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Development of a Humanoid Robot Arm for Use in Urban Environments

Brenton Noll
Bucknell University

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DEVELOPMENT OF A HUMANOID ROBOT ARM
FOR USE IN URBAN ENVIRONMENTS

by

Brenton A. Noll

(A Thesis)

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Approved: Steven B Shooter
Adviser

Charles W Kim
Department Chairperson

Engineering Thesis Committee Member

Keith W. Buffinton
Engineering Thesis Committee Member

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Abstract

The Bucknell Humanoid Robot Arm project was developed in order to provide a lightweight robotic arm for the IHMC / Bucknell University bipedal robot that will provide a means of manipulation and facilitate operations in urban environments. The resulting fabricated arm described in this thesis weighs only 13 pounds, and is capable of holding 11 pounds fully outstretched, lifting objects such as tools, and it can open doors. It is also capable of being easily integrated with the IHMC / Bucknell University biped.

This thesis provides an introduction to robots themselves, discusses the goals of the Bucknell Humanoid Robot Arm project, provides a background on some of the existing robots, and shows how the Bucknell Humanoid Robot Arm fits in with the studies that have been completed. After reading these studies, important items such as *design trees* and *operational scenarios* were completed. The completion of these items led to *measurable specifications* and later the *design requirements and specifications.*

A significant contribution of this thesis to the robotics discipline involves the design of the actuator itself. The arm uses of individual, lightweight, compactly designed actuators to achieve desired capabilities and performance requirements. Many iterations were completed to get to the final design of each actuator. After completing the actuators, the design of the intermediate links and brackets was finalized. Completion of the design led to the development of a complex controls system which used a combination of C language and Java.

1.0 Introduction

The world is quickly becoming more technologically advanced. It is beginning to rely more and more on robots to complete both simple and complicated tasks. The tasks these robots complete seem to be endless and can be seen in many fields such as manufacturing, military, police, and healthcare among others. [1]

Humanoid robots (robots with the combination of arms, legs and heads) are being further developed to be introduced into the world. They may not be fully incorporated into the everyday lives of humans, but particular fields will soon see a boost in humanoid robotics [2]. It seems like most will be used in military, police, and scientific studies or in situations where a robot can take the place of a human, eliminating the threat of putting a human into a hazardous environment. For example, bomb squads use robots to remove bombs from buildings and the military uses robots to search cars for Improvised Explosive Devices (IED). The main purpose of these robots is to allow a human, from a remote location, to control the robot. With this control, they'll be able to move the robot around and complete tasks using the vision platform and manipulators. The use of tele-operation in robotics is not a must but robots such as these take advantage of it.

The humans' ability to use its arms and hands to manipulate an object is extremely important in everyday life. The ability to mimic this ability is especially difficult when using robotics. Being able to grasp a piece of food firmly without crushing it, or simply to pick up a pencil and hold it properly are simple tasks for a human, but are rather difficult with a robot due to the lack of sensory inputs. Of course these senses can be mimicked with electronics, but it also increases the complexity of the robot.

1.1 Project Goal

The Humanoid Robot Arm project was developed in conjunction with the Bucknell University / Institute for Human and Machine Cognition (IHMC) Walking Bipedal Robot project. Figure 1 shows the biped.

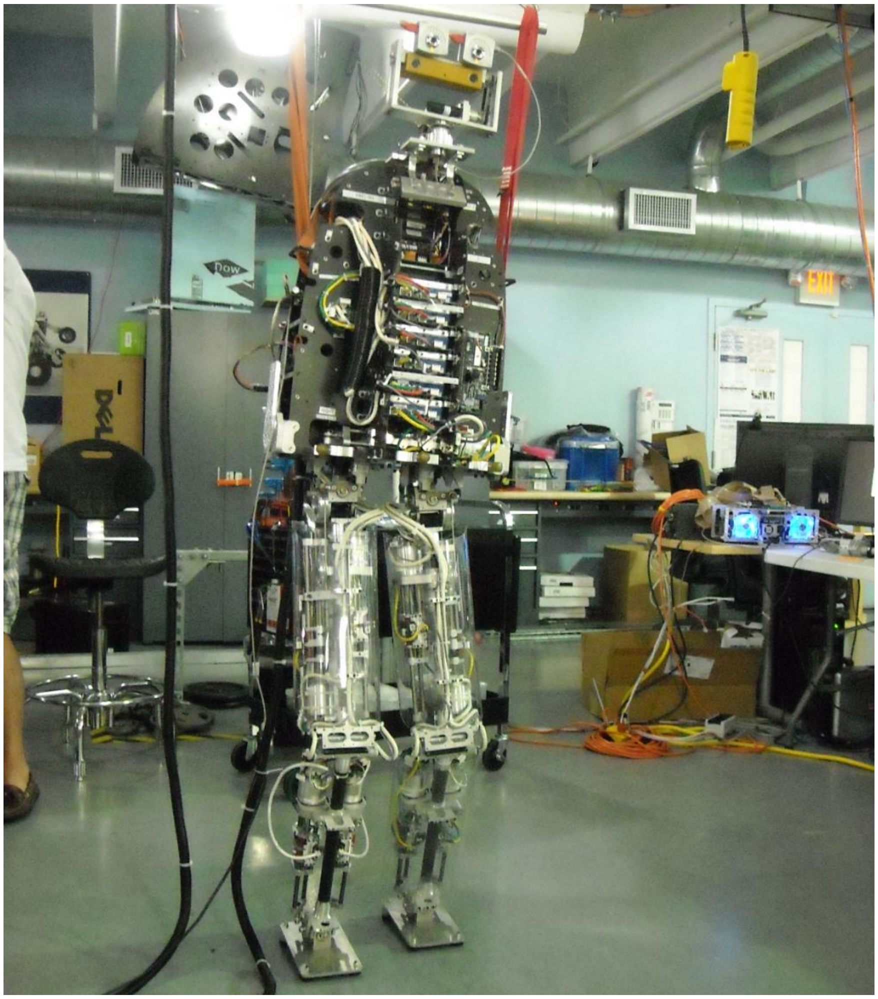

Figure 1: Bucknell / IHMC Walking Biped [5]

The overall goal of the Bucknell / IHMC Walking Bipedal Robot project was to develop a two legged walking robot that will be able to maneuver through complex urban environments where wheeled robots cannot [3] [4]. Being that urban environments were created for humans, the Bipedal Robot will be better suited, like a human, for the tasks it will encounter. Opening and walking through doors or fitting through tight spaces would be a rather difficult task for a wheeled robot to complete due to its bulkiness and lack of “agility”.

The current biped has 12 degrees of freedom. Each leg has three at the hip, one at the knee, and two at the ankle. Each of these joints is powered by SEA’s (Series Elastic Actuators). The biped has ability to walk slowly and is controlled by complex control algorithms that also act as a fall recovery or rebalance system [5]. In the future these algorithms, as well as the robot, will be refined to be more efficient and more robust [4]. The biped also uses a capture point system in order to know where to step next. This system also aids the balance recovery system [5].

Additional humanoid parts have been developed. A new foot design, which incorporated pressure sensors, was created in 2009 by a senior design group at Bucknell University. The foot was further developed to reduce the weight and improve the functionality of the design. Another part that was developed was the head, or vision platform, by another Bucknell University senior design group in 2010. The Humanoid Robot Arm is another addition to the Bipedal Robot platform. The arm will allow for the biped to complete small tasks such as open doors and move objects to complete an overall objective.

1.2 Literature Review

As stated before, robots are being used all over in industry, military, and healthcare. Robots are being developed to eliminate threats to humans, make jobs easier and in some special cases they are being integrated onto the human body for personal use [1][6]. This section discusses the many uses of robots starting with basic designs and ending with robots that are most related to the Bucknell Humanoid Robot Arm Project.

Starting with possibly the most simple are manufacturing robots. Robots being used to pick and place items have been used widely in manufacturing for 4 or 5 decades [1]. In manufacturing of cars, robots are used in almost every aspect of their assembly [1]. Robots can be more precise and accurate than humans as well. Jobs that could be done by humans, like machining of parts, are also being replaced by robots to increase job efficiency, part reliability and repeatability [1].

Robots are also being used to aid workers in assembly of cars. In order to move fully assembled items, like dash boards, workers use robots to move the dash boards into the car. Without the robot, the dash would have to be assembled inside the car where there is less space. With the robot, workers can assemble it outside where there is plenty. Being able to move the fully assembled dash directly into the car greatly reduces the amount of time and labor needed to complete that particular task. Figure 2 and Figure 3 show jobs similar to those discussed which involve robots. Robots improve product quality, reduce time and labor costs, and boost overall manufacturer profitability by incorporating the efficiencies associated with utilizing machines versus human labor.

Figure 2: GM workers aided in door assembly [7]

Figure 3: GM spot weld assembly line [8]

Other robots are used to eliminate the threat of bombs and can be used in situations where humans can't be present, such as an area that has a chemical or nuclear threat. The military calls these robots Unmanned Ground Vehicles (UGV) and are similar to a remote control race car. All input is given by a human from a remote location. Figure 4 shows a Foster-Miller Talon SWORDS UGV robot. It is able to travel in urban environments and has the ability to have weapons attached to it and has been used in Iraq and Afghanistan wars [9].

Figure 4: Foster-Miller Talon SWORDS [9]

Figure 5: General Atomics MQ-1 Predator in flight [10]

Robots are not only being used on the ground but in the air as well in the form of Unmanned Aerial Vehicles (UAV). For example, the General Atomics MQ-1 Predator, shown in Figure 5, is used to scout areas for enemy threats while at the same time, eliminating the possibility of a pilot being injured or killed. The MQ-1 Predator can view, engage, and fire missiles at a ground target all by the control of a human at a safe location. UAV are being used widely in Afghanistan and Iraq to eliminate enemy threats as well as inform ground troops of an enemy presence. [10]

All of these robots show the significance of the Humanoid Robot Arm project. Their similarities will help set a base for what technology is available and what steps are being taken to further develop robots. The Humanoid Robotic Arm project will use these developments, attempt to take them further, and hopefully improve them.

Figure 6 shows several aspects of robots that will be discussed and how they relate to the development of the Humanoid Robot Arm.

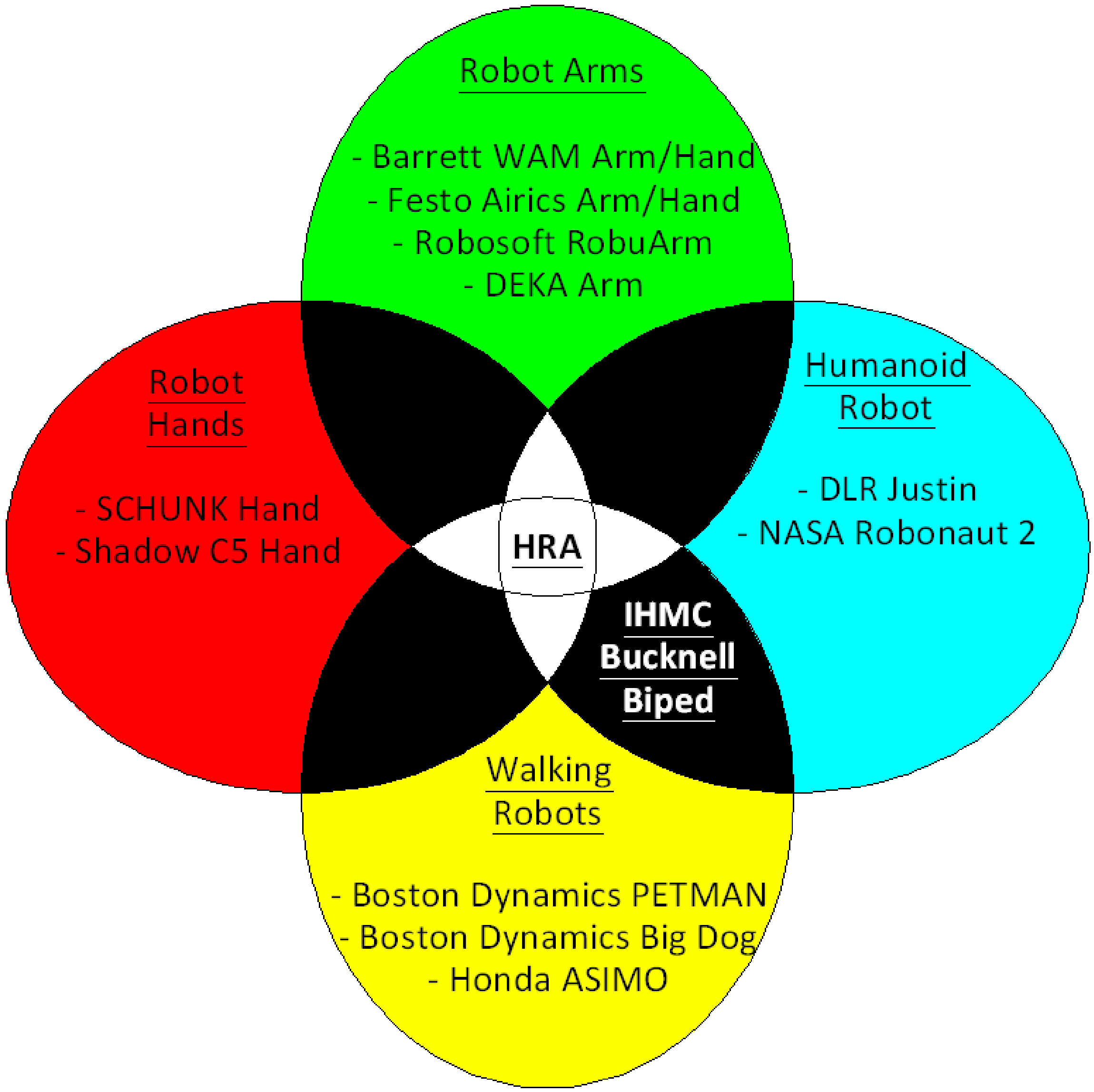

Figure 6: Humanoid Robot Arm Venn Diagram

Robot Arms

The development of robotic arms has been increasing due to improvements in the items used to create them. Improvements in things such as actuators and motors are allowing robotic arms to become lighter and more powerful [2] [11]. Innovations in sensors such as tactile sensors and force feedback are putting robotic arms one step closer to the abilities of a human arm [2]. Many arms exist on the market right now, but only a few will be discussed in the next section.

The first robotic arm discussed is the Robosoft RobuArm shown in Figure 7. The RobuArm was developed by Robosoft and was intended to be put on mobile devices. Robosoft also develops a gripper that can be attached to the arm for gripping of items. Compared to its weight of 88 pounds, the robot has a very low payload of 5.5 pounds. It has a very simple design with only three servos and three brushless motors [12]. The RobuArm is commercially available.

Figure 7: Robosoft RobuArm [12]

The Barrett WAM, shown in Figure 8, comes in two styles, one with four DOF (degrees of freedom) and the other with seven DOF. Both have very high dexterity and have a position repeatability of .3mm and .6mm respectively. It uses brushless motors along with a high speed, zero backlash cable drive system. With the hand attached it is able to grip and hold items weighing nearly nine pounds [13] [14]. Like the RobuArm, the Barrett WAM is also commercially available.

Figure 8: Barrett WAM arm [13]

Figure 9: Festo AIRICS arm [15]

Possibly the most human-like arms created would be the Festo Airics arm, Figure 9, and the DEKA Arm. The Festo Airics arm was developed to show how mechatronics and human anatomy can be combined. It uses Piezo proportional valves and 30 air muscles along with a human-like skeleton to control all of its movement. The Airics arm is also able to write as well as grip items. It is also shown in its videos lifting a small dumbbell [15].

The DEKA arm (DEKA is derived by using the first two letters of its founders full name Dean Kamen) shown in Figure 10, is a state of the art prosthetic arm built by DARPA **(**Defense Advanced Research Projects Agency) and DEKA under the lead of Dean Kamen [6] [16].

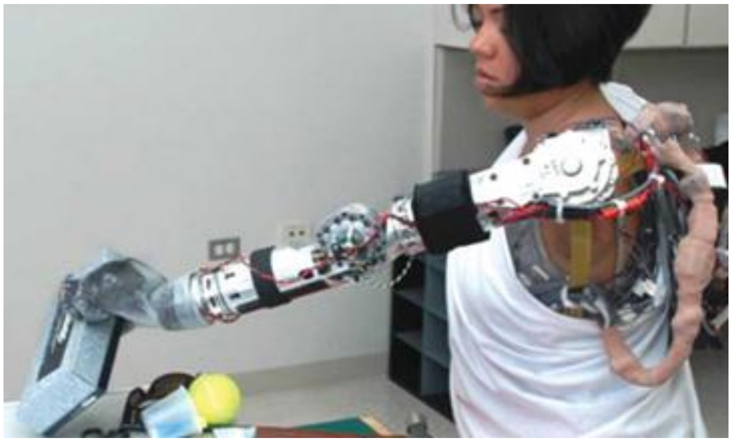

Figure 10: DEKA Prosthetic arm [6]

The arm was sponsored by the Pentagon and Department of Defense to develop a prosthetic arm for wounded soldiers coming home from the wars in Iraq and Afghanistan. When designing the arm, cost was not a concern. The DEKA team only used the best in materials, motors, actuators, sensors etc when making the arm [6] [16]. The result was an almost humanlike arm. For testing, patients were chosen to try the prosthetic arm. These patients were equipped with the prosthetic arms and had the sensors for the arm attached to their bodies. Electric signals sent to arm muscle nerve endings were detected by these sensors in order to control the DEKA arm [6]. After the sensors were connected to the correct muscle nerves, the patient could simply think about moving their arm and the prosthetic would move. A man that hadn't fed himself for many years was able to pick up a bowl and spoon and feed himself [6]. The DEKA arm compares so closely to the movement of a human arm and hand that it has 18 DOF's and a human has 22 DOF's. This made motor choice, circuitry and controls a very difficult area for the DEKA research group but the results of the DEKA prosthetic arm seem to be very promising for use in the future.

Robot Hands

Related to robotic arms are robotic hands. They make it possible for the arm to be able to manipulate an object. The SCHUNK hand, shown in Figure 11, is a three fingered robotic hand that has tactile sensors built into the finger tips and mid phalange.

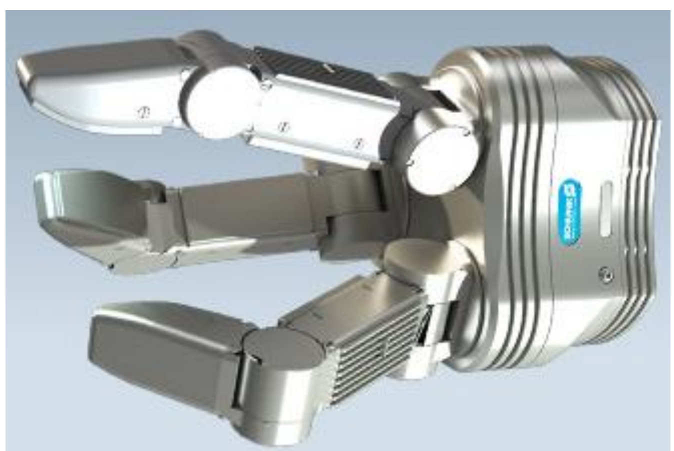

Figure 11: SCHUNK Dexterous Hand [18]

The three finger design allows the hand to hold many shapes like rectangles, spheres, cylinders and disks [17]. The hand weighs approximately 4.3 pounds. Although not very human-like, the SCHUNK hand could be used a lot on a robotic arm for everyday activities [17].

Figure 12: Shadow C5 [19]

The Shadow C5 hand, shown in Figure 12, is a five fingered robotic hand that has 17 degrees of freedom. Each finger has 3 DOF and the thumb has 5 DOF [19]. The hand is made up of many different materials including steel, aluminum, acetyl, and polycarbonate. The entire hand is moved by 20 motors which are connected to each joint of the hand. The Shadow C5 hand also has many sensors which include force and position. The C5 hand is very complex and weighs about 9 pounds.

Humanoid Robots

Most recently, advances in robots that mimic the upper torso of humans have been created [20]. This group and the following humanoid robot group are most closely related to the Humanoid Robot Arm project because they have humanoid arms.

Figure 13: NASA Robonaut 2 [21]

NASAs' Robonaut 2, Figure 13, is a humanoid robot used to aid astronauts in completing tasks outside of the shuttle and was developed specifically to be used in outer space. It has humanlike movement as well as humanlike strength [22]. Its hand has very high dexterity and can outperform a human hand when in a bulky space suit [23]. Despite having many motors in the arm and hand, 17 in total, the Robonaut arm is very light weight compared to other robotic arms of its size weighing in at 21 pounds [22]. The hand is able to grip tools and use them to complete tasks like repairs on a shuttle and the arm aids in lifting heavy items. Robonaut is controlled by an astronaut from a remote location using telepresence controls.

DLRs' Rollin' Justin, shown in Figure 14, is also a humanoid robot. Based on a 4 wheeled platform, Justin has the ability to carry objects as well as manipulate them with its hands [24] [25].

Figure 14: DLR Rollin' Justin [24]

Justin was developed to show the advances being made in robot arm control, particularly bi-arm control. Each arm has a creative design which keeps all the axes of the motors, like in a human, in line, making the controls system easier to program and control [25]. One arm weighs approximately 30 pounds and can hold slightly more than its own weight when moving slowly. At high speeds, the arm is able to move 15 pounds of weight. Justin also has a head which has a vision system incorporated [25]. This vision system allows for the interaction with objects and humans.

Other advances are being made in robots that walk. Boston Dynamics' Big Dog, shown in Figure 15, was developed to carry heavy equipment for military personnel and allows soldiers to carry more essential items [26].

Figure 15: Boston Dynamics Big Dog [26]

Big Dog is a 4 legged robot with a rather large load capacity of approximately 150 kg (330 lb) [26]. It is able to walk up and down hills and over complicated terrain like rocks and snow covered hills. It also has push and fall recovery which is demonstrated beautifully in a video shot by Boston Dynamics where Big Dog walks over ice and is able to recover after falling to a knee. (Shown at approximately 53 seconds: http://www.bostondynamics.com/dist/BigDog.wmv)

A newer approach to robots is becoming more popular. Bipedal robots are being created to mimic the walking and running abilities of a human [2]. Boston Dynamics has created a bipedal walking robot called PETMAN, Figure 16. Although tethered, it is able to walk and run [27].

Figure 16: Boston Dynamic PETMAN [28]

Figure 17: Honda Asimo [29]

A more interesting bipedal humanoid robot is the Honda ASIMO, Figure 17. It is able to run, walk, dance, move up and down steps, and more [29] [30]. Bucknell University and IHMC have created a bipedal humanoid robot and are continuing to improve its design.

1.3 Thesis Goals and Organization

The goal of the Bucknell Humanoid Robot Arm project was to develop a lightweight and compact humanoid robot arm to facilitate operations in an urban environment. The arm will be used with the IHMC Bucknell bipedal walking robot project. After successful completion of the robot arm, it will be able to accomplish predetermined tasks. Some example scenarios in which the robot arm will be able to operate within are discussed in Section 2.2 – Operational Scenarios.

The organization of this project was broken down into multiple areas of development. First was the literature review which consisted of researching existing robotic arms and robotic hands as well as existing technologies such as motors, actuators, transmission systems etc.

After completing the research, the initial design began. This consisted of coming up with multiple designs and weighing them against each other to find the design that best fits the needs of the robot. The overall arm design was broken down into individual joints. Each was made to be modular to allow them to be removed or replaced easily and leave the possibility of them being used on other robot platforms. Full drawings of each part of the arm were created using CAD software. These individual parts were then put into assembly drawings in order to eliminate any problems, such as clearance issues, that may be present.

After the drawings were completed, fabrication began. All off the shelf items, including motors, fasteners, wiring etc, were ordered. Then, the custom parts created during the design process were made in the Bucknell PDL. After all custom parts were made and other items were ordered, the robot arm was assembled and tested.

The testing process consisted of seeing whether or not the robot met the predetermined specifications and criteria discussed in Section 2.3 – Measureable Specifications. Figure 18 shows a tree of the process and order of how all of these steps were completed. Having this diagram gave a clear path for completion of the Bucknell Humanoid Robot Arm.

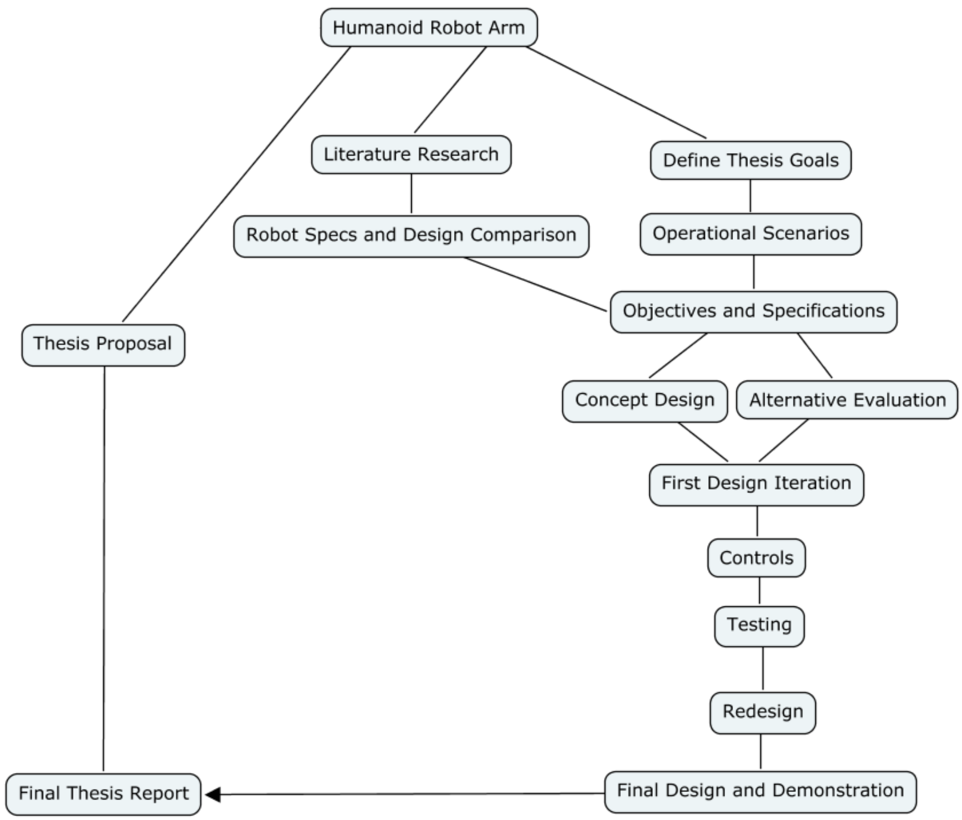

Figure 18: Development Tree

2.0 Design Objectives and Specifications

Before the design Bucknell Humanoid Robot Arm could begin, the overall objectives of the design had to be specified. By using things such as objective trees and operational scenarios, measurable specifications could be specified.

2.1 Objective Tree

The Humanoid Arm Project had many steps towards its completion. An objective tree was created in order to better understand the process of how it will be completed while at the same time obtain some measurable specifications for the robot arm itself. These various areas are shown by the tree in Figure 19.

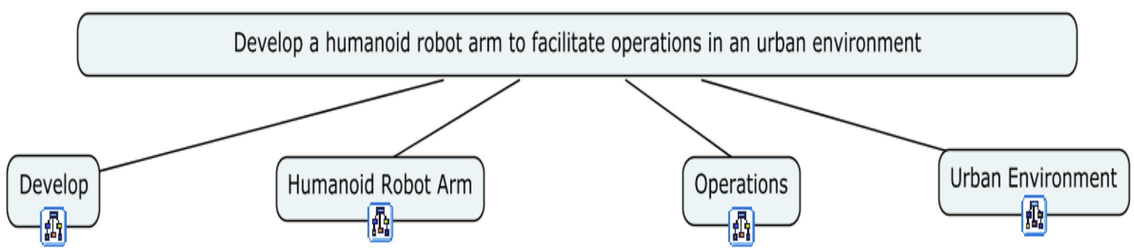

Figure 19: Main Objective Tree

Develop

The first area is the development stage of the Bucknell Humanoid Robot Arm. The development area is broken down in to various other areas. One of which is research. Shown by Figure 20, time was spent exploring existing robots and other technology to find what is the state of the art. The pros and cons of each were taken and compared. By comparing these pros and cons a design path was created for the Bucknell Humanoid Robot Arm.

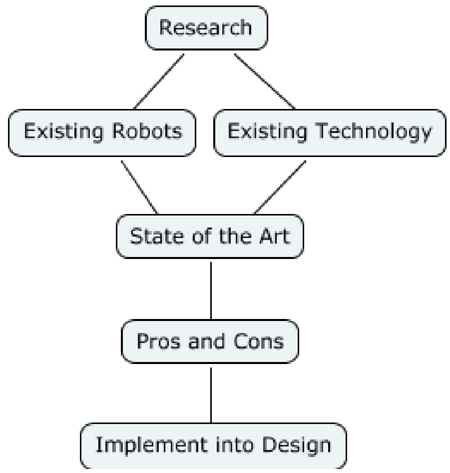

Figure 20: Research Tree

The Design portion of the development was broken down into the arm and hand. This allowed for a modular design of each part. The hand was designed by one of the 2011 Bucknell Mechanical Engineering Senior Design Teams. All information mentioned below was used in the development of the hand. Figure 21 shows the many parts that had to be designed. Three dimensional drawings were created to help visualize the full assembly while at the same time try to eliminate and problems before fabrication began.

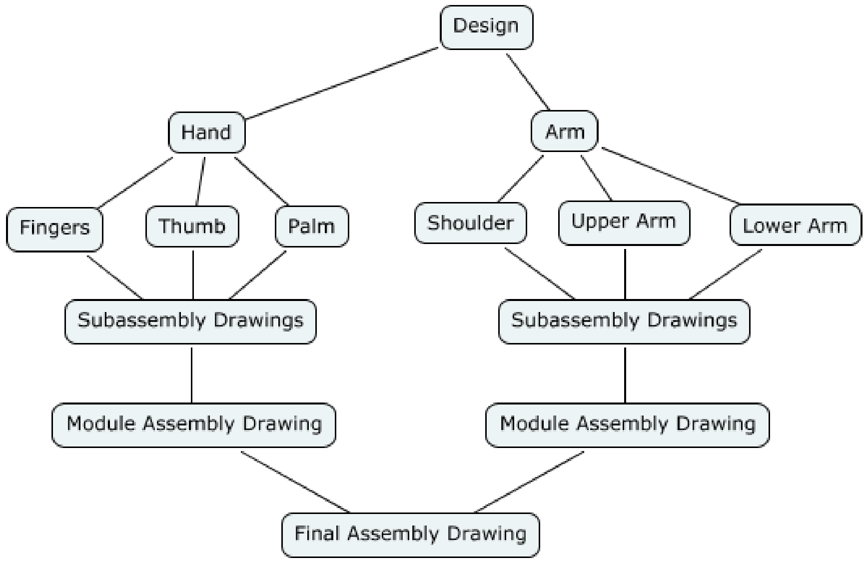

Figure 21: Design Tree

Fabrication, shown in Figure 22, was broken down into budget, custom parts and ordered parts. The custom parts were those that were created in the design portion of the development. Ordered parts included things such as motors, actuators, wiring, controller, fasteners, etc.

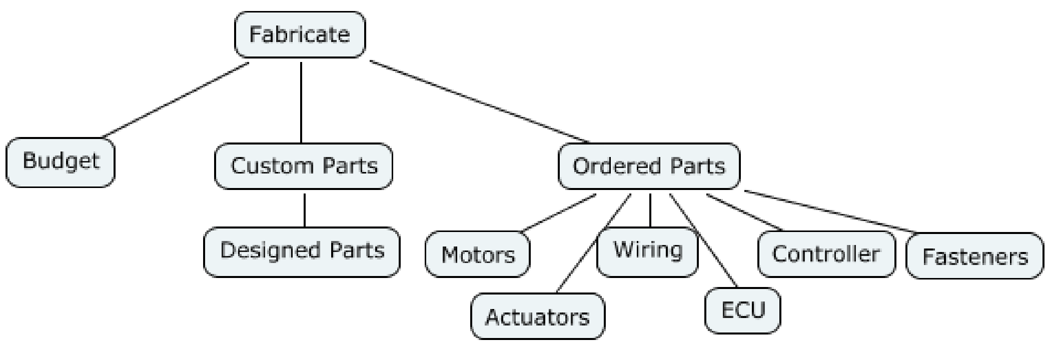

Figure 22: Fabricate Tree

Humanoid Arm

The State of the Art portion of the Humanoid Arm, shown in Figure 23, was dependent on the final design. When the final design was determined, the best parts were chosen. This helped the project demonstrate the use of state-of-the-art parts and technology as well as contribute to the development of these parts and the uses they may have.

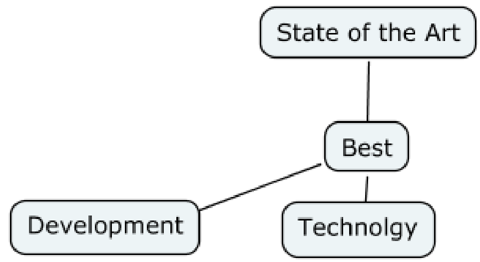

Figure 23: State of the Art Tree

The capabilities of the Bucknell Humanoid Robot Arm and Hand had a couple specified capabilities. Shown by Figure 24, the complete arm would be able to lift, grip, and manipulate objects. These items included tools and other similar objects.

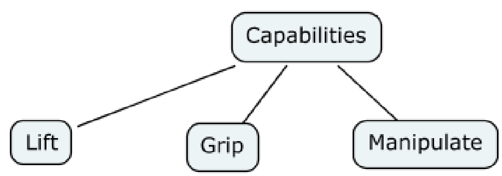

Figure 24: Capabilities Tree

Shown by Figure 25, the robot was broken down to show what the characteristics of the robot would be. The robot will be humanlike with and arm and a hand. Both the arm and hand are modular which means both are easily removed or attached. This also means they will have a bracket that will allow them to be attached to other arms or platforms.

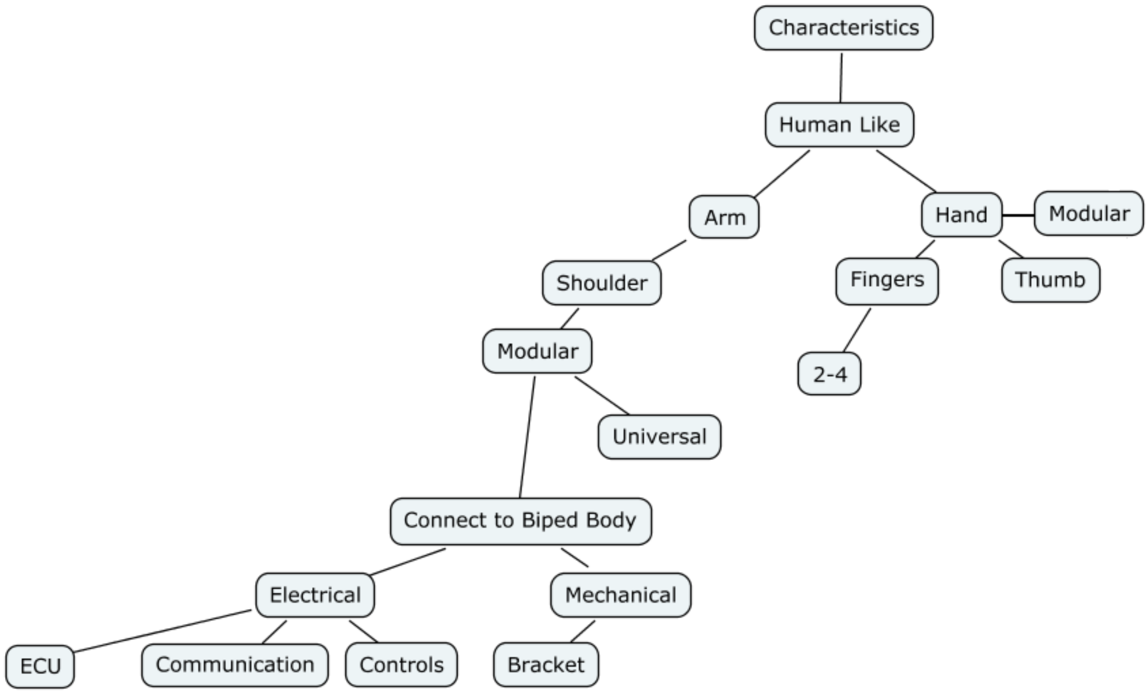

Figure 25: Characteristics Tree

The hand will have a thumb and two to four fingers. These fingers will have to have motors or be actuated in some way. The thumb will be the same. The arm will have a modular shoulder that will connect to the biped body via a bracket. The electrical system will be based near the top of the arm in order to eliminate and unnecessary moments on the arm.

Operations

The operations of the Bucknell Humanoid Robot Arm will be discussed more in depth in Section 2.2– Operational Scenarios.

Urban Environment

The biped robot will be used in urban environments, so it is only appropriate to place the Bucknell Humanoid Robot Arm in the same environment. An urban environment has a dense human population like in a city. A city has buildings with people, stairways, doorways, furniture etc. that the robot will be faced with. The Bucknell Humanoid Robot Arm had to be able to handle these types of obstacles. The characteristics tree is shown in Figure 26.

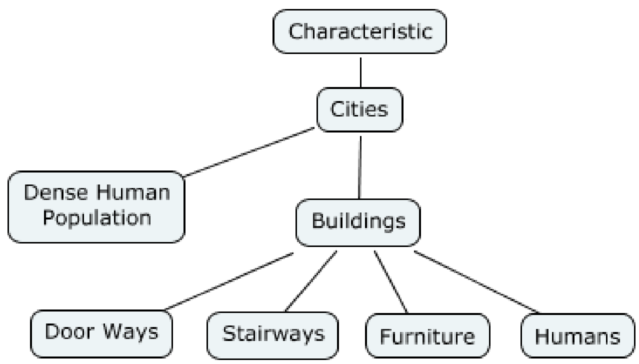

Figure 26: Urban Environment Characteristics Tree

2.2 Operational Scenarios

There are many scenarios in which a robot can be used. As a start to this particular project, the Bucknell Humanoid Robot Arm would be usable in some situations, later described, that a human would face. The scenarios described below are not the only scenarios the arm would be faced with, but rather a short list of examples. These scenarios were later used to define the design-measurable specifications such as motor torques, load capacity, wrist torque, and hand grip force.

Scenario #1 - Robot Must Retrieve a Box from the Second Floor of an Office Building

The building is in an urban environment. Inside the building are obstacles such as doors, tables, stairs etc. These obstacles must be passed by the robot in order retrieve the box on the second floor.

The robot enters the building by opening the main door. Opening the door is aided by its visual system as well as its robotic arm and hand. Entering the building, the robot enters a hallway. After moving down the hallway it travels to another door in which it has to open. Aided by its arm and hand, the robot opens the door. The robot travels up the stairs, and if needed, uses its arm to aid in balancing by holding the railing. It reaches the top of the steps and opens a third door, again aided by its arm and hand. Entering a second hallway, the robot meets a new obstacle. A cart has been left in the hallway and needs to be moved. The robot uses its arm and hand to grab and push the cart out of the way. It continues down the hall to the office where the box is located. The robot opens yet another door to enter the office. Inside, the robot finds a table with several boxes on it. The robot grabs each box to identify the proper box. After finding the correct box, the robot continues out the office door, down the steps, and exits out the front door.

<u>Scenario #2</u> – Robot Must Retrieve a Small Explosive Device from Inside a One Floor House

The house is in a rural environment. The robot must travel past obstacles found in most houses to retrieve the explosive device. The device is located in a bedroom at the rear of the house. The robot is being used as a bomb squad aid.

The robot enters the house by opening the front door using his arm and hand. He enters the living room of the small house and is faced with chairs and a couch. It makes it way past these obstacles being sure to recognize and avoid them. The robot moves down a narrow hallway towards a bedroom door and opens it using its arm and hand.

Inside the room is a bed. The robot walks around the bed, again recognizing is presence as well as avoiding contact with it. On the opposite side of the bed the device sits on a stand. The robot uses its arm and hand to pick up the small device. From there, the robot moves outside bypassing all previous obstacles. All humans are clear from the area as this eliminates the threat of possible injury. The robot places the device in an explosive container. The bomb squad moves in to remove the explosive container.

<u>Scenario #3</u> – Robot is Used to Retrieve a Series of Wrenches

The robot is expected to be able to recognize, pick up, and deliver a series of tools to a human.

The robot is helping a human with getting tools. The human requests a 1/2" wrench. The robot moves to the tool box, grabs the handle, and pulls open the drawer. Inside are a group of labeled wrenches. The robot looks for the 1/2" wrench and finds it. He grabs the wrench with his hand and shuts the drawer. The wrench is then delivered to the human. The same process is taken for three more wrenches of various sizes: open tool box, find wrench, grab with hand, close drawer, and deliver to the human.

2.3 Measureable Specifications

The operational scenarios show many actions and movements the robot arm needs to be able to complete. Being able to grip, push, pull, move, and manipulate are all very important attributes the robot arm must possess. From the scenarios, different measurable aspects were found. Below are the specifications the robot arm and hand were supposed to meet.

Robot Arm

Most of the movement the robot arm will be doing will be used to push, pull, and lift. From Scenario #1 and Scenario #2, the robot is expected to open a door. Testing was completed, using a spring scale, to find a common pulling force to open a door. Each door had the spring scale attached to its handle and was pulled. The highest force seen was recorded. All pulling forces were similar and found to be between nine and eleven pounds (40 to 49 N).

Scenario #1 and Scenario #2 also required the robot to pick up an object. Due to most tools weighing no more than a one or two pounds at the most, a payload of five pounds was found to be an acceptable amount of weight. Compared to the amount of force required to pull a door open, the final payload looked likely to be higher than five pounds.

Scenario #3 offers a different obstacle. The robot is expected to open a tool chest drawer. Testing was done, again using a spring scale, and the results showed a pushing and pulling force of ten pounds (45 N) for a large tool chest drawer. A desk drawer was also tested and the result was 3.5 pounds (15.75 N). Another obstacle confronted was lifting wrenches. Testing of various tools, including a hammer, vise grips, large crescent wrench, 7/8” wrench, and a large screwdriver, was also conducted. The weights of these tools, in the same order, are as follows: two pounds (9 N), one pound (4.5 N), one pound (4.5 N), ¾ pound (3 N), and ½ pound (2 N). All the tools are very light and are minimal compared to the forces needed to open a door. All of these forces are minimum forces needed to complete a task. A factor of safety will be implemented to ensure these tasks are completed.

Robot Hand

Similar to the arm, the scenarios previously discussed in Section 2.2 allowed conclusions to be drawn about the specifications the robot hand should be able to meet. Scenario #1 and Scenario #2 helped decide the wrist torque specification. Testing found that a torque of 2 ft-lb (2.8 Nm) was needed to rotate a door knob in order to open it. Using a lever arm of a known length attached to the door handle, a spring scale was attached and the force required to fully rotate the handle was recorded. This force and known length were then used to calculate the torque required to open the door knob or handle.

The last thing that needs to be discussed, which not only involves the hand but the arm as well, is the motion to open a door. Because the robot, at this point, will only have one arm, the motion to open a door with one arm is rather complicated. When a human opens a door with one arm, the door handle is twisted, and the door is in essence thrown back towards them. This throw allows for just enough time to get the hand to the other side to prevent it from shutting. This complex motion seems to be elementary for a human but for a robot could prove to be rather hard to mimic.

With the design objectives and specifications specified, the design of the Bucknell Humanoid Robot Arm began. The values found in the Measurable Specifications section were used throughout the entire design process to find things such as the power and torque at each joint of the arm.

3.0 Design Process

The process gone through in order to select a proper or optimum design for any robot can be very extensive. In the case of the Bucknell Humanoid Robot Arm, balancing strength requirements and maneuverability with the requirement of a lightweight robot arm posed many challenges. Design requirements along with design specifications had to be determined before any other steps could be taken.

A simulation was created using a simple arm design that would give a basis for the final arm, which is discussed in the following sections. This simulation gave results for torque and power outputs for each joints motor and in turn allowed for the proper selection of motors. With these numbers in hand, several ideas for arm layouts were developed. From there, a final design was chosen, designed, and refined.

3.1 Design Requirements and Specifications

In order for the robot arm to be considered successful it would have to meet the chosen requirements and specifications set by both the IHMC and Bucknell University robotics teams. These requirements and specifications were refined using the Operational Scenarios discussed in Section 3.2. The requirements that were set forth are as follows. The robot arm must:

- Be able to open a door
    - This is important for use in urban environments. Every urban environment has doors and the robot will most definitely come across a door and therefore should be able to open one.

- Be able to lift small objects such as tools, boxes, etc
    - This is also an important requirement. The robot needs to be able to lift objects in order to complete tasks such as those discussed in the operational scenarios.
- Be as lightweight as possible
    - The robot arms' whole basis is built around weight. Compared to if it were heavier, being lightweight would allow the arm to use less power while at the same time lower the power requirements of the main torso.
- Look humanlike
    - The arm will be put onto a humanoid robot which was built to resemble a human torso and legs. Therefore it would only be appropriate for the arm to also look humanlike.

Table 1 below shows the design specifications.

Table 1: Bucknell Humanoid Robot Arm Design Specifications

Design Specifications		
Specification	Desired Value	Justification
DOF	4	4 DOF would allow the arm to move to almost any position desired. The joints would have to be in the correct orientation in order to achieve this. More DOF would allow the arm to move to more positions but would also increase the overall weight of the arm.
Position Accuracy @ the end effector	<1"	This number was chosen by looking at an object, closing one's eyes and then reaching for the object. From the results, it was shown that a person can still effectively grab the object without any problem. With the high resolution encoders available, this number should be highly achievable.

Max Speed @ each joint	7.5 RPM	This number was chosen by timing how long it took to reach out, grab and object, and return to the previous position. Also, it was chosen by timing the amount of time it took to rotate from beside the leg to above the head.
Total Length	22.75 in	Length of a human arm outstretched from shoulder to wrist for an average male being 5’9”. [31]
Max Weight	<15 lb	The average human arm weighs approximately 8 lb. Being that the BHRA will be made of materials such as aluminum and carbon fiber it will be relatively light until motor and gears are added which include materials such as steel and copper. Comparing to other robotic arms, some of which are very heavy, 15 pounds was a reasonable weight to try to achieve. [31]
Max Load Outstretched	5 lb	Most tools, which include heavier tools like hammers, weigh no more than 5 pounds. This seemed like an achievable weight as well as a reasonable weight to be able to lift.
Max Load-to-Weight ratio	0.33	Comparable to other robotic arms on the market. (See Literature Review: Robot Arms)

With all of the design requirements and specifications set, further development of the arm was able to occur.

3.2 Robot Arm Simulation

Before making the simulation model, several layouts were discussed to decide which would be the best layout for the robot arm. These models can be seen in Figures 27, 28, 29 and, 30. Discussions were conducted among the team about how many DOF would be needed and if adding more would be beneficial to the robot arm. Adding more DOF would increase the arms ability to reach certain points, but in the end would add more weight to the arm. By creating a model that was more closely related to the final design, the simulation would be more accurate.

Figure 27 shows the simplest layout of all, Layout 1. It is a 3 DOF arm with two points of rotation at the shoulder and one at the elbow. After exploring this design, it was found that this layout would not provide enough motion for the arm to reach the needed points physically or in the correct orientation. It was eliminated from the possible layouts.

Figure 28 and 29, Layouts 2 and 3, were very similar in their designs. Layout 2 has all of the joints rotated 90 degrees to each other starting at the shoulder while Layout 3 has all of them rotated 90 degrees to each other except for the elbow joint being in the same plane as the joint before it. Although both layouts had 4 DOF, one more than Layout 1, neither of them created the desired motion nor did they look very human-like because the arm had to move to strange positions to reach certain points.

Layout 4, Figure 30, is basically Layout 1 with a rotation added to the mid upper arm. With this DOF added, it not only looked human-like, but also created the desired motion needed to complete the previously discussed operational scenarios. This was the chosen layout for the simulation model. Further refinement was done to make the arm more efficient and look more human-like. The final simulation layout can be seen in Figure 31. The final layout created two important positives compared to the other layouts. It allowed the shoulder motors, 3 DOF, to be at the top of the arm. Using hand calculations, this reduced the motor requirements substantially because there would not be the extra moment from motors being further out from the shoulder. Instead, it would only be lifting the elbow joint and the mass at the end of the arm.

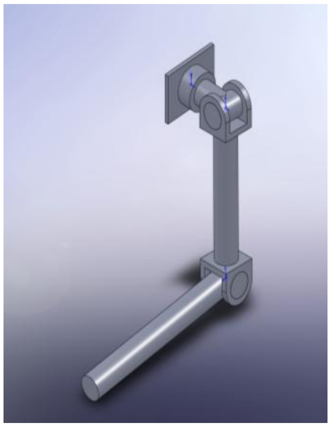

Figure 27: Layout Option 1

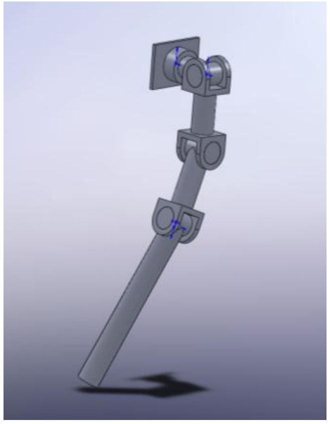

Figure 28: Layout Option 2

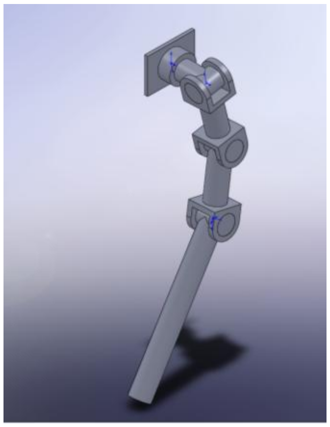

Figure 29: Layout Option 3

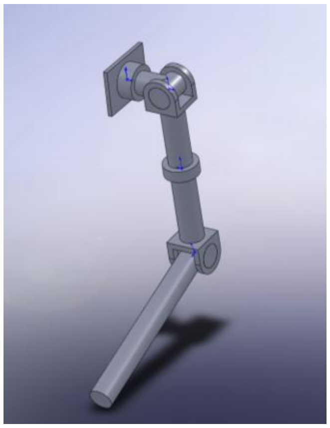

Figure 30: Layout Option 4

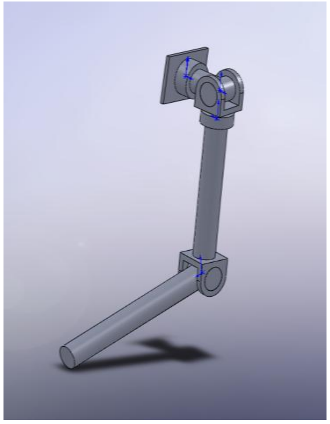

Figure 31: Simulation Model

With the base model created, the simulation of the Bucknell Humanoid Robot Arm was created using Yobotics Simulation Construction Set (SCS), which was developed by several members at IHMC. Many robotic simulation software programs exist such as Microsoft Simulation Studio, RoboLogix, and Webots but because Bucknell was working with IHMC to develop the Bucknell Humanoid Robot Arm and SCS was used to develop M2V2, Yobotics SCS seemed like a good simulation software package to use. Yobotics SCS is a Java based program that allows for very accurate robotic simulations to be created and torque, power, and motion analysis to be done.

First, Yobotics SCS was used to get a basic simulation model. This was done by using link lengths from the Solidworks model, shown in Figure 32, created to get a basis for the rest of the simulation. The joints and links were created with masses larger than the estimated final masses to get a good starting point for finding motor masses. The Yobotics SCS model can be seen in Figure 33.

