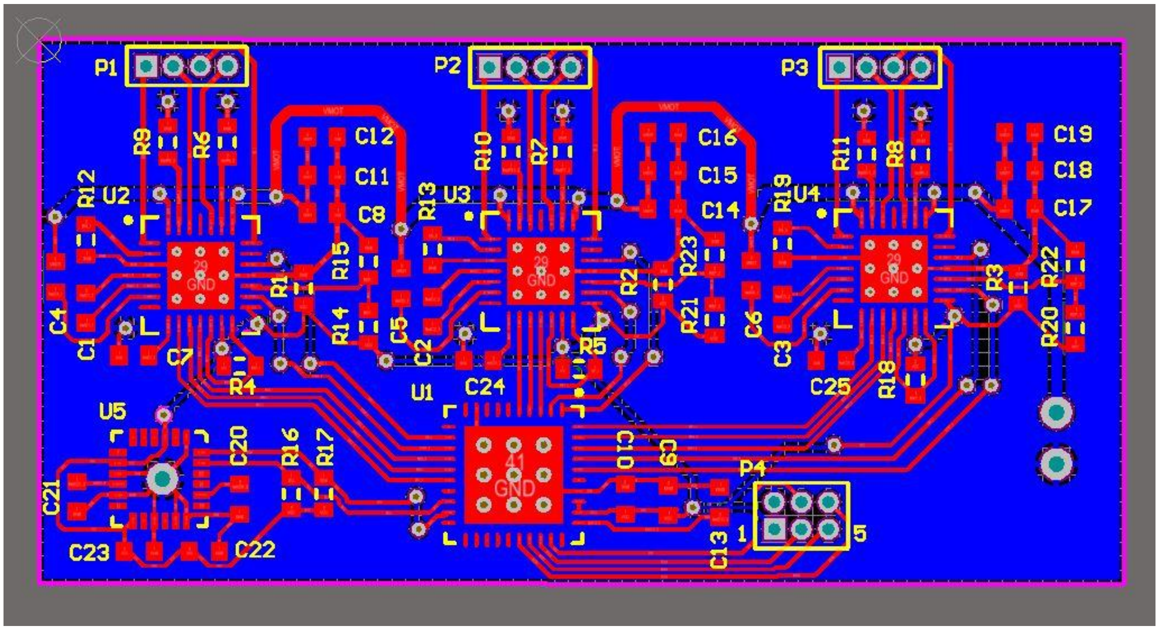
Kinematic synthesis for equipment servicing end effects

Requirement	Weight	Parallel Guided	Synthesized	Chebyshev
Push Buttons	0.15	3	2	2
Flip Switches	0.15	3	3	3
Turn Knobs	0.2	1	4	5
Manipulate Pipes	0.4	1	4	5
Read Instructions	0.1	3	3	3
Score		1.8	3.45	4.05