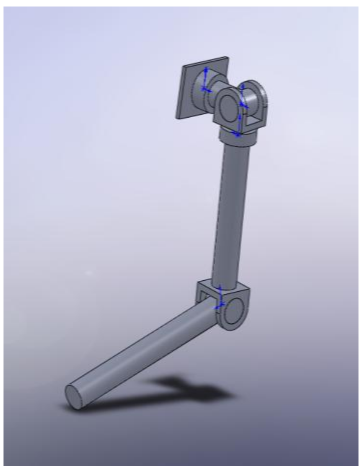

Figure 32: Solidworks Model

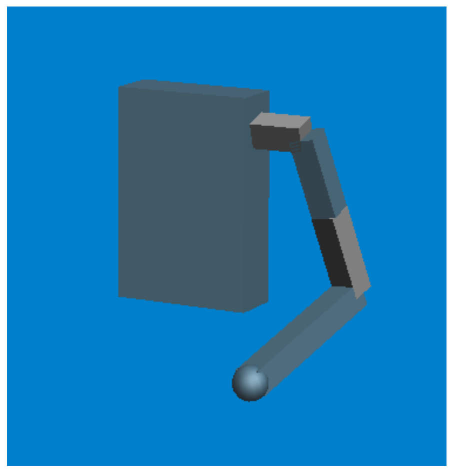

Figure 33: Yobotics SCS Model

Using Yobotics SCS, torque and power values for each link were obtained. To get these values, much iteration was done. These iterations started at the elbow and worked their way up to the shoulder. While creating the simulation coding, erratic behavior was observed while the arm was moving. Torque and power numbers were very high and would oscillate when the desired position was reached even with very high PID (Proportional, Integral, Differential) gain values. It was discovered that gravity compensation had to be built into the simulation code for the arm. Gravity compensation was then built into the code and the erratic behavior was eliminated giving smoother torque and power curves. With the simulation working properly, it was believed that solid numbers could be obtained from it. The simulation code can be found in Appendix A: Simulation Code, as well as in the Bucknell Urban Robots netspace. (P:\UrbanRobots\private\Nick's Summer Work\Simulations\ArmFirstAttempt\Arm1\src\armstuff)

Each joint had a requirement of moving at 7.5 RPM which allowed the simulation to find power values. With that in mind, motors that met the requirements for torque, speed, and power were selected. Using motor masses in the simulation, the torque requirements of the joints were recalculated. The final required values for torque, speed, and power are shown in Table 2: Torque and Power Values Found from Yobotics SCS.

Table 2: Torque and Power Values Found from Yobotics SCS

Joint	**Torque Required**	**Speed Required**	**Power Required**
Shoulder (3)	41 Nm (32 ft-lb)	.78 rad (7.5 RPM)	42 W
Elbow	16 Nm (12 ft-lb)	.78 rad (7.5 RPM)	21 W
Wrist	5 Nm (1.5 ft-lb)	.78 rad (7.5 RPM)	6 W

Figure 34 shows a screenshot of the Yobotics SCS software and torque graphs of each joint.

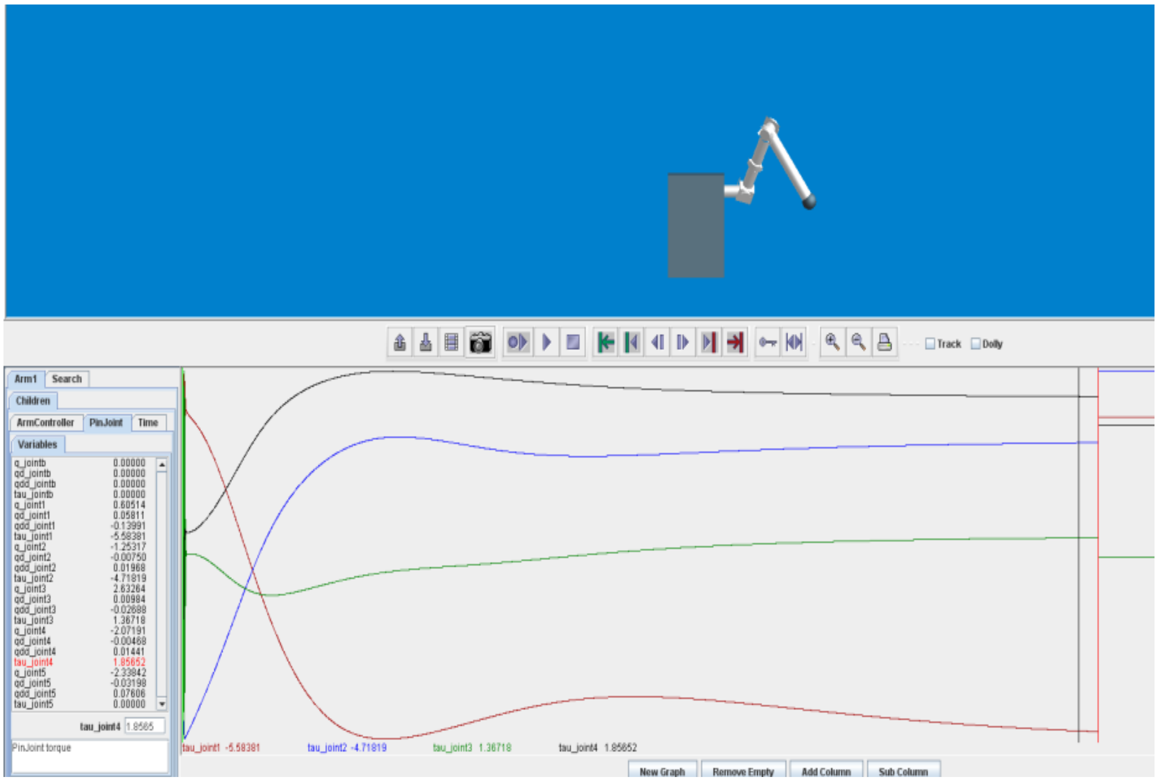

Figure 34: Yobotics SCS showing Torque Curves

In parallel to SCS, Working Model was used to check the numbers that were calculated by the simulation. This was done to ensure the numbers were accurate. In Working Model, the lever arm was given a velocity to reach and torque and power values were obtained. An example can be seen in Figure 35. Comparing the numbers from each program, it was found that the values calculated using SCS matched those found in Working Model. These numbers were checked again by changing masses in the simulation as well as Working Model and similar numbers, again, were found between the programs verifying the accuracy of the simulation.

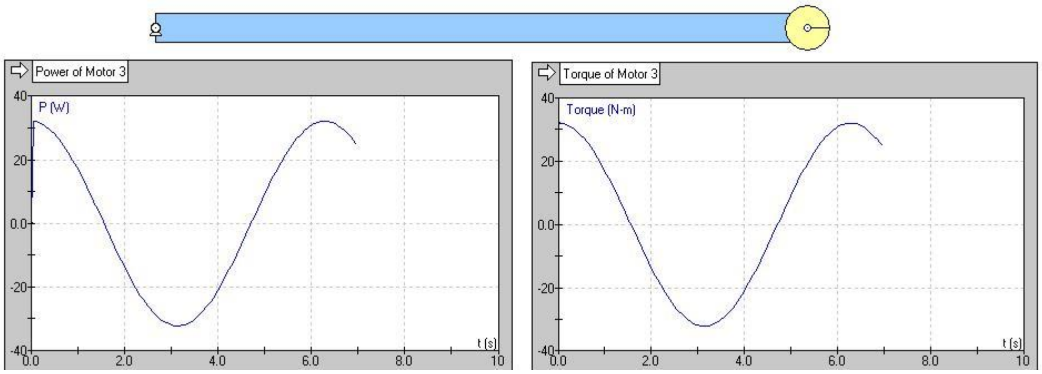

Figure 35: Working Model Analysis

Table 3: SCS to Working Model Torque and Power Comparison

Joint	**Torque SCS**	**Torque WM**	**Power SCS**	**Power WM**
Shoulder (3)	41 Nm	~ 40 Nm	42 W	~ 42 W
Elbow	16 Nm	~ 15 Nm	21 W	~ 20 W
Wrist	5 Nm	~ 5 Nm	6 W	~ 6 W

After validating the simulation, motor and gearing options were researched. This was done in order to obtain estimated joint masses for use in the simulation. By using these masses in SCS, more accurate joint torque and power requirements were found which further refined the arm design. When the motors and gearing were chosen, a factor of safety (FOS) of 1.5 was applied to ensure the joints had ample power and torque. Along with the FOS of 1.5 was an artificial FOS that could be found in the oversized link masses in the Solidworks model. This process was done over and over until "optimum" torque and power values, values that changed minimally after arm refinements, were found.

3.3 Arm Alternatives and an Evaluation of Each

The requirements of the arm state that a lightweight arm, which weighs less than 15 pounds, is to be built with max load-to-weight ratio of at least 0.3 and have the ability to lift five pounds fully outstretched. All of these requirements put a lot of emphasis on weight. Anything that could be done to cut weight had to be done. In order to find the best arm design and joint layout, multiple options had to be explored for the Bucknell Humanoid Robot Arm.

Each layout was compared to determine the overall size of the largest joint, which is the shoulder, by creating initial Solidworks models. Each model included appropriate motor selections as well as the gear train and any other items that would be needed such as cables and bevel gears. Each had their problems and design issues, all of which will be discussed in the following paragraphs.

The first of three options, shown in Figure 36, was a cable drive differential system. This layout was considered because the motors could be kept towards the top of the arm. It was believed that this would reduce motor power and torque requirements which in turn would lower the motor size and weight.

Figure 36: Cable Drive Differential Layout

The cable drive system was not necessarily the heaviest of the layouts but the bulkiness would lend a lot to its high final weight. The bulkiness also presented the problem of maneuverability. With the overall volume of the joints being very large, it would limit the arms movement and in turn limit the arm's workspace. At a minimum, the drum size would have to be four inches in diameter due to the bending radius requirements of the cable that would have to be used. The drums would also require a significant height, close to five inches, in order to get proper winding of the cable. This size comes from the two differently sized cable drums that would have to be used to ensure proper winding. This bulkiness doesn't include the multiple steps in gearing that would be needed to obtain the required torque and power at the joints.

The complexity and maintenance of the cable drive system is high. The need for cable readjustment would become very burdensome and high maintenance on an urban robot is not a desired attribute. Although bulky, the cable drive layout would put the motors near the base, or shoulder, of the arm which would reduce the moment the shoulder joints would see. Having a lower moment would allow for the use of smaller less powerful motors in the shoulder and possibly other joints. After creating a Solidworks model, it was found that the decreased moment was not obtained due to the joints being bulky and heavy.

The second of three options, shown in Figure 37, was a bevel gear differential system. Similar to the cable drive system, this layout was also considered because the motors could be kept towards the top of the arm and lower the weight of the motors. Like the cable drive system, complex two DOF joints could be made by rotating the motors in the same direction to move the joint up or down, or in opposite directions to obtain a twisting motion. It was believed this option could be very light weight and compact due its layout.

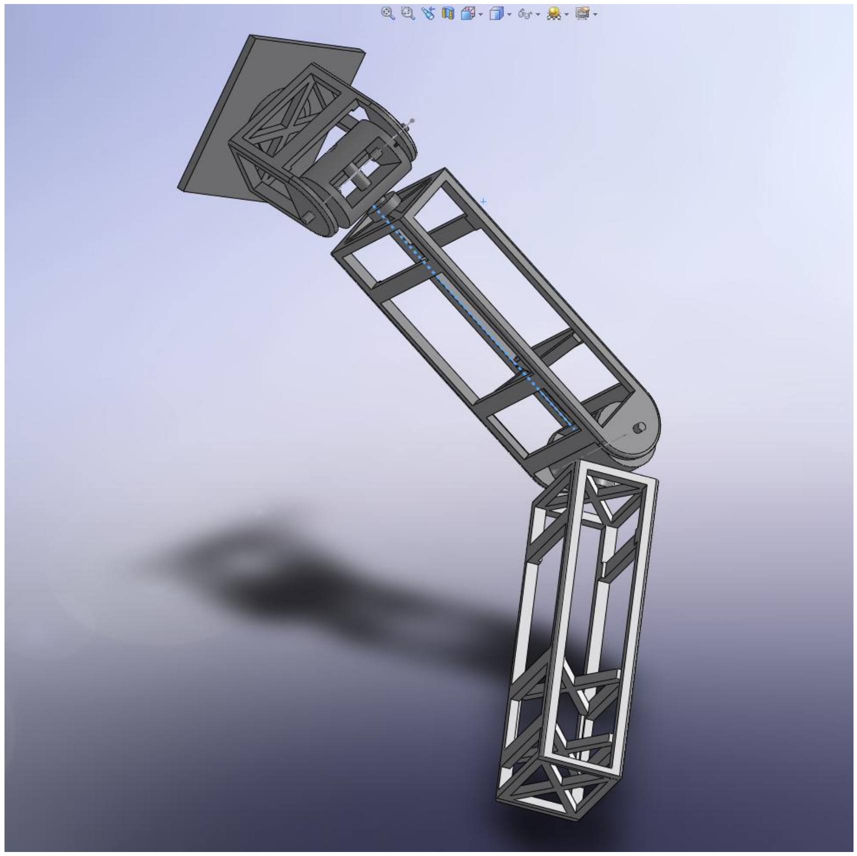

Figure 37: Bevel Gear Differential Layout

After creating a Solidworks model, it was found that this layout would be extraordinarily heavy compared to the other alternatives simply due to the weight of bevel gears. The bevel gears that would be used for this layout would be close to 1.5 pounds, or more, a piece and would cause the weight of the arm to be high. This was found with steel gears which were the only gears that had the strength to handle the torque requirements of the arm. One joint alone would weigh over six pounds and in the end, two joints nearly twelve pounds just in bevel gears. More weight would be added by motors that would also have to be larger in order to lift the heavier joints. This puts the weight of the arm well over the target weight of 15 pounds and would make that requirement unattainable.

The third alternative, shown in Figure 38, was the frameless motor with harmonic drive gear layout. This layout was discussed because of three main points. It would eliminate unneeded weight found in the steel casing of a framed motor (motor can be built into an aluminum joint frame), the motors had very high torques compared to brushed frames motors, the harmonic drives allowed for a single low backlash gear reduction, and the design would be compact.

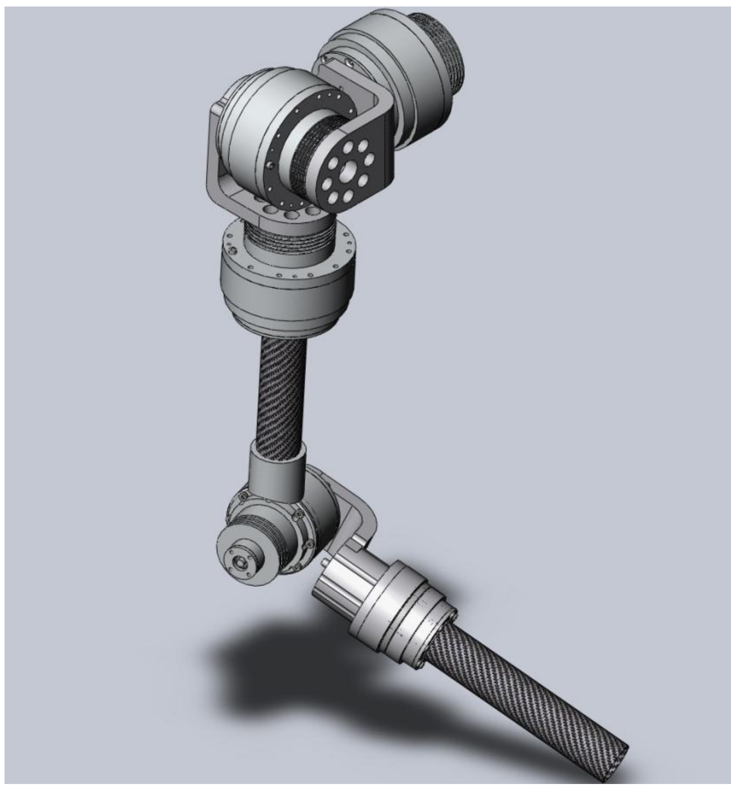

Figure 38: Frameless Motor with Harmonic Drive Layout

Again, the weight of the arm was very important. Eliminating the steel case and being able to have the motor physically built into the joints reduced the weight and overall volume of the joint. The motor and harmonic drive combined a high torque motor with a single gear reduction which reduced inefficiencies. Because harmonic drives have "zero" backlash, which is defined by Harmonic Drive Inc. as 1.5 arc minutes, or less that allows for better end effector accuracy compared to other gear heads.

After modeling a single joint, the heaviest joint would weigh approximately 1.4 pounds. With 5 DOF's, this would be around 7 pounds for all 5 joints (less than ½ the goal weight of 15 pounds). Of course, the lower joints would be smaller and would weigh less due to the power requirements being less and less material being needed to encase the motor. Also, the harmonic gears have zero backlash. This will reduce play in the joints making the end effector more accurate.

After exploring the options, each was evaluated. Shown in Table 4, the frameless motors with harmonic drives is the best fit for the requirements of the Bucknell Humanoid Robot Arm. It would be lighter and take up less space than the other two layouts that were considered. The only disadvantage to using this layout would be cost. Even though it has a higher cost, it is a tradeoff that had to be taken in order to keep the arm as light weight and compact as possible.

Table 4: Comparison Table for All Considered Layout

	Layout	**Backlash**	**Weight**	**Volume**	**Design Difficulty**	**Cost**	**Maintenance**
1	**Harmonic Drives**	**Low to none**	**Light**	**Small**	**Easy**	*High*	**Low**
2	**Cable Drive Diff.**	Low	Med.	*Large*	*Very Difficult*	**Low**	*High*
3	**Bevel Gear Diff.**	*High*	*Heavy*	*Large*	Med.	Med.	Med.

Although the disadvantages of this layout are small, some still exist. The main disadvantage was the machining and assembly time. Because the frameless motors have no outer shell, cases need to be machined into the joints rather than bolt hole patterns being drilled and the motors attached. This is a very complex task but can be done if extreme care is taken when machining the parts. Along with this machining, the motors and harmonic drives have to be concentric. Again, extreme care must be taken when machining the parts for the motor and harmonic drive alignment. With the alternatives compared and evaluated, the "Frameless Motor and Harmonic Drive" design was chosen because of its ability to be made into a lightweight and compact design.

3.4 Detailed Design of the Arm

As part of the design process, there were many things that had to be decided upon. For example, joint material, link connection material, what gear reduction would be used, what motors would be used, etc. Answering all of these questions would determine how the layout of the arm would move forward. From there, each joint, their internals, and brackets were designed.

Joint and Link Material Selection

Titanium and aluminum were two lightweight materials discussed for the joint and links of the Bucknell Humanoid Robot Arm. Titanium is a very strong material and is also very light. Its high tendency to deflect could cause problems if it were to be used for joint connection brackets where deflection can cause inaccuracies at the end effector. Titanium is also very expensive. Making a mistake during machining or in the design phase of the arm would prove to be very costly. Great care must be taken when machining titanium. A large supply of sharp tooling must be kept readily available. This lowers the chances of galling. Due to titanium's ductility, very rigid machine setups must be used to reduce deflection of the piece being machined. A lot of cutting lubricants along with low feed rates and high cutting speeds must be used when machining titanium.

Aluminum is a very light material as well. Compared to titanium, deflection is not as much of a concern unless under very high loads. Aluminum is also very cheap compared to titanium; almost 1/8 the price of titanium. This would be less costly if a mistake were made during the machining process. Aluminum is very forgiving when machining. An amateur with little experience can successfully machine aluminum with very little trouble. The strength-to-weight ratio is not nearly as high as titanium but this can be outweighed by the cost and the difficulty of machining it. With all things considered, aluminum was chosen for the main material of the Bucknell Humanoid Robot Arm.

The next consideration was the material used in the links of the arm. Aluminum was given great consideration because it would be used in the rest of the arm but it would be impractical to use it due to the amount of material required. Carbon fiber was also considered. Carbon fiber not only gives an increased esthetic appeal, but also gives the lightweight strength needed for the links. A 1" tube was found to result in a 0.007" deflection over 24" of span with 5 pounds at the end. The analysis for this can be found in Appendix B: Carbon Fiber Tube Deflection Analysis. The links would be much shorter than this and the deflection could become nearly negligible. Carbon fiber was the best choice for the links and therefore was chosen.

Gear Reduction and Motor Selection

Because the frameless motor and harmonic drive layout was chosen for the Bucknell Humanoid Robot Arm, the next step was to find the proper harmonic drive for each joint. Table 5 shows the torque requirements at each joint found using Yobotics SCS. This table was the basis for each harmonic drive choice as well as the motor choice. The values for torque and power were calculated during the simulation phase of the design.

Table 5: Torque and Power Values Found from Yobotics SCS

Joint	Torque Required	Speed Required	Power Required
Shoulder (3)	41 Nm (32 ft-lb)	.78 rad (7.5 RPM)	42 W
Elbow	16 Nm (12 ft-lb)	.78 rad (7.5 RPM)	21 W
Wrist	5 Nm (1.5 ft-lb)	.78 rad (7.5 RPM)	6 W

The harmonic drives, which were purchased from Harmonic Drive Inc, were relatively easy to pick because the required torque output was known. Looking at the specification sheet for the harmonic drives and finding the appropriate drive was very easy. Because the joints would often be hitting peak torque at startup, it was decided to use the “Repeated Torque Limit” column. An abridged version of the harmonic drives torque limits are shown in Table 6.

Table 6: Comparison Table for All CSD's Considered

CSD Size	**Limit for Repeated Peak Torque**		
	50:1	**100:1**	**160:1**
20 (Shoulder)	39 Nm	***57 Nm***	64 Nm
17 (Elbow)	23 Nm	***37 Nm***	
14 (Wrist)	12 Nm	***19 Nm***	

With the results from Table 6, the motor choice became easier. Brushless motors were selected because they are more efficient for their weight compared to brushed motors. This is due to their ability to produce more torque. Less power is wasted due to spark, and the brushes do not have to be replaced because they do not exist. When the search for frameless brushless DC motors was conducted, a provider with a wide variety of motor sizes was desired. The provider that was found was Emoteq.

Looking at Table 5, the required torque after reduction can be seen. In order to make calculations simpler and have ample strength in the harmonic drives, a 100:1 gear reduction was chosen. This allowed for lower torque values out of the motors, and because most of the speeds of the motors were very high, this gear reduction put the output speeds at a very reasonable value. With the gear reduction "variable" taken out of the equation, the motor selection became very easy. Table 7 shows that with the chosen gear reduction and motor choice, all of the required torques and speeds were met.

Table 7: Torque, Speed, Reduced Torque and Speed, and Power Values from Chosen Motors

Motor	HT2000 (Shoulder)	HT1500 (Elbow)	HT1000 (Wrist)
Torque	0.48 Nm	0.21 Nm	0.09 Nm
Speed	3986 RPM	7301 RPM	8580 RPM
Reduced Torque	48 Nm	21 Nm	9 Nm
Required Torque	41 Nm	16 Nm	5 Nm
Reduced Speed	39.86 RPM	73.01 RPM	85.80 RPM
Required Speed	7.5 RPM	7.5 RPM	7.5 RPM
Power	48 W	31 W	11 W
Required Power	42 W	21 W	6 W

These motors in particular were chosen not only because they theoretically met the required torques and speeds, but were also the lightest available. All of the motors were predicted to be a little overpowered but at the same time lighter than the motors that were closer to the required values. This was a great tradeoff considering one of the requirements was to build a robotic arm with a max load-to-weight ratio of 0.33. The motors listed in Table 7 were the final choices for the Bucknell Humanoid Robot Arm. The tables used to select the motors are located in Appendix C: Motor Selection.

Joint Design – Lower Case

Each joint in the Bucknell Humanoid Robot Arm are very similar in design due to frameless motors and harmonic drives being used. All joints were made to fit these two items and any remaining support was developed to fit around them. This allowed for very compact and lightweight joints to be created. In order to fully describe each joint design, the elbow joint will be discussed first. Any major differences in the shoulder joints and wrist joint will be described later in this section. Figure 39 below shows a cross section of the elbow joint with all of the components labeled.

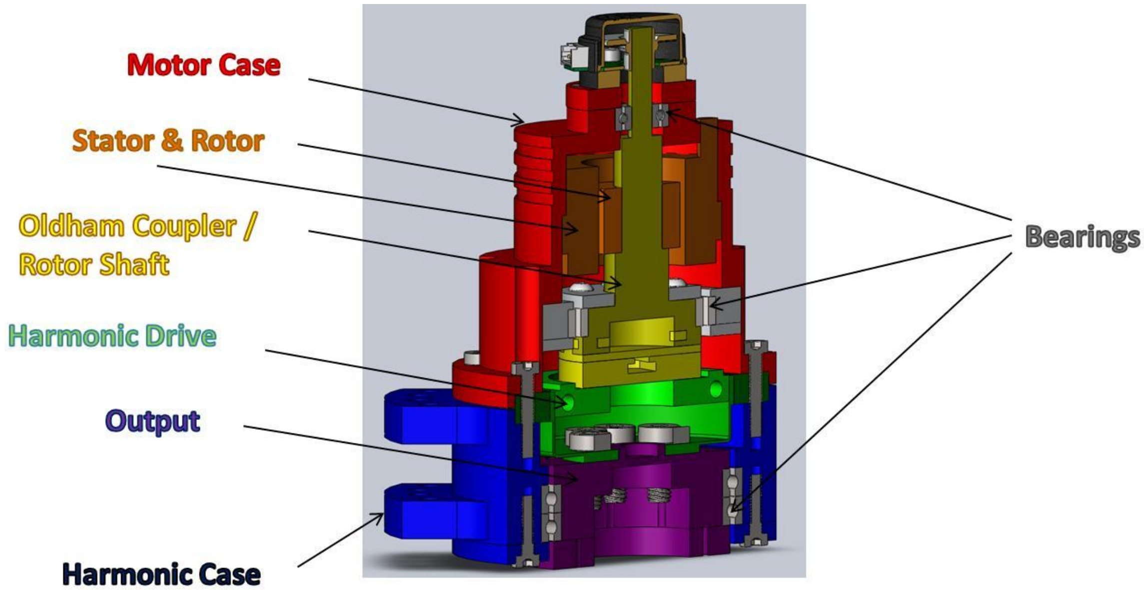

Figure 39: Detailed Cross Section of Elbow Joint

When creating the design for each joint, Solidworks was used to accurately create the 3D models as well as the 2D machine drawings. The first step in creating the elbow joint was creating a lower housing for the harmonic drive. Harmonic Drive Inc. has specified on their data sheets that certain areas require additional clearance space around the harmonic drive. These specifications can be found in the Harmonic Drive CSD Data Sheets: "Cup Type Component Sets & Housed Units". Figure 40 shows the model of the elbow joint harmonic drive – CSD 17. This was used to properly design a lower case shown in Figure 41.

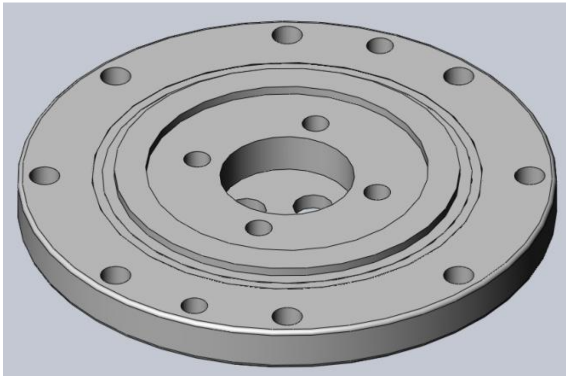

Figure 40: CSD 17 Harmonic Drive Model

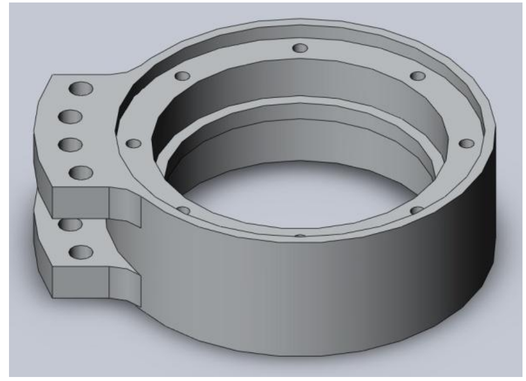

Figure 41: Lower Case of Elbow Joint

Supporting axial and radial loads on the harmonic drive was the next concern. Eliminating parts as well as weight was a very high priority, so angular contact bearings were used in order to manage both axial and radial loads. By increasing the angle of contact on the bearing race, more axial loads can be supported. This higher angle decreases the radial load support so the angle has to be selected to fit the application. To achieve this angle, a spacer must be placed between one of the races and the mounting surface.

In the Bucknell Humanoid Robot Arm, greater support was gained by combining two angular contact bearings and the required angle was more easily obtained by sandwiching the spacer between the two outer races of both bearings. The calculations used to select the proper bearings for each joint can be seen in Appendix D: Angular Contact Bearing Calculations. Table 8 shows the bearings, Kaydon Angular Contact Bearings, that were selected for each joint as well as the loads they would withstand and need to support. Lastly, Figure 42 and Figure 43 show the lower case with the harmonic drive and bearings installed.

Table 8: Joint Radial and Axial Loads and the Loads Supported by the Angular Contact Bearings for the Harmonic Drive Case

Bearing	Joint Radial	Joint Thrust	Radial Support	Thrust Support
Shoulder (KAA20AR0)	61 lb	17 lb	405 lb	960 lb
Elbow (KAA15AG0)	50 lb	12 lb	238 lb	560 lb
Wrist (KAA10AG0)	70 lb	11 lb	194 lb	450 lb

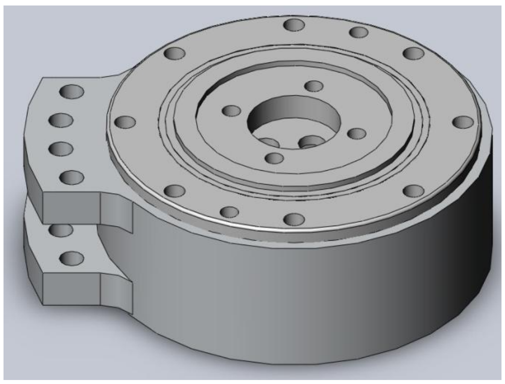

Figure 42: Case with Harmonic Drive Installed Top View

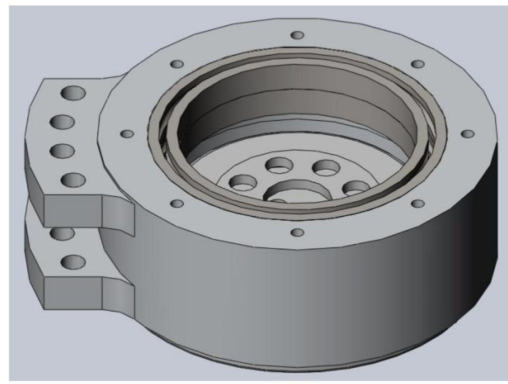

Figure 43: Case with Bearings Installed Bottom View

Completing the joint design creating parts that coupled the harmonic drive to the bearings while also creating an output boss for either a bracket or the previously mention carbon fiber tubing. After all pieces were assembled, proper bolt patterns were specified to hold the harmonic drive and bearings in place. This can be seen in the cross section view in Figure 44. Also, note the two flanges with holes in them on the outside of the harmonic case. This is where the shoulder to elbow bracket attaches.

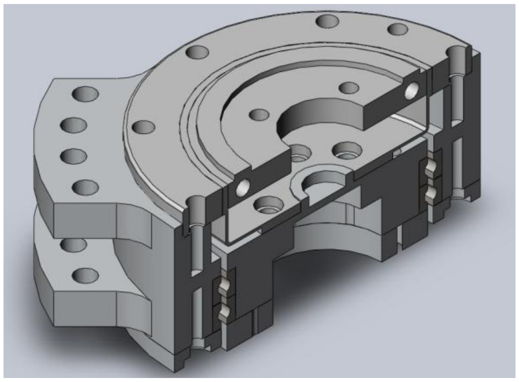

Figure 44: Cross Section of Lower Case. Harmonic Drive, Bearings, and Output Included

Joint Design- Upper Case

The next step was to design the upper case which houses the motor. Like the harmonic drive, the manufacturer has specified clearances and tolerances that the motor must be kept within. Figure 45 shows the model of the motor. From this model, like the harmonic drive model, a basic model of the outer case was created, shown in Figure 46.

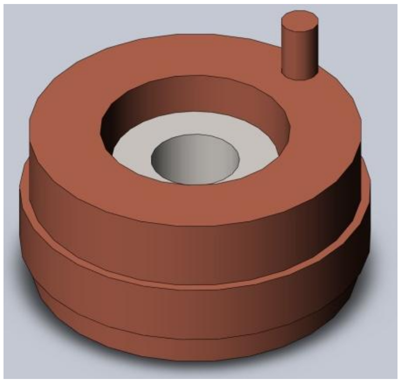

Figure 45: Solidworks Model of Elbow Motor

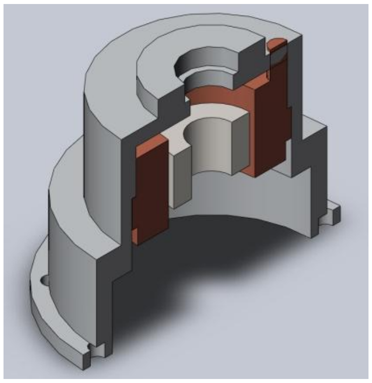

Figure 46: Solidworks Model of Upper Case with Motor Installed

After encasing the motor it had to be connected to the harmonic drive. At first it was thought that a direct shaft between the motor and harmonic drive would work, but after reading the Harmonic Drive Inc. specification sheet, it was found that a coupling was recommended due to the harmonic drives natural wave motion while spinning. This wave motion was accommodated by using an Oldham coupler in all of the joints. By incorporating the motor shaft into the coupler it was hoped that any inefficiencies in the coupling would be reduced. Figure 47 shows the Oldham coupler design along with the CSD wave generator and rotor in place.

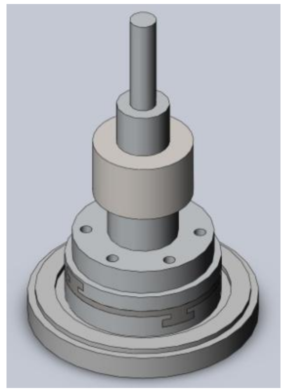

Figure 47: Oldham Coupler with Wave Generator and Rotor Installed

Just like the harmonic drive, the motor rotor had to be supported. This was done again using bearings. For this support, the shoulder and elbow joints all used Kaydon X type bearings while the wrist used regular radial bearings at the base of the shaft. To support the top of the shaft, all of the joints used radial bearings. Harmonic drives produce thrust when accelerating as well as decelerating, which was a larger concern than the radial load of the motor. The Kaydon X type bearings were able to support the radial and thrust loads produced by the larger CSD 20 and CSD 17 harmonic drives. The calculations for the Kaydon X type bearings can be found in Appendix E: X Type Bearing Calculations.

Table 9: CSD Thrust on Motor Case Bearings and the Selected Bearing Support Values

Bearing	**CSD Thrust Force**	**Thrust Support**
Shoulder 1 KAA10XL0	34 lb	370 lb
Shoulder 2 KAA10XL0	27 lb	370 lb
Shoulder 3 KAA10XL0	23 lb	370 lb
Elbow KAA10XL0	14 lb	370 lb
Wrist SSR-1458	10 lb	81 lb

For the wrist, a smaller diameter radial bearing was chosen that was capable of supporting the thrust produced by the smaller CSD 14 harmonic drive. Figure 48 shows the placement of the bearings. A final section view of the entire upper case is shown in Figure 49. All lower shaft bearings were placed in their own personal cases to ensure proper location and add support from the upper case.

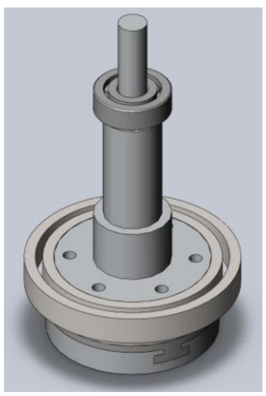

Figure 48: Oldham Coupler with Bearing Placement Shown

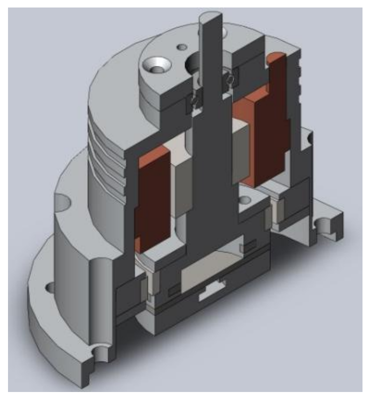

Figure 49: Cross Section of Elbow Upper Case

After both the upper and lower cases were designed, they were combined to complete the final housing. With the housings put together, it can be seen in Figure 50 that the rotor shaft and harmonic drive are fully supported. This support was extremely important considering the motors are able to spin at speeds between 4,000 and 8,000 RPM. Along with the speed, the strong attraction between the rotor and stator could have caused the rotor shaft to wobble and possibly cause the rotor to hit the stator if the alignment wasn't proper. This proper alignment of the motor and harmonic drive allowed for a smooth first time start up of the motor. Figure 51 and Figure 52 compare the final physical part to the final Solidworks model.

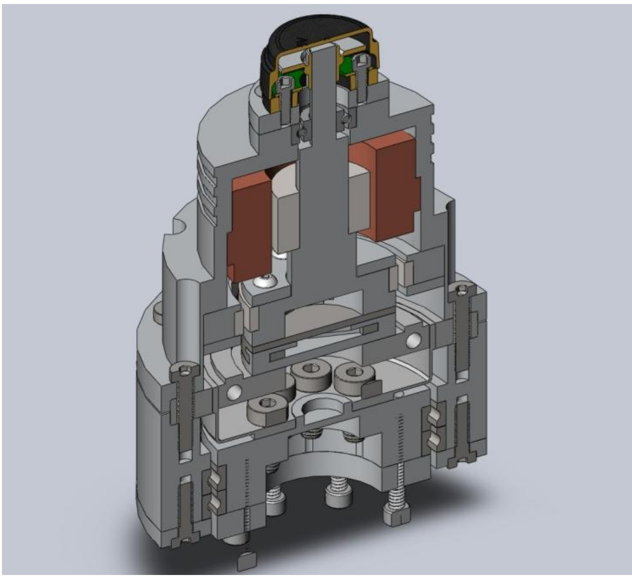

Figure 50: Cross Section of Assembled Elbow Joint

Figure 51: Final Assembled Elbow Joint

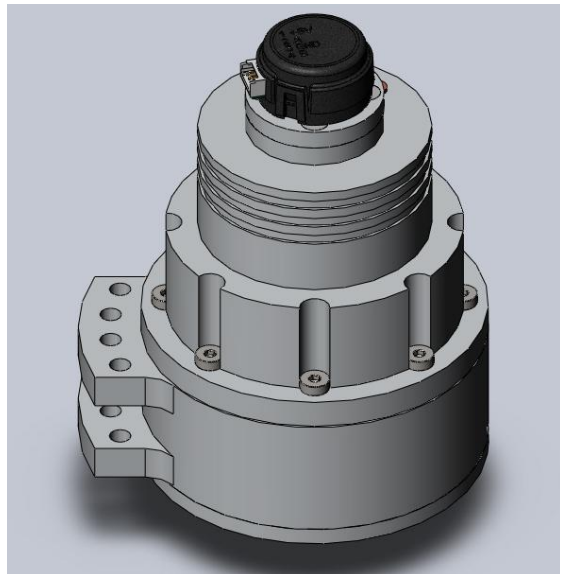

Figure 52: Assembled Model of the Elbow Joint

Wrist Differences

Like the elbow joint, the wrist design went through the same process of creating the lower harmonic case and the upper motor case. The main differences in the wrist are how the lower motor bearing is held in place, the location of the support bracket for the link, and of course, it being smaller in size than the elbow. Shown in Figure 53, it can be seen that the wrist has the same layout as the elbow.

Figure 54 shows the fully assembled model. Due to limited space in the motor housing, the lower motor bearing support is fastened from the outside of the housing, unlike the elbow joint. This not only allowed for a more compact design but also some weight reduction. Lastly, the link bracket is located on the motor housing. The bracket design is similar to the elbow, just in a different location. Figure 55 shows how the motor housing attaches to the elbow-wrist bracket.

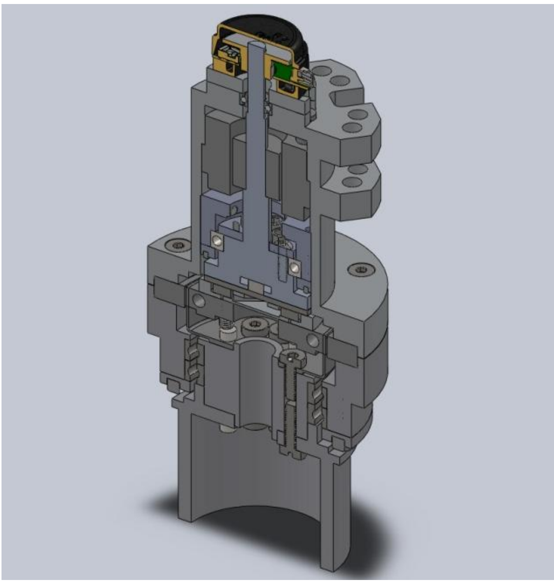

Figure 53: Cross Section of Wrist Joint Model

Figure 54: Fully Assembled Solidworks Model

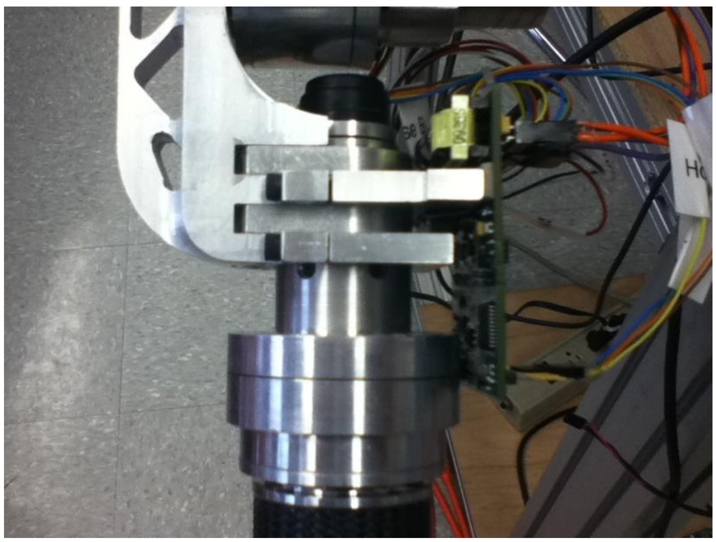

Figure 55: Wrist Joint Attached at to Link Bracket

Shoulder Differences

Out of all of the joints the shoulder was the most complex, and although the largest, was the most compact. Much of the design was focused on finding a way to put the encoder inside the housing as well as find a way to run wires up the center of the joint.

Again, the shoulder went through the same process as the wrist and elbow to design the housings around the motor and the harmonic drive.

The first step after designing housings around the motor and harmonic drive was trying to fit the encoder inside the assembly, rather than having it on the exterior similar to the elbow and wrist joints. Having the encoder inside allowed for the shoulder joint to be compact and more aesthetically appealing while keeping the encoder safe. In order to fit the encoder into the upper housing, the housing had to be made about 0.50 inches taller than it would have been if the encoder would have been placed outside of the housing. A taller housing was a reasonable tradeoff for keeping the delicate encoder wheel safe. The encoder layout and design can be seen in Figure 56 where the encoder reader is in red and the encoder wheel is in green.

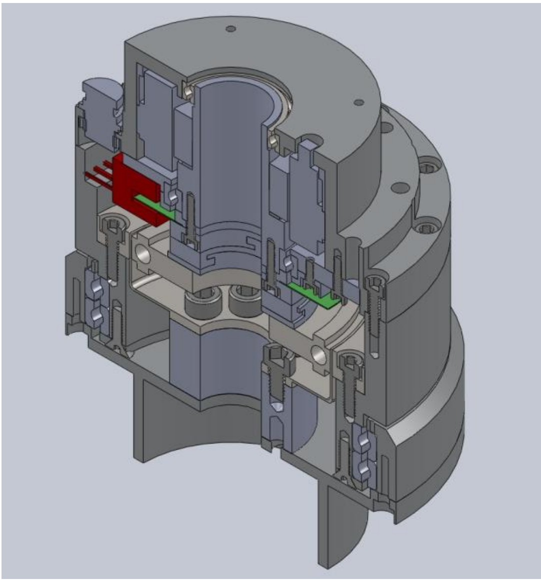

Figure 56: Shoulder Joint - Encoder Position

After fitting the encoder inside the housing, the next step was making accommodations for wires to pass up the center of the joints. Again, this would not only protect the wires, but make the arm more aesthetically appealing. Shown in Figure 57, the items colored in orange were all made hollow through the center to allow for wires to pass through them. Making the parts hollow also made the parts lighter, which added to the overall goal of the project of making the arm as light as possible. The final assembly of the shoulder housing can be seen in Figure 58. Notice the quick disconnect connector for the encoder on the left of the motor housing.

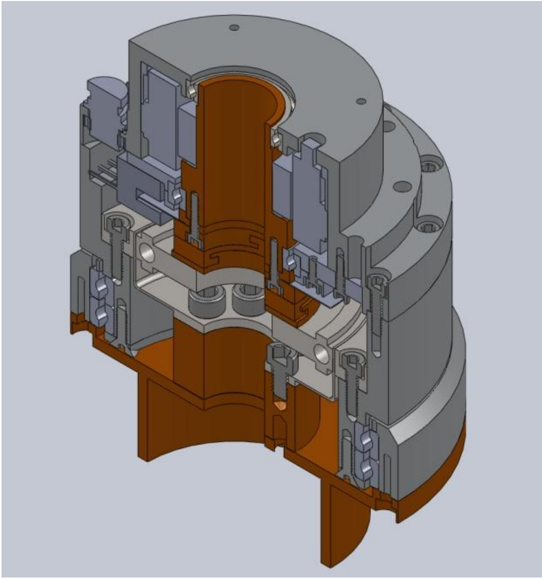

Figure 57: Shoulder Joint - Pass Through

Figure 58: Final Assembled Shoulder Joint

The Passive Wrist Joint

The last joint to be designed was the passive wrist joint. A human arm and hand are connected by a flexible wrist that bends during certain situations. The Bucknell Humanoid Robot Arm is no different. A passive wrist was designed to aid in flexing the wrist when the arm picks up objects or most importantly when the arm opens a door. To obtain this flex, a torsion spring was used inside of the connection bracket between the arm and hand. Also, a positive stop design was implemented to only allow the joint to rotate between zero and 90 degrees. This design can be seen in Figure 59.

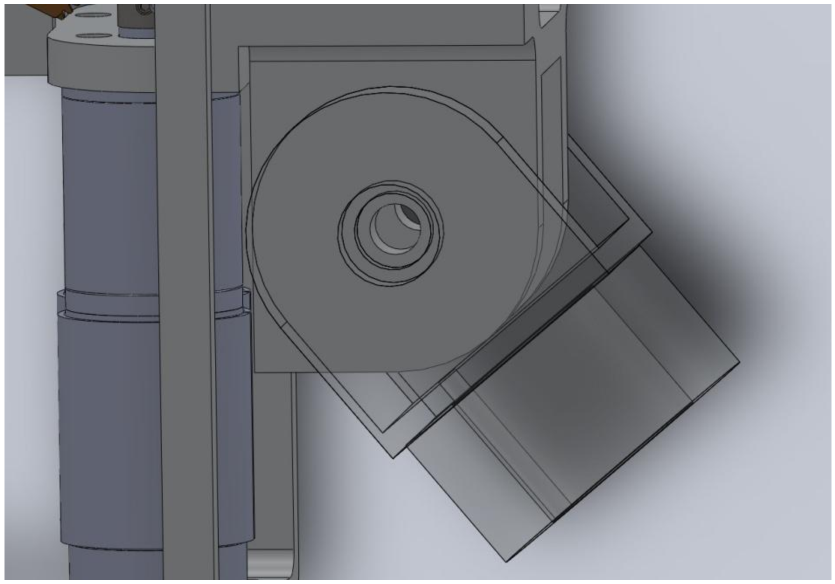

Figure 59: Solidworks Model of Passive Wrist

Using a simple torsion spring calculation for ten pounds, the force required to open a door, and a deflection of 90 degrees, it was found that a spring with a constant of 23.5 inch-pounds was needed. The closest available spring constant, without going over, was 22.5. This spring was selected and used in the passive wrist. Figure 60 shows the final wrist assembled.

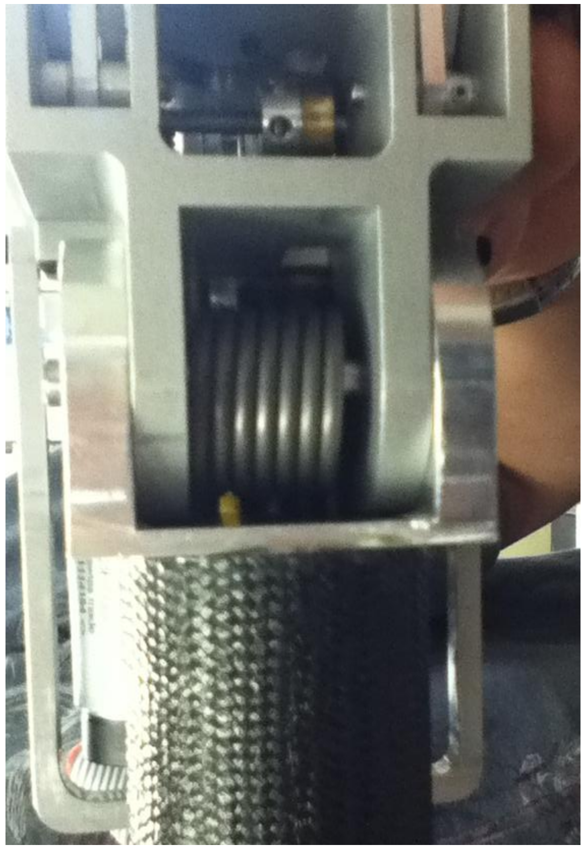

Figure 60: Passive Wrist Joint

Arm Brackets

The Bucknell Humanoid Robot Arm has to be as sturdy and rigid as possible to eliminate any deflection. Any large amount of deflection would cause the hand to be in an improper position. With that said, the brackets of the arm, which are also made with 7075 aluminum like the motor and harmonic housings, have to be as sturdy as possible, while also being as lightweight as possible. To ensure that all of the brackets were strong enough, FEA analysis was conducted on each. The forces used on each bracket were calculated using the table found in Appendix F: Joint Torque and Bracket Force Table. When testing, a factor of safety of 3 was used. This number was chosen to account for dynamic and static loads on the brackets as well additional weight the arm may or may not be able to hold. Also, with this FOS of 3, all FEA performed on the brackets represent a worst case loading scenario.

The first bracket analyzed was shoulder bracket one. This bracket holds all of the weight of the arm. Shoulder bracket one can be seen in Figure 61.

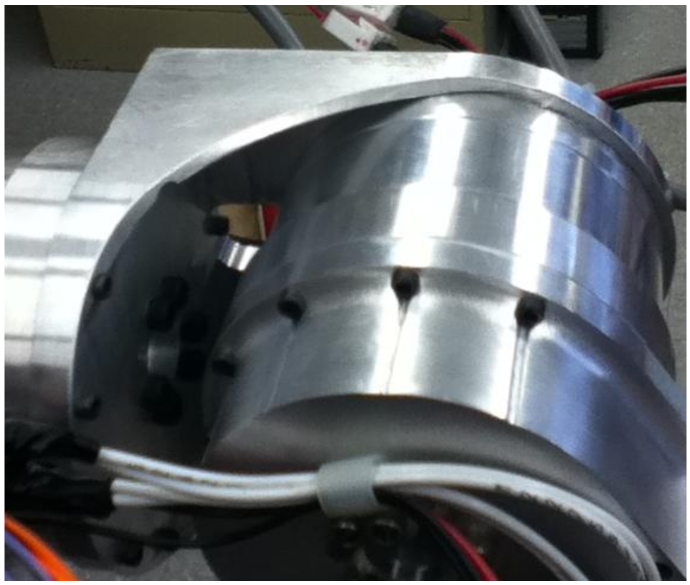

Figure 61: Shoulder Bracket 1 (Top Left)

Any deflection in this bracket would result in a large positioning inaccuracy at the hand. Figure 62 shows the deflection plot by applying 39 lb on the bracket at the surfaces since this is where the bracket would be held. The resultant deflection was 0.0011 inches. This deflection occurred at the farthest point of the bracket, the circled area in red of Figure 62, and would only be present if a large amount of force was applied to the arm. Also, rigidity would also be increased once the motor housing was attached to the bracket. Less than 2 thousandths of an inch was an acceptable amount of deflection with a factor of safety of 3.

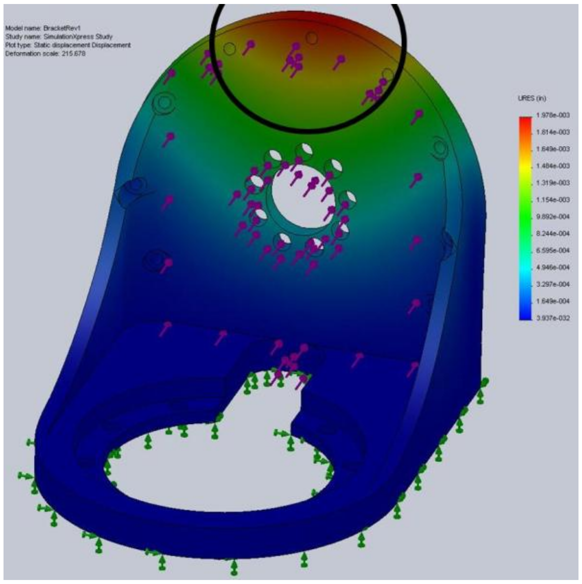

Figure 62: Deflection Results for Shoulder Bracket 1

The next bracket was shoulder bracket two. This bracket also had to hold a lot of weight, approximately 11 pounds, and could cause inaccuracies in the hand position if a large amount of deflection was present in the bracket. Shoulder bracket two can be seen in Figure 63.

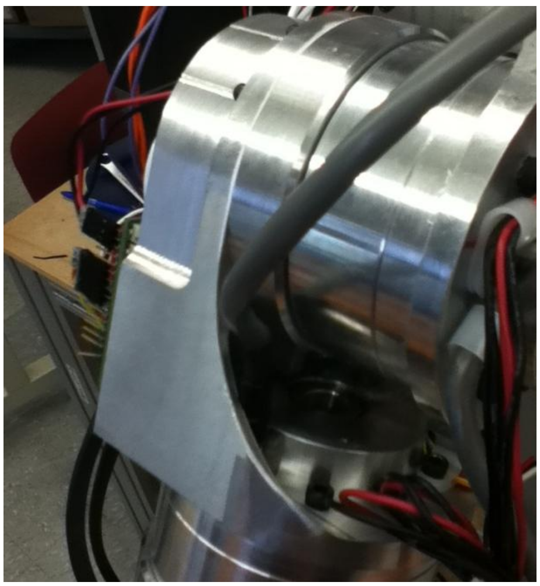

Figure 63: Shoulder Bracket 2 (Left)

A force of 33 lb was applied to the arm which resulted in a deflection of 0.001324 inches. Similar to bracket one, less than two thousandths was found at the very end of the bracket. Again, the rigidity would increase with the attachment of the shoulder motor housing. Figure 64 shows the deflection plot. This bracket has the output built into it similar to the first shoulder bracket, but offset, which aligned all of the joints in a straight line. The main portion of the bracket has the same shape as bracket one, but is extended at the bottom (bottom left of Figure 64).

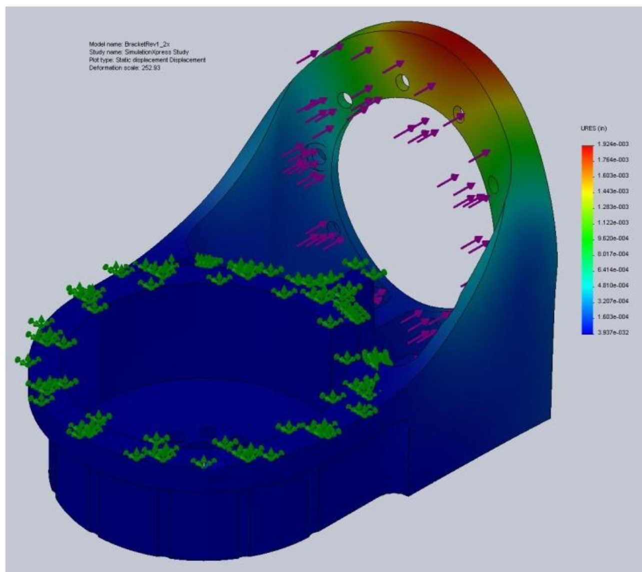

Figure 64: Deflection Results for Shoulder Bracket 2

The bracket that connected the shoulder to the elbow was a different design than the previous two discussed. It has flanges that fit into the elbow joints harmonic drive case and a boss for the carbon fiber tube. Figure 65 shows the elbow bracket.

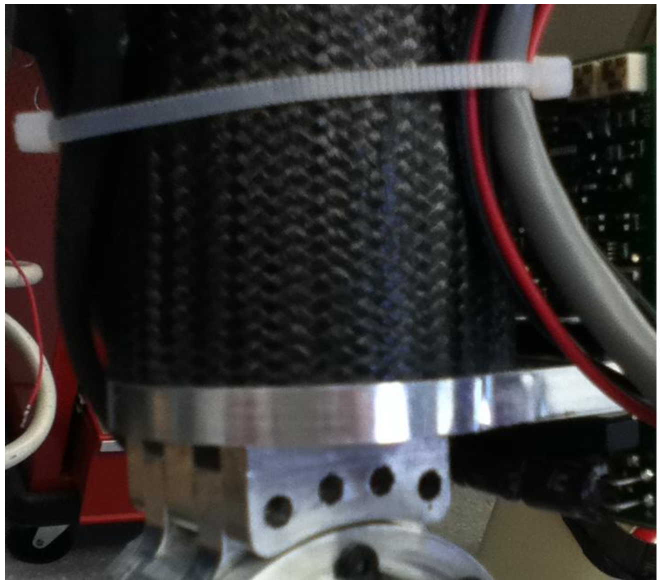

Figure 65: Elbow Bracket Attached to the Arm

Applied to the elbow bracket was 28 lb, which resulted in a maximum deflection of 0.0007 inches. This is a completely negligible amount of deflection and was an acceptable amount. The flange thickness could have been reduced, but due to how important bracket rigidity was, it was left at the initial thickness. Figure 66 shows the deflection plot for the elbow bracket. This bracket also served as an amplifier mount for the elbow. This bracket can be seen protruding from the bracket on the left of Figure 66, and on the right of Figure 65 where the amplifier can be seen. For the pins in this bracket, 5/32" pins were used. A simple sheer calculation was conducted on these pins and the diameter selected was found to be acceptable.

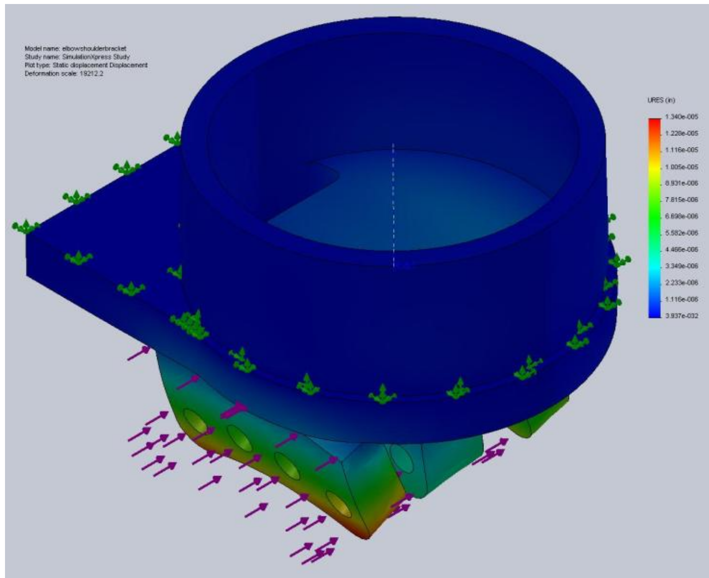

Figure 66: Deflection Results for Elbow Bracket

The final bracket analyzed was the wrist bracket. This bracket was the most problematic due to its long length and small width. Being that its shape is similar to a pillar, it has a tendency to bend when a small load is applied, such as one pound. Figure 67 shows the wrist bracket.

Figure 67: Wrist Bracket Attached Between the Wrist and Elbow

Strengthening the bracket and minimizing this tendency was the number one task when designing the bracket, although, keeping it as lightweight as possible was also very important. To do this a ladder design was put down the side of the bracket. Compared to just having a solid brace on the side, this truss design strengthened it while also eliminating some weight. The force applied to the wrist bracket was 24 lb, which resulted in a deflection of 0.0004 inches at the very end of the bracket. Figure 68 shows the deflection plot of the wrist bracket.

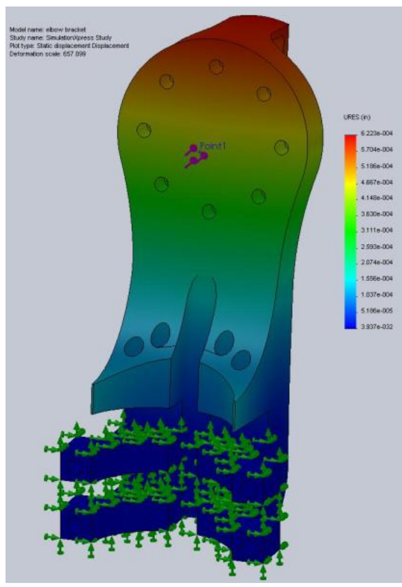

Figure 68: Deflection Results for Wrist Bracket

Throughout the entire design process an emphasis was put on weight and size to meet the requirement of making a lightweight and compact arm. All of the parts of the Bucknell Humanoid Robot Arm went through many iterations to ensure this requirement was met.

4.0 Controls

The control system for the Bucknell Humanoid Robot Arm is very complex and required many steps to complete the main task of being compatible with the Biped. Not many control boards support Java, which is the programming language of choice at IHMC, so steps had to be taken to make the motors work with Java. The system diagram shown in Figure 69 shows the various pieces of the control system needed to control the motion of the Bucknell Humanoid Robot Arm.

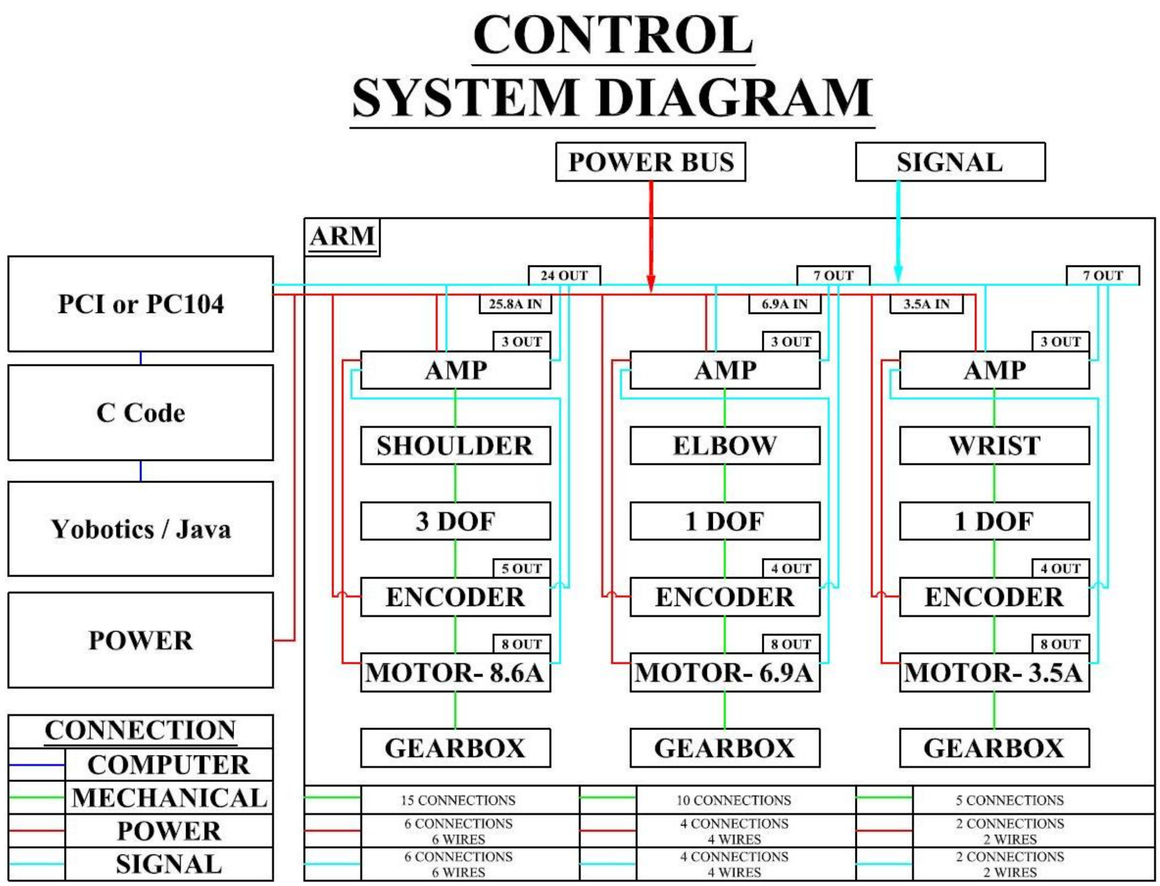

Figure 69: System Diagram

4.1 The Control Board

Because the arm uses brushless DC motors, the first step was to purchase a brushless motor control board. The motor control board must:

- Be compatible with brushless DC motors
- Be available in a PC-104 version to be compatible with the Biped
- Control multiple motors

After finding many different cards, the one that met all of the requirements was the PMD Prodigy Control board. Figure 70 shows the PCI integration point on the system diagram.

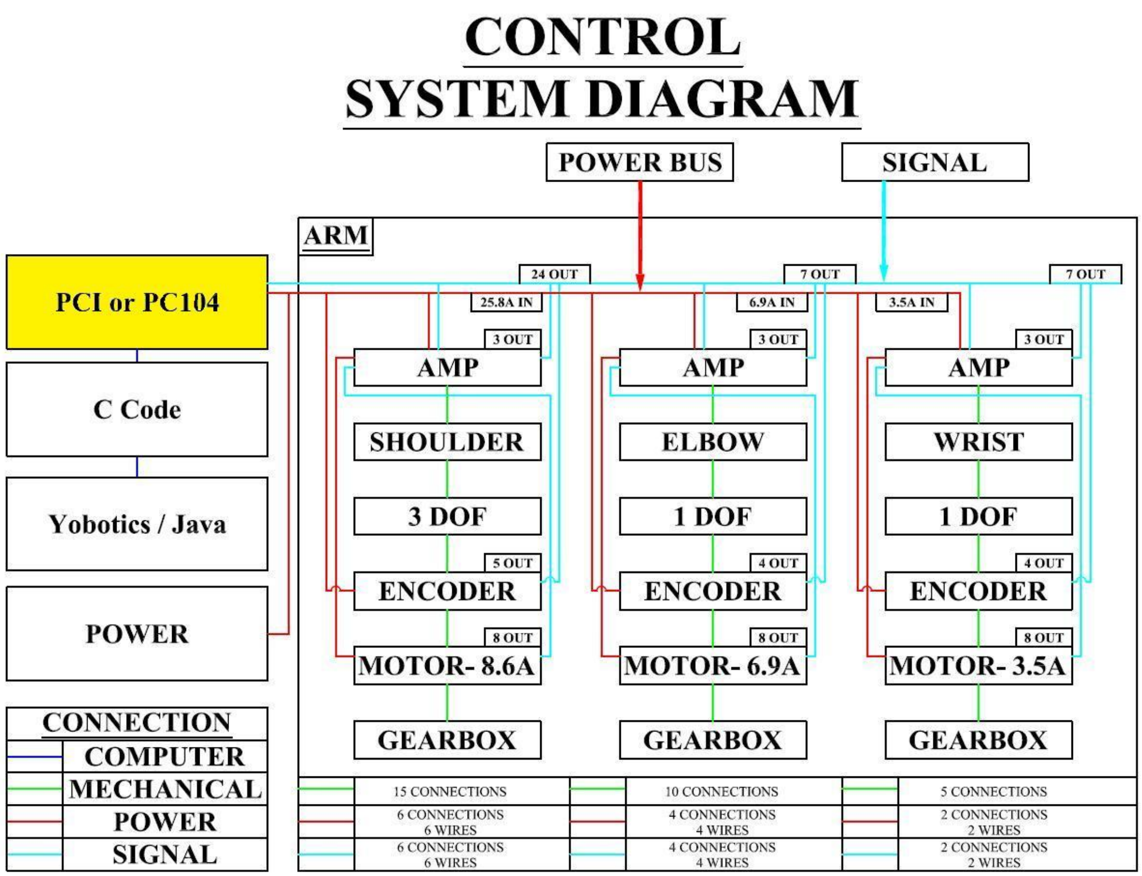

Figure 70: PCI Card in the Control System

In order to ease the testing process, Prodigy PCI cards were purchased. This allowed for all testing and initial startup to be completed from a PC. Any fine tuning and tweaking of the controls would be minimal when they were transferred over to the PC-104. Because the Prodigy card doesn't have any amplifiers built into it, these had to be bought as well. The amplifiers will be discussed in the following section 4.2 - The Amplifiers.

The PMD Prodigy controller uses feedback loop data given by encoders to put the motor in the proper position. It also uses a PID control system to properly move the motor at a desired velocity and acceleration, while optimizing response, steady state error, and overshoot. The Prodigy control card serves as the interface between the software code and the arm hardware.

In order to control the motors, code must be written using programming languages such as C or Visual Basic. Using these programming languages, things such as PID gains, motion paths, and homing positions can be set, among other things. Using these other programming languages allowed for a more customizable control system compared to scripts made available by PMD's control software, Pro-Motion. The PMD Prodigy control board is shown in Figure 71.

Figure 71: Prodigy PCI card [32]

4.2 The Amplifiers

The PMD Prodigy card has no built in amplifiers, so external amplifiers had to be purchased. This proved to be more complex than initially thought. Small powerful amplifiers were very hard to find but eventually an amplifier that met specified requirements was found. Those requirements are as follows.

The amplifier must:

- Be 48 V compatible
- Be able to put out at least 8 A continuous (shoulder motor continuous current)
- Be compatible with brushless motors
- Be as lightweight as possible
- Be as small as possible

The amplifier that was chosen was an Advanced Motion Control AZBE20A8. The amplifiers position in the system diagram is shown in Figure 72.

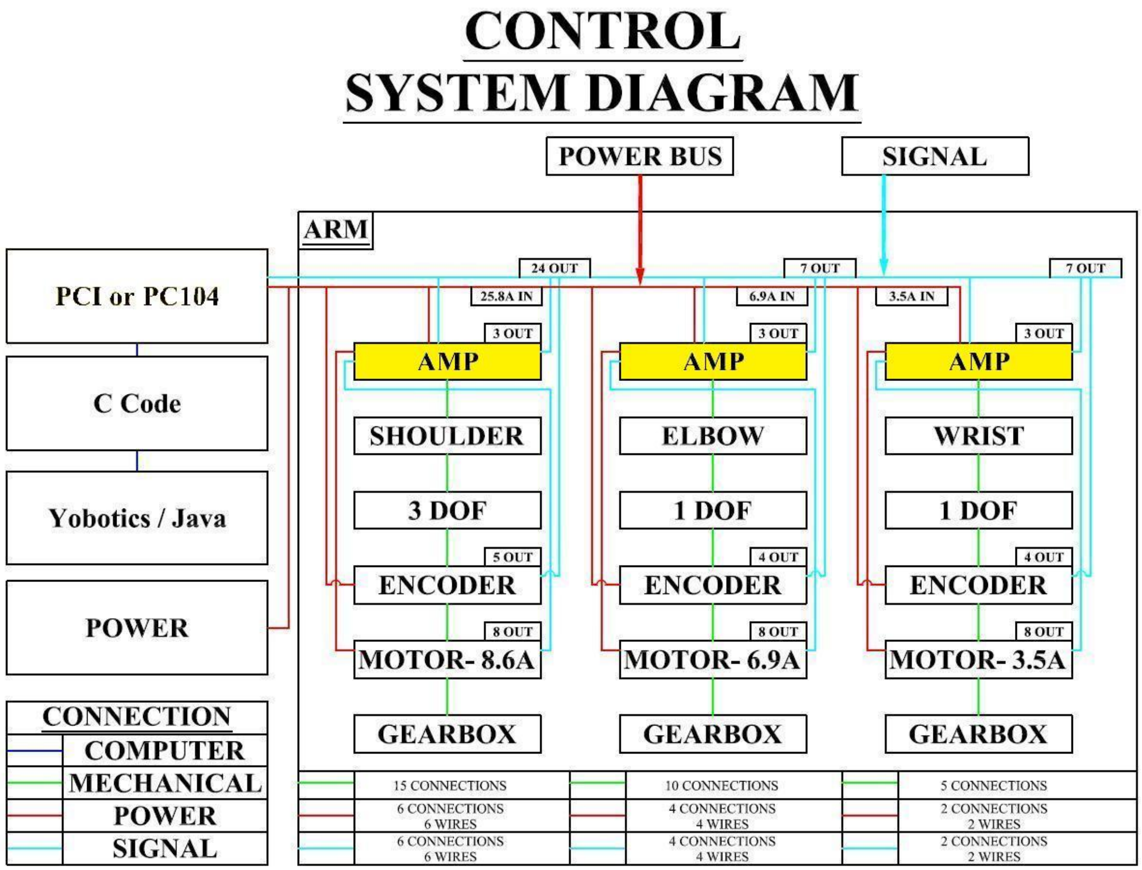

Figure 72: Amplifier Position in System Diagram

Not only is this amplifier compatible with brushless motors, it also has a wide range of supported voltages ranging from 10V to 80V which meets the 48V requirement. This amplifier was also the smallest amplifier that was found. Another bonus found when buying this amplifier is that it commutates the motors itself and only requires an analog signal from the Prodigy board. These amplifiers are able to take the analog signal and by adjusting potentiometers on the amplifier, the motors direction can be balanced or centered to prevent any motion offset. Having met all of the requirements, this amplifier was bought and used for all joints in the arm. The amplifier is shown in Figure 73.

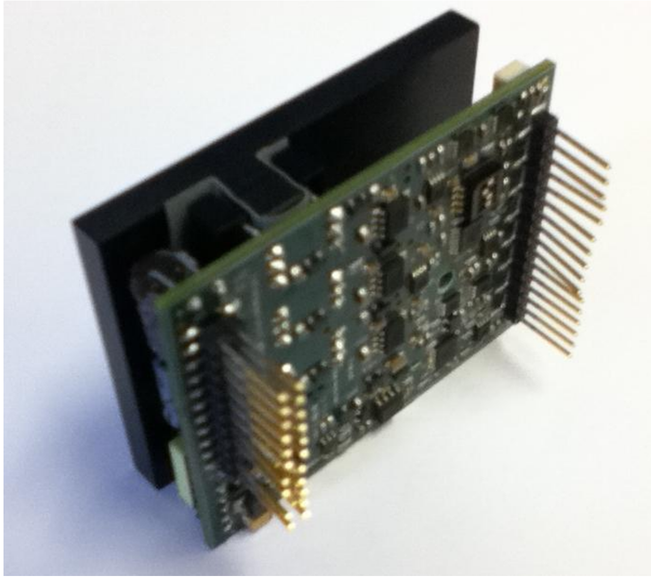

Figure 73: Advanced Motion Control Amplifier

Due to the small size of the amplifiers, 2” by 2.5”, they were able to be mounted on the arm local to each joint. This reduced the number of wires that had to be run up the arm to the control board because all of the wires from the motor were run directly to the amplifiers. The remaining wires were analog signal wires, which were small gauge, and four wires for power and ground. The other option of remotely mounting the amplifiers would have resulted in 8 additional wires, per motor, having to be run up the arm.

4.3 Initial Motor Testing

After choosing the control board and amplifiers, testing on the individual motors was completed. This was done prior to assembly of the arm to prove the motors would run properly. Using the PMD GUI (graphical user interface), called Pro-Motion, each motor was tested to make sure they moved properly. Pro-Motion is a C based GUI that allows for PID and trajectory control of the motors. Pro-Motion is also a very reliable program that can be used to debug then entire control system.

Each motor was connected individually without the harmonic drive to ensure any problems that may have occurred were not due to the harmonic drive. During this time, the amplifiers and the PID gains were tuned to their respective actuators to allow for smoother operation.

After each motor ran properly by itself, their respective harmonic drives were attached and further testing was completed. With the harmonic drives attached, further PID control tuning occurred to smooth out any problems due to the load the harmonic drive put on the motor. For example, the shoulder motors would oscillate with a high frequency until the PID gains were adjusted. Later, testing was completed with the arm assembled. This testing will be discussed in the upcoming section, 5.0- Testing Results.

4.4 C Code and DLL

The Prodigy PCI card that was chosen for the Bucknell Humanoid Robot Arm can be controlled using either C or Visual Basic. The decision was made to use C because it can be used more effectively over a larger range of operating systems such as Windows and Linux. With the programming language chosen, the initial control code could be written. This code was written by Phillip Diefenderfer, a member of the Bucknell Urban Robotics team.

The first step was writing a simple program that would move the motors and communicate with the encoders. After many modifications were made to the example code provided by PMD, proper communication with the encoders was established and the motors moved. Along with a PID controller, the acceleration, velocity, and position were added to the C code. All of these values were obtained from the testing previously conducted using Pro-Motion, and the position was selected by the user. The motors were now controllable through the written C code.

Similar to the Pro-Motion GUI, each motor was tested individually using the now modifiable C code. After all problems were eliminated the harmonic drives were connected and tested. This verified that the motors would work properly with the C code.

The next step was finding a way to communicate with Yobotics SCS through Java. In order to be able to control the motors from Java and Yobotics SCS, a decision was made to create a DLL or Dynamically Linked Library. Using this DLL, Java and Yobotics SCS could use the C code that interfaced with the motor controls. The DLL compiles two header files that can be found in Appendix N: DLL Compiled C Code.

This DLL was created using the JNI or Java Native Interface, which creates functions in Java called native methods. Java is able to execute the C functions inside the DLL that drive the motors by calling the native methods. From there, the Java simulation program written for Yobotics SCS was altered to work with the DLL and make the motors move. Figure 74 shows where the C Code and DLL fit into the system diagram.

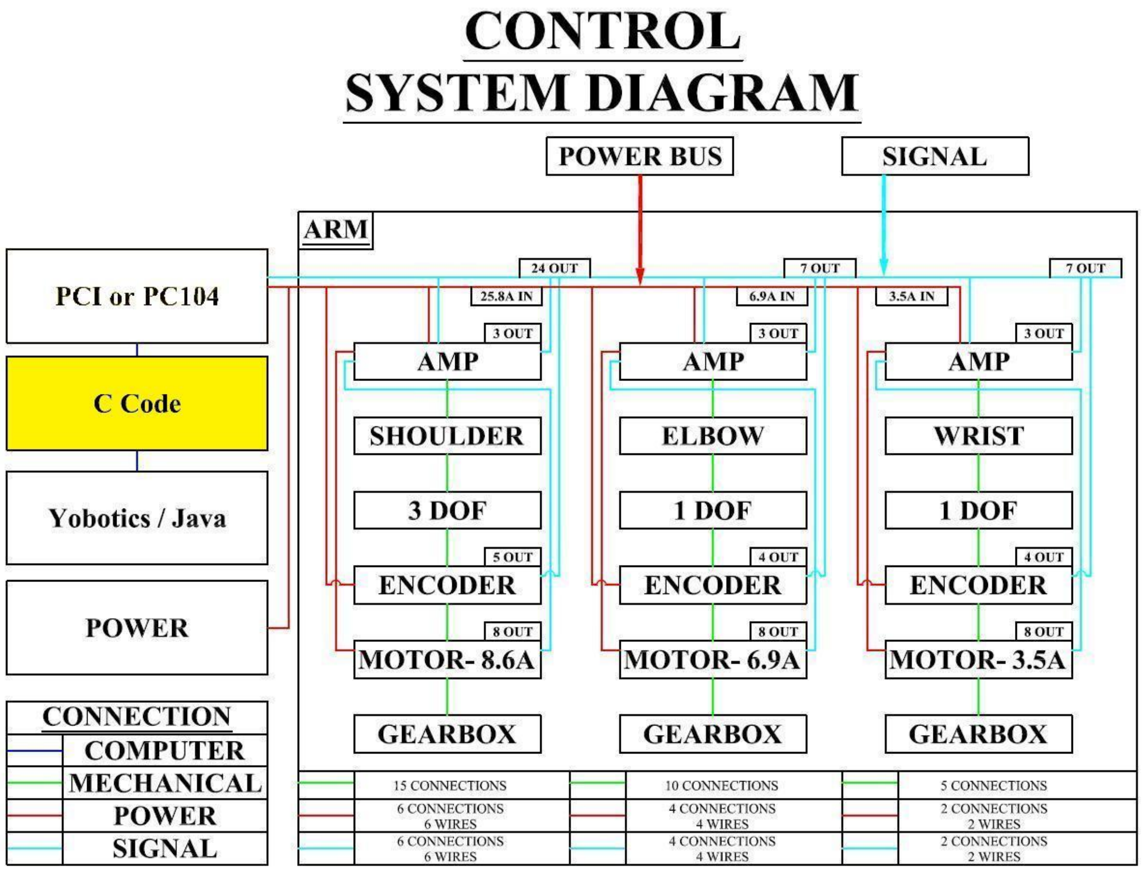

Figure 74: C Code in the System Diagram

4.5 Java and Yobotics SCS

The same program used to simulate the robot arms movement, Yobotics SCS, can also be used to move the actuators of the arm. The Java control code was written by Phillip Diefenderfer and the Java simulation code was written by Nicholas Oren, both members of the Bucknell Urban Robotics team. With further refinement of the Java controls, Yobotics SCS could control the arm and also have the simulation move along with it. The same kinematic equation used in the Yobotics SCS program can also be used outside of Yobotics SCS to control the arm as well by simply eliminating the Yobotics

SCS portion of the code. This allows the use of Java, without out the clutter of Yobotics SCS. The integration point of the Yobotics SCS and the Java code is shown in Figure 75.

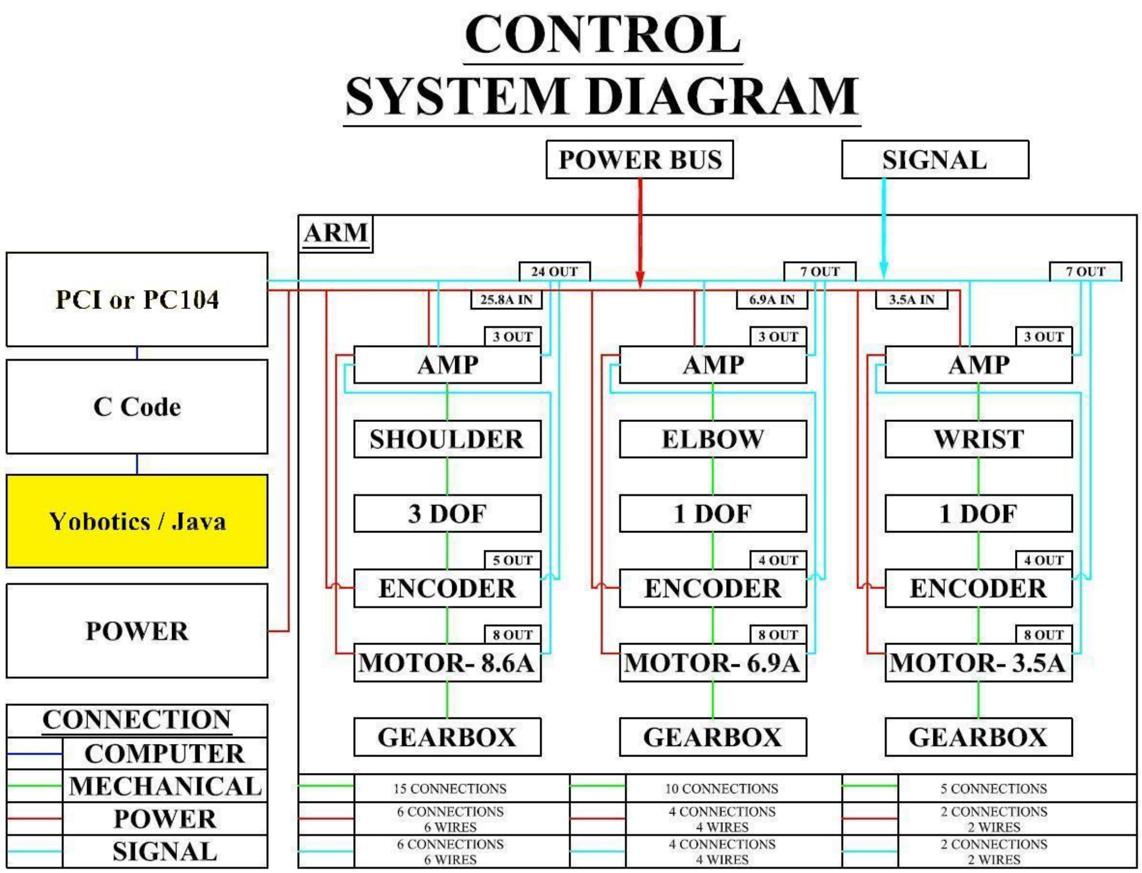

Figure 75: Yobotics SCS and Java in the System Diagram

To create a connection to the DLL, Java files were created called objects. One object file was created to represent the motors and another created to represent the Prodigy PCI cards. These objects provided the connection needed between Yobotics SCS virtual motors and the physical motors on the Bucknell Humanoid Robot Arm. Functions could then be called in these object files to set the velocity, acceleration, and the PID gain values. Other functions were also written to command the motor to a specified position or angle.

This same set up allowed Yobotics SCS to control the motors by sending them to certain positions pulled from the simulation program. These values were then transferred to the motors through the DLL. All of this together creates a more user-friendly system of controls for someone that understands C and Java. The Java Yobotics SCS control code can be found in Appendix O: Java and Yobotics SCS Control Code.

5.0 Testing Results

Testing was the one task that brought everything together and showed whether all the design specifications and requirements were met. Looking back at the design requirements and specifications, listed below and in Table 8 respectively, tests were developed to evaluate each requirement and specification.

- Be able to open a door
- Be able to lift small objects such as tools, boxes, etc
- Be as lightweight as possible
- Look humanlike

Table 10: Design Specifications

Design Specifications	
Specification	Desired Value
DOF	4
Position Accuracy @ the end effector	Less than 1”
Max Speed @ each joint	7.5 RPM
Total Length	22 ¾ in
Max Weight	<15 lb
Max Load Outstretched	5 lb
Max Load-to-Weight ratio	0.33
Open a Door	Can Open Door

Each test, beforehand, was created to ensure that the proper procedure was followed and records of each test were taken. Step-by-step procedures were produced along with the materials required to perform those tests. Table 9 shows these test procedures and materials needed for each test. The lifting of objects was incorporated into the max load test. Whether or not the arm looks humanlike was a matter of opinion and the majority agreed the arm look humanlike.

Table 11: Test Procedures for Bucknell Humanoid Robot Arm

Test #	Specification	Procedure	Required Materials
1	DOF	1. Count degrees of freedom. The DOF associated with the wrist is passive. 2. If DOF is > 4, condition is met	N/A
2	Position Accuracy @ the end effector	1. Place a whiteboard 15 in. from the base of the arm. Place a marker in the hand 2. Set the arm at a known position such that the marker marks a spot on the whiteboard. 3. Send the arm to another position that does not make contact with the white board. 4. Send the arm back to the initial position. 5. Repeat motion 5 times. 6. If marks are within 1 in. of the original, the condition is met.	1. Whiteboard 2. Marker 3. Caliper
3	Max Speed @ each joint	1. Mark a point on a joint. 2. Set the motor to maximum rotation. 3. Time how long it takes to make ¼ or ½ rotation. (dependent on rotational space of joint) 4. If rotation is > 7.5 RPM, condition is met.	1. Marker 2. Stopwatch
4	Total Length	1. Put the arm out at full extension. 2. Measure length with a measuring tape. 3. If length around 22.75 in, condition is met	1. Measuring tape
5	Max Weight	1. Place entire assembly (hand and arm) on scale 2. If weight is <15 lb, condition is met.	1. Scale
6	Max Load Outstretched	1. Set the arm at full extension, hand in closed position. 2. Place spring scale on end of arm.	1. Spring Scale

		3. Pull until arm begins to sag. 4. If greater than 5 lb, condition is met.	
7	Max Load-to-Weight ratio	1. Divide the max load outstretched value by the weight of the assembly. 2. If less than 0.33, condition is met	N/A
8	Open a Door	1. Place hand on door handle. 2. Power arm and pull door open. 3. If door opens, condition is met.	1. Door

After completion of each test, it was shown that the Bucknell Humanoid Robot Arm either met or exceeded the expectations of the design. The results from each test are shown in Table 10.

Table 12: Design Specification Test Results for the Bucknell Humanoid Robot Arm

Design Specification Test Results		
Specification	Desired Value	Value Reached
DOF	4	5 power + 1 passive
Position Accuracy @ the end effector	<1"	0.75"
Max Speed @ each joint	7.5 RPM	9.4 RPM
Total Length	22.75 in	Approximately 22.75 in
Max Weight	<15 lb	13.25 lb
Max Load Outstretched	5 lb	11 lb
Max Load-to-Weight ratio	0.33	0.83
Open a Door	Can Open Door	Opened un-sprung door successfully

5.1 Test #1 – Number of DOF's

The number of degrees of freedom was very important because it ultimately decided how many positions in space the robot is able to reach. At the start of the project, the arm was thought to only need 4 DOF. This number of DOF's would allow the arm to reach many points in space. Later, it was realized that more dexterity in the arm was needed, in particular twist of the forearm and of the wrist. The Bucknell Humanoid Robot Arm ended up having 5 DOF's in total plus 1 passive DOF at the wrist in which a spring was used to allow for flex. With a total of 6 DOF's, the Bucknell Humanoid Robot Arm passed the requirement of having 4 or more DOF's. Figure 76 clearly shows each DOF including the passive joint at the wrist connection to the hand.

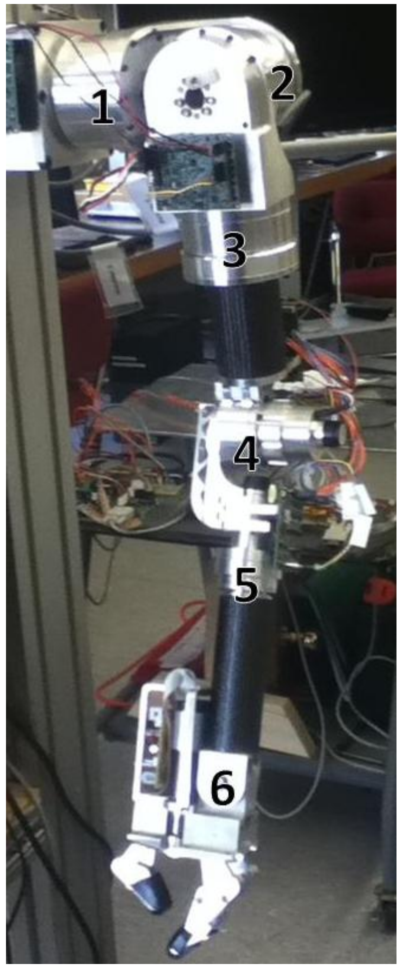

Figure 76: Bucknell Humanoid Robot Arm DOF's

5.2 Test #2 – Position Accuracy of the End Effector

The next test was to test the accuracy of the arm. Before the test began, a marker was attached to the arm using tape and nylon straps. The arm was then moved from its starting point to a predetermined position. This position was marked on a dry erase board that was placed in front of the arm. To prevent the board from moving the wheels on the board were locked. This was repeated a total of five times, and the distance between the farthest two points was measured. The resulting distance was 0.75 inches, which is below the required value of one inch, so the Bucknell Humanoid Robot Arm met its requirement of less than one inch. Figure 77 shows a snapshot from the test video which can be seen on YouTube. (http://www.youtube.com/watch?v=wotx8j6vAWY)

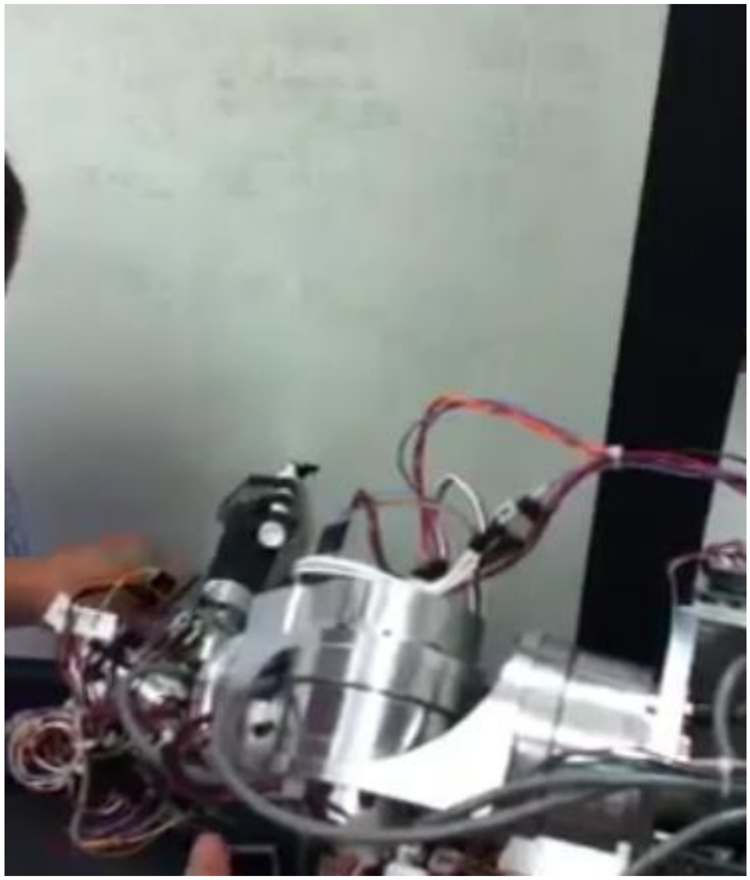

Figure 77: Bucknell Humanoid Robot Arm Accuracy Test

5.3 Test #3 – Max Joint Speed

Because the arm had to move at a relatively brisk speed, it was thought that 7.5 RPM was a relatively good speed. It allowed the arm to complete tasks in a timely manner but wasn't so slow that tasks took a long time to complete. It is also a safe speed to test at. Being that this was the first revision of the arm, having an overly fast arm was not needed. Testing the joint speed was very easy. Each joint had 2 points marked at certain limits in the joint motion. These points specified a certain angle. With this angle known, each joints rotation was timed. With these 2 values, the RPM values for each joint were found. All joints met or exceeded the 7.5 RPM value with the arm fully extended. With the elbow folded up to the upper arm, the shoulder joints were able to achieve an RPM value of 9.4 RPM. The requirement of 7.5 RPM at each joint was met by the Bucknell Humanoid Robot Arm.

5.4 Test #4 – Total Arm Length

Similar to the DOF test, this was a simple test to conduct. With the arm fully outstretched, the arm measured approximately 22.75 inches to the wrist. Therefore, the arm met the requirement of measuring 22.75 inches from shoulder to wrist. Figure 78 shows the arm being measured from shoulder to wrist.

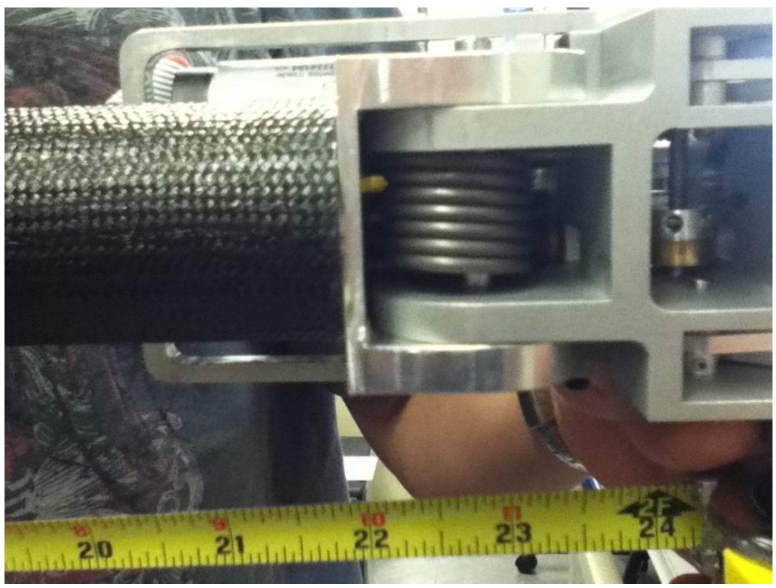

Figure 78: Arm Measurement

5.5 Test #5 – Max Arm Weight

Keeping the arm as light as possible was one of the most important tasks of the entire project. Compared to other arms reviewed in the section 1.2 - Literature Review, the Bucknell Humanoid Robot Arm's requirement of weighing less than 15 pounds was extreme compared to other arms. Most of the other arms weighed more than 20 pounds. Being able to complete tasks similar to the other reviewed robot arms, at a lower weight, would have been a great outcome of the project. After completely assembling the arm, it was placed on a scale. Including the hand, the arm weighed 13.25 pounds. Because this is a little over 1.5 pounds lighter than the required weight, the Bucknell Humanoid Robot Arm met its requirement of weighing less than 15 pounds. Figure 79 shows the arm being weighed.

Figure 79: Arm Max Weight Test

5.6 Test #6 – Max Load Fully Outstretched

Having a test that proved the calculations and design work done on the arm was also very crucial. This number provided a solid support to the design of the arm. When testing the max load of the arm, the arm's initial test was to hold 5 pounds fully outstretched. The arm did this with little struggle. Because this was one of the first tests completed, the amount of weight was not increased until the remaining tests were completed. Figure 80 shows the arm during the first strength test. Video of this test can be found on YouTube. (http://www.youtube.com/watch?v=4dbtwkQ5nGo)

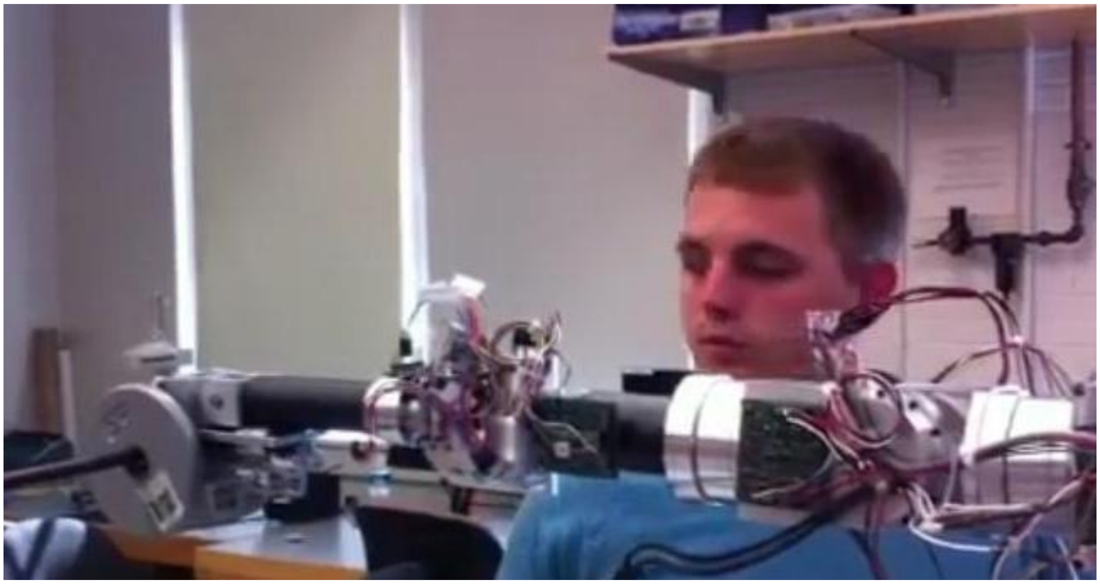

Figure 80: Outstretched Strength Test

After completion of the other tests, more weight was applied. The arm was set to a fully outstretched position. A spring scale was attached to the hand and weight was gradually applied until the arm began to drop. The amount of weight that was held before the arm began to sag was a little over 11 pounds. The arm met and exceeded its requirement of holding 5pounds fully outstretched.

5.7 Test #7 – Max Load-to-Weight Ratio

The max load-to-weight ratio requirement was also a very simple test to conduct. Taking the values of the max load fully outstretched weight and the weight of the arm and dividing them a value was found. It was decided that the arm should be able to lift 1/3 of its weight or have a max load-to-weight ratio of 0.33. After finding the fully outstretched strength weight, 11.00 lb, and the arm's weight, 13.25lb, the max load-to-weight ratio came out to 0.83. With this number exceeding the required max load-to-weight ratio of 0.33, the Bucknell Humanoid Robot Arm met its max load-to-weight ratio requirement.

5.8 Test #8 – Opening a Door

The only test that the arm did not succeed at was opening a door with a return damper system, but did successfully open a normal door without any struggle. With the power supply system used during testing, the arm was limited to 5 A per motor. The shoulder motors are rated at 8 A and this increase in current may provide enough torque to open the door.

This test was the most important task to the project because the arm would be put into urban environments where doors would be a regularly introduced obstacle. This was also the most complex of all the tasks expected to be completed by the Bucknell Humanoid Robot Arm. Figure 81 shows the arm successfully opening the normal door. Video of the Bucknell Humanoid Robot Arm opening a door can be found on YouTube. (http://www.youtube.com/watch?v=8_ilCur-am4)

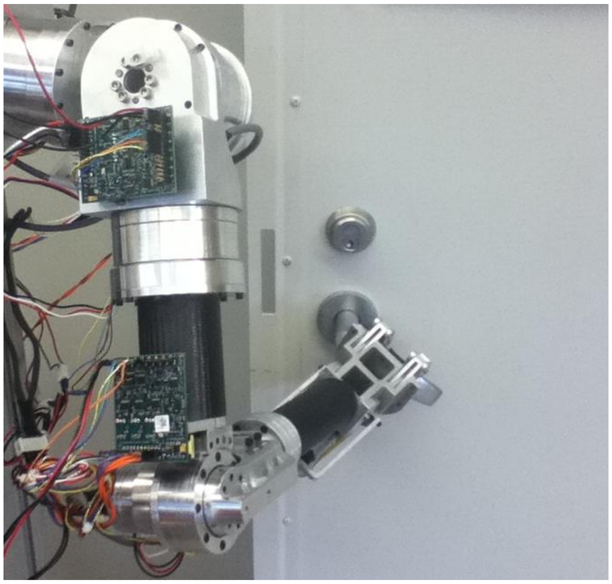

Figure 81: Successful Opening of a Door

Having completed the all of the tests and meeting all of the requirements, the arm could be considered a success. This success can be contributed to a lot of things, but most of it is due to the amount time spent making the arm as lightweight and compact as possible.