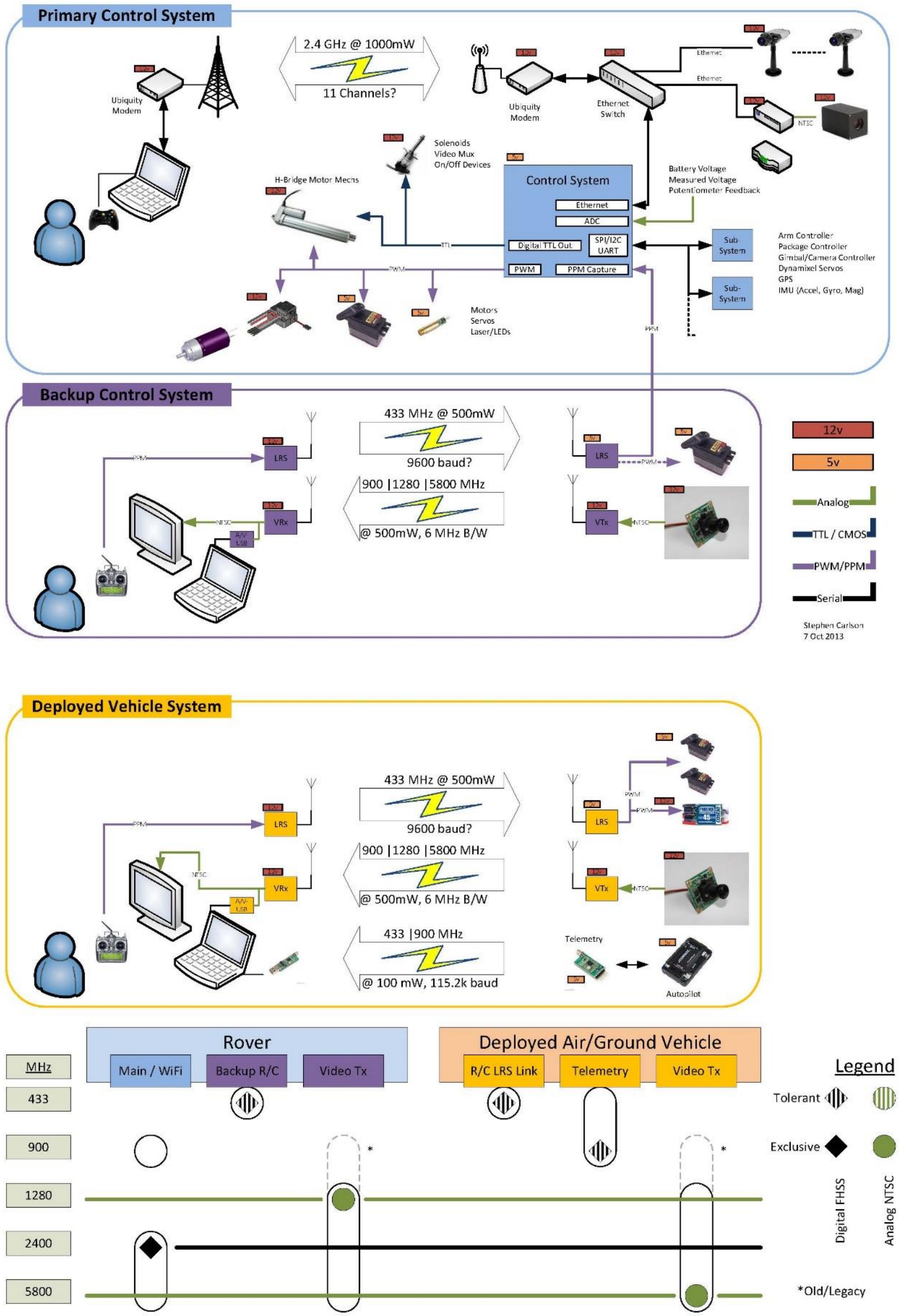
Decision matrix for equipment servicing end effects

Arm Link Material Choices	***Carbon Fiber Tube***	***Carbon Fiber Rails***	***Aluminum Rails***	***Round Al Tubing***	***Reference: Square Al tubing***
Strength	+	+	-	-	=
Weight	+	+	+	+	=
Torsion resistance	+	-	-	+	=
Ease of Mounting	=	+	+	-	=
Cost	-	-	+	=	=
Number of +	*3*	*3*	*3*	*2*	*0*
Number of -	*1*	*2*	*2*	*2*	*0*
Number of =	*1*	*0*	*0*	*1*	*5*
Total	*2*	*1*	*1*	*0*	*0*

Arm Link Material Decision Matrix: The above matrix shows the process we used to determine the material choice for the links of the rover arm. While this matrix suggests that we should use carbon fiber tubing, which was the ideal material we selected, the cost was a greater factor than the other requirements and made carbon fiber prohibitive. Consequently we are using aluminum rails in the final design.



Communications Gimbal PCB Layout



Rover Systems Block Diagram