6.0 Realization

As with any project, there are many things learned along the way. The most important thing is evaluating what worked and what did not. This section will look at each step in the creation of the Bucknell Humanoid Robot Arm.

6.1 Realization – Design Objectives and Specifications

The design objectives and specifications portion was broken down into various sections to better describe what was expected of the arm. The first thing used was the Objective Tree. The Objective Tree worked well because it gave a great understanding of how the arm would be developed and also gave a route to finding design specifications. These design specifications were easily found due to the very fine detail the Objective Tree provided.

With the development of the Objective Tree came Operational Scenarios. The Operational Scenarios gave great insight into different environments such as office buildings or homes, and objects the robot arm may come in contact with, such as tools or doors. Knowing these environments and objects led to great information such as measureable specifications. These provided values like the amount of force needed to open a door. Knowing all of this information created a solid base for the design of the arm.

6.2 Realization – Design Process

The design process took the most time out of everything. The first step, which was probably the most crucial was coming up with an initial design and finding the torque, speed, and power values of each joint. By doing this, a great base was established for the future arm designs and the final arm design. Using the initial design, a simulation program was developed to find the previously mentioned values. These were then compared to other programs values and hand calculations which showed that the simulation program worked well and was a success.

Having a good simulation program allowed the solid modeling, motor selection, and gear train selection to begin. Exploring various designs and comparing the advantages and disadvantages of each made for a final design selection that was a compact and lightweight design. This lightweight and compact design was further lightened and made more compact by many iterations of the design, which in the end took more time but made for a solid design.

The method used for selecting the motors and gear train also worked well. By considering the different gear reductions available and combining them with appropriate motors, the required torque and speed values were obtained. Having these parts specified led to the design of the joints of the arm.

The individual joint designs were broken down, and depending on the size of the motors and harmonic drives, were designed with minor differences. These differences helped make each actuator lighter and more compact by only using the amount of material necessary and taking advantage of available space like the hollow portion inside of the shoulder joint. This is part of the reason why the arm ended up being lighter than required.

After completion of the joint designs, the brackets that connect them were created. Each bracket was specifically made to fit the joints properly and when put under load, deflect as little as possible. These brackets were then analyzed using FEA and showed very little deflection, less than two thousandths of an inch. The arm was then assembled using Solidworks to get the proper link lengths and overall arm length of 22.75 inches. All of these things combined created a good final design.

There are random times when certain actuators will stall or bind when running. Because the actuators run flawlessly otherwise, one explanation is mechanical problems due to the machining not being precise enough. The motors and harmonic drives are drastically affected by any small amount of misalignment. So any machining problems will cause the motors to run improperly. Another explanation may be a motor that is intermittently bad. For example, one of the halls may be sensing part of the time and causing a problem off and on.

6.3 Realization – Controls

The controls portion of the Bucknell Humanoid Robot Arm project worked, but was one of the most complex parts of the project due to everything having to be compatible with the Biped. The control cards were selected and by using the PMD GUI, the actuators were able to be moved. This was a big jump in the development of the controls because none of the actuators had been run previously.

Independent of the PMD GUI, C Code was written to control the motors. This was also a success and a good starting point to getting the motors running in Java and Yobotics SCS. With the C Code, a DLL was made. This DLL allowed the Java control code to communicate with the control card. Using Java, the DLL successfully ran and the actuators were controllable.

With a successful Java application, a control system was written using Java. This control code was also successful after many iterations.

6.4 Realization – Testing

As shown in Section 5.0 – Testing Results, the arm met or exceeded most of its requirement except for one which was open a spring damped door. All other requirements were met.

The first requirement of having four or more DOF's was verified by counting the number of actuators plus the passive wrist joint which gave six DOF's all together.

Next the accuracy test was completed. This was successfully completed by attaching a marker to the arm and placing a dry erase board in front of the arm. The arm successfully moved from point A to point B five consecutive times, resulting in an accuracy distance of 0.75 inches.

The next two tests were both simply done. The total length of the arm was measured using a tape measure along the length of the arm. The weight was done by weighing the arm on a digital scale as well as a spring scale. The resulting values, approximately 22.75 inches and 13.25 pounds, met the specified requirements.

The fully outstretched load test was also successful. The arm was set to a fully outstretched position and weight was added until the arm began to drop. This test worked out well and the resulting weight was 11 pounds which doubled the specified requirement of holding five pounds.

The max-load-to-weight test was also a success due to the arm being lightweight and lifting double the amount for which it was designed. The end result was a max load-to-weight ratio of 0.83.

Lastly, and probably the most important test was opening a door. Setting the arm in front of a door, the arm was placed on the door handle. The first try was with a spring dampened door. The arm struggled a bit when trying to open the door, which was conducted three times. After unsuccessfully opening the spring dampened door, the arm was moved to a normal un-damped door. After placing the arm on the door handle, the arm opened the normal door twice which was considered a success.

7.0 Future Modifications and Lessons Learned

Overall, the Bucknell Humanoid Robot Arm project was a success. But, with any project, modifications can always be made to make it better whether those changes are made to the current model or the future version. The first thing that can be done with the Bucknell Humanoid Robot Arm in the future is have the parts outsourced to a professional machine shop that has better, more precise equipment than the Bucknell PDL. This will ensure all the parts are made as they were designed. By having precision machined parts, one of the most complicated parts, the Oldham coupler, could be eliminated from the design. The Oldham coupler could be a large source of power loss in the arm, and eliminating it could further improve the test results.

An Oldham coupler can be very efficient, about 90% efficient, but if the parts aren't made correctly the efficiency will drop. Shown in the blue printed drawings in Appendices P, Q, and R, the Oldham couplers are the most inaccurate parts. The inaccuracy of the parts ranges from three thousandths to two hundredths. With these combined inaccuracies the mating tolerances are high, close to twenty five thousandths which is beyond the required one thousandth of an inch.

A lot of time was spent creating the housings for the motors and harmonic drives. Using framed motors and framed harmonic drives may be an option worth exploring. Since the requirement of having a 15 pound arm was exceeded by nearly 1.5 pounds the added weight of the framed motors and harmonic drives may not put the arm over the desired weight. With these parts being assembled with high precision, the previously mentioned machined parts could be eliminated. The only parts that would have to be machined would be the connection brackets and the intermediate parts to connect the motors to the harmonic drives.

The next thing that can be changed is making the overly strong parts, such as the arm brackets, lighter. This would reduce the weight of the parts as well as the overall weight of the arm. The parts could be analyzed with a FOS of two rather than three, which would make them weaker but still have acceptable deflection values of less than two thousandths. Though this is a consideration, the weight saved by making the brackets lighter may not be a considerable enough amount to be worth the time spent doing it.

The wrist and elbow motor housings could also be changed. Like the shoulder joints, they could have press-out pin slots added to them to ease motor removal. This would protect the motors from being heated in order to melt the adhesive holding them in.

The wiring on the Bucknell Humanoid Robot Arm was cluttered and could be reorganized and made more manageable. For example, quick disconnects could be used everywhere there is a wire termination. Some of the places they could be used are on the motors, encoders, and at the breakout box. This would make for safer more robust connections.

A continuation of the wiring redesign would be sending the encoder wires directly to the amplifiers. This would reduce the number of wires being sent up the arm by a total of 23 wires, which would reduce the wiring clutter. Lastly, another addition should be limit switches. These would allow for the arm to be homed electronically rather than the arm being manually set to a home position.

All of these changes combined would make the arm design better. It would allow for easier assembly and disassembly, possibly increase the efficiency of the actuators, as well as improve the test results which are already great.

8.0 Conclusion

Robotics is a rapidly growing discipline that is spread throughout a vast number of fields. Shown in the literature review, there are many robots that serve various purposes, and each was built using state-of-the-art standards. The Bucknell Humanoid Robot Arm project used these robots as models. With that said, the Humanoid Robot Arm could be of great significance to the robotics field. Like the other great robots in the field, it also used state-of-the-art technology and parts. By using this technology and these parts, a lightweight, compact, five DOF robot arm was built, and was able to successfully meet all of its design requirements and specifications. The only task it was not able to complete was opening a spring loaded door, but it was successful at opening an un-damped door. Although this task was not completed, and many challenges were introduced during the development of the Bucknell Humanoid Robot Arm, overall the project was a success.

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Appendices

Appendix A: Simulation Code

```
package armstuff;
import com.yobotics.simulationconstructionset.*;
import java.util.Scanner;
import java.util.StringTokenizer;
import java.io.*;
public class ArmController implements RobotController
{
	private MotorTest motor;
	private YoVariable tau_joint1, tau_joint2, tau_joint3, tau_joint4, tau_joint5,
			q_joint1, q_joint2, q_joint3, q_joint4, q_joint5,
			qd_joint1, qd_joint2, qd_joint3, qd_joint4, qd_joint5,
			qdd_joint1, qdd_joint2, qdd_joint3, qdd_joint4, time;
	private double tau1 , tau2, tau3, tau4,
					power1, power2, power3, power4,
					Kp1=20, Kd1 =25, Mul1 = .325/50*2.4,
					Kp2 = 20, Kd2=9,  Mul2 = 12.5/50,
					Kp3 = 2.2, Kd3 = .8, Mul3 = 1.1,
					Kp4 = 2, Kd4 = .7, Mul4 = 4,
					theta1=0, theta2=0, theta3=0, theta4=0,
					thetaC1 = 0, thetaC2=0, thetaC3=0, thetaC4=0,
					d1 =0, d2=0, d3=0, d4=0, Tmax12 = 30, Tmax34 =
30, pmax = 50,
					x = 5, y = 10, z =12, t_final = 1,
		tolerance = .2, divisions = 100;
				/*Kp1=22*2, Kd1 =9/5, Mul1 = .0325/2,
				  Kp2 = 22,      Kd2=9/5,  Mul2 = 1.25/2,
					Kp3 = 22; Kd3 = 9/2.5; Mul3 = 0.0325/4;
					Kp4 = 13; Kd4 = 3; Mul4 = .40/4;      */
		/*Kp3 = 20; Kd3 = 13; Mul3 = .325/50;
		Kp4 = 11; Kd4 = 1.5; Mul4 = 4.0/50;*/
		private final YoVariableRegistry registry = new
YoVariableRegistry("ArmController");
	public ArmController(ArmRobot state)
	{
	motor = new MotorTest();
		motor.setup();

		/*gets the current state of the robots joint1 values
		q_joint1 is the position of the joint
```

```
            qd_joint1 is the velocity of joint
            tau_joint1 is the torque at the joint
            to access or change the value of the joint use the .val extension*/
        q_joint1 = state.getVariable("q_joint1");
        qd_joint1 = state.getVariable("qd_joint1");
        qdd_joint1 = state.getVariable("qdd_joint1");
        tau_joint1 = state.getVariable("tau_joint1");

        q_joint2 = state.getVariable("q_joint2");
        qd_joint2 = state.getVariable("qd_joint2");
        qdd_joint2 = state.getVariable("qdd_joint2");
        tau_joint2 = state.getVariable("tau_joint2");

        q_joint3 = state.getVariable("q_joint3");
        qd_joint3 = state.getVariable("qd_joint3");
        qdd_joint3 = state.getVariable("qdd_joint3");
        tau_joint3 = state.getVariable("tau_joint3");

        q_joint4 = state.getVariable("q_joint4");
        qd_joint4 = state.getVariable("qd_joint4");
        qdd_joint4 = state.getVariable("qdd_joint4");
        tau_joint4 = state.getVariable("tau_joint4");

        q_joint5 = state.getVariable("q_joint5");
        qd_joint5 = state.getVariable("qd_joint5");
        tau_joint5 = state.getVariable("tau_joint5");

        time = state.getVariable("t");
        }

        public void doControl()
        {
        double w_noload = 9620, t_stall = .268, gear_ratio=100; //t_stall in mNm and
w_noload in rpm
            if(time.val == 0)
            {
            boolean check = false;
            double minAngle2 = 80;//in degrees
            double minAngle4 = 45;//in degrees

            theta1 = q_joint1.val;
            theta2 = q_joint2.val;
            theta3 = q_joint3.val;
            theta4 = q_joint4.val;
```

```
while((theta1 <= q_joint1.val+2*Math.PI)&&((check == false)))
        {
                //increments theta1
                theta1 = theta1 + 2*Math.PI/divisions;
                while((theta2 <= q_joint2.val+2*Math.PI)&&(check == false))
                {
                        theta2 = theta2 + 2*Math.PI/divisions;
                        while((theta3 <= q_joint3.val+2*Math.PI)&&(check ==
false))
                        {
                                theta3 = theta3 + 2*Math.PI/divisions;
                        while((theta4 <= q_joint4.val+2*Math.PI)&&(check ==
false))
                                {
                                        theta4 = theta4 + 2*Math.PI/divisions;
                                        System.out.println("elbow updated"); //
=============================================================
===============                                         double C1 =
Math.cos(theta1), S1 = Math.sin(theta1),
                                                        C2 = Math.cos(theta2), S2 =
Math.sin(theta2),
                                                        C3 = Math.cos(theta3), S3 =
Math.sin(theta3),
                                                        C4 = Math.cos(theta4), S4 =
Math.sin(theta4),
                                                        L1 = 3, L2 = 4.75, L3 = 5, L4 = 10;
        double currentX = -L2*C1*S2 - L3*C1*S2 + L4*(-C1*C4*S2 - (C1*C2*C3 -
S1*S3)*S4),
          currentY = -L2*S1*S2 - L3*S1*S2 + L4*(-C4*S1*S2 - (C2*C3*S1 +
C1*S3)*S4),
          currentZ = L1 + L2*C2 + L3*C2 + L4*(C2*C4 - C3*S2*S4);
if((currentX - tolerance < x)&&(x < currentX+tolerance))
        {
                f((currentY - tolerance < y)&&(y < currentY+tolerance))
                {
                if((currentZ - tolerance < z)&&(z < currentZ+tolerance))
                                                        {
if((theta2 <= (180-minAngle2)*Math.PI/180)||(theta2 >=
(180+minAngle2)*Math.PI/180))
                                                                {
if((theta4 <= (180-minAngle4)*Math.PI/180)||(theta4 >=
(180+minAngle4)*Math.PI/180))
                                                                        {
        FileOutputStream fout;
```

```
            try
                                                                                {
        fout = new FileOutputStream ("thetas.txt");
theta1 = -Math.PI/2;
theta2 = -Math.PI/2;
theta3 = -Math.PI/2;
theta4 = -Math.PI/2;*/
        new PrintStream(fout).println (theta1 + " " + theta2 + " " + theta3 + " " + theta4);
fout.close();
                                                                                }
        catch (IOException e)
                                                                                {
        System.err.println ("Unable to write to file");
        System.exit(-1);
                                                                                }
                                                        thetaC1 = theta1;
                                                        thetaC2 = theta2;
                                                        thetaC3 = theta3;
                                                        thetaC4 = theta4;
                                                        check = true;
                                                                }
                                                         }
                                                    }
                                                  }
                                             }
                                            }
                                            //reset theta 4, for next loop
                                            theta4 = q_joint4.val;
                                    }
                                    //reset theta 3, for next loop
                                    theta3 = q_joint3.val;
                            }
                            //reset theta 2, for next loop
                            theta2 = q_joint2.val;
                    }
                            if(check == false)
                            {
                                    System.out.println("No Solutions Exist");
                            }
            else
            {
                    FileInputStream fin;
                    try
                    {
```

```
                    fin = new FileInputStream ("thetas.txt");
String readin = new DataInputStream(fin).readLine();
StringTokenizer st = new StringTokenizer(readin, " ");
                    String t1 = st.nextToken();
                    String t2 = st.nextToken();
                    String t3  = st.nextToken();
                    String t4 = st.nextToken();
                    thetaC1 = Double.valueOf(t1.trim()).doubleValue();
                    thetaC2 = Double.valueOf(t2.trim()).doubleValue();
                    thetaC3 = Double.valueOf(t3.trim()).doubleValue();
                    thetaC4 = Double.valueOf(t4.trim()).doubleValue();
                  }
                  catch (IOException e)
                  {
                        System.err.println ("Unable to read the file");
                        System.exit(-1);
                  }
            }
            /*if((time.val<t_final)&&(time.val>.5))
            {
                    thetaC1 = thetaC1/2*(1-Math.cos(Math.PI*time.val/t_final));
                    thetaC2 = thetaC2/2*(1-Math.cos(Math.PI*time.val/t_final));
                    thetaC3 = thetaC3/2*(1-Math.cos(Math.PI*time.val/t_final));
                    thetaC4 = thetaC4/2*(1-Math.cos(Math.PI*time.val/t_final));
            }*/
                        /*
                    if(thetaC1 >= 2*Math.PI)
                    {
                        thetaC1 = thetaC1-2*Math.PI;
                    }
                    if(thetaC1 < 0)
                    {
                        thetaC1 = thetaC1+2*Math.PI;
                    }
                    if(thetaC2 >= 2*Math.PI)
                    {
                        thetaC2 = thetaC2-2*Math.PI;
                    }
                    if(thetaC2 < 0)
                    {
                        thetaC2 = thetaC2+2*Math.PI;
                    }
                    if(thetaC3 >= 2*Math.PI)
                    {
```

```
        thetaC3 = thetaC3-2*Math.PI;
    }
    if(thetaC3 < 0)
    {
        thetaC3 = thetaC3+2*Math.PI;
    }
    if(thetaC4 >= 2*Math.PI)
    {
        thetaC4 = thetaC4-2*Math.PI;
    }
    if(thetaC4 < 0)
    {
        thetaC4 = thetaC4+2*Math.PI;
    }
    double cur1 = q_joint1.val, cur2 = q_joint2.val, cur3 =
q_joint3.val, cur4 = q_joint4.val;
    if(cur1 >= 2*Math.PI)
    {
        cur1 = cur1-2*Math.PI;
    }
    if(cur1 < 0)
    {
        cur1 = cur1+2*Math.PI;
    }
    if(cur2 >= 2*Math.PI)
    {
        cur2 = cur2-2*Math.PI;
    }
    if(cur2 < 0)
    {
        cur2 = cur2+2*Math.PI;
    }
    if(cur3 >= 2*Math.PI)
    {
        cur3 = cur3-2*Math.PI;
    }
    if(cur3 < 0)
    {
        cur3 = cur3+2*Math.PI;
    }
    if(cur4 >= 2*Math.PI)
    {
        cur4 = cur4-2*Math.PI;
    }
```

```
if(cur4 < 0)
{
        cur4 = cur4+2*Math.PI;
}
if(time.val == 0)
{
if(thetaC1 > Math.PI)
{
        if((cur1 < thetaC1)&&(cur1 > Math.PI))
        {
                d1 = 0;
        }
        else
        {
                d1 = 1;
        }
}
if(thetaC1 <= Math.PI)
{
        if((cur1 > thetaC1)&&(cur1 < Math.PI))
        {
                d1 = 1;
        }
        else
        {
                d1 = 0;
        }
}
if(thetaC2 > Math.PI)
{
        if((cur2 < thetaC2)&&(cur2 > Math.PI))
        {
                d2 = 0;
        }
        else
        {
                        d2 = 1;
        }
}
if(thetaC2 <= Math.PI)
{
        if((cur2 > thetaC2)&&(cur2 < Math.PI))
        {
                        d2 = 1;
```

```
        }
        else
        {
                d2 = 0;
        }
}
if(thetaC3 > Math.PI)
{
        if((cur3 < thetaC3)&&(cur3 > Math.PI))
        {
                d3 = 0;
        }
        else
        {
                d3 = 1;
        }
}
if(thetaC3 <= Math.PI)
{
        if((cur3 > thetaC3)&&(cur3 < Math.PI))
        {
                d3 = 1;
        }
        else
        {
                d3 = 0;
        }
}
if(thetaC4 > Math.PI)
{
        if((cur4 < thetaC4)&&(cur4 > Math.PI))
        {
                d4 = 0;
        }
        else
        {
                d4 = 1;
        }
}
if(thetaC4 <= Math.PI)
{
        if((cur4 > thetaC4)&&(cur4 < Math.PI))
        {
                d4 = 1;
```

```
                }
                else
                {
                        d4 = 0;
                }
            }
            FileOutputStream fout2;
                try
                {
                   fout2 = new FileOutputStream ("dir.txt");

          new PrintStream(fout2).println (d1 + " " + d2 + " " + d3 + " " +
d4);
                   fout2.close();
                }
                catch (IOException e)
                {
                        System.err.println ("Unable to write to file");
                        System.exit(-1);
                }
          }
            FileInputStream fin2;
            try
            {
            fin2 = new FileInputStream ("dir.txt");
            String dirs = new DataInputStream(fin2).readLine();

            StringTokenizer s = new StringTokenizer(dirs, " ");
            String d1s = s.nextToken();
            String d2s = s.nextToken();
            String d3s = s.nextToken();
            String d4s = s.nextToken();
            d1 = Double.valueOf(d1s.trim()).doubleValue();
            d2 = Double.valueOf(d2s.trim()).doubleValue();
            d3 = Double.valueOf(d3s.trim()).doubleValue();
            d4 = Double.valueOf(d4s.trim()).doubleValue();
            }
            catch (IOException e)
                {
                        System.err.println ("Unable to write to file");
                        System.exit(-1);
                }
            double[] T_Grav = new double[4];
    T_Grav = getGrav(q_joint1.val,q_joint2.val,q_joint3.val,q_joint4.val);
```

```
if(d1 == 0)
{
        tau1=(Kp1*(thetaC1 - q_joint1.val)-
(qd_joint1.val*Kd1))*Mul1 + T_Grav[0];
}
if(d1 == 1)
{
        tau1=(-Kp1*(-thetaC1 + (2*Math.PI+q_joint1.val))-
(qd_joint1.val*Kd1))*Mul1 + T_Grav[0];
}
if(d2 == 0)
{
    tau2=(Kp2*(thetaC2 - q_joint2.val)-(qd_joint2.val*Kd2))*Mul2 +
T_Grav[1];
}
if(d2 == 1)
{
tau2=(-Kp2*(-thetaC2 + 2*Math.PI + q_joint2.val)-(qd_joint2.val*Kd2))*Mul2 +
T_Grav[1];
}
if(d3 == 0)
{
    tau3=(Kp3*(thetaC3 - q_joint3.val)-(qd_joint3.val*Kd3))*Mul3 +
T_Grav[2];
}
if(d3 == 1)
{
tau3=(-Kp3*(-thetaC3 + (2*Math.PI+q_joint3.val))-(qd_joint3.val*Kd3))*Mul3 +
T_Grav[2];
}

if(d4 == 0)
{
tau4=(Kp4*(thetaC4 - q_joint4.val)-(qd_joint4.val*Kd4))*Mul4 + T_Grav[3];
}
if(d4 == 1)
{
tau4=(-Kp4*(-thetaC4 + (2*Math.PI+q_joint4.val))-(qd_joint4.val*Kd4))*Mul4 +
T_Grav[3];
}
w_noload = 9620;
t_stall = .268;
w_noload = w_noload * 3.14159/30*1/gear_ratio;
t_stall = t_stall*gear_ratio;
```

```
double tlim1=  t_stall-t_stall/w_noload*Math.abs(qd_joint1.val),
      tlim2=  t_stall-t_stall/w_noload*Math.abs(qd_joint2.val),
      tlim3=  t_stall-t_stall/w_noload*Math.abs(qd_joint3.val),
      tlim4=  t_stall-t_stall/w_noload*Math.abs(qd_joint4.val);
if(Math.abs(tlim1) < Math.abs(tau1))
{
          if(tau1<0)
          tau1=-Math.abs(tlim1);
          if(tau1>0)
          tau1=Math.abs(tlim1);
}
if(Math.abs(tlim2) < Math.abs(tau2))
{
          if(tau2<0)
          tau2=-Math.abs(tlim2);
          if(tau2>0)
          tau2=Math.abs(tlim2);
}
if(Math.abs(tlim3) < Math.abs(tau3))
{
          if(tau3<0)
          tau3=-Math.abs(tlim3);
          if(tau3>0)
          tau3=Math.abs(tlim3);
}
if(Math.abs(tlim4) < Math.abs(tau4))
{
          if(tau4<0)
          tau4=-Math.abs(tlim4);
          if(tau4>0)
          tau4=Math.abs(tlim4);
}
 power1 = tau1*qd_joint1.val;
 power2 = tau2*qd_joint2.val;
 power3 = tau3*qd_joint3.val;
 power4 = tau4*qd_joint4.val;
 if(time.val == 0)
 {
 FileOutputStream fout;
        try
        {
fout = new FileOutputStream ("power.txt");
new PrintStream(fout).println (time.val + " " + power1 + " " + power2 + " " + power3 + "
" + power4 + "\n");
```

```
                                        fout.close();
                                    }
                                    catch (IOException e)
                                    {
                                            System.err.println ("Unable to write to file");
                                            System.exit(-1);
                                    }
                            }
                            else
                            {
                                    File file = new File("power.txt");
                                                    try
                                        {
                                            FileWriter writer = new FileWriter(file, true);
writer.write(time.val + " " + power1 + " " + power2 + " " + power3 + " " + power4 +
"\r\n");
                                            writer.flush();
                                            writer.close();
                                        }
                                        catch (IOException e)
                                        {
                                            e.printStackTrace();
                                        }
                            }
                            /*
                        double[] T_Grav1 = new double[4];
                        T_Grav1 =
getGrav(q_joint1.val,q_joint2.val,q_joint3.val,q_joint4.val);
                          tau1 = T_Grav1[0];
                          tau2= T_Grav1[1];
                          tau3 = T_Grav1[2];
                          tau4 =T_Grav1[3];*/
                         tau_joint1.val= tau1;
                         tau_joint2.val= tau2;
                         tau_joint3.val= tau3;
                         tau_joint4.val= tau4;
        }
        public YoVariableRegistry getYoVariableRegistry()
        {
                return registry;
        }
        public double[] getGrav(double th1, double th2, double th3, double th4)
        {
                double[] tq;
```

```
			double g = 9.81, m1 = 1.131, m2 = .43091, m3 = .8986, m4 = 4.5962,
					Lcm1 = .04332,		Lcm2 = .0531,Lcm3 =  .0884, Lcm4
= .222,
					L1 = .0762,	L2 = .12065, L3 = .127, L4 = .254;
			double C1 = Math.cos(th1), S1 = Math.sin(th1),
				C2 = Math.cos(th2), S2 = Math.sin(th2),
				C3 = Math.cos(th3), S3 = Math.sin(th3),
				C4 = Math.cos(th4), S4 = Math.sin(th4);
			tq = new double[4];
tq[0] = g*(Lcm4*m4*C1*S3*S4 + S1*((Lcm2*m2 + L2*m3 + Lcm3*m3 + L2*m4 +
L3*m4 + Lcm4*m4*C4)*S2 + Lcm4*m4*C2*C3*S4));
tq[1] = (-g)*C1*(C2*(Lcm2*m2 + L2*m3 + Lcm3*m3 + L2*m4 + L3*m4 +
Lcm4*m4*C4) - Lcm4*m4*C3*S2*S4);
			tq[2] = g*Lcm4*m4*(C3*S1 + C1*C2*S3)*S4;
			tq[3] = g*Lcm4*m4*(C4*S1*S3 + C1*((-C2)*C3*C4 + S2*S4));
			return tq;
		}
}
```

Appendix B: Carbon Fiber Tube Deflection Analysis

Force (F)	5
Pi	3.14
Outside Diameter (OD)	1
Wall Thickness	0.04
Inside Diameter (ID)	0.92
Length (L)	12
Moment of Inertia (MI)	0.01391447
Modulus of Elasticity (E)	34000000
Deflection (D)	0.006087611 inches

Moment of Inertia for a Tube
MI = (PI*(OD^4 - ID^4))/64
Deflection for a Hollow Tube
D = (F*L^3)/(3*E*M)

Appendix C: Motor Selection

GOOD	**Shoulder**	41 Nm	.78 rad/s or 7.5 rpm
Motor			
Voltage	Motor	Diameter (mm)	50.02
48	HT2000		
P (W)	RPM	Torque (Nm)	55 or 50 W motor
48	3986	0.480	

Gearhead			
	Reduction 1	Tmax Out 1	RPMmax Out 1
	100	48	39.860
Gearhead #	CSD-20-100	Tdes	RPM_Tdes
Diameter (mm)		41	5.813
Efficiency	1		

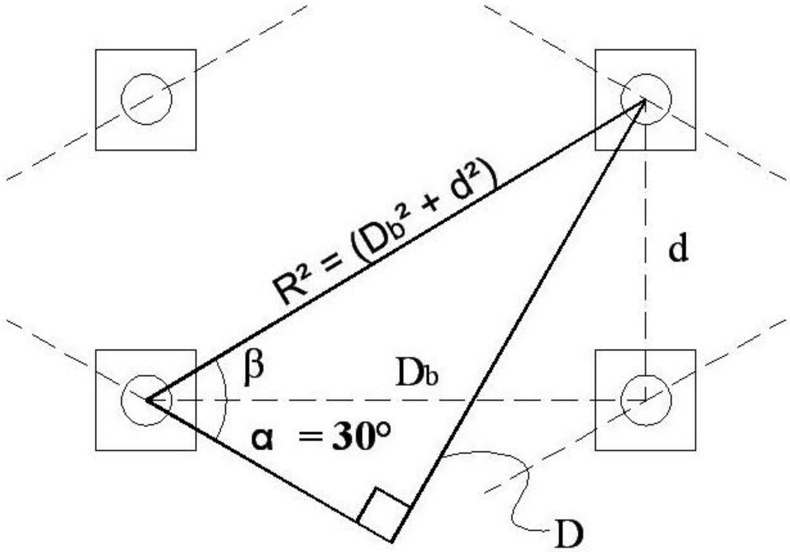
GOOD	**Elbow**	16 Nm	.78 rad/s or 7.5 rpm
Motor			
Voltage	Motor	Diameter (mm)	20.93333333
48	HT01500		
P (W)	RPM	Torque (Nm)	20 or 25 W motor
31	7301	0.210	

Gearhead			
	Reduction 1	Tmax Out 1	RPMmax Out 1
	100	21	73.010
Gearhead #	CSD-17-100	Tdes	RPM_Tdes
Diameter (mm)		16	17.383
Efficiency	1		

GOOD	**Wrist**	2 Nm	.78 rad/s or 7.5 rpm
Motor			
Voltage	Motor	Diameter (mm)	2.616666667
48	HT1000		
P (W)	RPM	Torque (Nm)	5 W motor
11	8580	0.090	

Gearhead			
	Reduction 1	Tmax Out 1	RPMmax Out 1
	100	9	85.800
Gearhead #	CSD -14-100	Tdes	RPM_Tdes
Diameter (mm)		5	38.133
Efficiency	1		

Appendix D: Angular Contact Bearing Calculations



d = distance between bearings

α = ACB angle

Db = distance between bearing pockets

R = affective ACB distance

$$\beta = \operatorname{atan}\frac{d}{D_b}$$

$$\frac{\alpha}{\sin\alpha} = \frac{\beta}{\sin\beta}$$

$$D = R\sin(\beta+\alpha)$$

	Shoulder1	**KAA20AR0**			
				ft-lb	**in-lb**
a	30		**Static TQ**	11.42	137.04
B	6.340191746				
d	0.25			**lb**	
D	1.341506351		**Fr**	60.90666667	
Db	2.25		**Fa**	60.53414533	
R	2.263846285		**Ft**	17.08	

	Shoulder2	**KAA20AR0**			
				ft-lb	**in-lb**
a	30		**Static**	11.42	137.04

			TQ		
B	6.340191746				
d	0.25			**lb**	
D	1.341506351		**Fr**	60.90666667	
Db	2.25		**Fa**	60.53414533	
R	2.263846285		**Ft**	14.98	

	Shoulder3	**KAA20AR0**			
				ft-lb	**in-lb**
a	30		**Static TQ**	11.42	137.04
B	6.340191746				
d	0.25			**lb**	
D	1.341506351		**Fr**	60.90666667	
Db	2.25		**Fa**	60.53414533	
R	2.263846285		**Ft**	13.28	

	Elbow	**KAA15AG0**			
				ft-lb	**in-lb**
a	30		**Static TQ**	6.97	83.64
B	6.340191746				
d	0.1875			**lb**	
D	1.006129763		**Fr**	49.56444444	
Db	1.6875		**Fa**	49.26129515	
R	1.697884713		**Ft**	12.13	

	Wrist	**KAA10AG0**			
				ft-lb	**in-lb**
a	30		**Static TQ**	6.97	83.64
B	8.972626615				
d	0.1875			**lb**	
D	0.756129763		**Fr**	70.43368421	
Db	1.1875		**Fa**	69.57178477	
R	1.202211504		**Ft**	11.00	

Appendix E: X Type Bearing Calculations

Shoulder1	KAA10XL0	CSD 20
F	45.53	**33.58**
T	39.81	
D	0.05	
B	5.60	
T/D	783.67	

Shoulder2	KAA10XL0	CSD 20
F	35.87	**26.46**
T	30.18	
D	0.05	
B	5.60	
T/D	594.10	

Shoulder3	KAA10XL0	CSD 20
F	30.24	**22.31**
T	24.57	
D	0.05	
B	5.60	
T/D	483.62	

Elbow	KAA10XL0	CSD 17
F	19.20	**14.16**
T	12.80	
D	0.04	
B	4.10	
T/D	296.40	

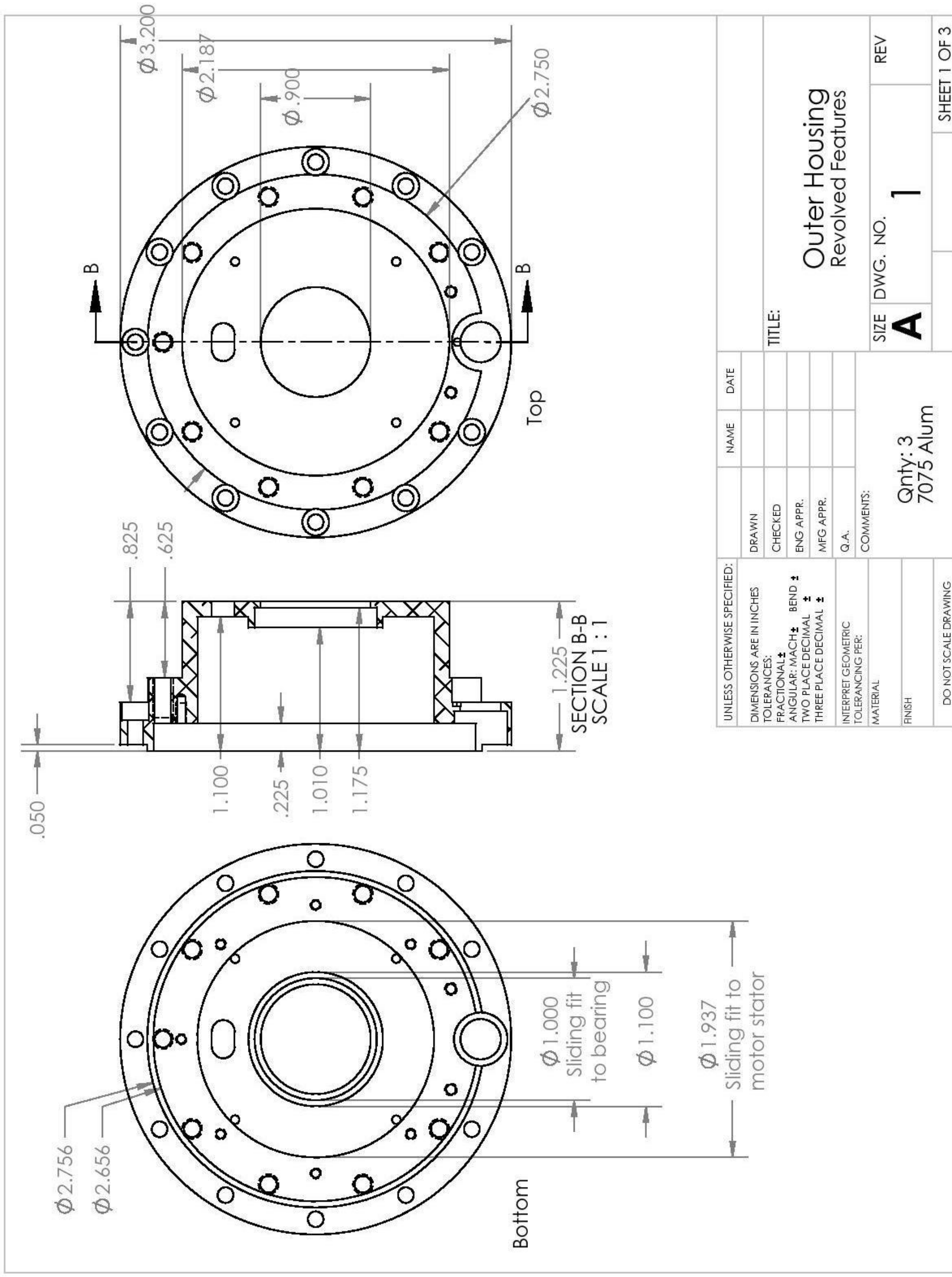
Wrist	KAA10AG0	CDS 14
F	13.68	**10.09**
T	8.08	
D	0.04	
B	2.10	
T/D	227.18	

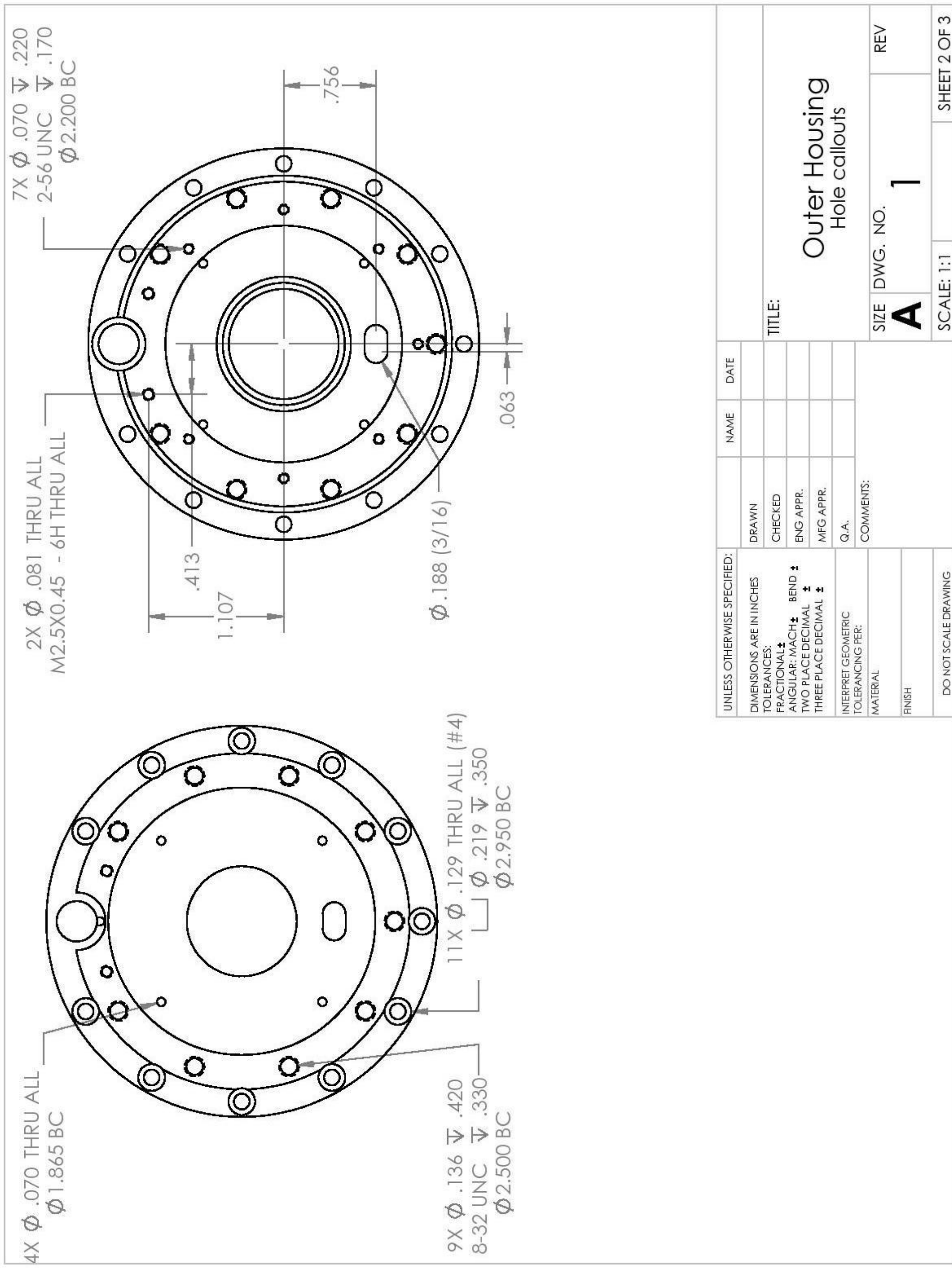
Appendix F: Joint Torque and Bracket Force Table

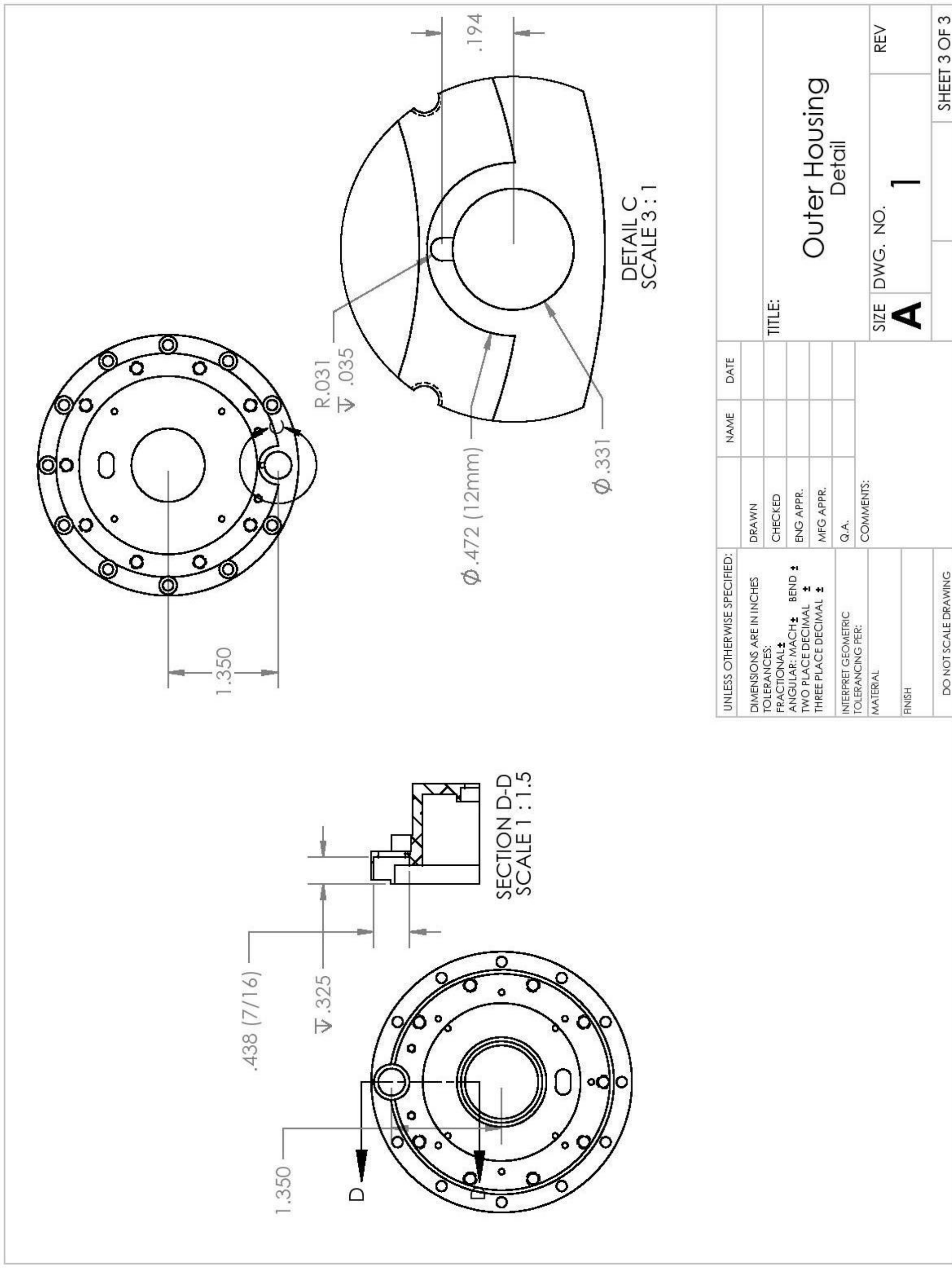
	Mass	Dist. from Base	S1 Torque	Dist. From S2	S2 Torque	Dist. from S3	S3 Torque	Dist. from Elbow	Elbow Torque	Dist. from Wrist	Wrist Torque	
Shoulder 1	1.50	1.25	20.74									
Bracket 1	0.60	3.28	0.16									
Shoulder 2	1.50	4.88	0.61	0.00	15.26							
Bracket 2	0.60	6.53	0.33	1.65	0.08							
Shoulder 3	1.50	8.13	1.02	3.25	0.41	0.00	12.20					
Bracket 3	0.20	14.38	0.24	9.50	0.16	6.25	0.10					
Elbow	1.15	15.88	1.52	11.00	1.05	7.75	0.74	0.00	6.11			
Bracket 4	0.34	17.38	0.49	12.50	0.35	9.25	0.26	1.50	0.04			
Wrist	0.79	19.38	1.28	14.50	0.95	11.25	0.74	3.50	0.23	0.00	3.79	
Hand + Mass	7.00	25.88	15.09	21.00	12.25	17.75	10.35	10.00	5.83	6.50	3.79	
	15.18		28.12	Nm	20.69	Nm	16.55	Nm	8.28	Nm	5.14	Nm

Bracket Forces	SB1	SB2	Elbow	Wrist
	13.08	10.98	9.28	7.79

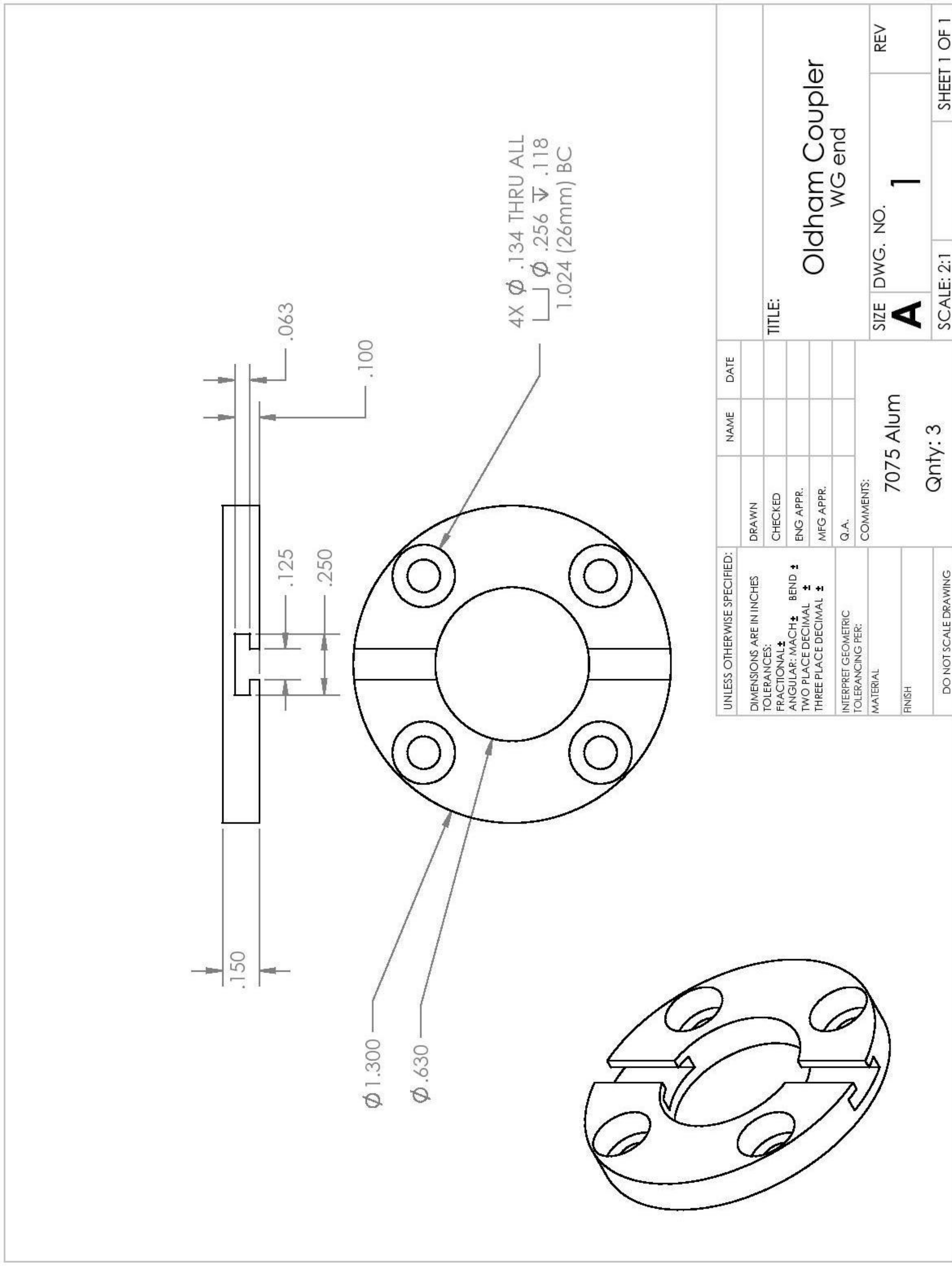
Appendix G: Shoulder Joint Drawings

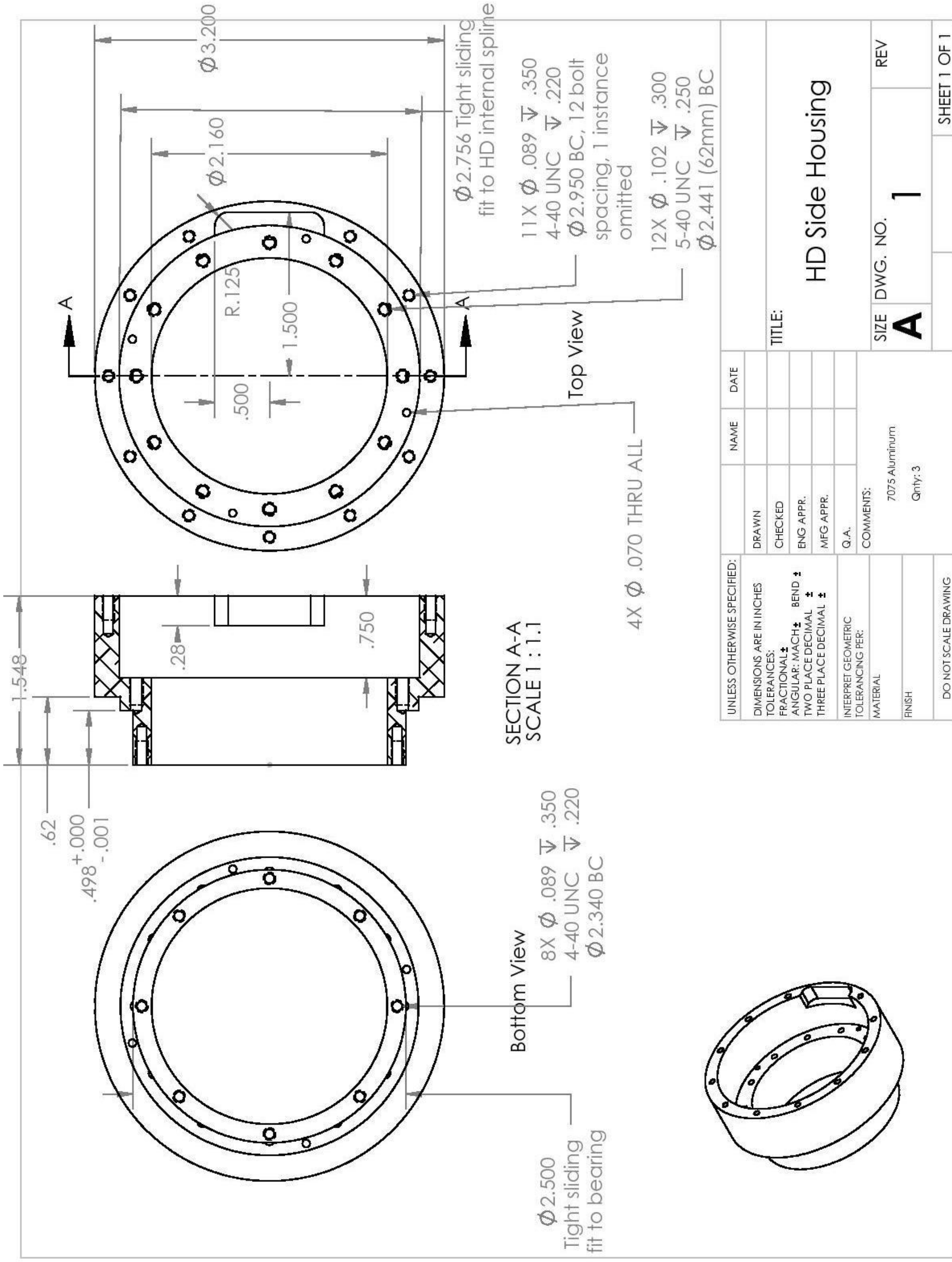


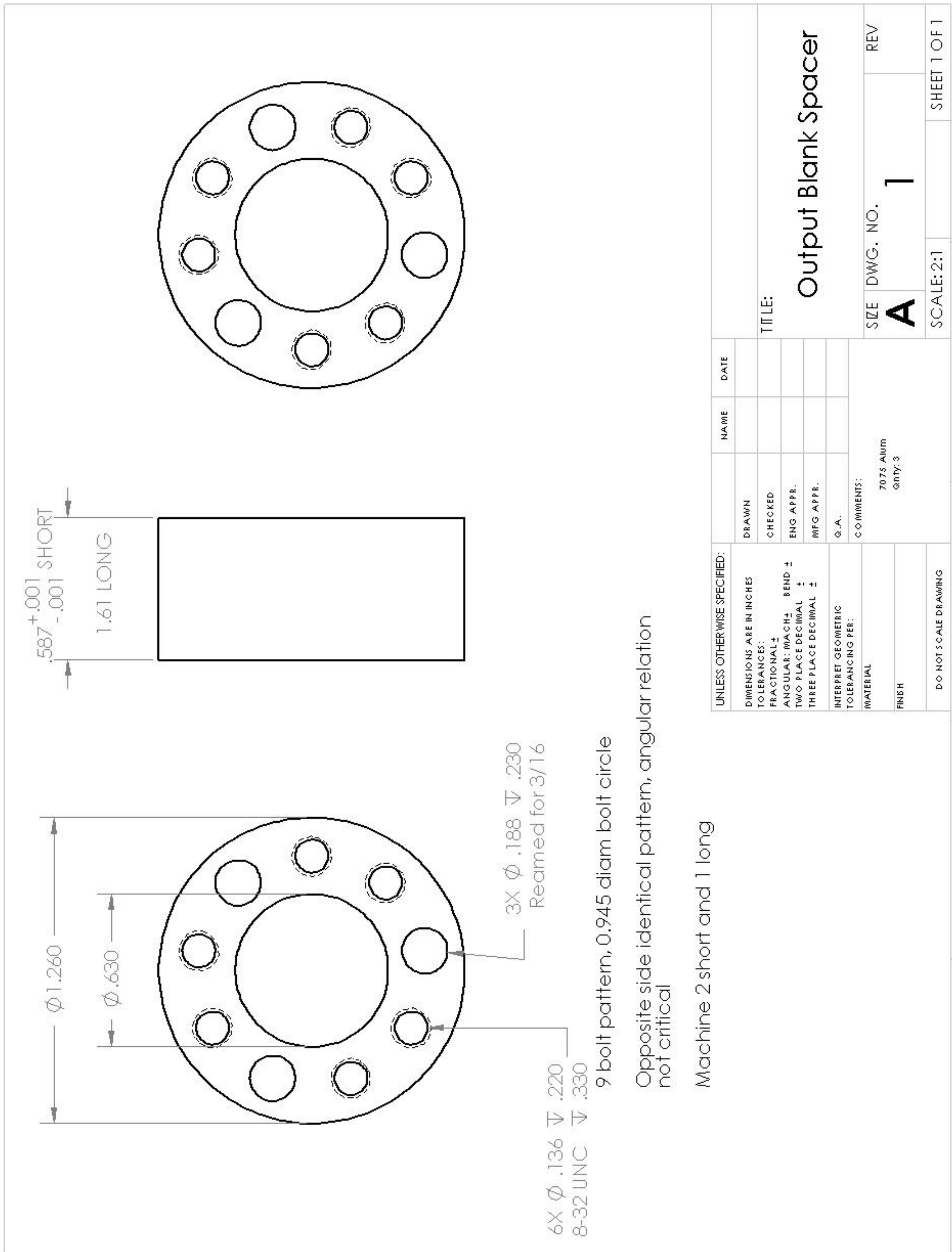

7X Ø .070 ↧ .220
2-56 UNC ↧ .170
Ø2.200 BC
.756
2X Ø .081 THRU ALL
M2.5X0.45 - 6H THRU ALL
.413
1.107
.063
Ø .188 (3/16)
4X Ø .070 THRU ALL
Ø1.865 BC
11X Ø .129 THRU ALL (#4)
⌴ Ø .219 ↧ .350
Ø2.950 BC
9X Ø .136 ↧ .420
8-32 UNC ↧ .330
Ø2.500 BC
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Outer Housing
Hole callouts
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
SHEET 2 OF 3
1
2
3
4
5



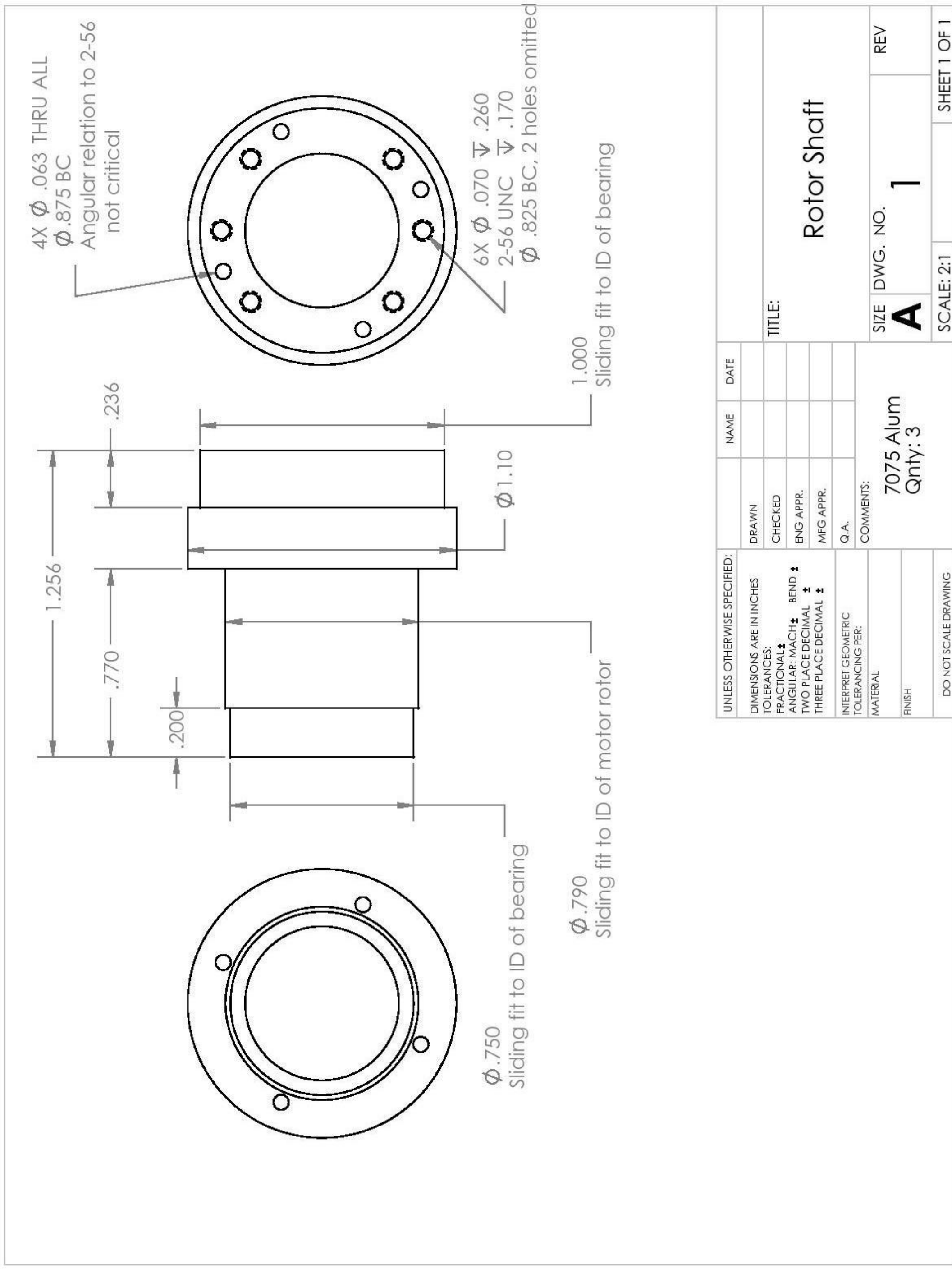
.438 (7/16)
.325
1.350
D
SECTION D-D
SCALE 1 : 1.5
1.350
R.031
.035
Ø.472 (12mm)
Ø.331
.194
DETAIL C
SCALE 3 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Outer Housing
Detail
SIZE
A
DWG. NO.
1
REV
SHEET 3 OF 3

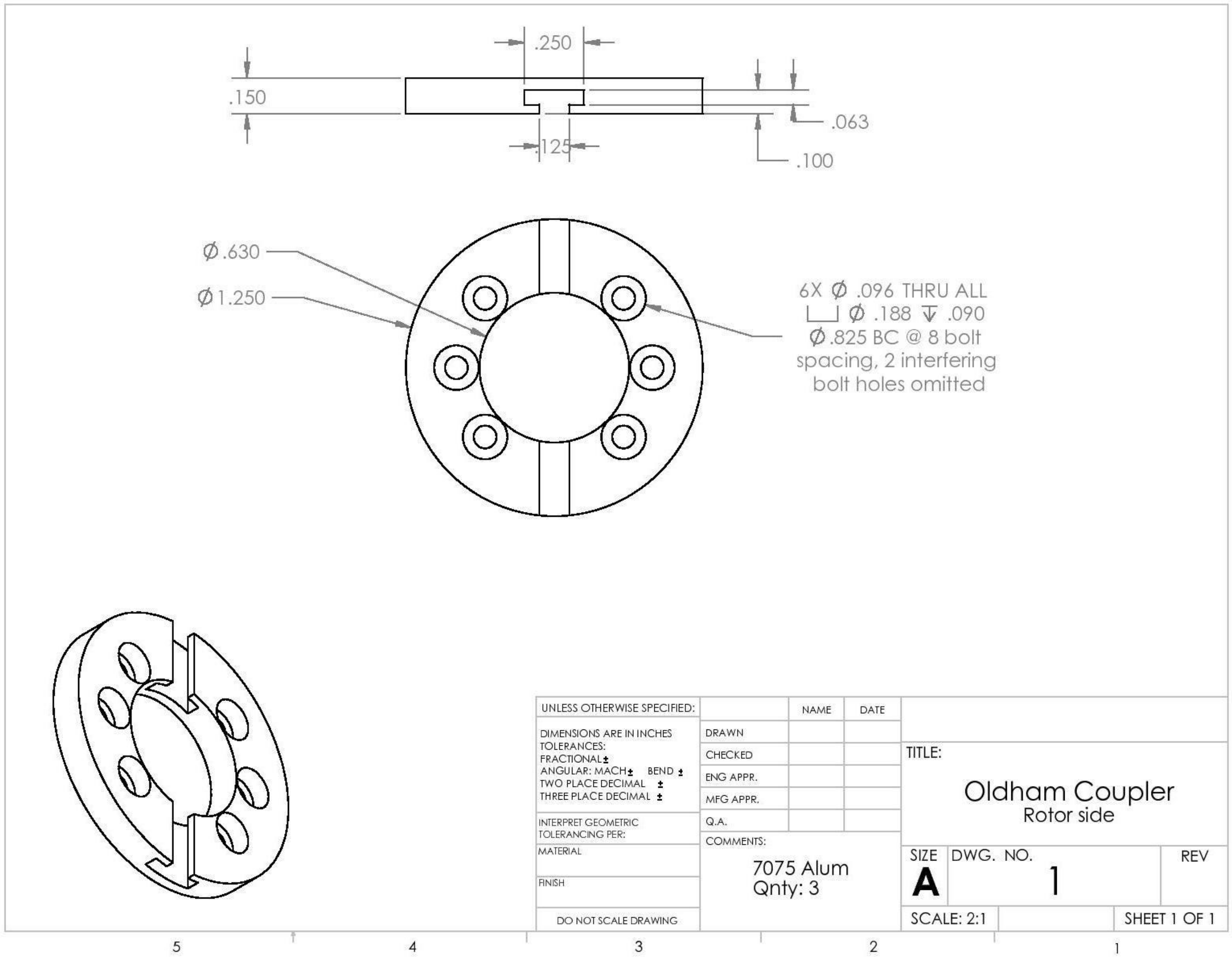

.063
.100
.125
.250
.150
Ø1.300
Ø.630
4X Ø .134 THRU ALL
⌴ Ø .256 ↧ .118
1.024 (26mm) BC
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Oldham Coupler
WG end
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1


Ø3.200
Ø2.756 Tight sliding fit to HD internal spline
Ø2.160
11X Ø .089 ↧ .350
4-40 UNC ↧ .220
Ø2.950 BC, 12 bolt spacing, 1 instance omitted
12X Ø .102 ↧ .300
5-40 UNC ↧ .250
Ø2.441 (62mm) BC
R.125
1.500
.500
A
A
Top View
4X Ø .070 THRU ALL
1.548
.28
.750
.62
.498 +.000 -.001
SECTION A-A
SCALE 1 : 1.1
Bottom View
8X Ø .089 ↧ .350
4-40 UNC ↧ .220
Ø2.340 BC
Ø2.500
Tight sliding fit to bearing
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Aluminum
Qnty: 3
TITLE:
HD Side Housing
SIZE
A
DWG. NO.
1
REV
SHEET 1 OF 1
1
2
3
4
5

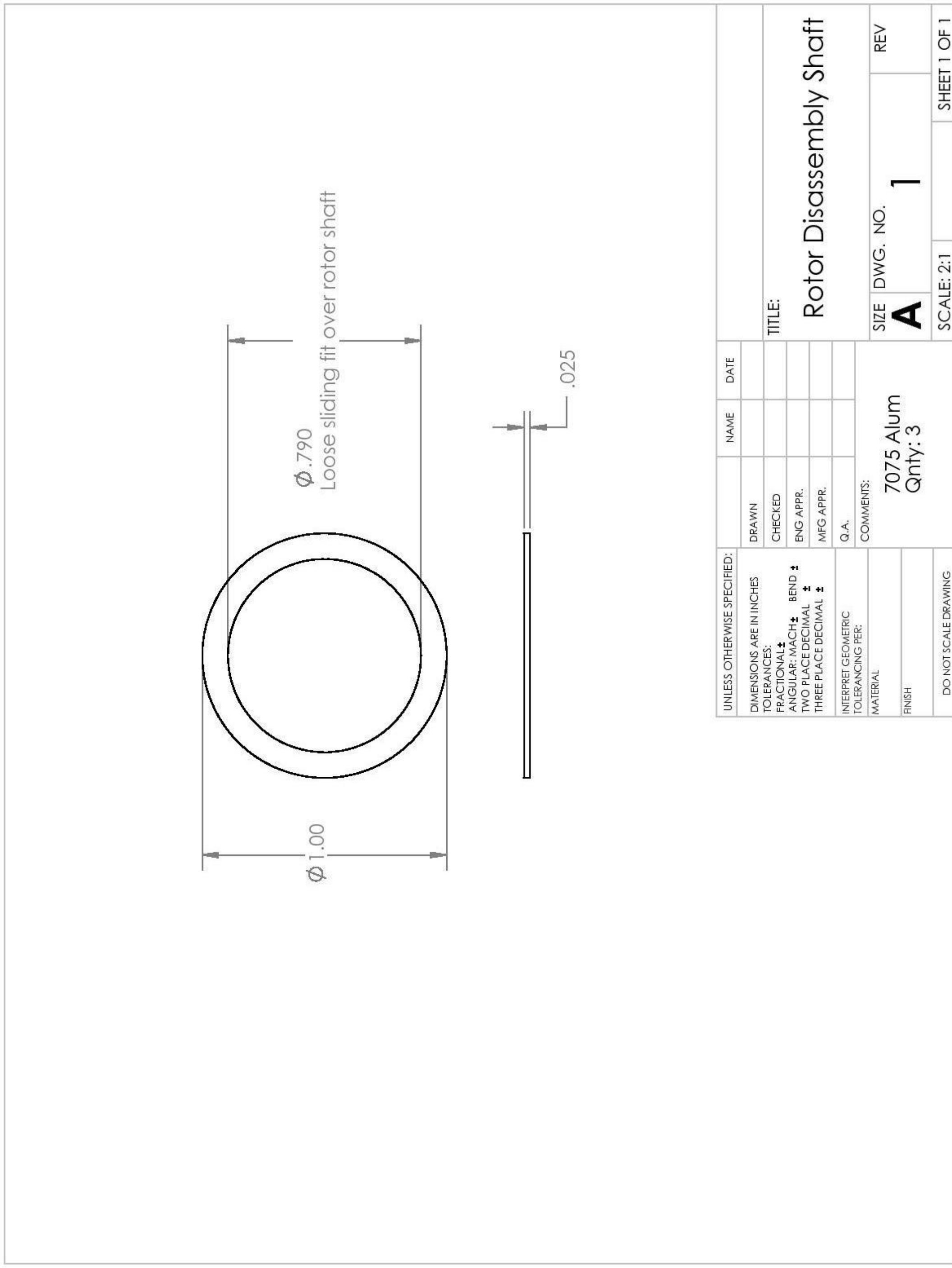


Ø1.260
Ø.630
6X Ø.136 ↧ .220
8-32 UNC ↧ .330
3X Ø .188 ↧ .230
Reamed for 3/16
.587 +.001 -.001 SHORT
1.61 LONG
9 bolt pattern, 0.945 diam bolt circle
Opposite side identical pattern, angular relation not critical
Machine 2 short and 1 long
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Output Blank Spacer
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1

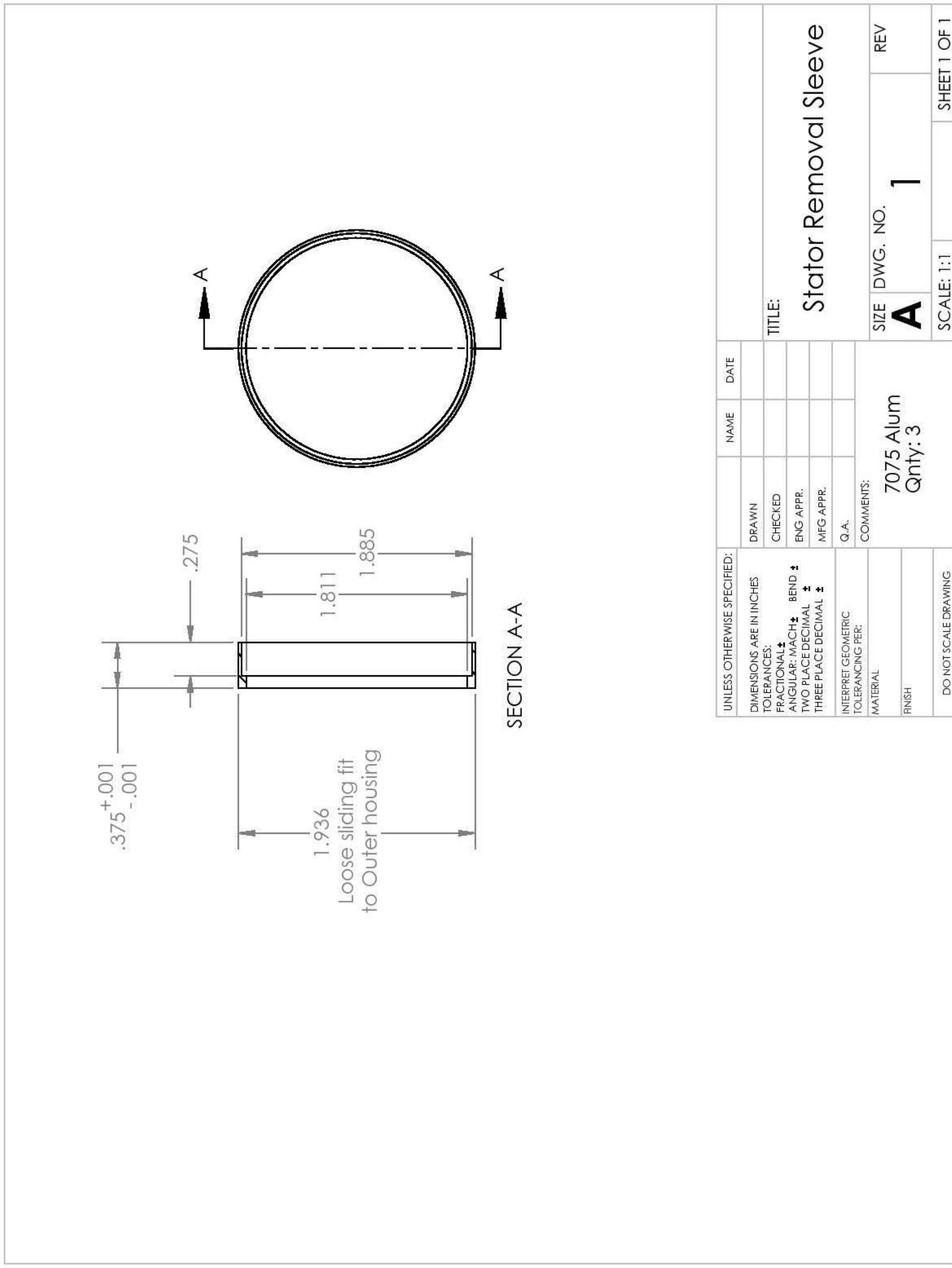

4X Ø .063 THRU ALL
Ø .875 BC
Angular relation to 2-56
not critical
6X Ø .070 ↧ .260
2-56 UNC ↧ .170
Ø .825 BC, 2 holes omitted
Sliding fit to ID of bearing
.236
1.000
Sliding fit to ID of bearing
1.256
.770
.200
Ø 1.10
Sliding fit to ID of motor rotor
Ø .790
Sliding fit to ID of bearing
Ø .750
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Rotor Shaft
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
1
2
3
4
5

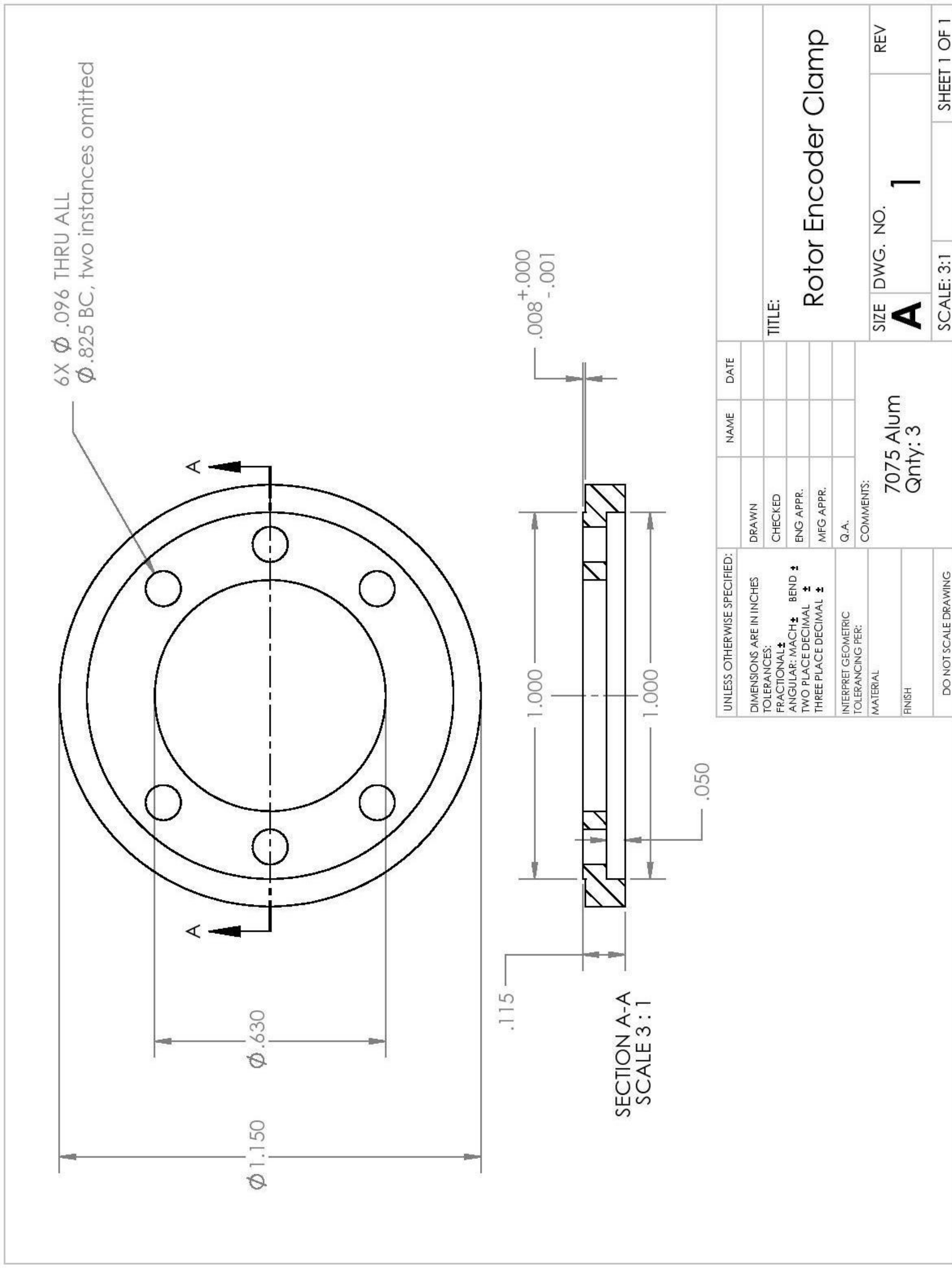


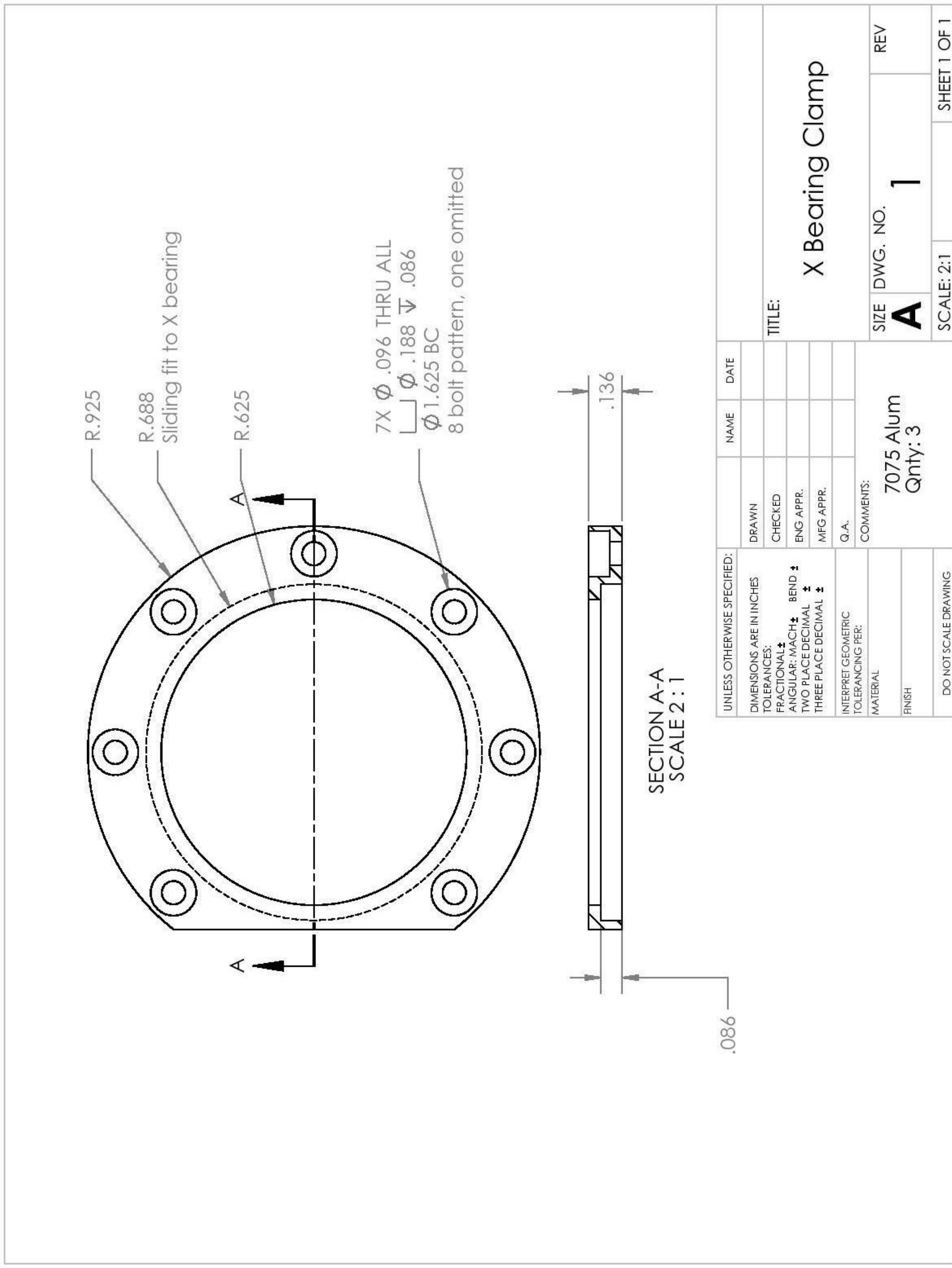
.250
.150
.125
.063
.100
Ø.630
Ø1.250
6X Ø .096 THRU ALL
Ø .188 ↧ .090
Ø.825 BC @ 8 bolt
spacing, 2 interfering
bolt holes omitted
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Oldham Coupler
Rotor side
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
5
4
3
2
1

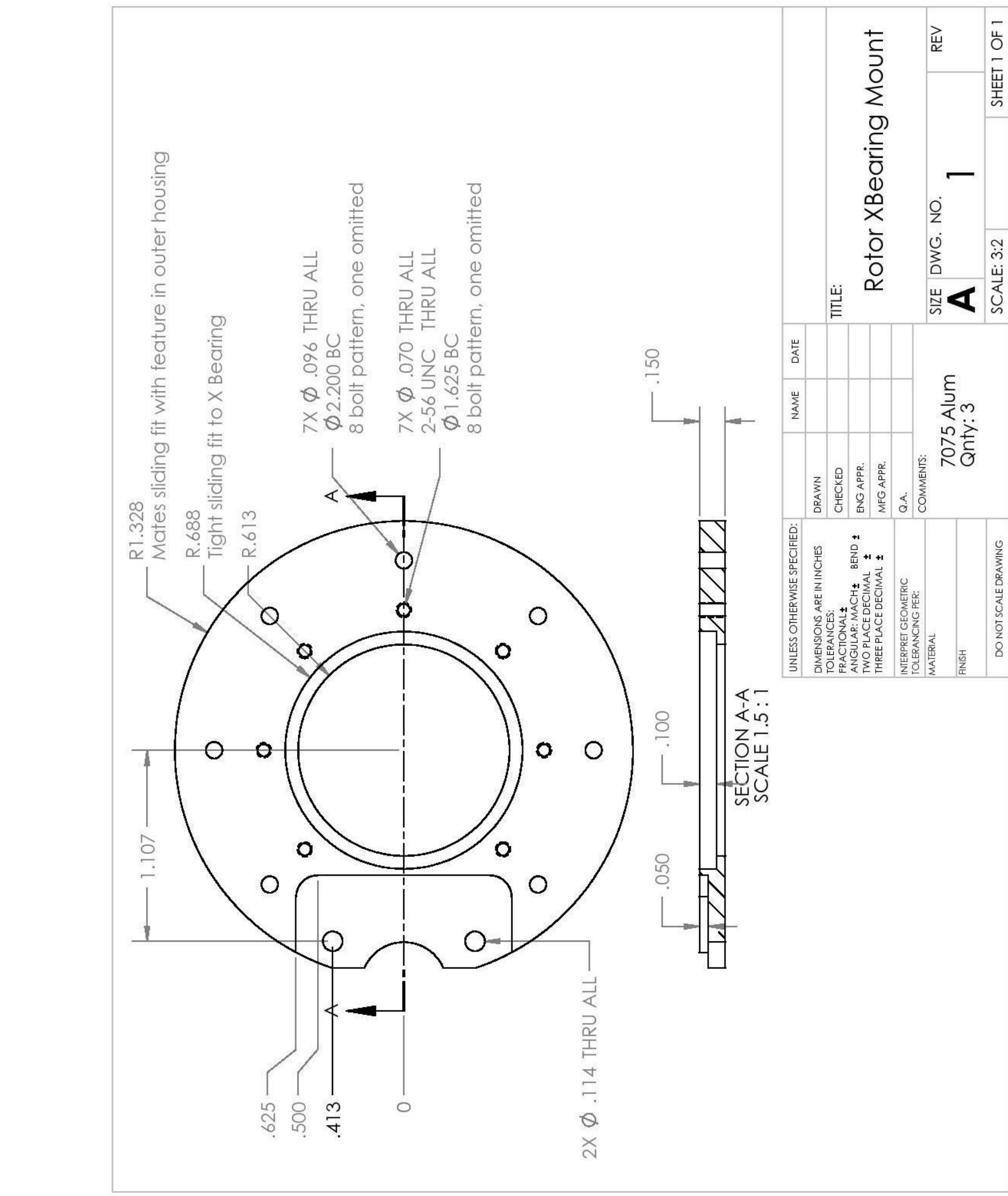


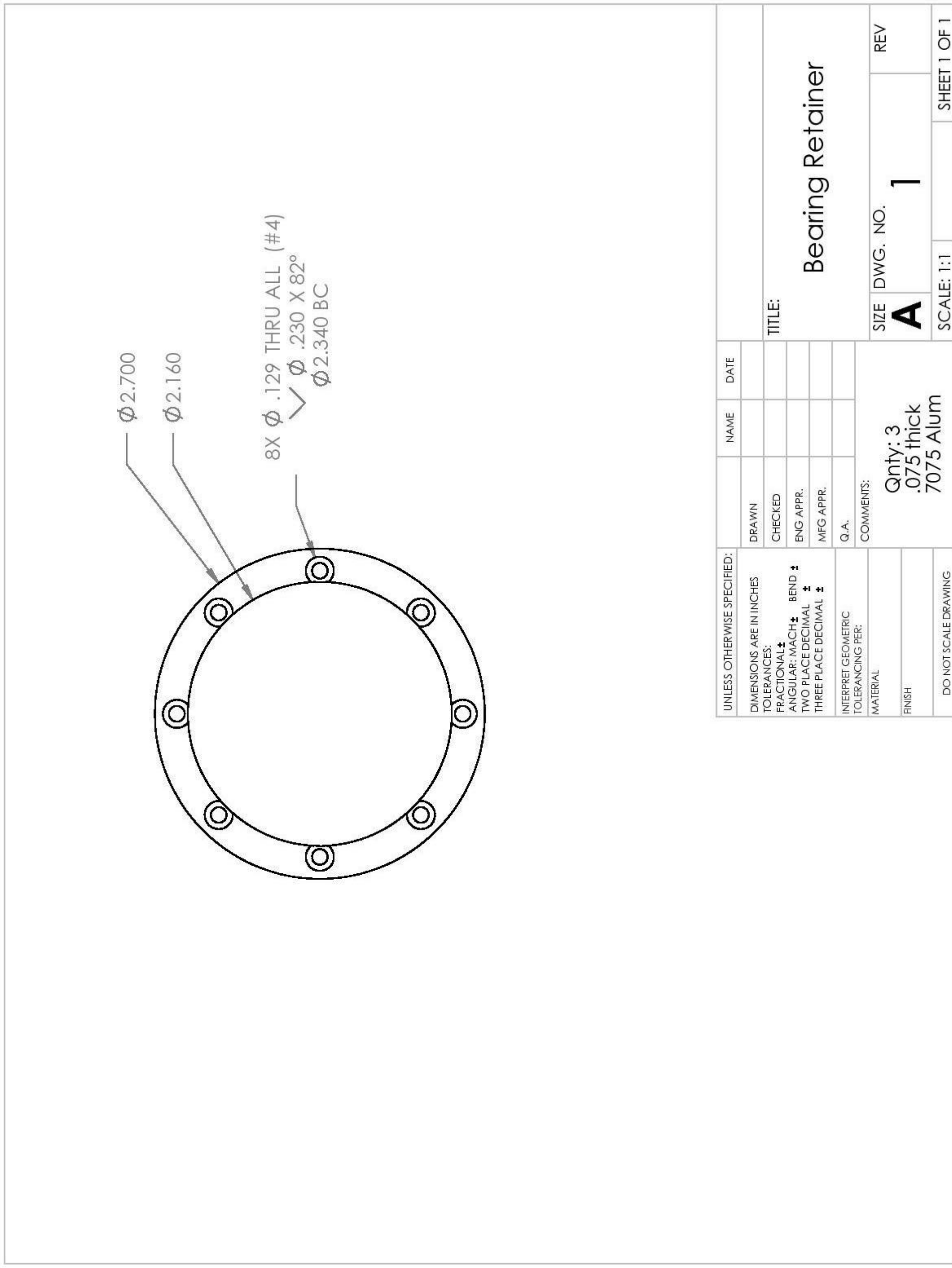
Ø.790
Loose sliding fit over rotor shaft
.025
Ø1.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Rotor Disassembly Shaft
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1


Stator Removal Sleeve
TITLE:
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
SECTION A-A
A
A
.275
1.811
1.885
.375 +.001 -.001
1.936
Loose sliding fit
to Outer housing
1
2
3
4
5

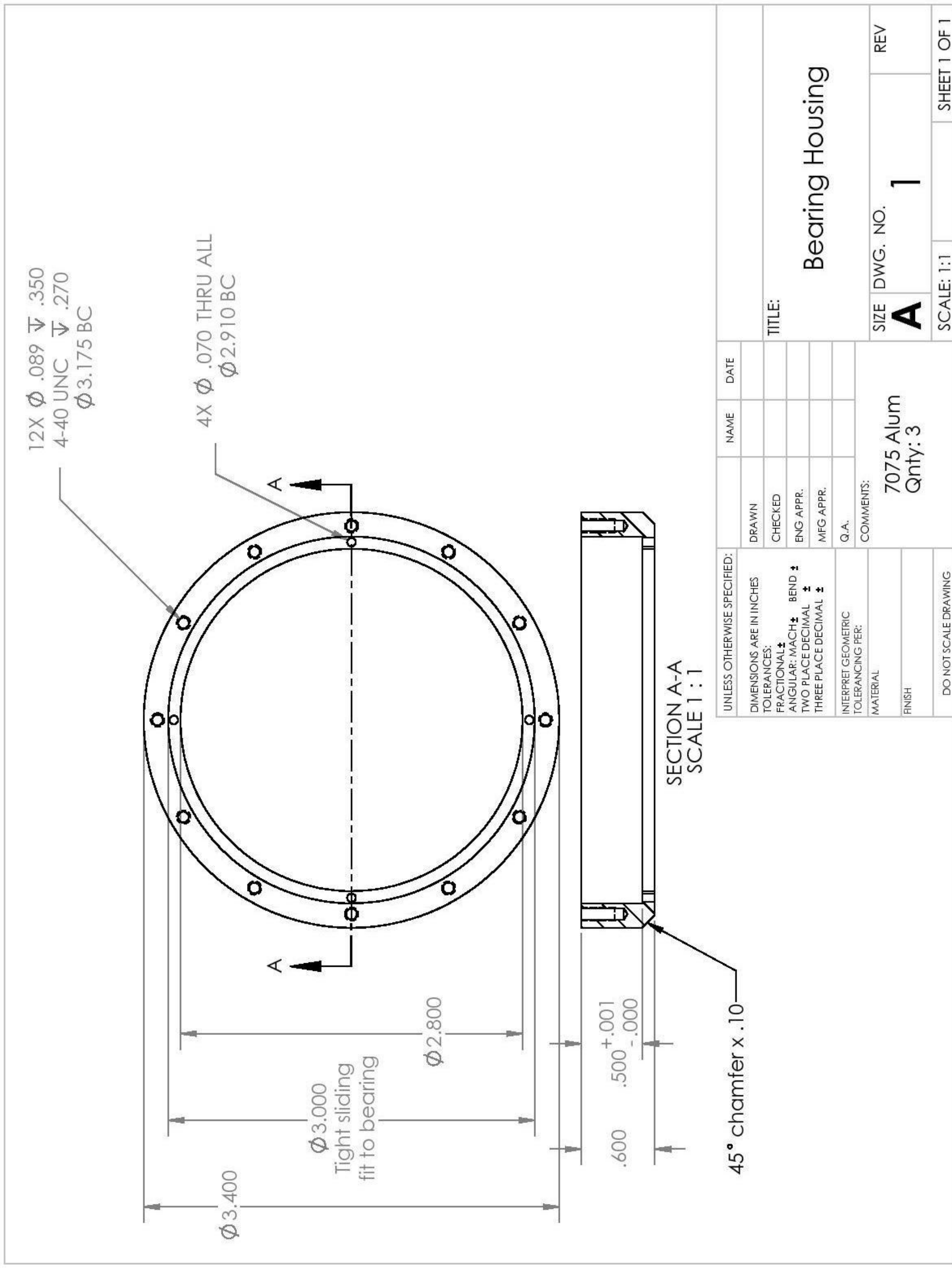

6X Ø .096 THRU ALL
Ø .825 BC, two instances omitted
A
A
1.000
1.000
.008 +.000 -.001
.050
.115
Ø .630
Ø 1.150
SECTION A-A
SCALE 3 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Rotor Encoder Clamp
SIZE
A
DWG. NO.
1
REV
SCALE: 3:1
SHEET 1 OF 1
1
2
3
4
5

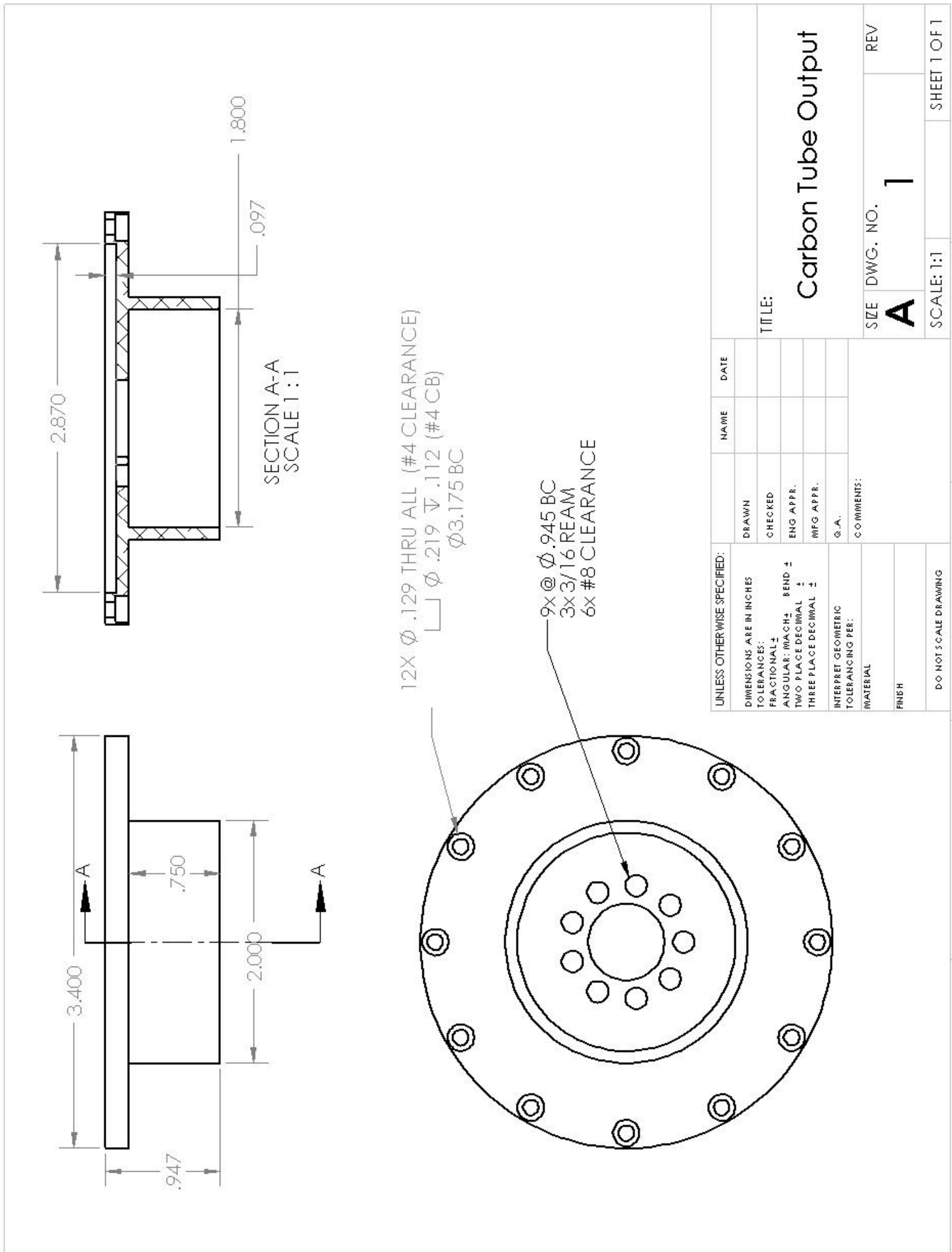

R.925
R.688
Sliding fit to X bearing
R.625
7X Ø.096 THRU ALL
⌴ Ø.188 ↧ .086
Ø1.625 BC
8 bolt pattern, one omitted
.136
.086
A
A
SECTION A-A
SCALE 2 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
X Bearing Clamp
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
1
2
3
4
5


R1.328
Mates sliding fit with feature in outer housing
R.688
Tight sliding fit to X Bearing
R.613
7X Ø .096 THRU ALL
Ø2.200 BC
8 bolt pattern, one omitted
7X Ø .070 THRU ALL
2-56 UNC THRU ALL
Ø1.625 BC
8 bolt pattern, one omitted
1.107
.625
.500
.413
0
2X Ø .114 THRU ALL
A
A
.150
.100
.050
SECTION A-A
SCALE 1.5 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Rotor XBearing Mount
SIZE
A
DWG. NO.
1
REV
SCALE: 3:2
SHEET 1 OF 1
1
2
3
4
5

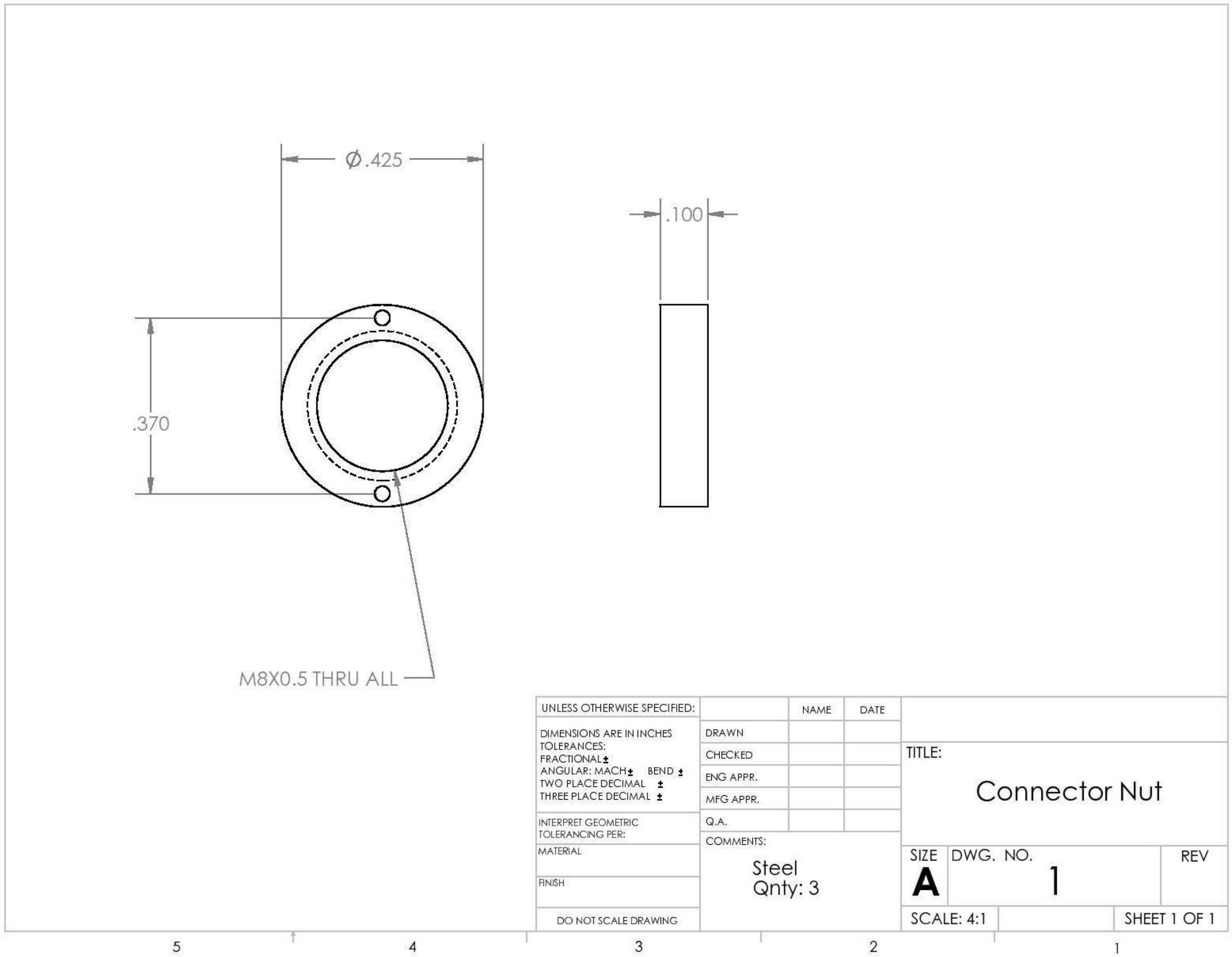


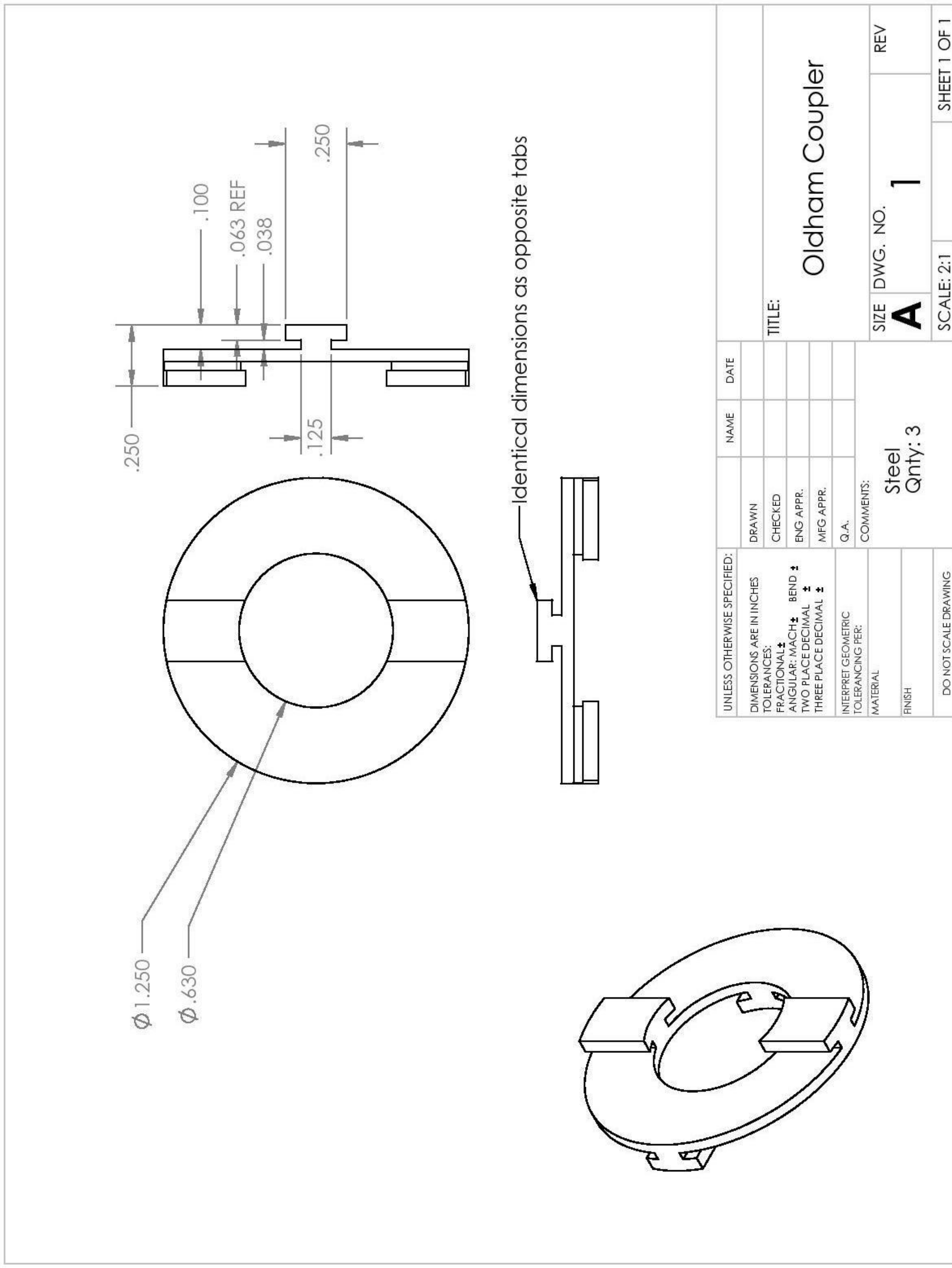
Ø2.700
Ø2.160
8X Ø .129 THRU ALL (#4)
Ø .230 X 82°
Ø2.340 BC
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Qnty: 3
.075 thick
7075 Alum
TITLE:
Bearing Retainer
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
SHEET 1 OF 1
1
2
3
4
5

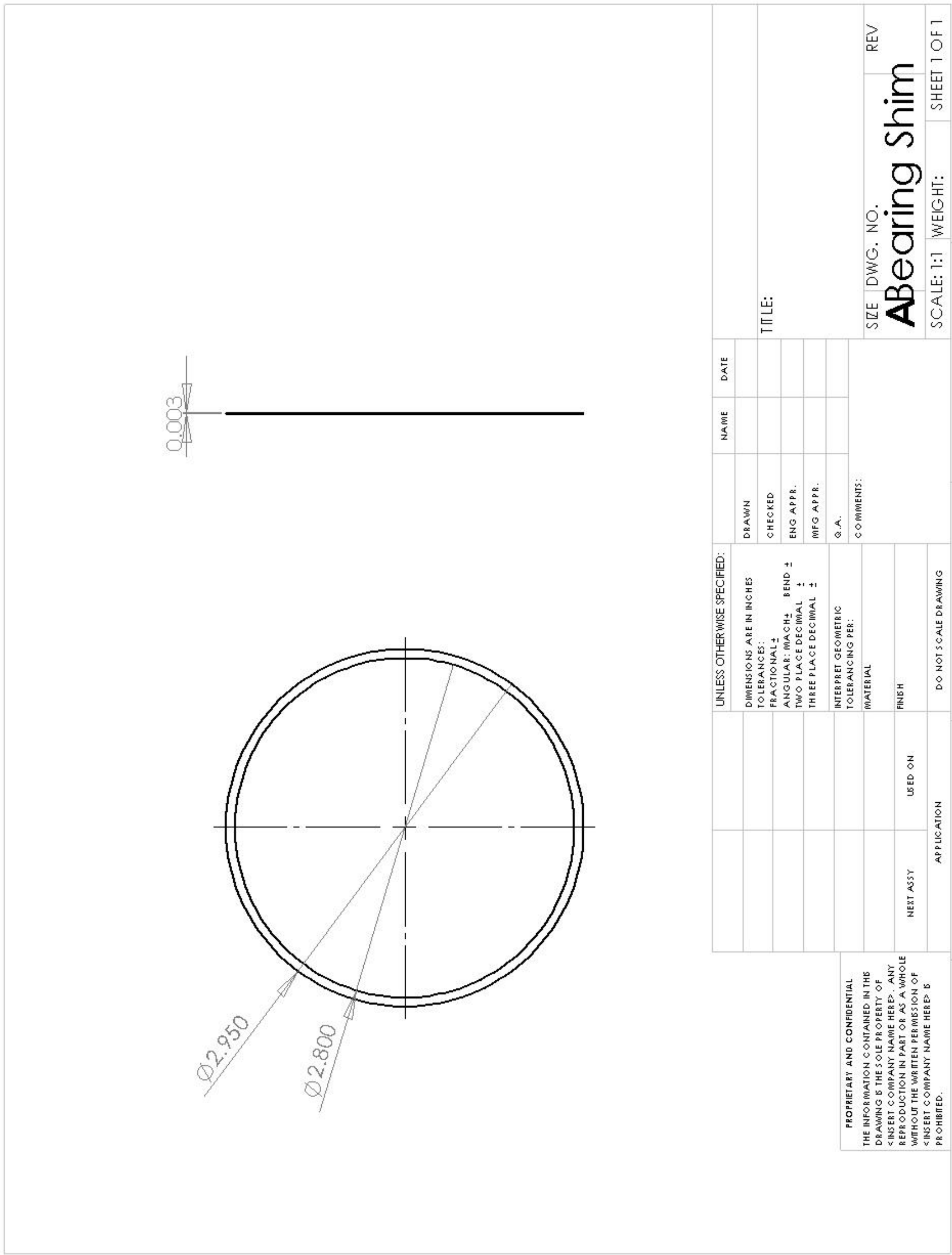

12X Ø .089 ↧ .350
4-40 UNC ↧ .270
Ø3.175 BC
4X Ø .070 THRU ALL
Ø2.910 BC
A
A
SECTION A-A
SCALE 1 : 1
Ø2.800
Ø3.000
Tight sliding
fit to bearing
Ø3.400
.600
.500 +.001 -.000
45° chamfer x .10
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Bearing Housing
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
SHEET 1 OF 1
1
2
3
4
5



1.800
.097
2.870
SECTION A-A
SCALE 1 : 1
12X Ø .129 THRU ALL (#4 CLEARANCE)
⌴ Ø .219 ↧ .112 (#4 CB)
Ø3.175 BC
9X @ Ø .945 BC
3X 3/16 REAM
6X #8 CLEARANCE
3.400
.750
2.000
.947
A
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
Carbon Tube Output
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
SHEET 1 OF 1
1
2
3
4
5


Ø.425
.100
.370
M8X0.5 THRU ALL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Steel
Qnty: 3
TITLE:
Connector Nut
SIZE
A
DWG. NO.
1
REV
SCALE: 4:1
SHEET 1 OF 1
5
4
3
2
1


.100
.063 REF
.038
.250
.250
.125
Identical dimensions as opposite tabs
Ø1.250
Ø.630
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Steel
Qnty: 3
TITLE:
Oldham Coupler
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
1
2
3
4
5


Ø2.950
Ø2.800
0.003
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
A
Bearing Shim
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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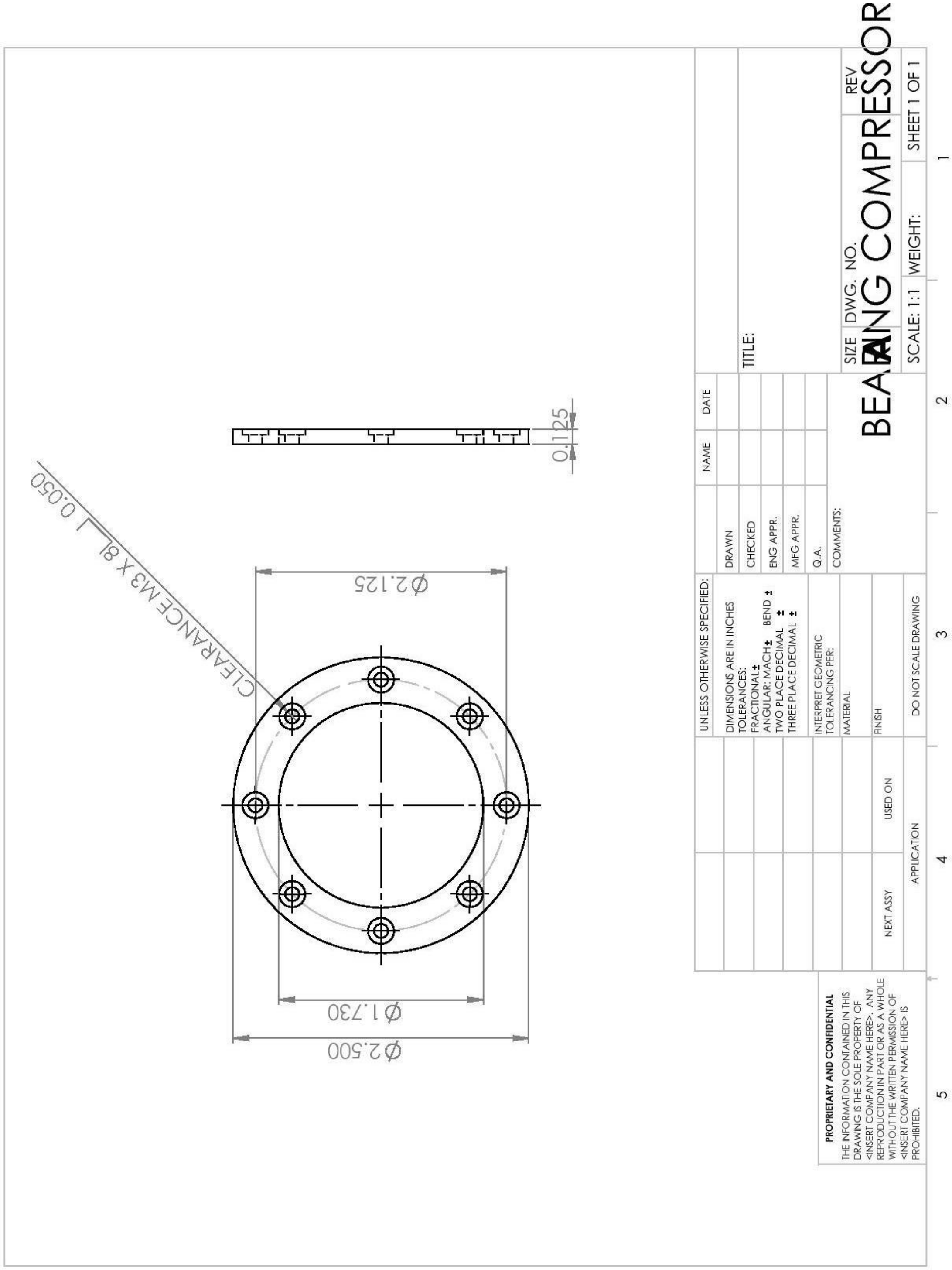
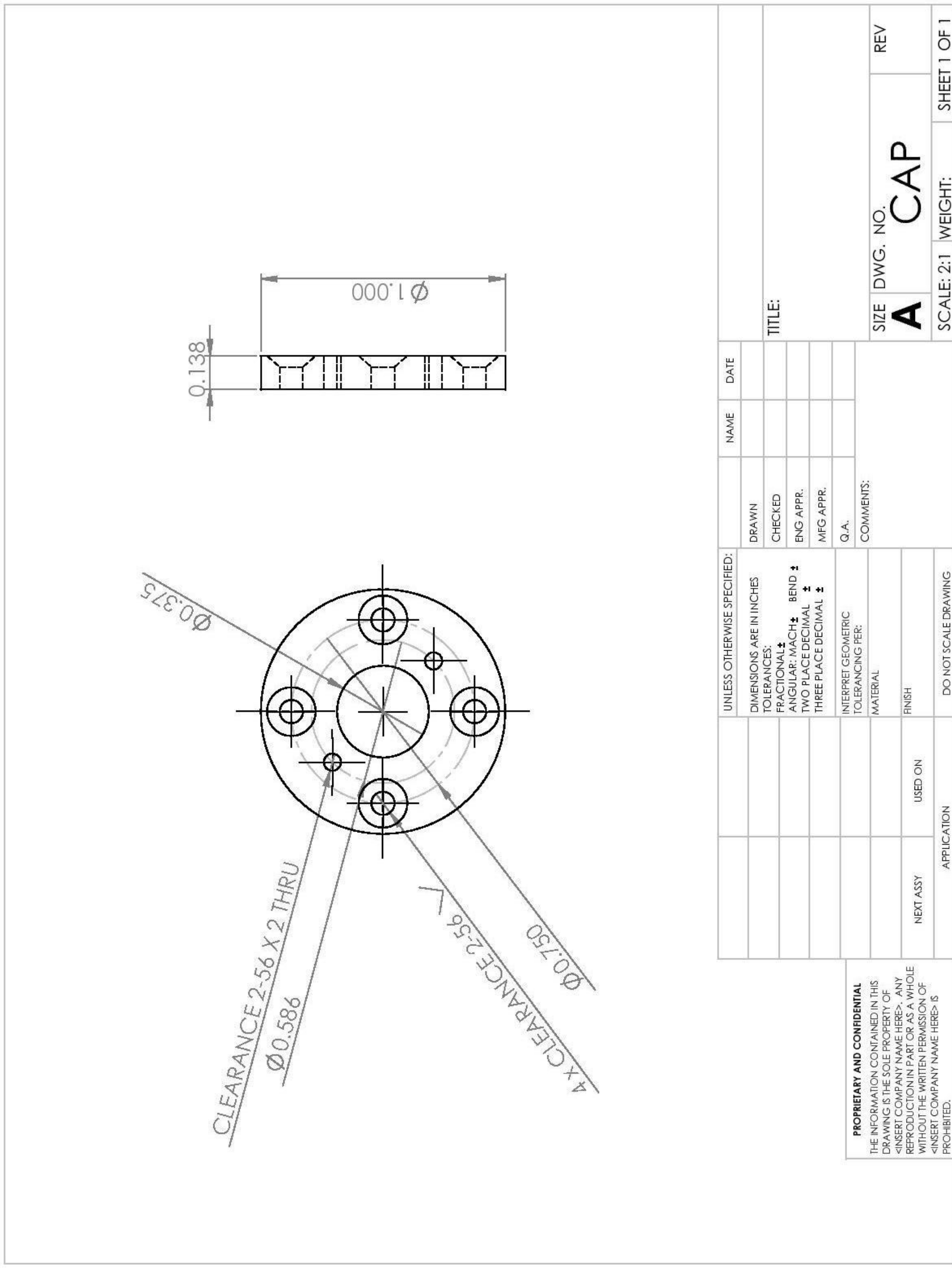
1
2
3
4
5

Appendix H: Elbow Joint Drawings




Ø1.000
0.138
Ø0.375
CLEARANCE 2-56 X 2 THRU
Ø0.586
4 X CLEARANCE 2-56
Ø0.750
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
CAP
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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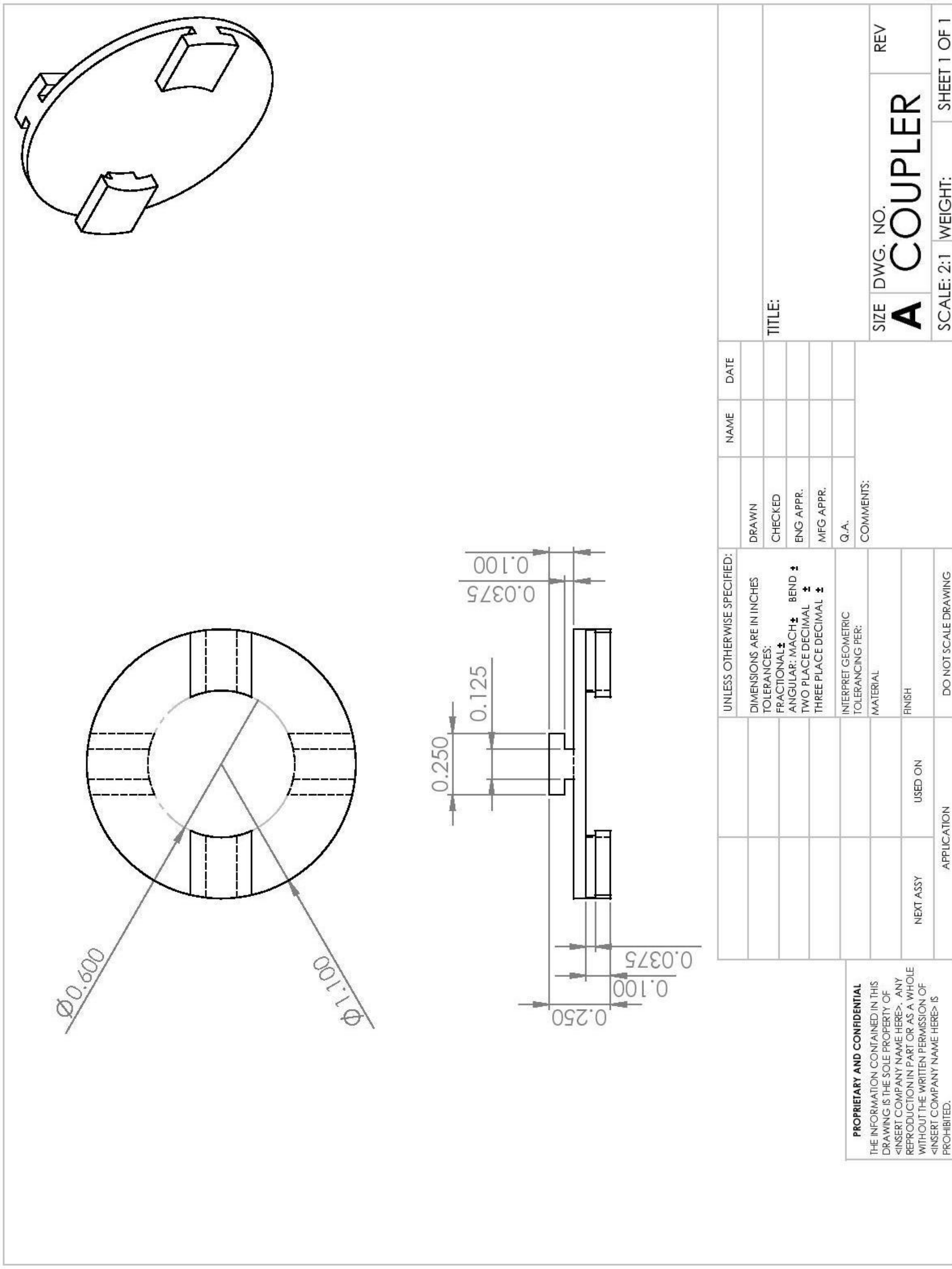
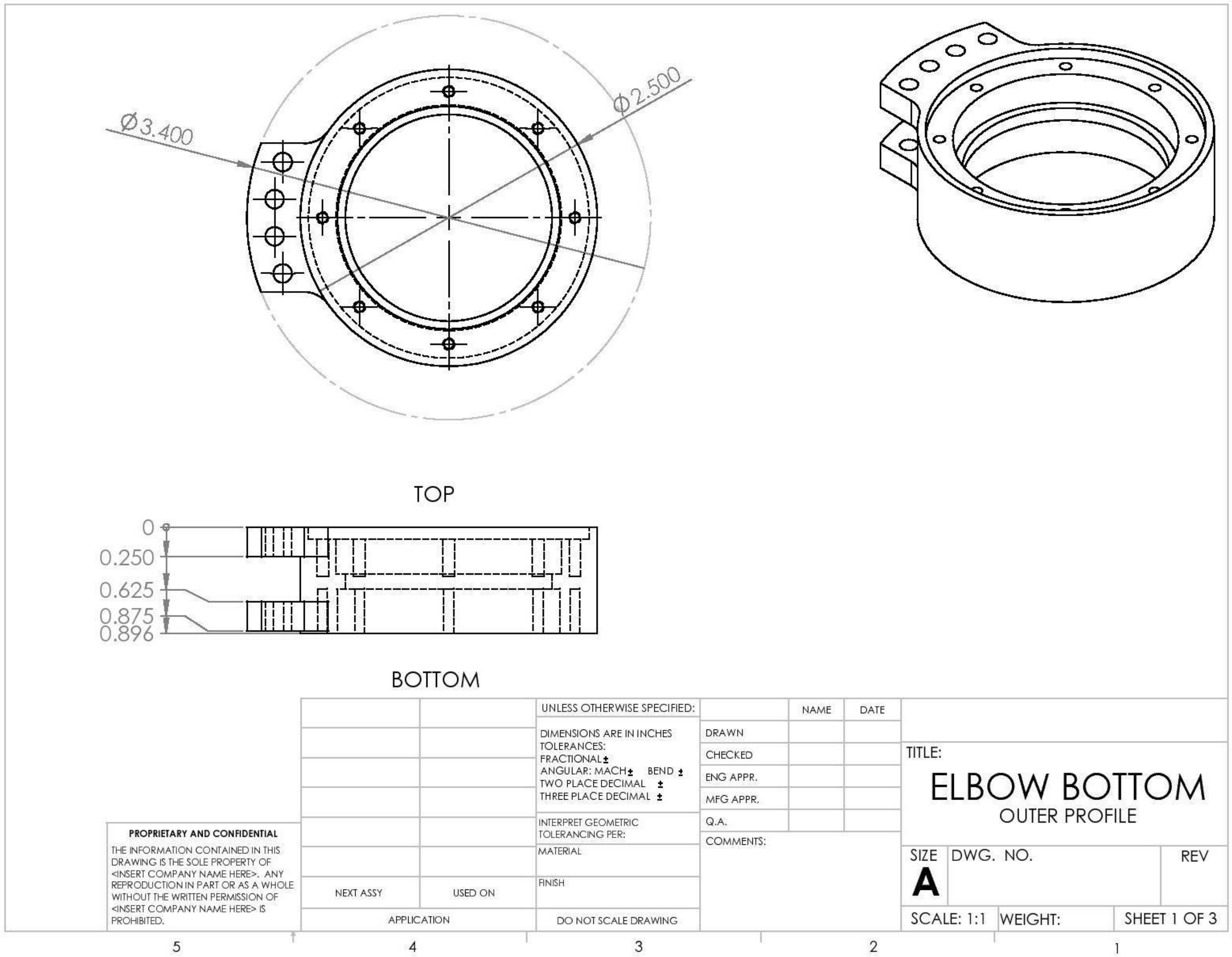
1
2
3
4
5


Ø0.600
Ø1.100
0.250
0.125
0.100
0.0375
0.0375
0.100
0.250
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
COUPLER
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
1
2
3
4
5



Ø3.400
Ø2.500
TOP
0
0.250
0.625
0.875
0.896
BOTTOM
PROPRIETARY AND CONFIDENTIAL
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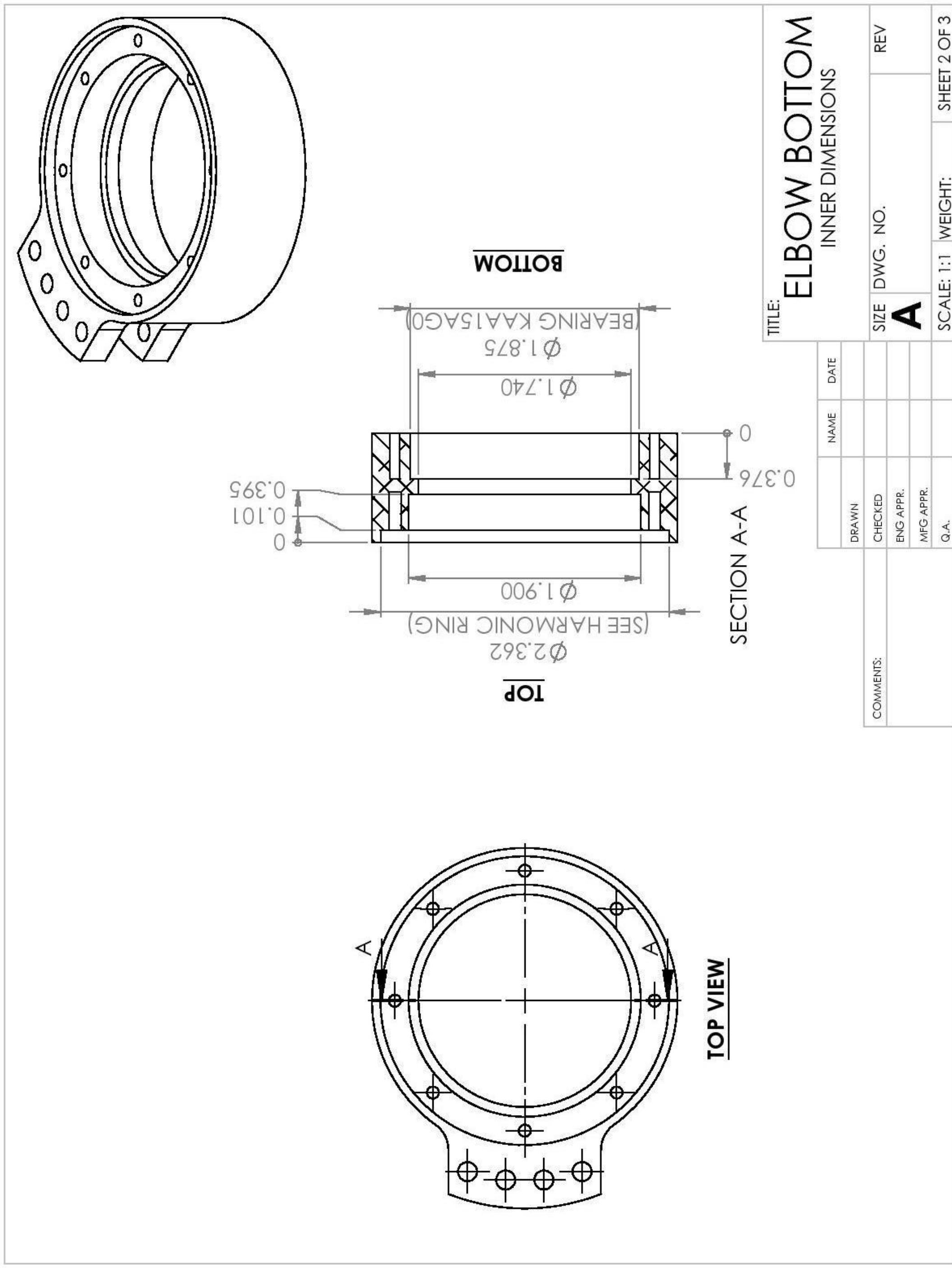
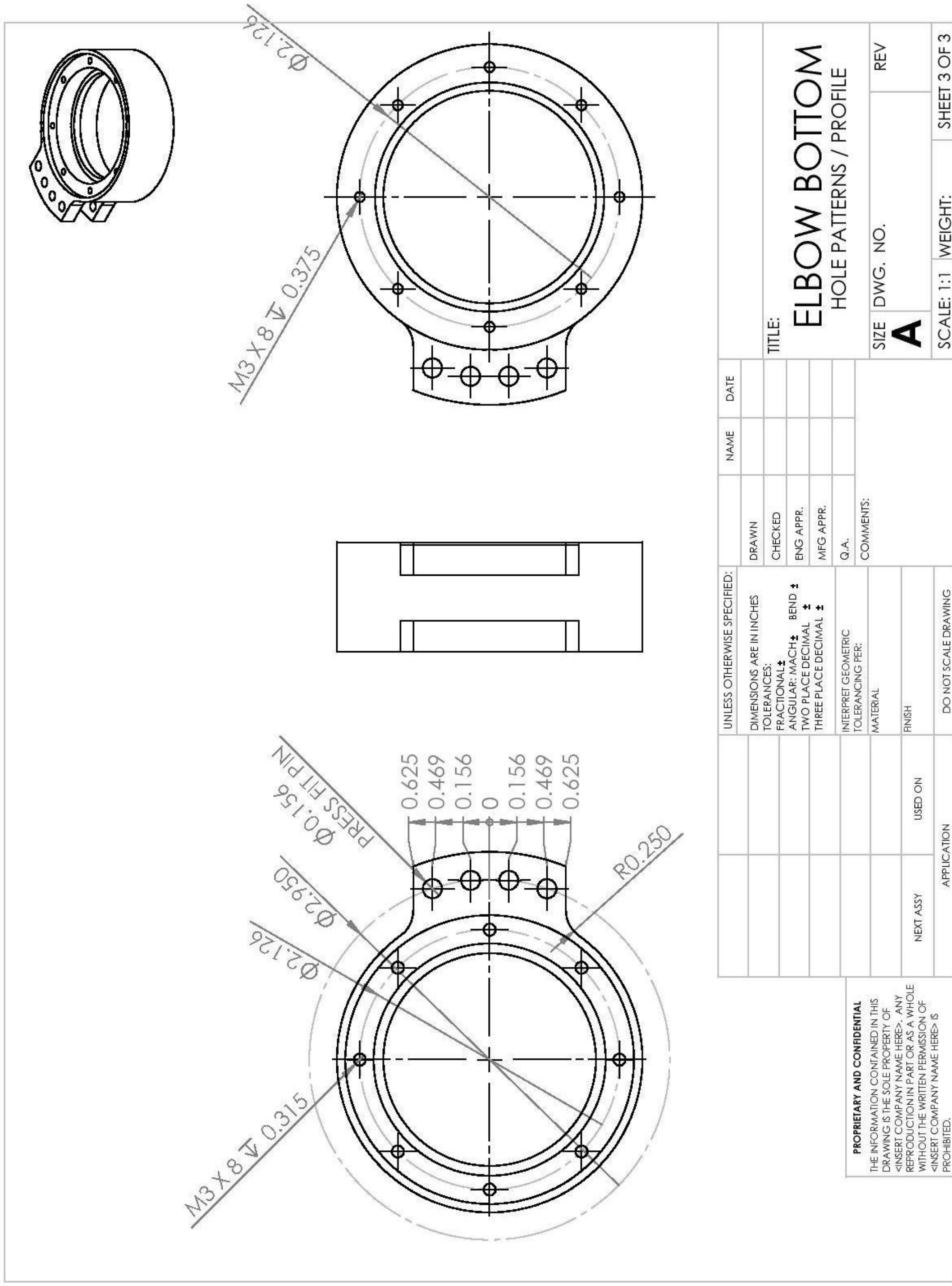
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
ELBOW BOTTOM
OUTER PROFILE
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 3
5
4
3
2
1


ELBOW BOTTOM
INNER DIMENSIONS
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 2 OF 3
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
NAME
DATE
COMMENTS:
BOTTOM
(BEARING KAA15AG0)
Ø1.875
Ø1.740
0
0.376
0.395
0.101
0
SECTION A-A
Ø1.900
(SEE HARMONIC RING)
Ø2.362
TOP
A
A
TOP VIEW
1
2
3
4
5


ELBOW BOTTOM
HOLE PATTERNS / PROFILE
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 3 OF 3
M3 X 8 ↧ 0.375
Ø2.126
M3 X 8 ↧ 0.315
Ø2.950
PRESS FIT PIN
Ø0.156
R0.250
0.625
0.469
0.156
0
0.156
0.469
0.625
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
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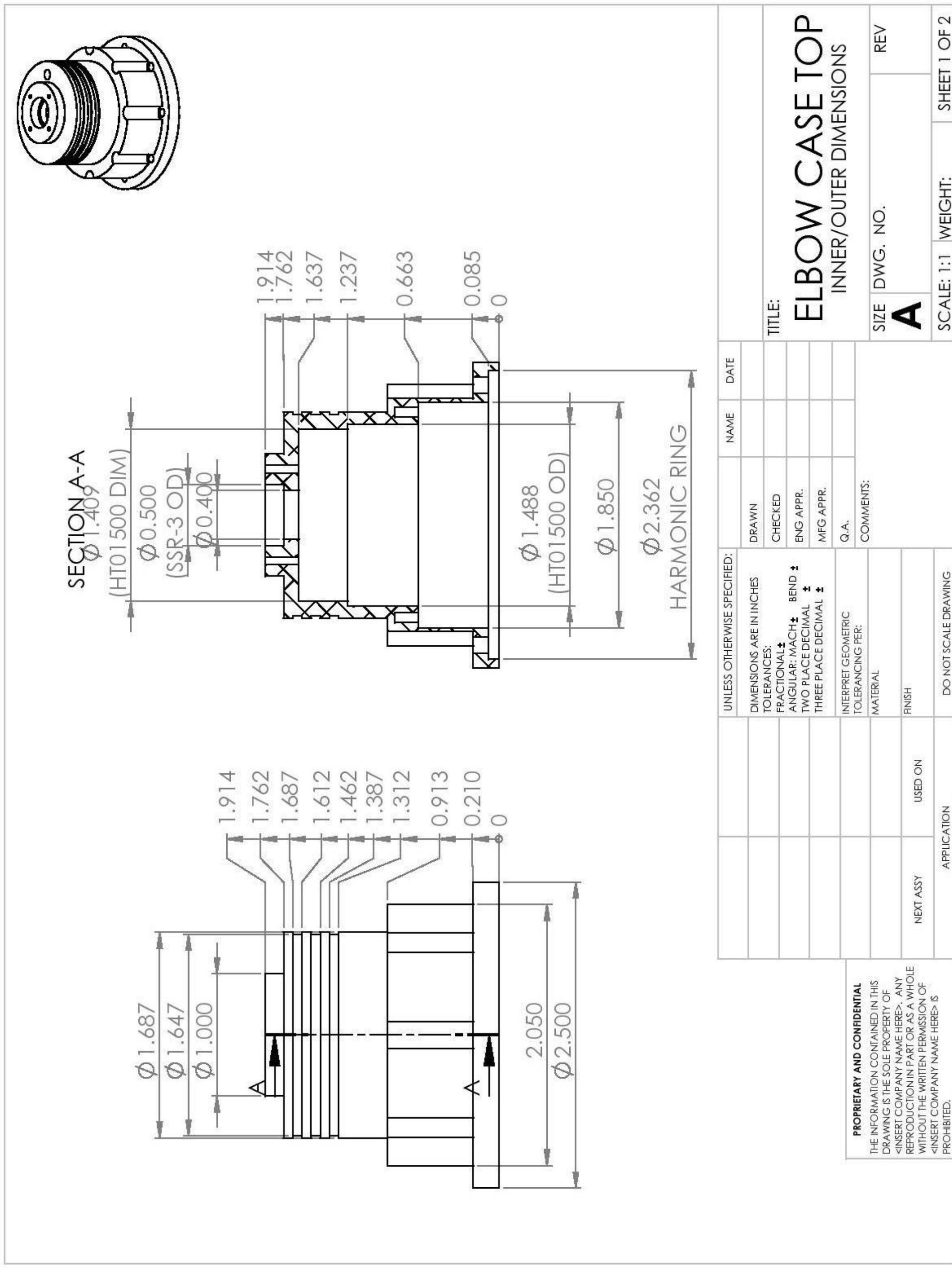
1
2
3
4
5


SECTION A-A
Ø1.409 (HT01500 DIM)
Ø0.500 (SSR-3 OD)
Ø0.400
Ø1.488 (HT01500 OD)
Ø1.850
Ø2.362 HARMONIC RING
1.914
1.762
1.637
1.237
0.663
0.085
0
Ø1.687
Ø1.647
Ø1.000
2.050
Ø2.500
1.914
1.762
1.687
1.612
1.462
1.387
1.312
0.913
0.210
0
ELBOW CASE TOP
INNER/OUTER DIMENSIONS
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
NEXT ASSY
USED ON
APPLICATION
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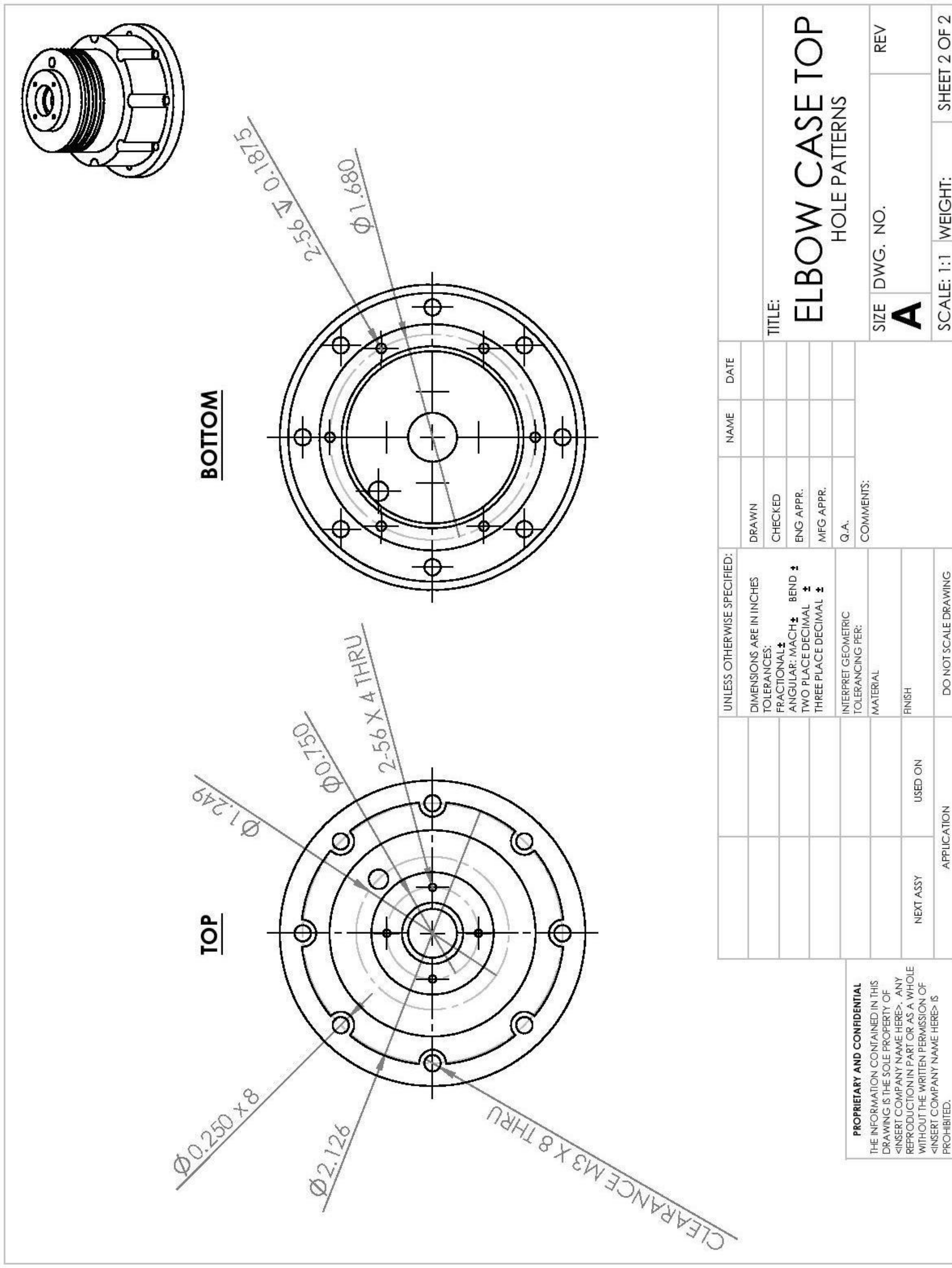
TOP
BOTTOM
Ø1.249
Ø0.750
2-56 X 4 THRU
Ø0.250 X 8
Ø2.126
CLEARANCE M3 X 8 THRU
2-56 ↧ 0.1875
Ø1.680
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
ELBOW CASE TOP
HOLE PATTERNS
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 2 OF 2
NEXT ASSY
USED ON
APPLICATION
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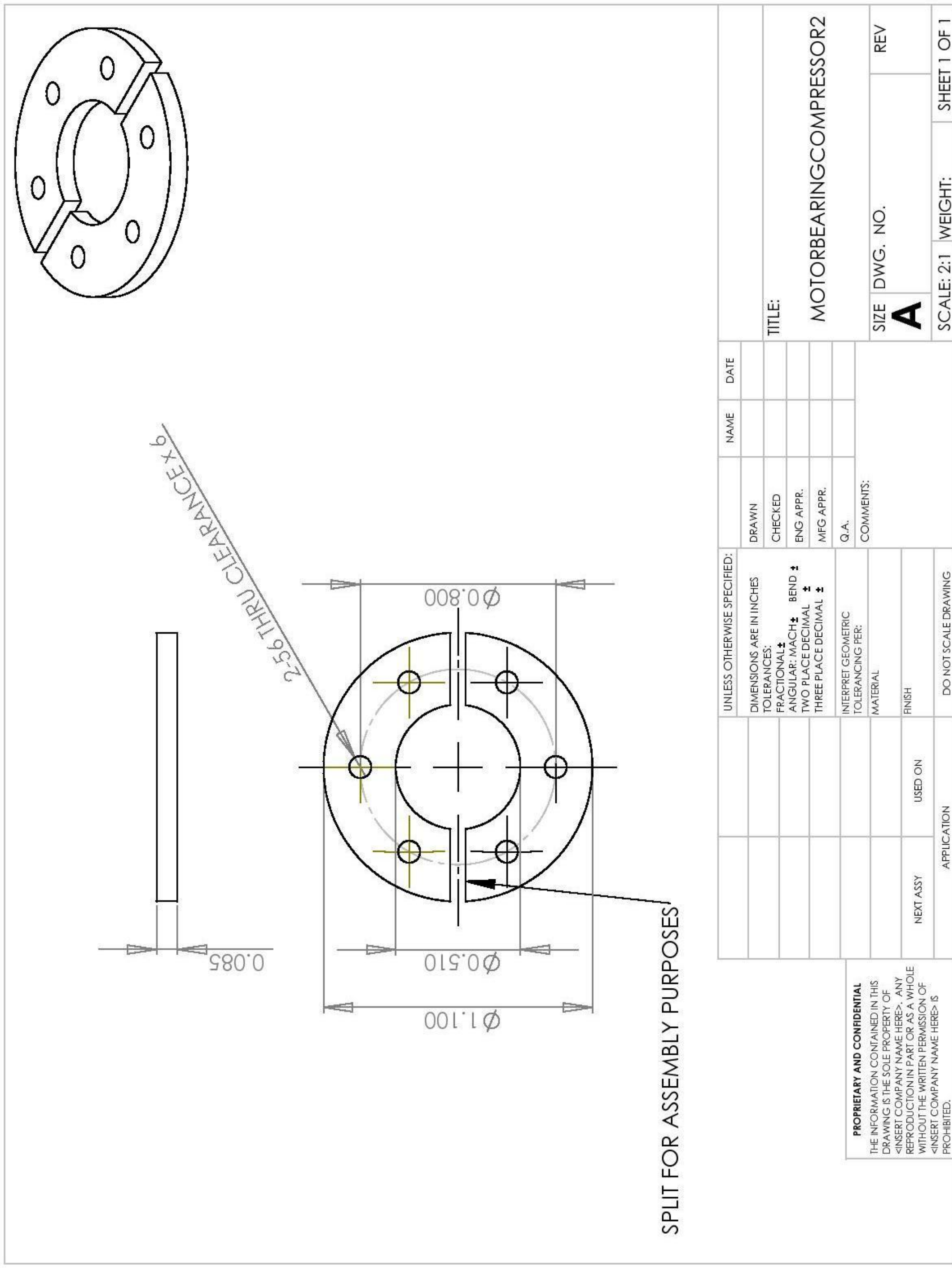
1
2
3
4
5


2-56 THRU CLEARANCE x 6
Ø0.800
Ø0.510
Ø1.100
0.085
SPLIT FOR ASSEMBLY PURPOSES
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
MOTORBEARINGCOMPRESSOR2
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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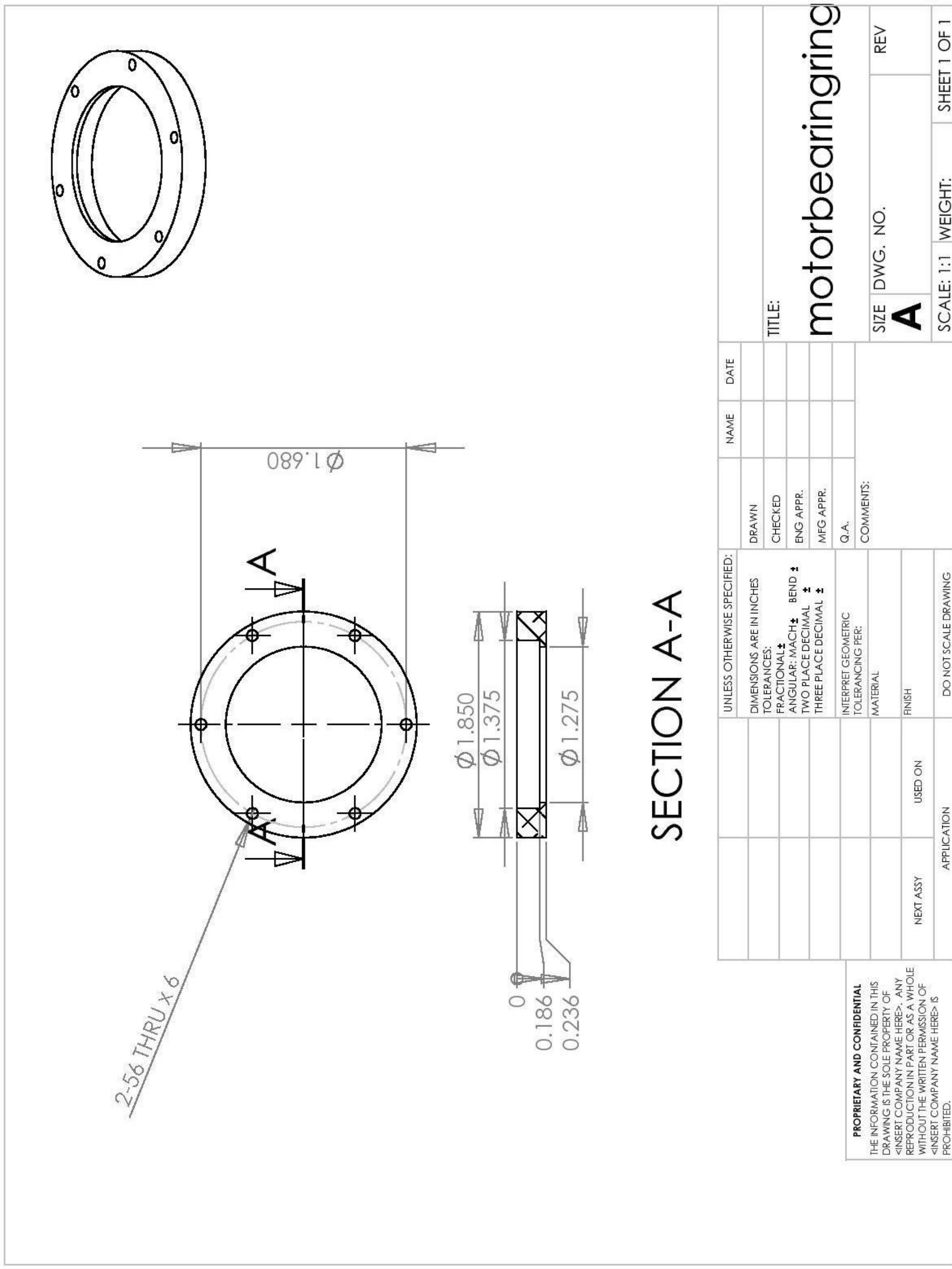
1
2
3
4
5


2-56 THRU x 6
A
A
Ø1.680
Ø1.850
Ø1.375
Ø1.275
0
0.186
0.236
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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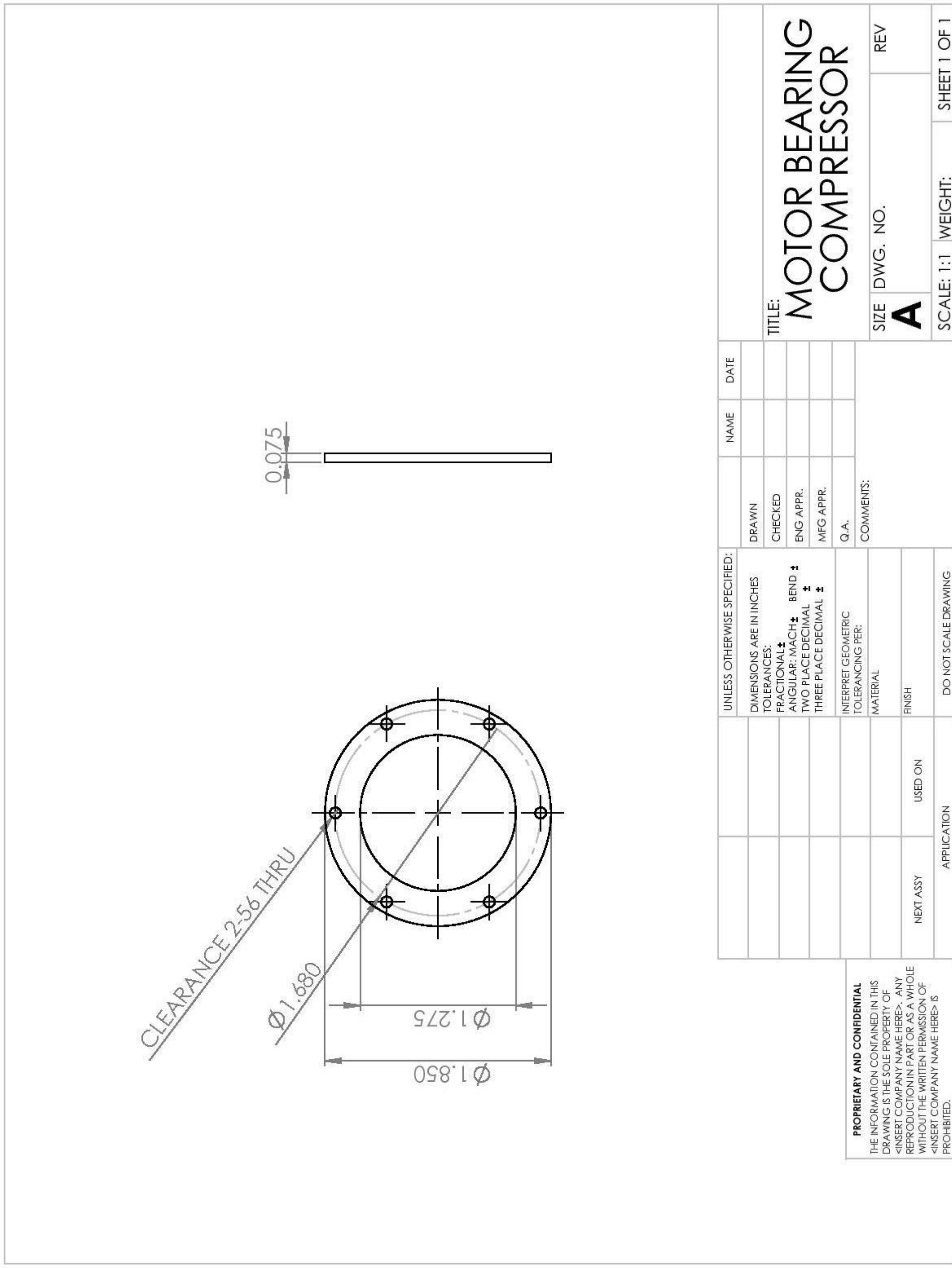
TITLE:
motorbearingring
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5



0.075
CLEARANCE 2-56 THRU
Ø1.680
Ø1.275
Ø1.850
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
MOTOR BEARING COMPRESSOR
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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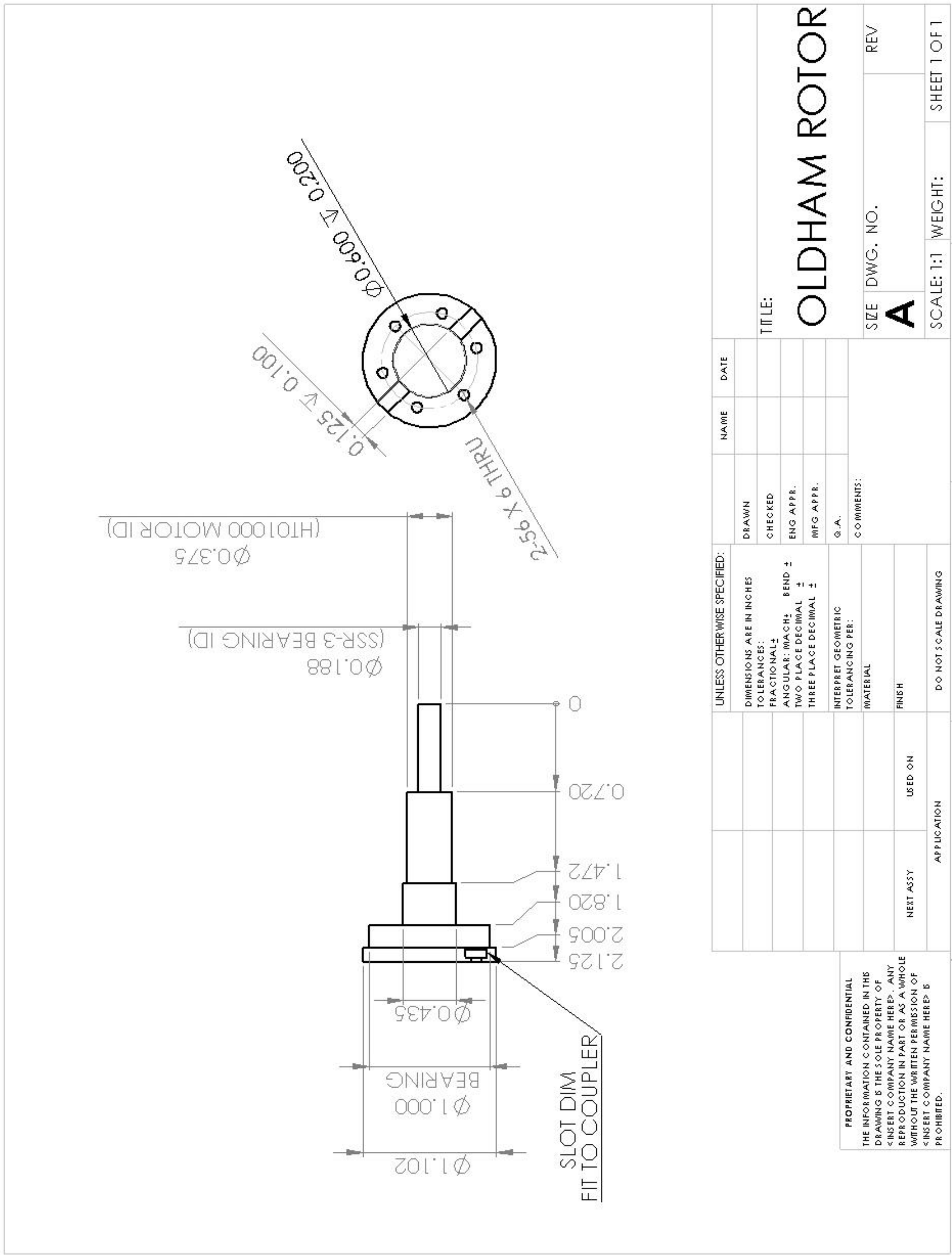
1
2
3
4
5


Ø0.600 ⊽ 0.200
0.125 ⊽ 0.100
2-56 X 6 THRU
Ø0.375
(HT01000 MOTOR ID)
Ø0.188
(SSR-3 BEARING ID)
0
0.720
1.472
1.820
2.005
2.125
Ø0.435
Ø1.000
BEARING
Ø1.102
SLOT DIM
FIT TO COUPLER
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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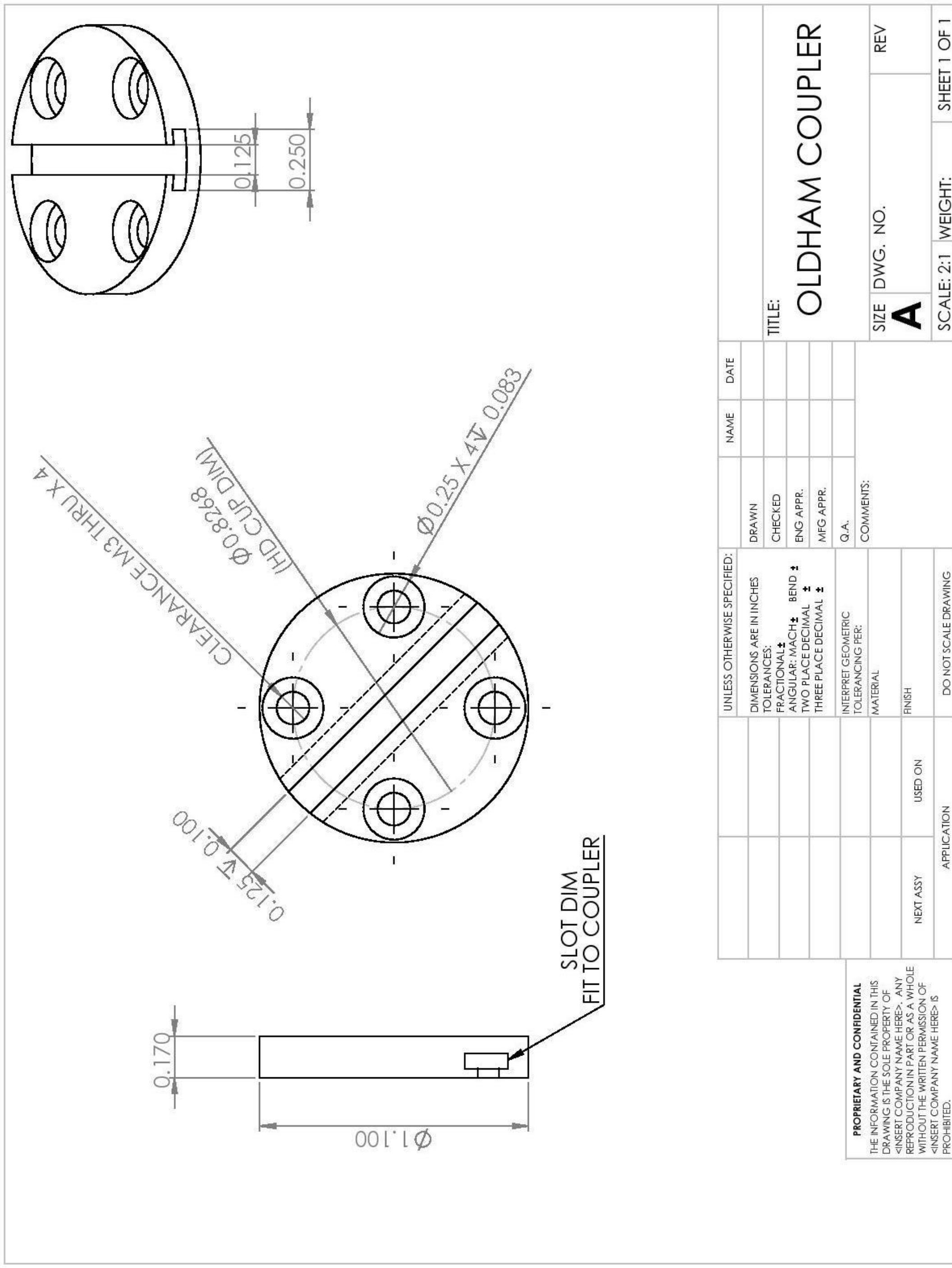
TITLE:
OLDHAM ROTOR
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



OLDHAM COUPLER
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
0.125
0.250
Ø0.25 X 4↧ 0.083
Ø0.8268
(HD CUP DIM)
CLEARANCE M3 THRU X 4
0.125 ↧ 0.100
SLOT DIM
FIT TO COUPLER
0.170
Ø1.100
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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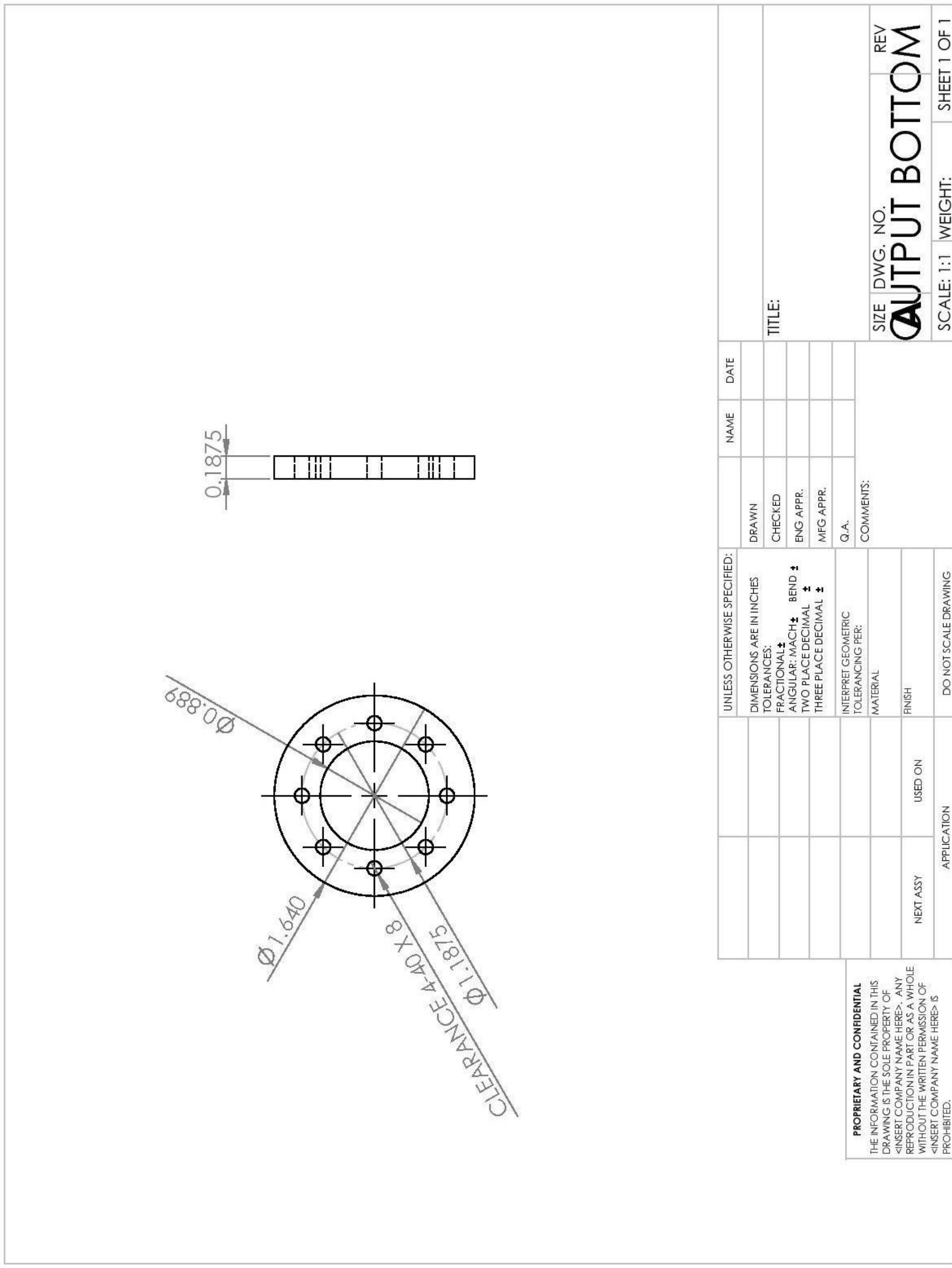
1
2
3
4
5


Ø0.889
Ø1.640
CLEARANCE 4-40 X 8
Ø1.1875
0.1875
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
TITLE:
SIZE
A
DWG. NO.
OUTPUT BOTTOM
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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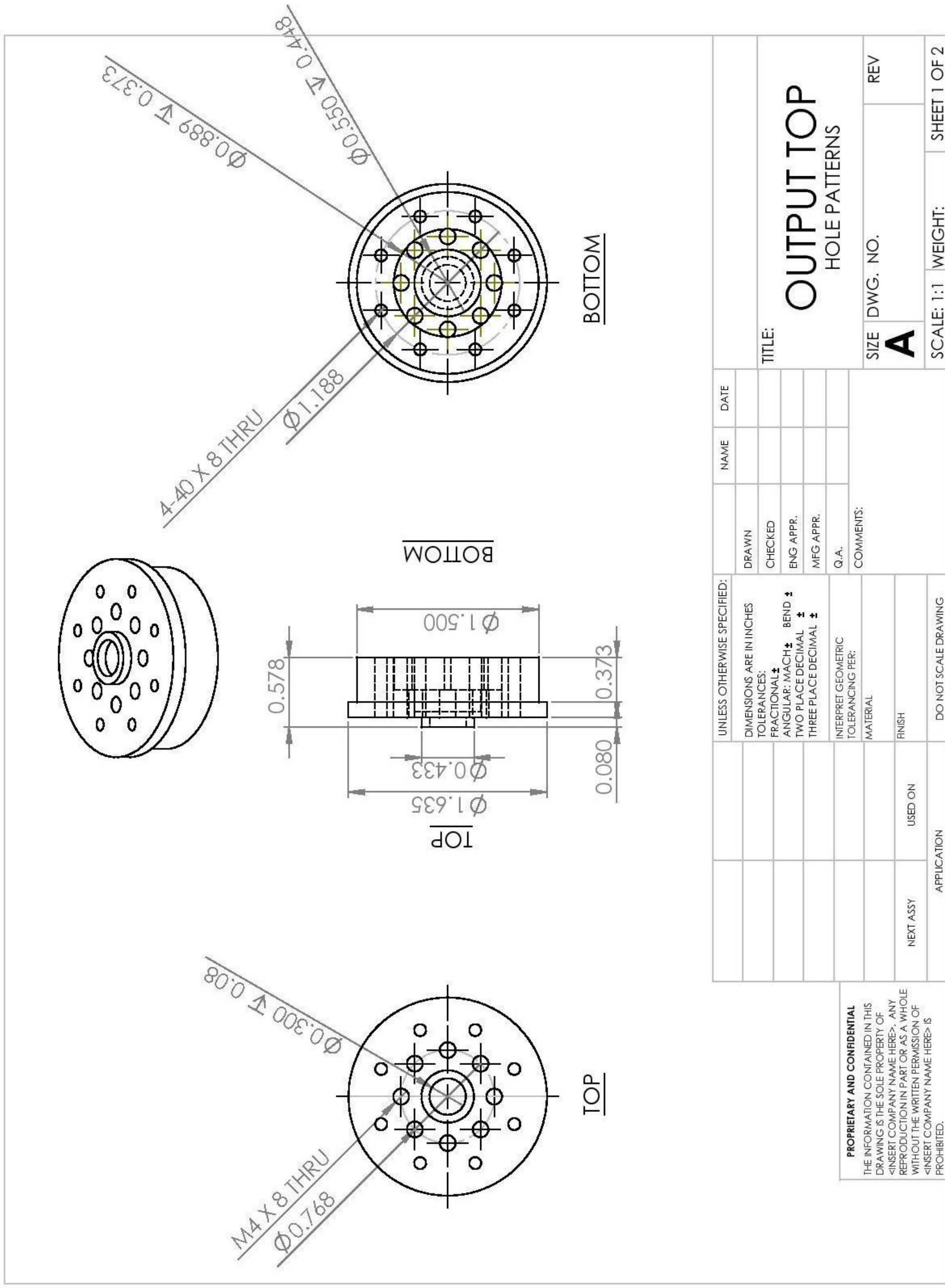
1
2
3
4
5



Ø0.889 ↧ 0.373
Ø0.550 ↧ 0.448
4-40 X 8 THRU
Ø1.188
BOTTOM
Ø1.500
0.578
0.373
BOTTOM
0.080
Ø0.433
Ø1.635
TOP
Ø0.300 ↧ 0.08
M4 X 8 THRU
Ø0.768
TOP
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
OUTPUT TOP
HOLE PATTERNS
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 2
PROPRIETARY AND CONFIDENTIAL
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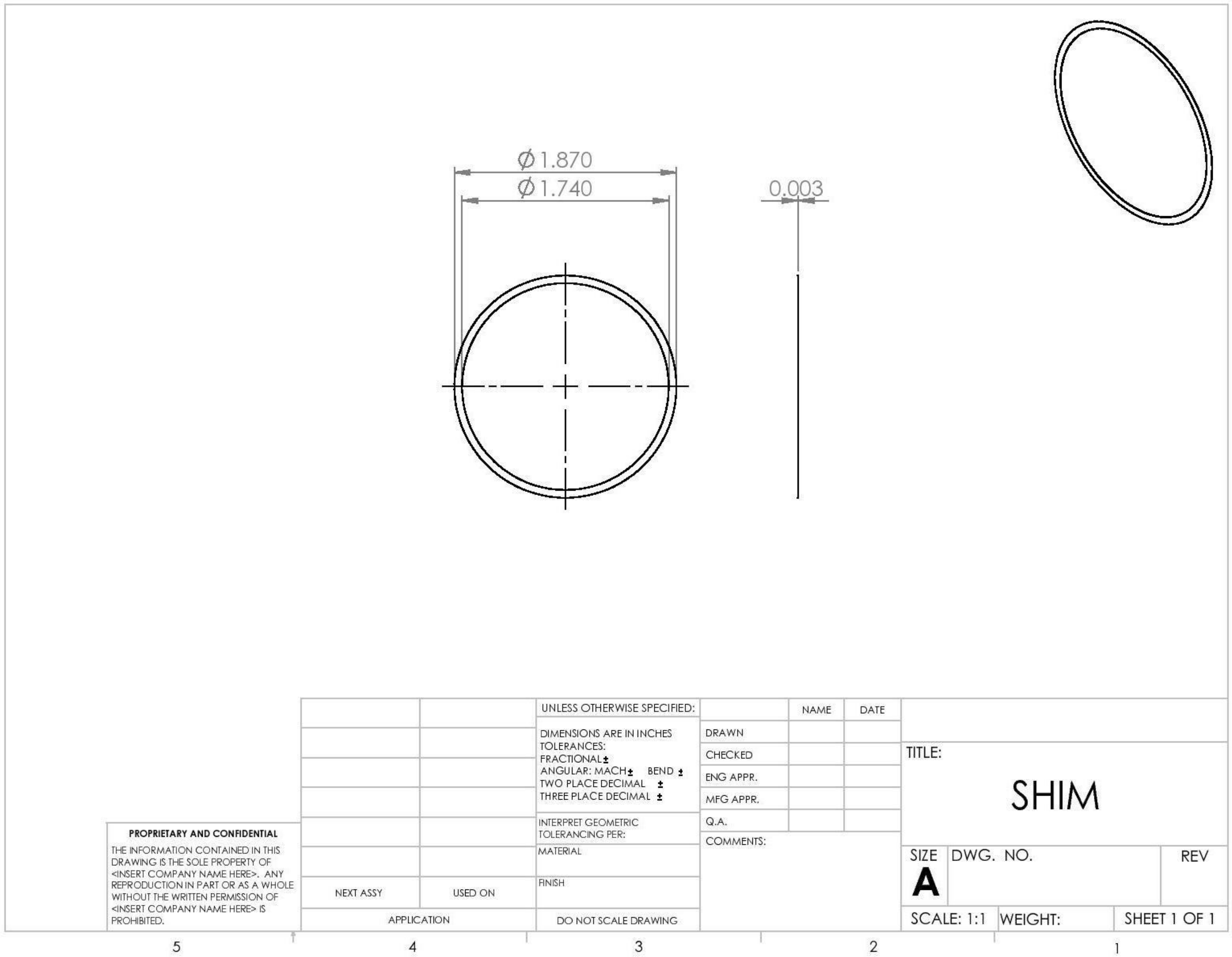
5
4
3
2
1


Ø1.870
Ø1.740
0.003
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SHIM
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
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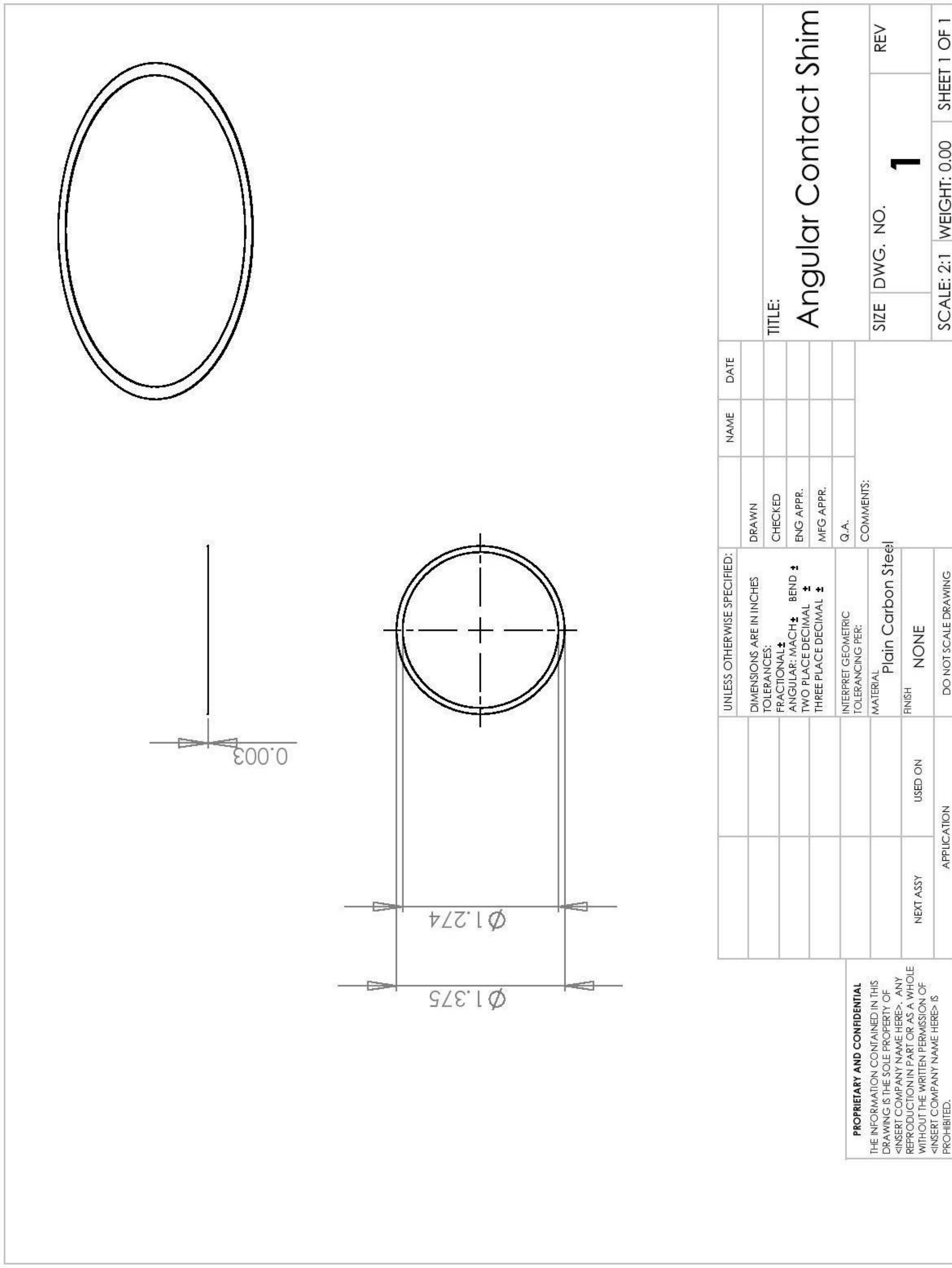
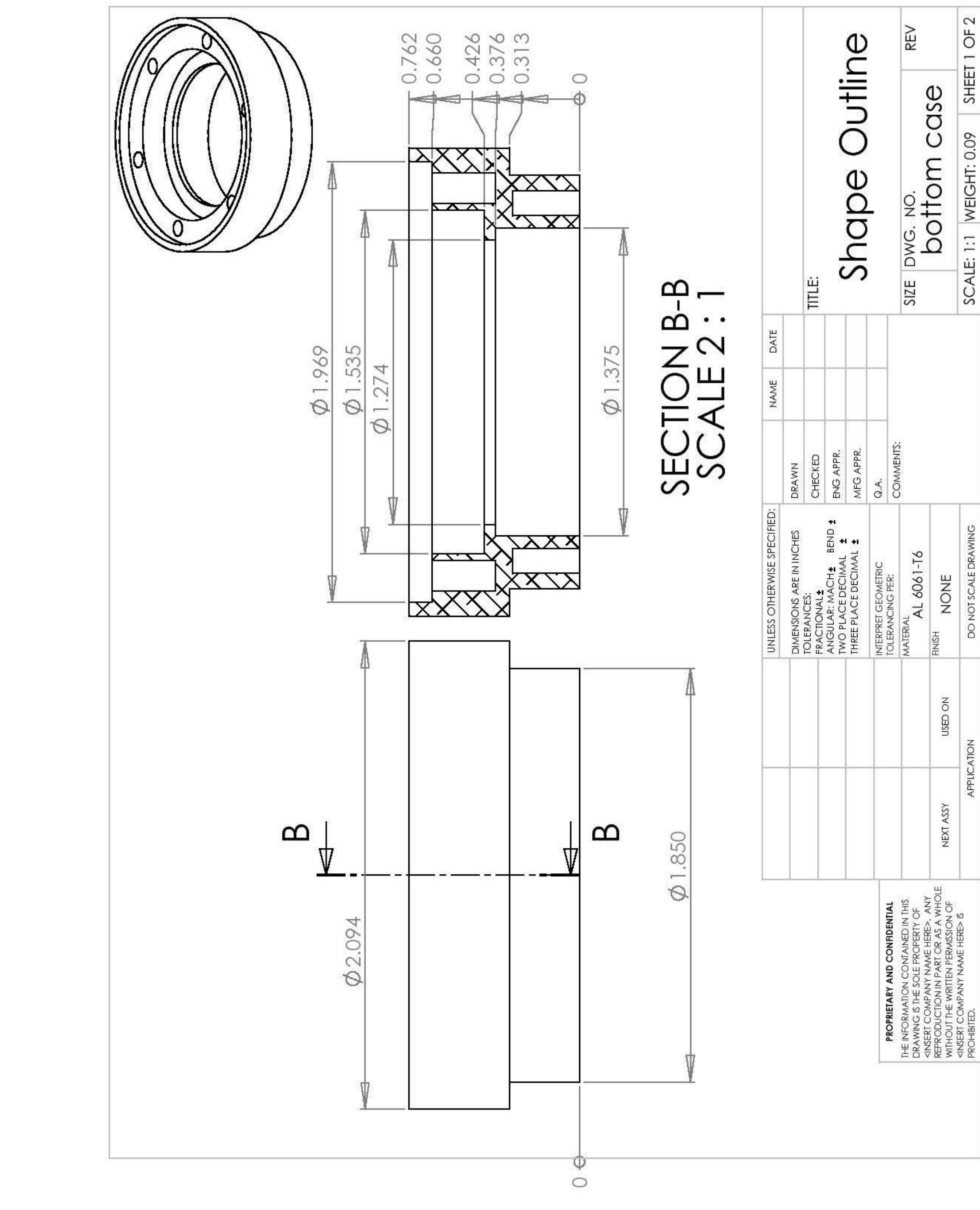
5
4
3
2
1

Appendix I: Wrist Joint Drawings




0.762
0.660
0.426
0.376
0.313
0
Ø1.969
Ø1.535
Ø1.274
Ø1.375
SECTION B-B
SCALE 2 : 1
B
B
Ø2.094
Ø1.850
0
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
AL 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Shape Outline
SIZE
DWG. NO.
bottom case
REV
SCALE: 1:1
WEIGHT: 0.09
SHEET 1 OF 2
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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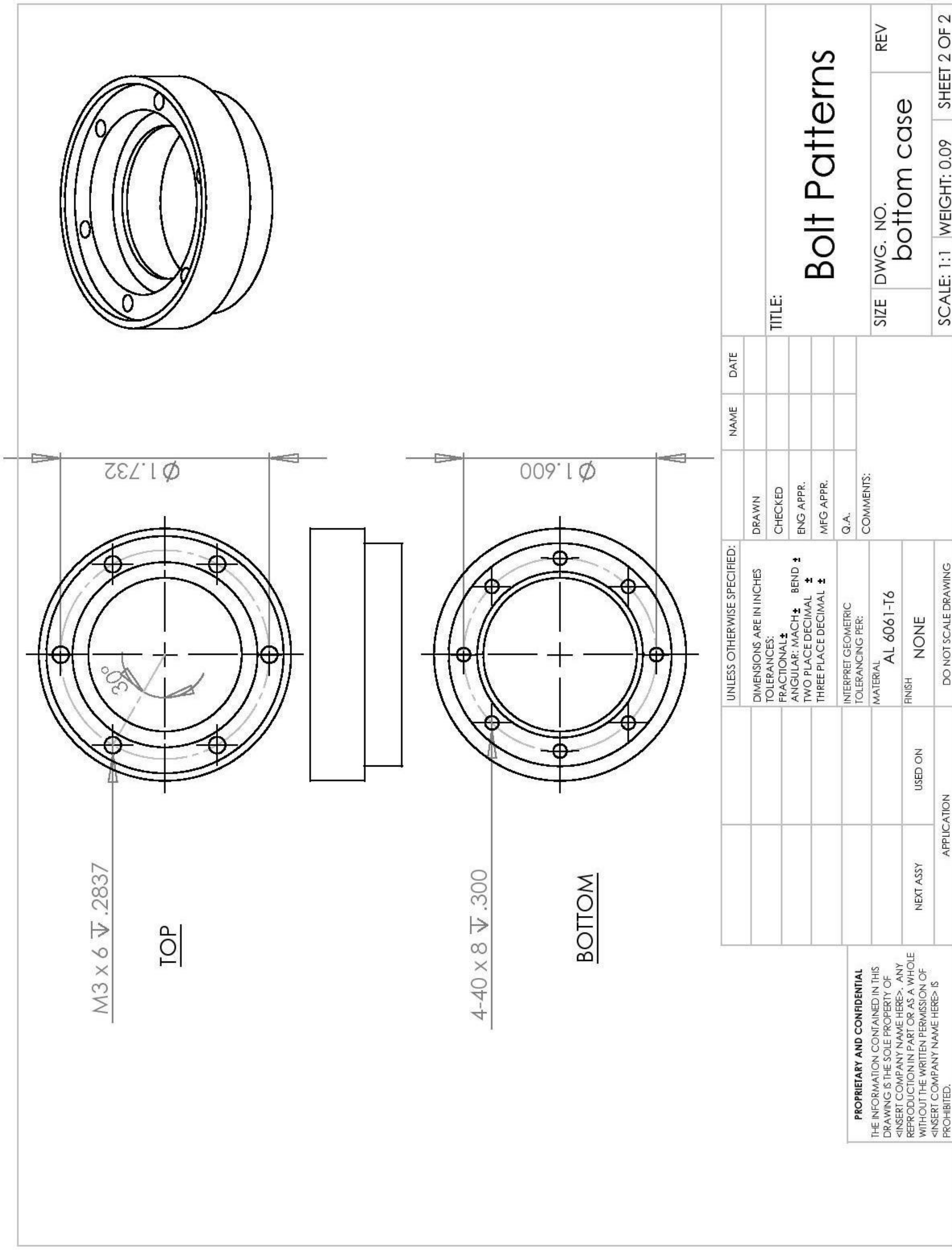
1
2
3
4
5



Ø1.732
Ø1.600
30°
M3 x 6 ↧ .2837
TOP
4-40 x 8 ↧ .300
BOTTOM
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
AL 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bolt Patterns
SIZE
DWG. NO.
bottom case
REV
SCALE: 1:1
WEIGHT: 0.09
SHEET 2 OF 2
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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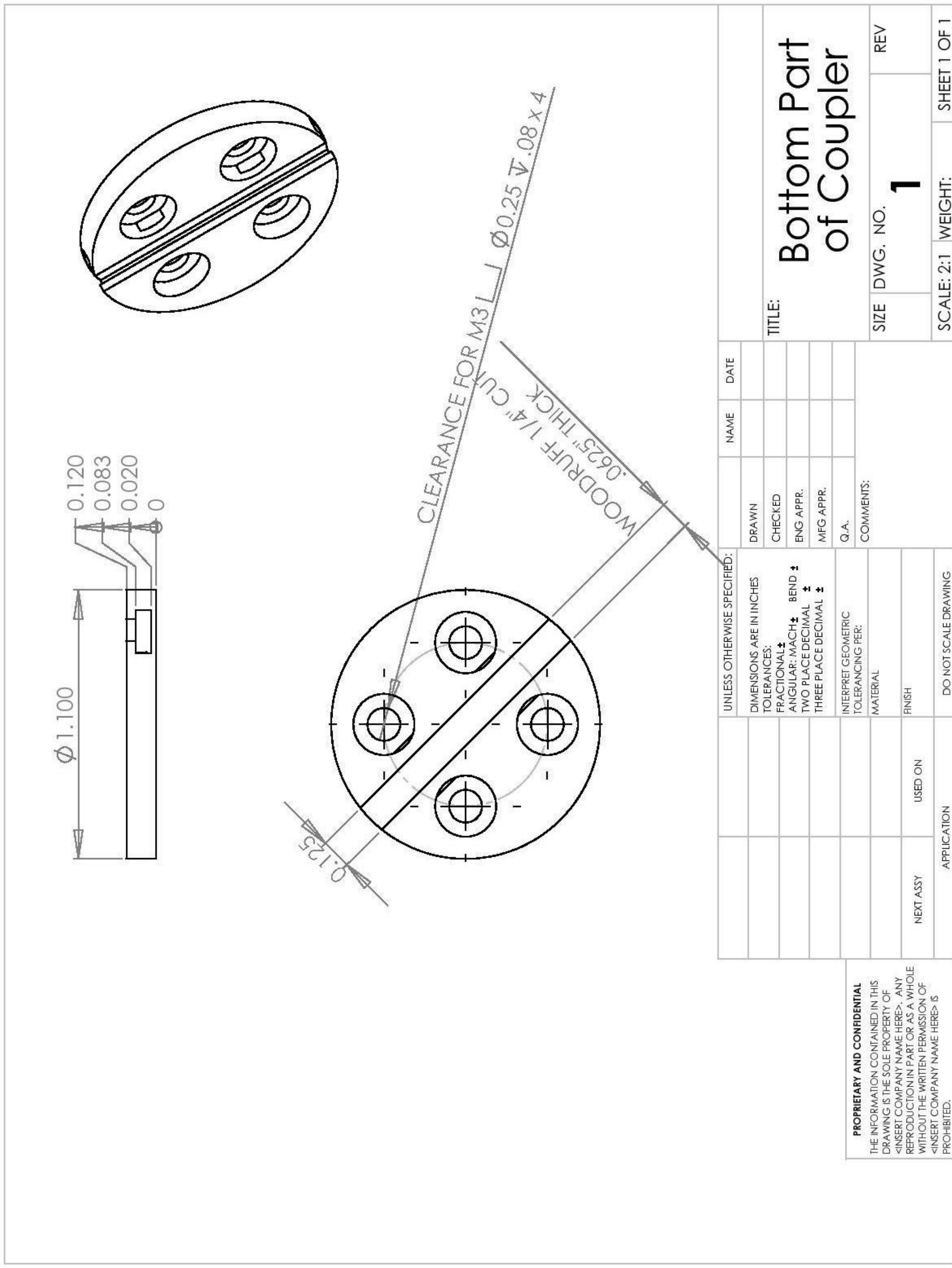
5
4
3
2
1


Ø1.100
0.120
0.083
0.020
0
CLEARANCE FOR M3 ⌴ Ø0.25 ↧.08 x 4
WOODRUFF 1/4" CUT .0625" THICK
0.125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bottom Part of Coupler
SIZE
DWG. NO.
1
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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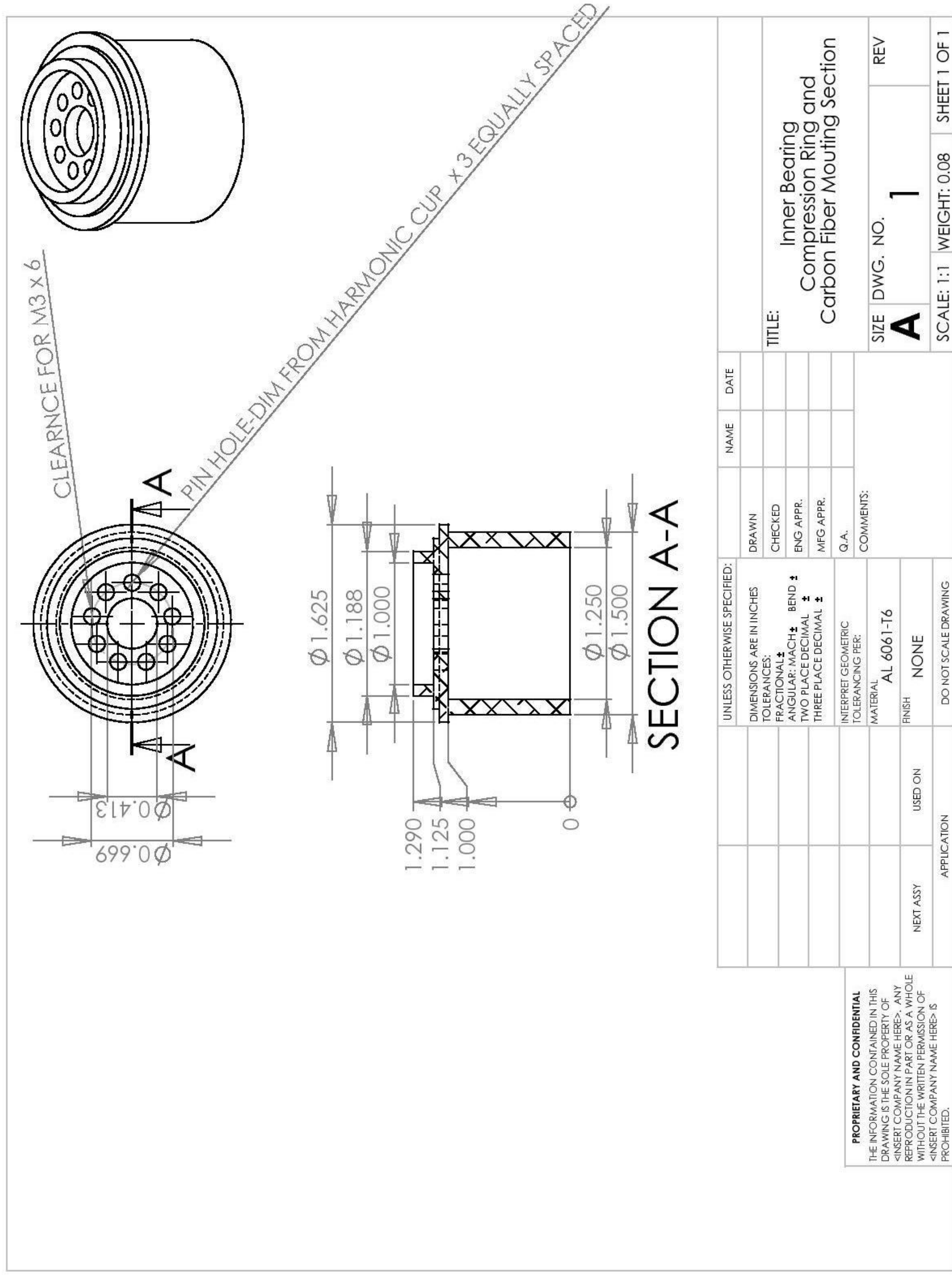
1
2
3
4
5


CLEARNCE FOR M3 x 6
PIN HOLE-DIM FROM HARMONIC CUP x 3 EQUALLY SPACED
A
A
Ø0.413
Ø0.669
Ø1.625
Ø1.188
Ø1.000
Ø1.250
Ø1.500
1.290
1.125
1.000
0
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
AL 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Inner Bearing Compression Ring and Carbon Fiber Mouting Section
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
WEIGHT: 0.08
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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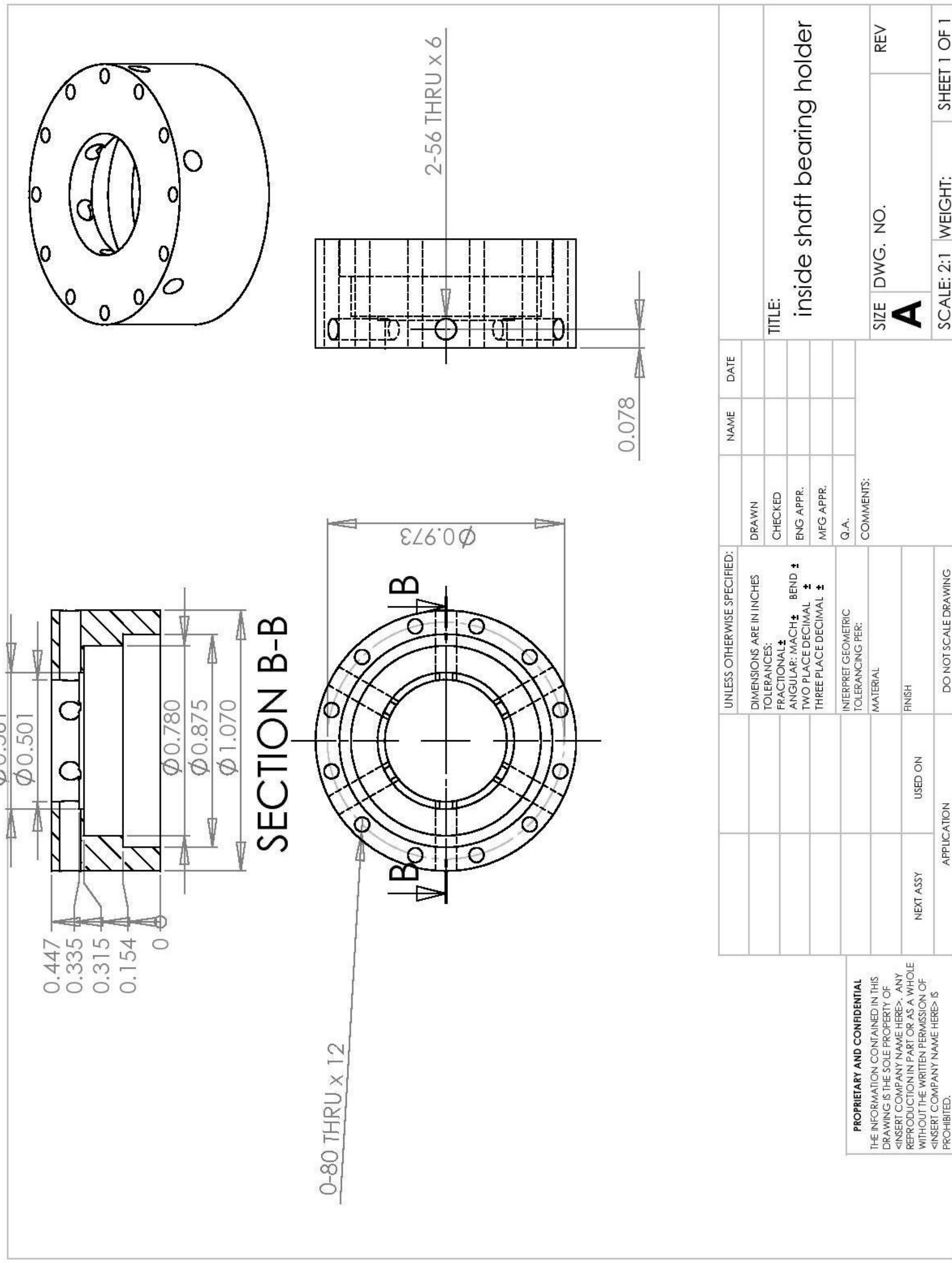
5
4
3
2
1



2-56 THRU x 6
0.078
Ø0.561
Ø0.501
Ø0.780
Ø0.875
Ø1.070
0.447
0.335
0.315
0.154
0
SECTION B-B
B
B
Ø0.973
0-80 THRU x 12
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
inside shaft bearing holder
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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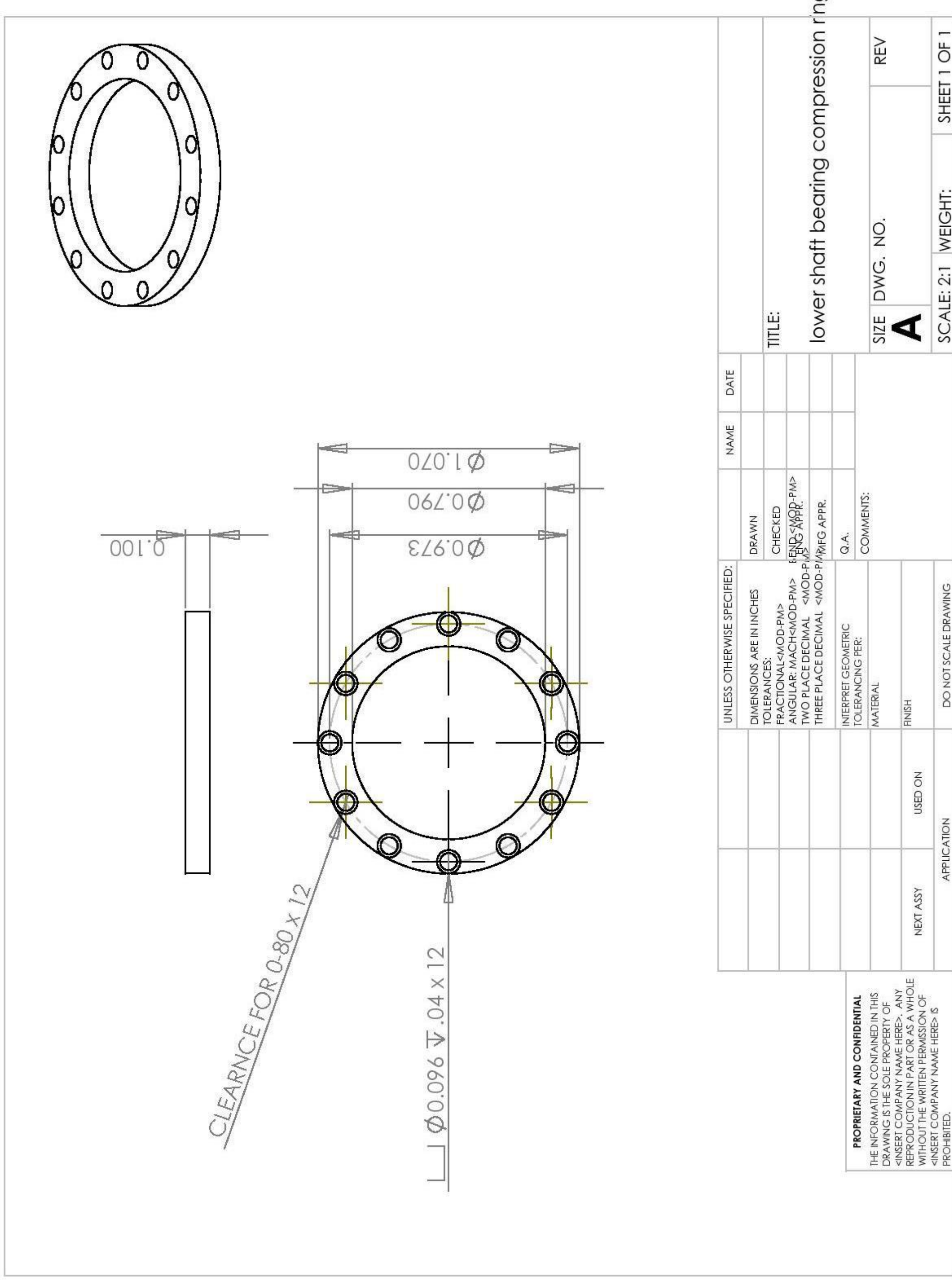

lower shaft bearing compression ring
Ø1.070
Ø0.790
Ø0.973
0.100
CLEARNCE FOR 0-80 x 12
Ø0.096 ↧.04 x 12
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL<MOD-PM>
ANGULAR: MACH<MOD-PM> BEND <MOD-PM>
TWO PLACE DECIMAL <MOD-PM>
THREE PLACE DECIMAL <MOD-PM>
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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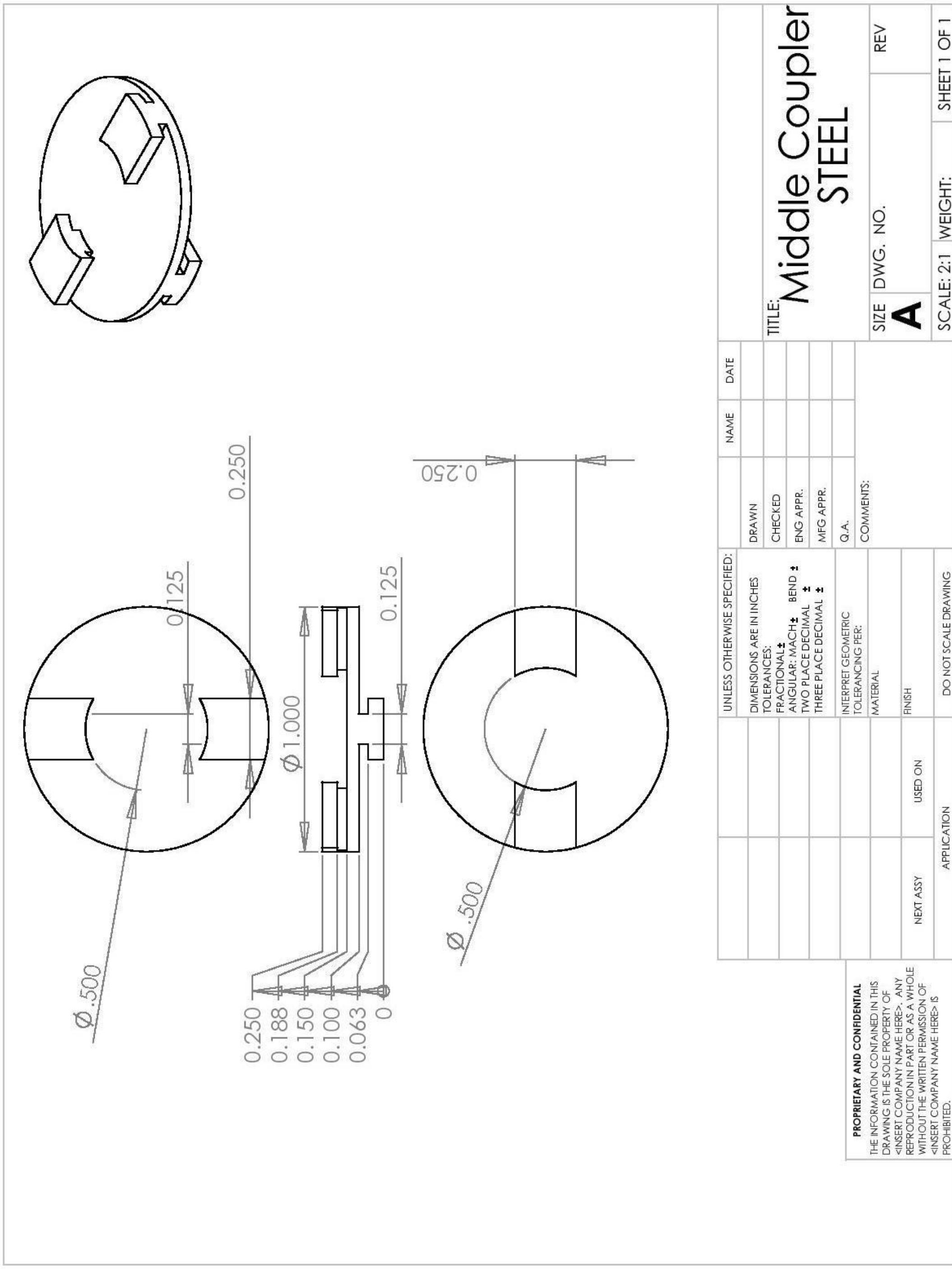
Ø.500
0.125
0.250
Ø1.000
0.125
0.250
Ø.500
0.250
0.188
0.150
0.100
0.063
0
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Middle Coupler
STEEL
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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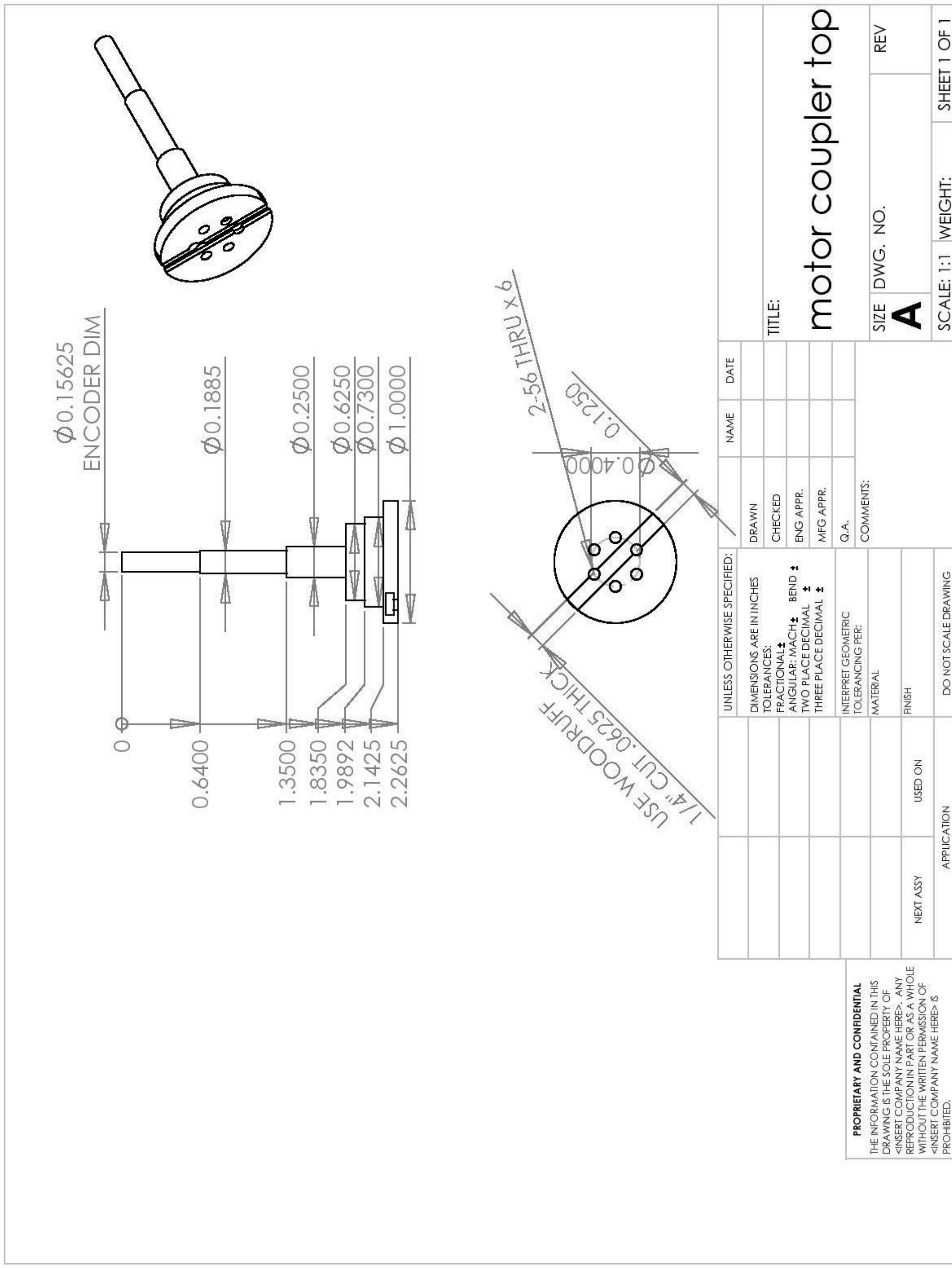
5
4
3
2
1


Ø0.15625
ENCODER DIM
Ø0.1885
Ø0.2500
Ø0.6250
Ø0.7300
Ø1.0000
0
0.6400
1.3500
1.8350
1.9892
2.1425
2.2625
2-56 THRU x 6
0.1250
Ø0.4000
USE WOODRUFF
1/4" CUT .0625 THICK
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
motor coupler top
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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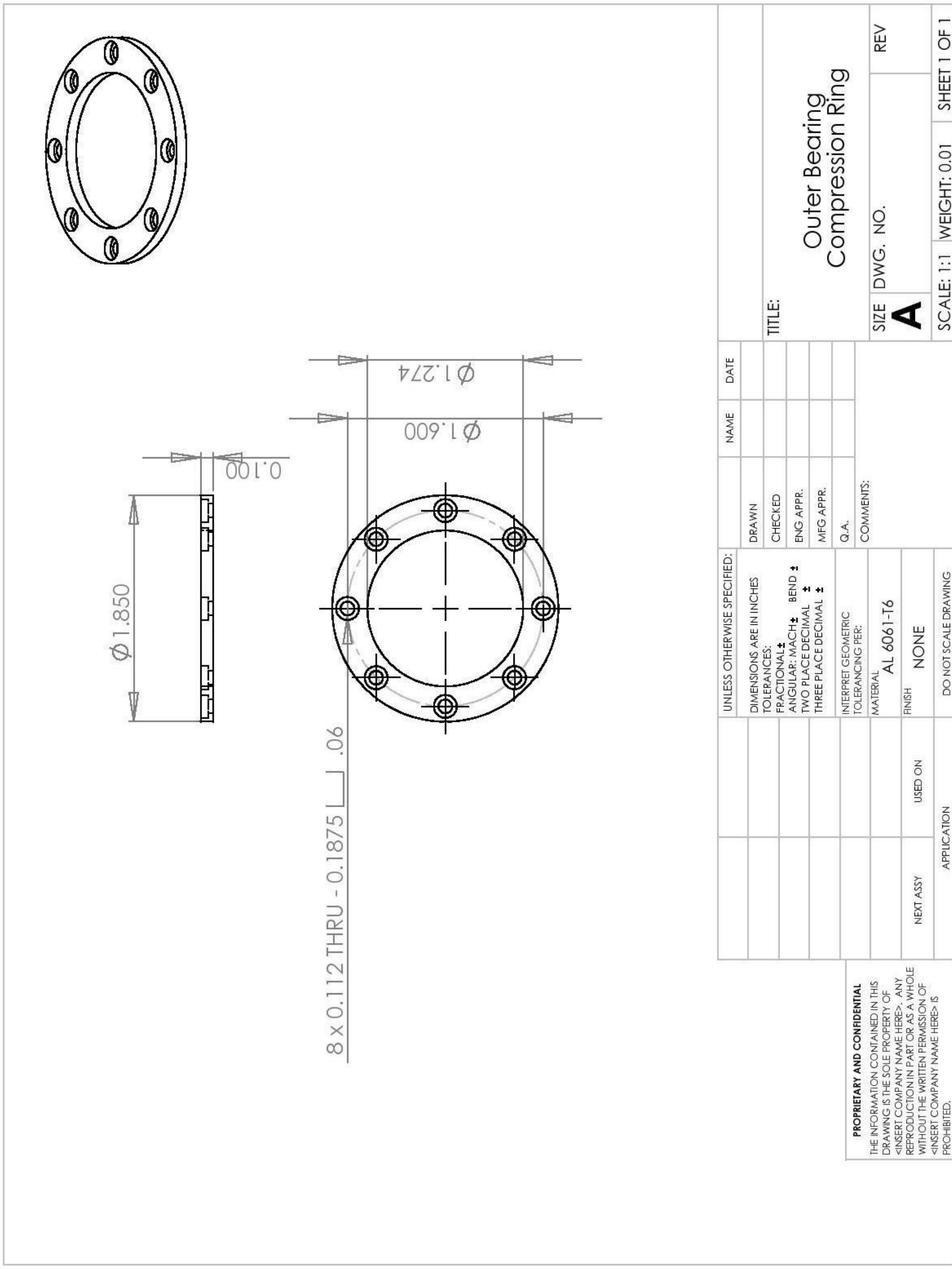
Ø1.850
0.100
Ø1.600
Ø1.274
8 x 0.112 THRU - 0.1875 ⌴ .06
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
AL 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Outer Bearing Compression Ring
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT: 0.01
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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1
2
3
4
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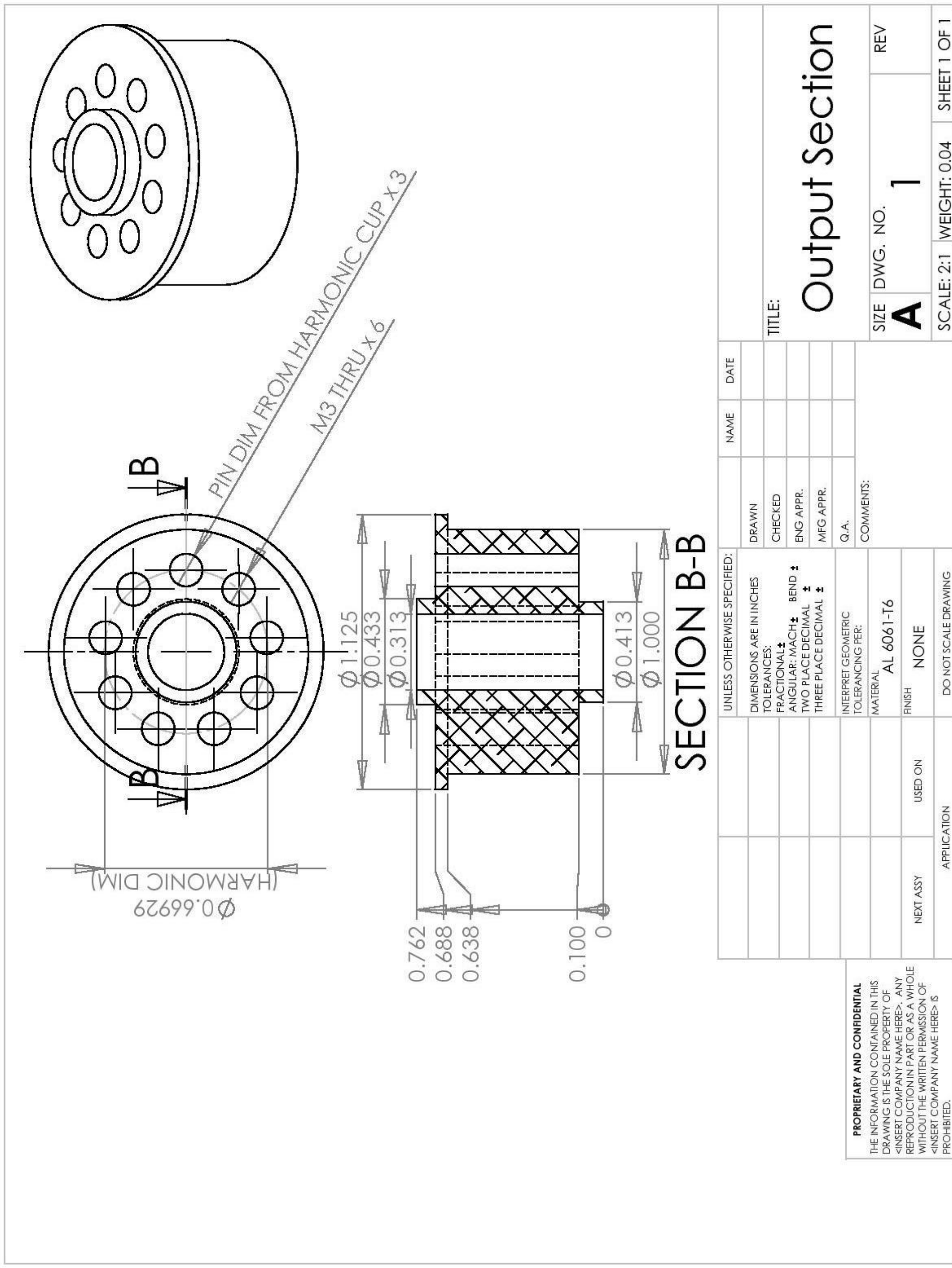
PIN DIM FROM HARMONIC CUP x 3
M3 THRU x 6
B
B
Ø0.66929
(HARMONIC DIM)
Ø1.125
Ø0.433
Ø0.313
Ø0.413
Ø1.000
SECTION B-B
0.762
0.688
0.638
0.100
0
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
AL 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
TITLE:
Output Section
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
WEIGHT: 0.04
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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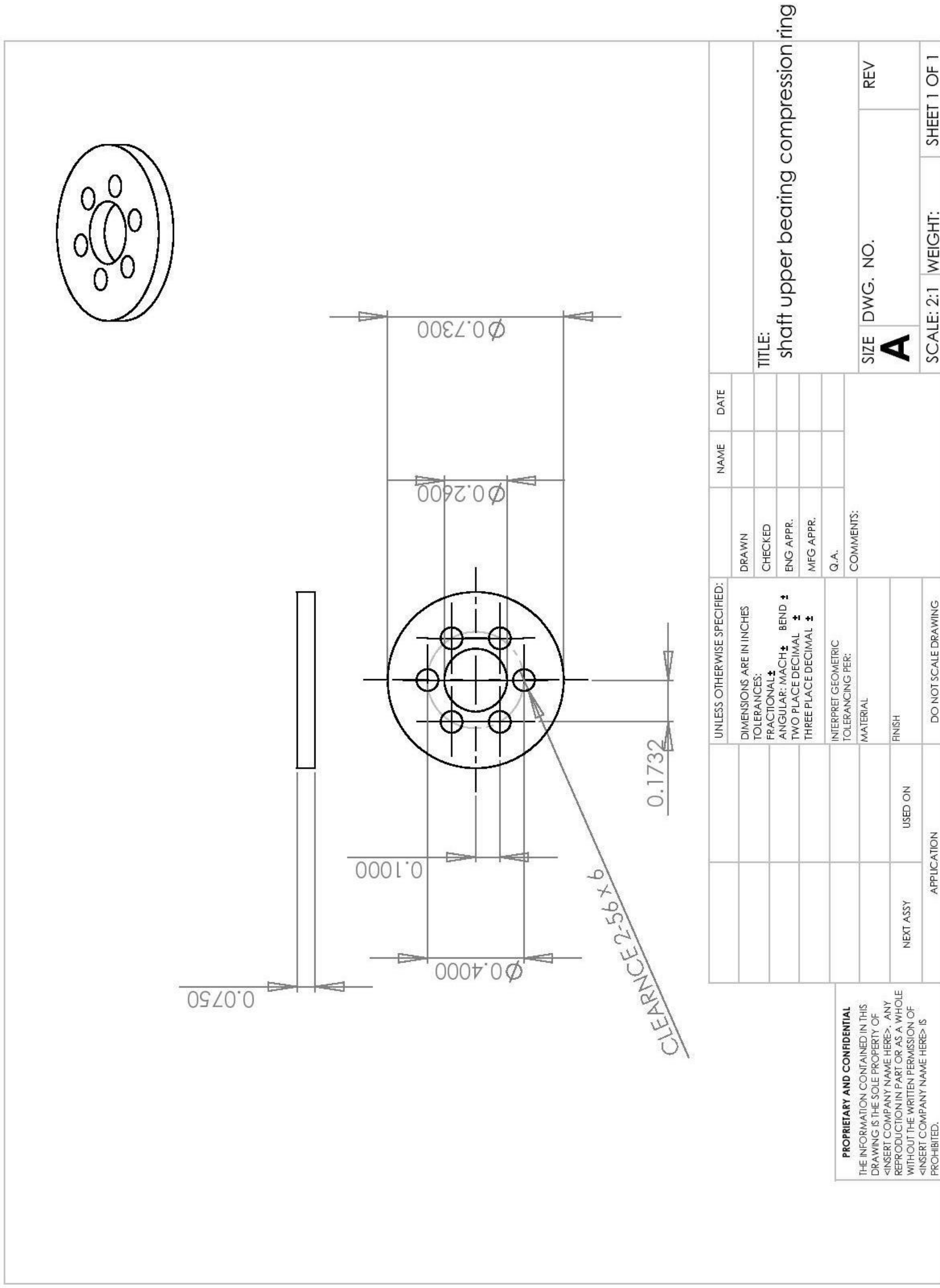
1
2
3
4
5



TITLE:
shaft upper bearing compression ring
SIZE A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
Ø0.7300
Ø0.2600
Ø0.4000
0.1000
0.1732
0.0750
CLEARNCE 2-56 x 6
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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1
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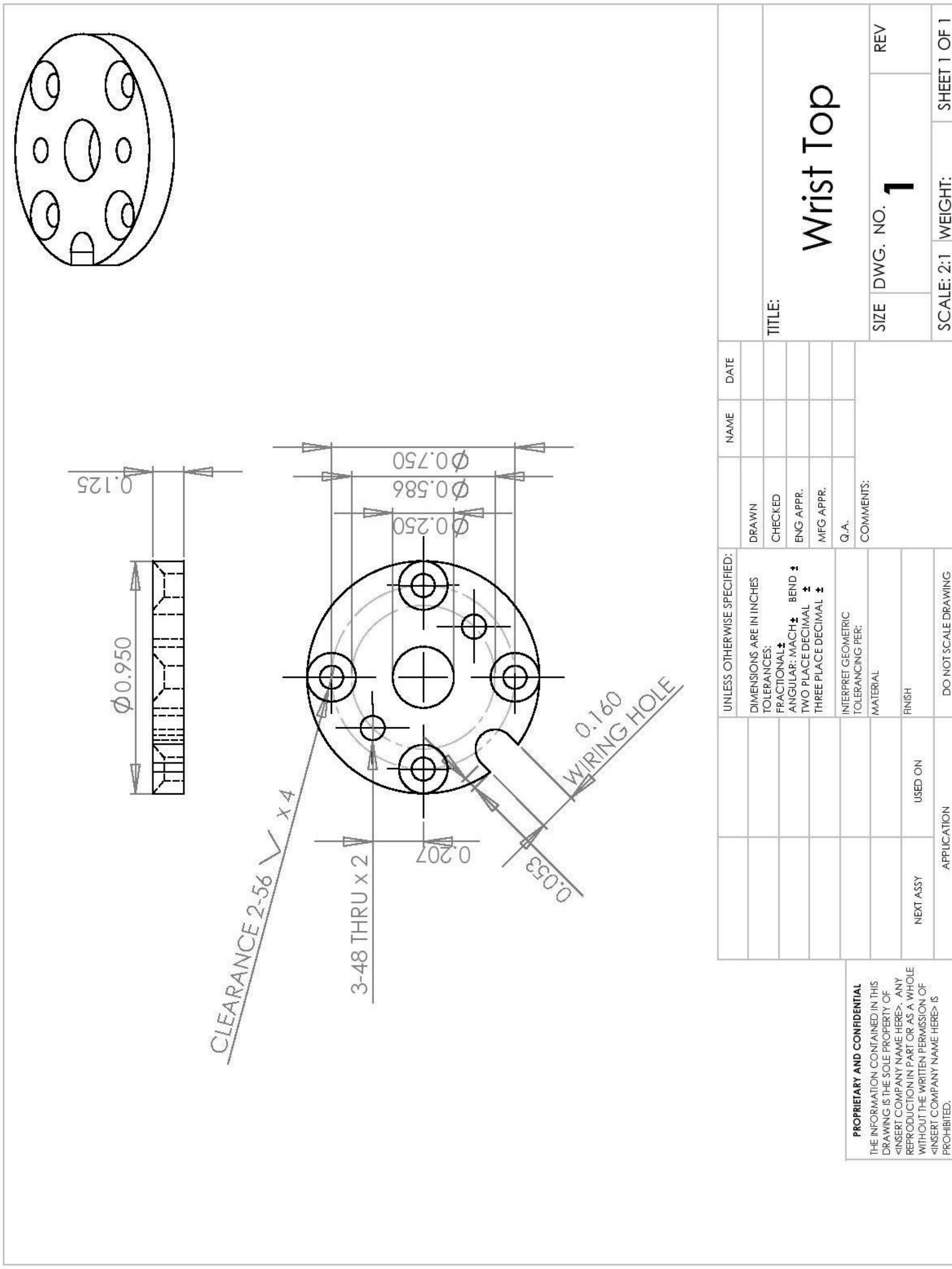
3
4
5



Ø0.950
0.125
Ø0.750
Ø0.586
Ø0.250
0.160
WIRING HOLE
0.053
0.207
3-48 THRU x 2
CLEARANCE 2-56 ✓ x 4
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Wrist Top
SIZE
DWG. NO.
1
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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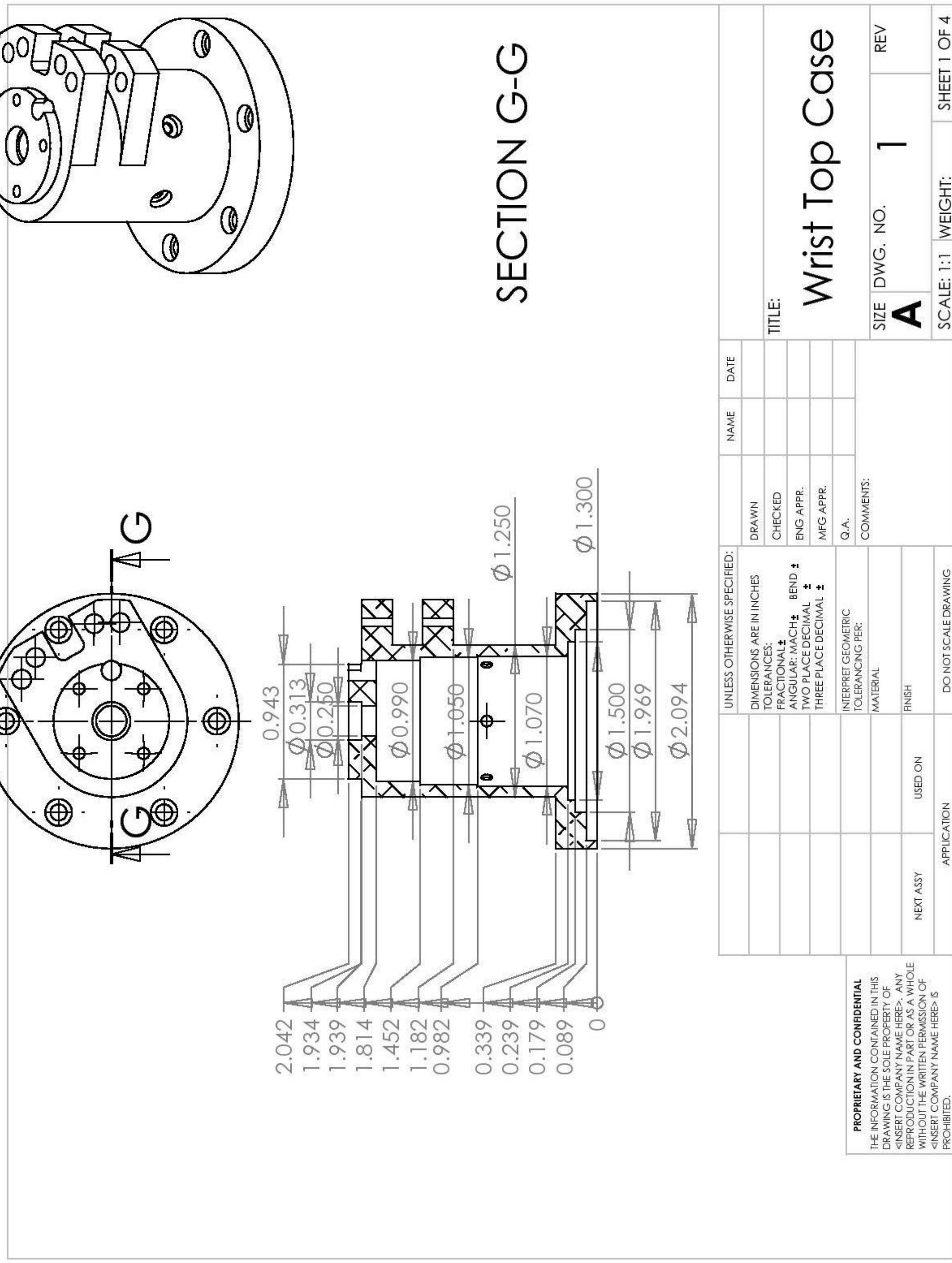
5
4
3
2
1


SECTION G-G
G
G
0.943
Ø0.313
Ø0.250
Ø0.990
Ø1.050
Ø1.070
Ø1.250
Ø1.300
Ø1.500
Ø1.969
Ø2.094
2.042
1.934
1.939
1.814
1.452
1.182
0.982
0.339
0.239
0.179
0.089
0
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Wrist Top Case
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 4
PROPRIETARY AND CONFIDENTIAL
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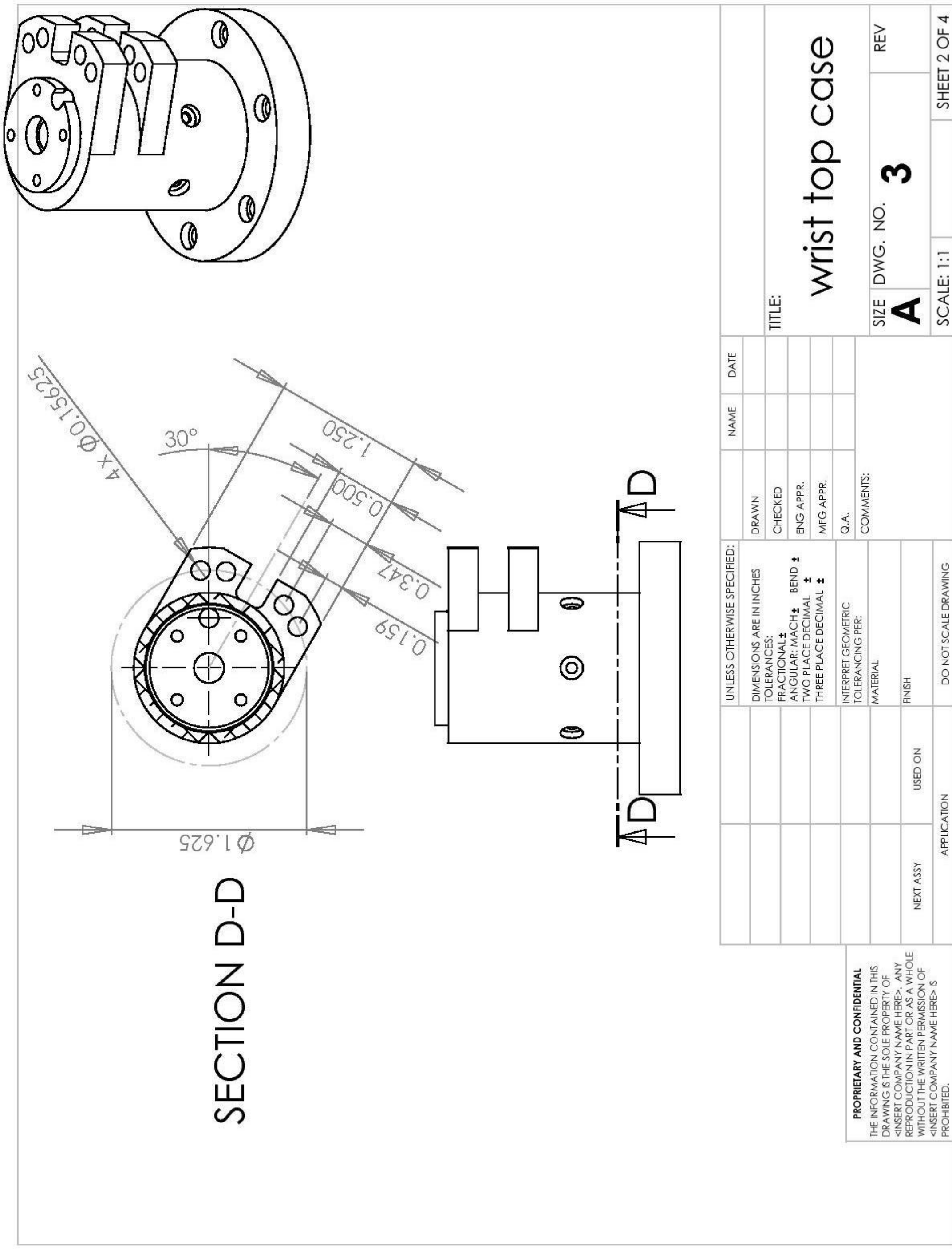
2
3
4
5


SECTION D-D
Ø1.625
4X Ø0.15625
30°
1.250
0.500
0.347
0.159
D
D
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
wrist top case
SIZE
A
DWG. NO.
3
REV
SCALE: 1:1
SHEET 2 OF 4
PROPRIETARY AND CONFIDENTIAL
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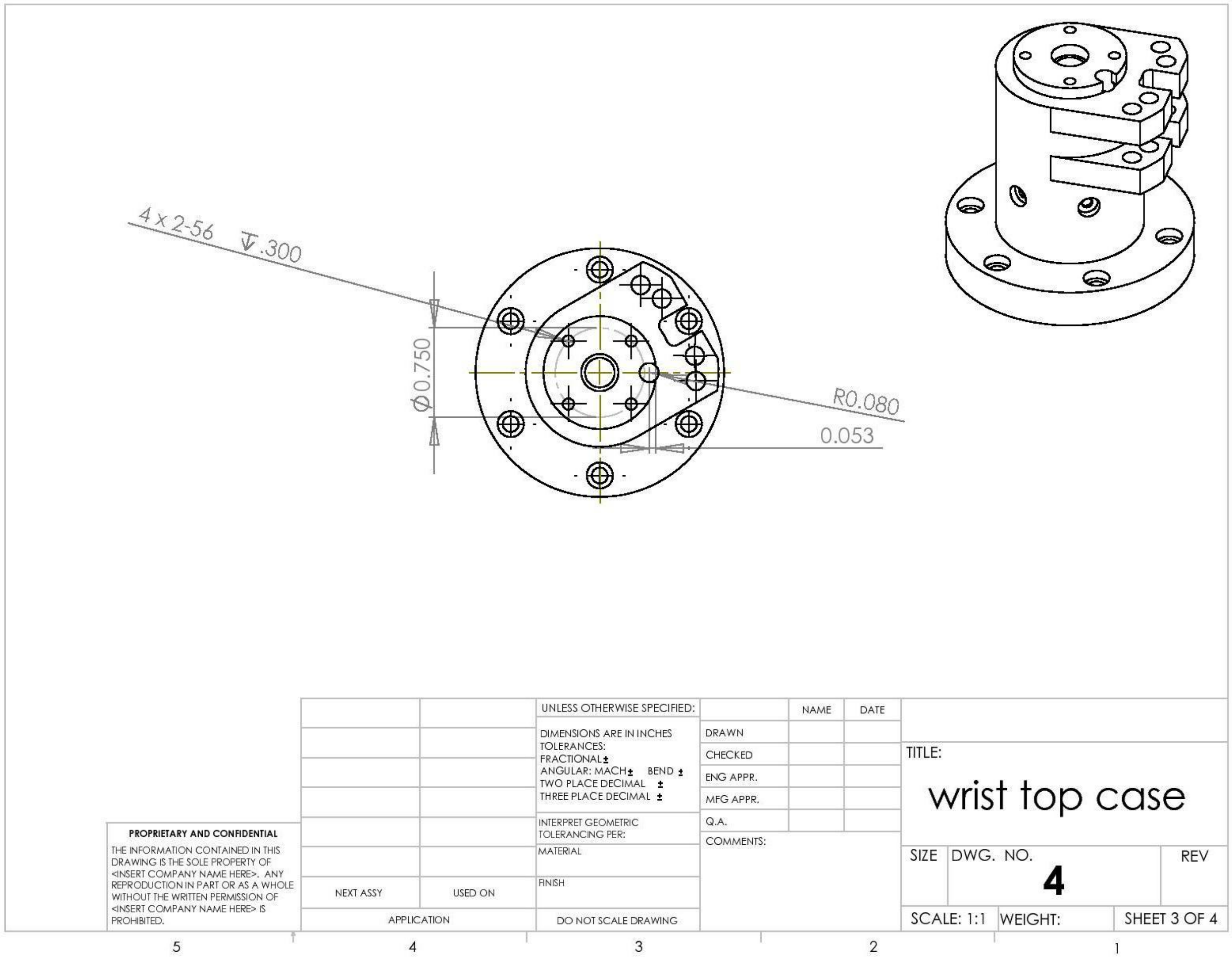
5
4
3
2
1


4 x 2-56 ⊽.300
Ø0.750
R0.080
0.053
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
wrist top case
SIZE
DWG. NO.
4
REV
SCALE: 1:1
WEIGHT:
SHEET 3 OF 4
PROPRIETARY AND CONFIDENTIAL
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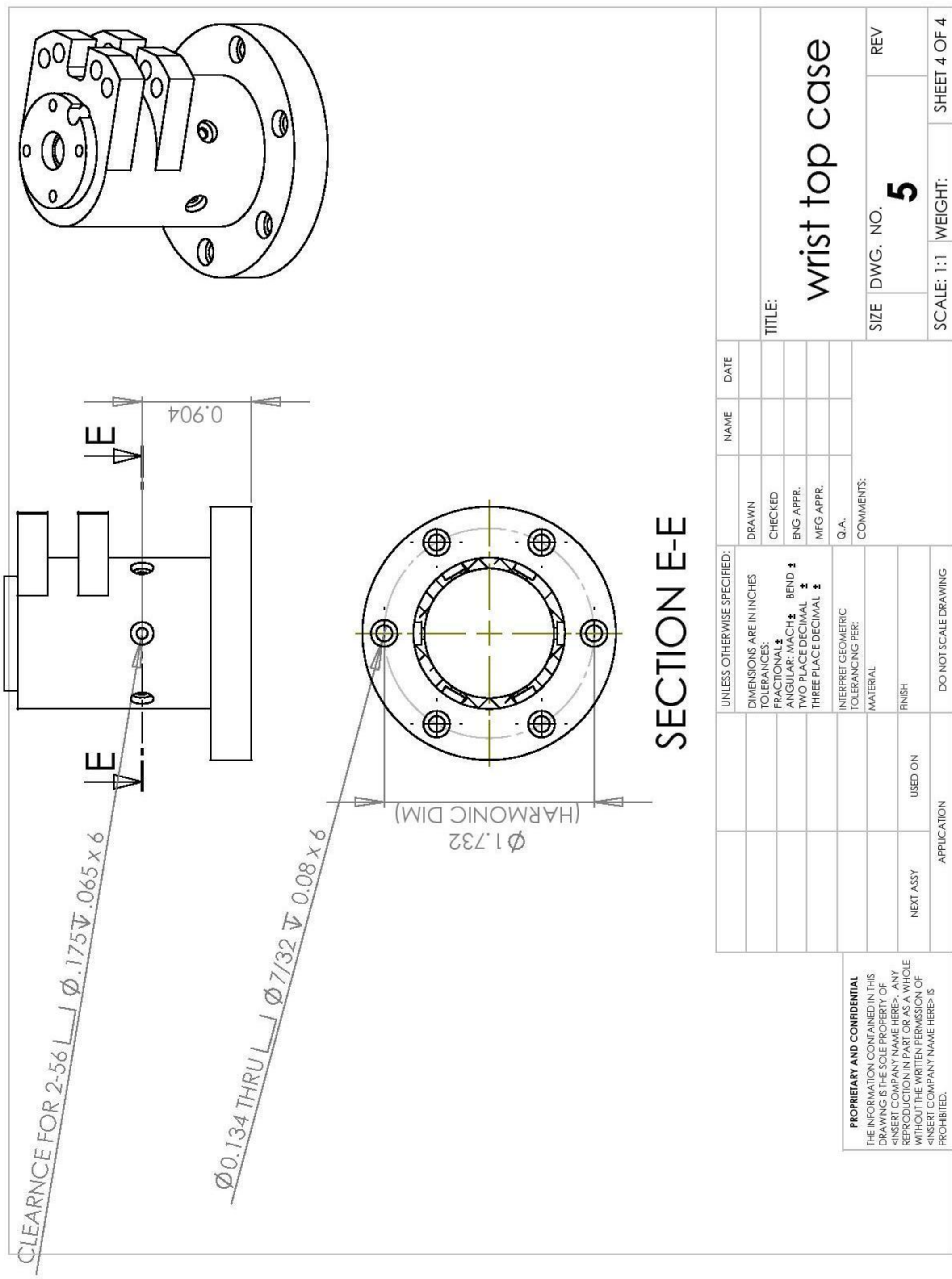
5
4
3
2
1


CLEARNCE FOR 2-56 ⌴ Ø.175 ↧ .065 x 6
Ø0.134 THRU ⌴ Ø7/32 ↧ 0.08 x 6
Ø1.732
(HARMONIC DIM)
0.904
E
E
SECTION E-E
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
wrist top case
SIZE
DWG. NO.
5
REV
SCALE: 1:1
WEIGHT:
SHEET 4 OF 4
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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2
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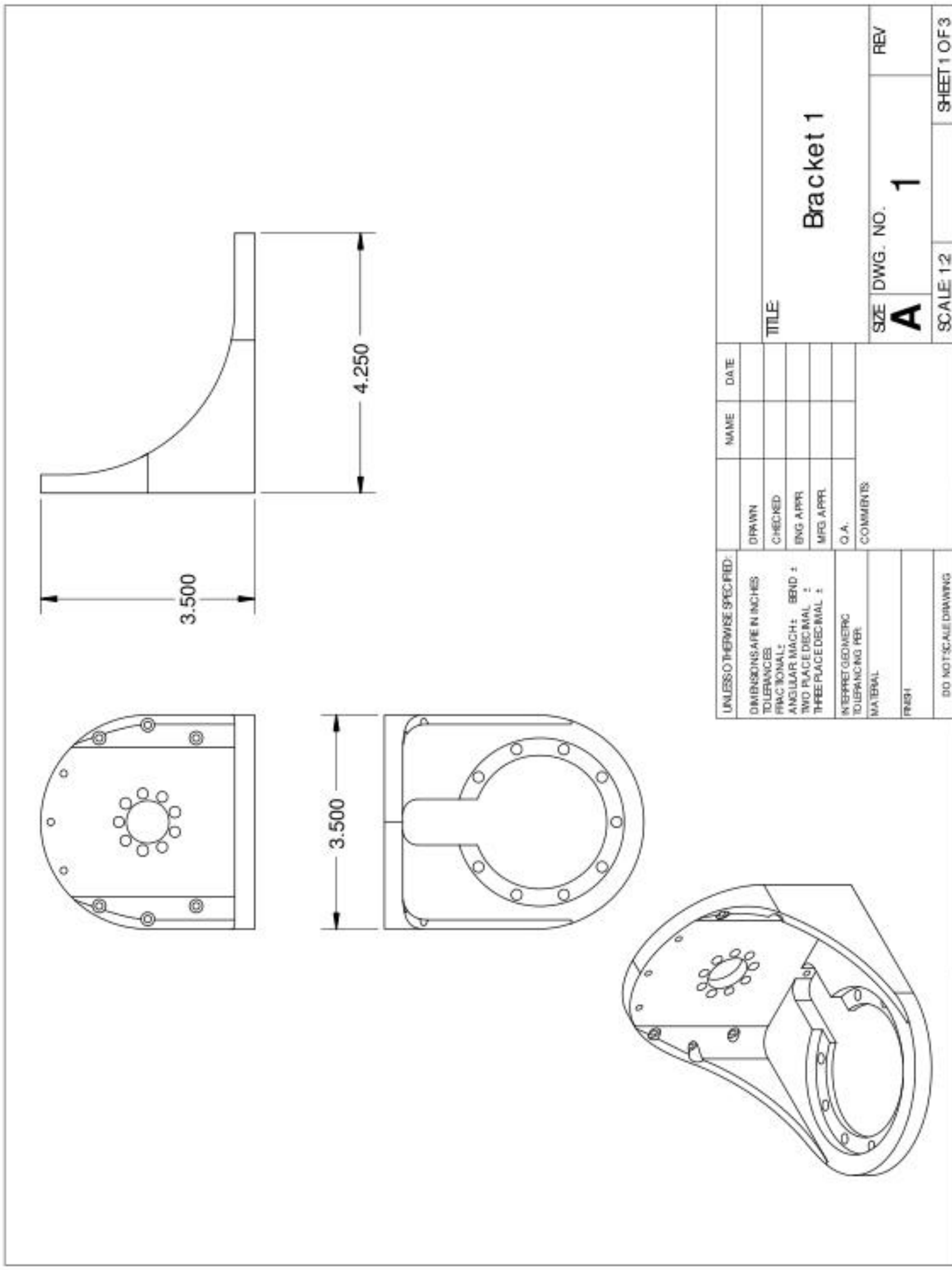
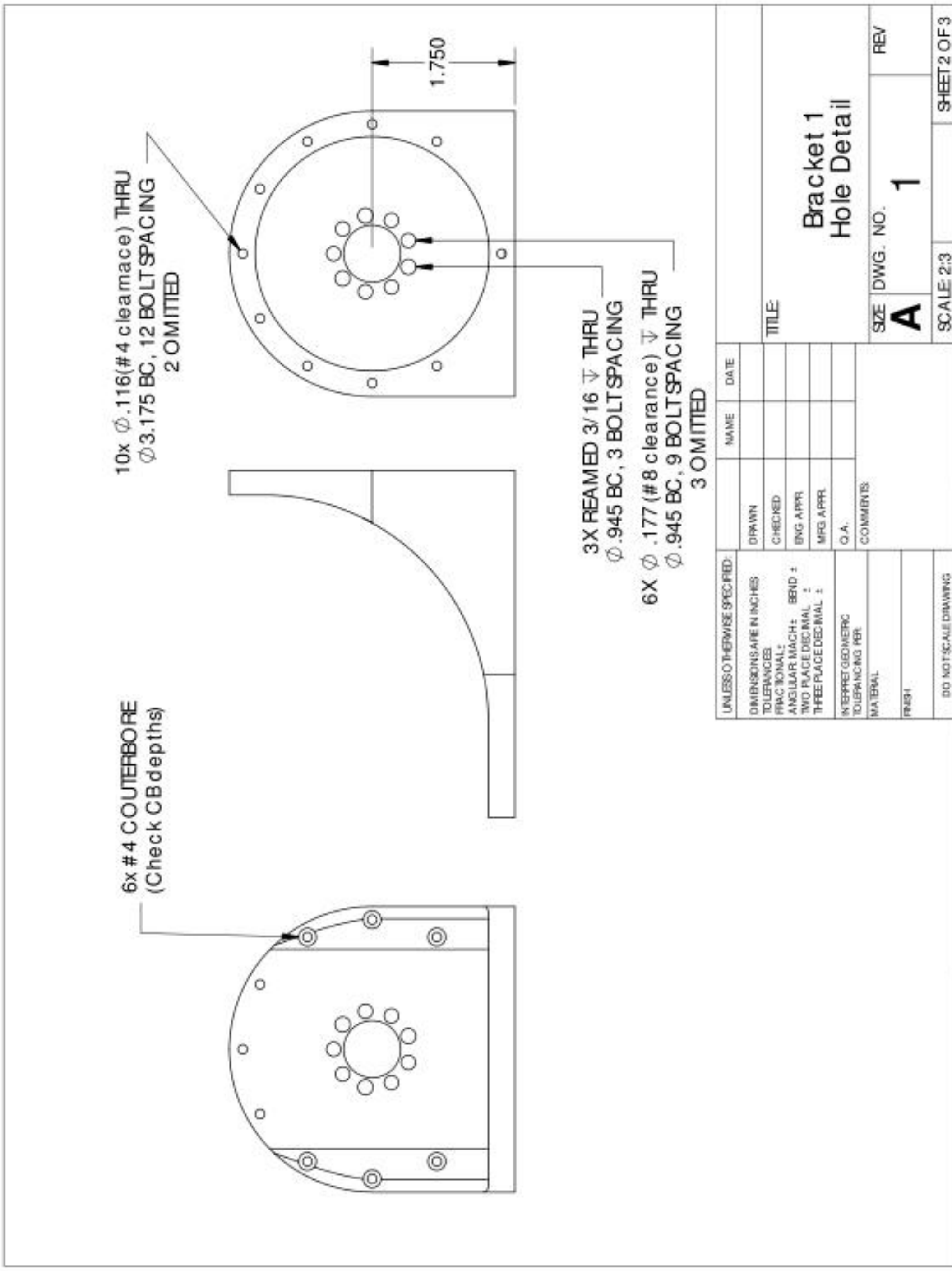
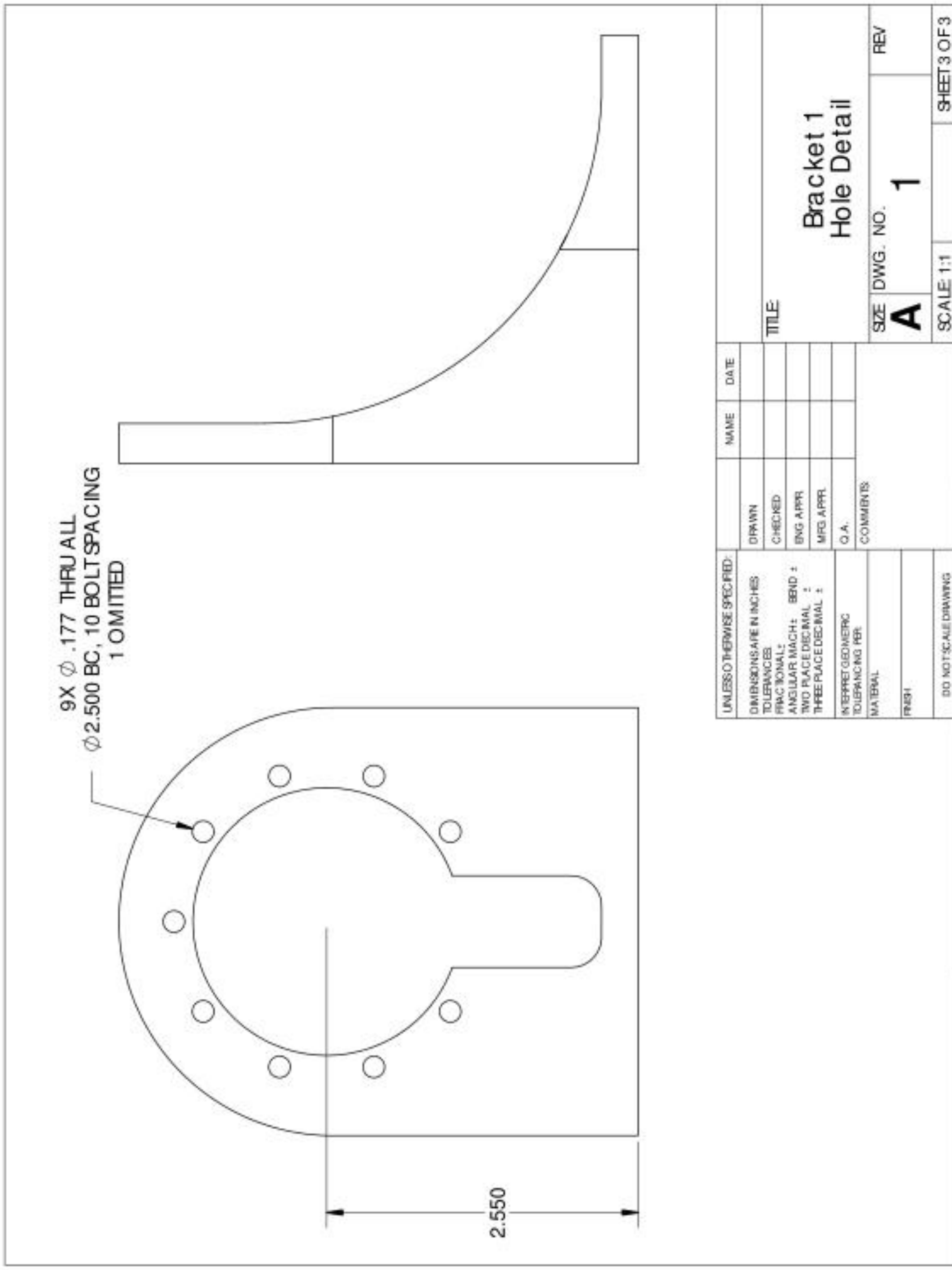
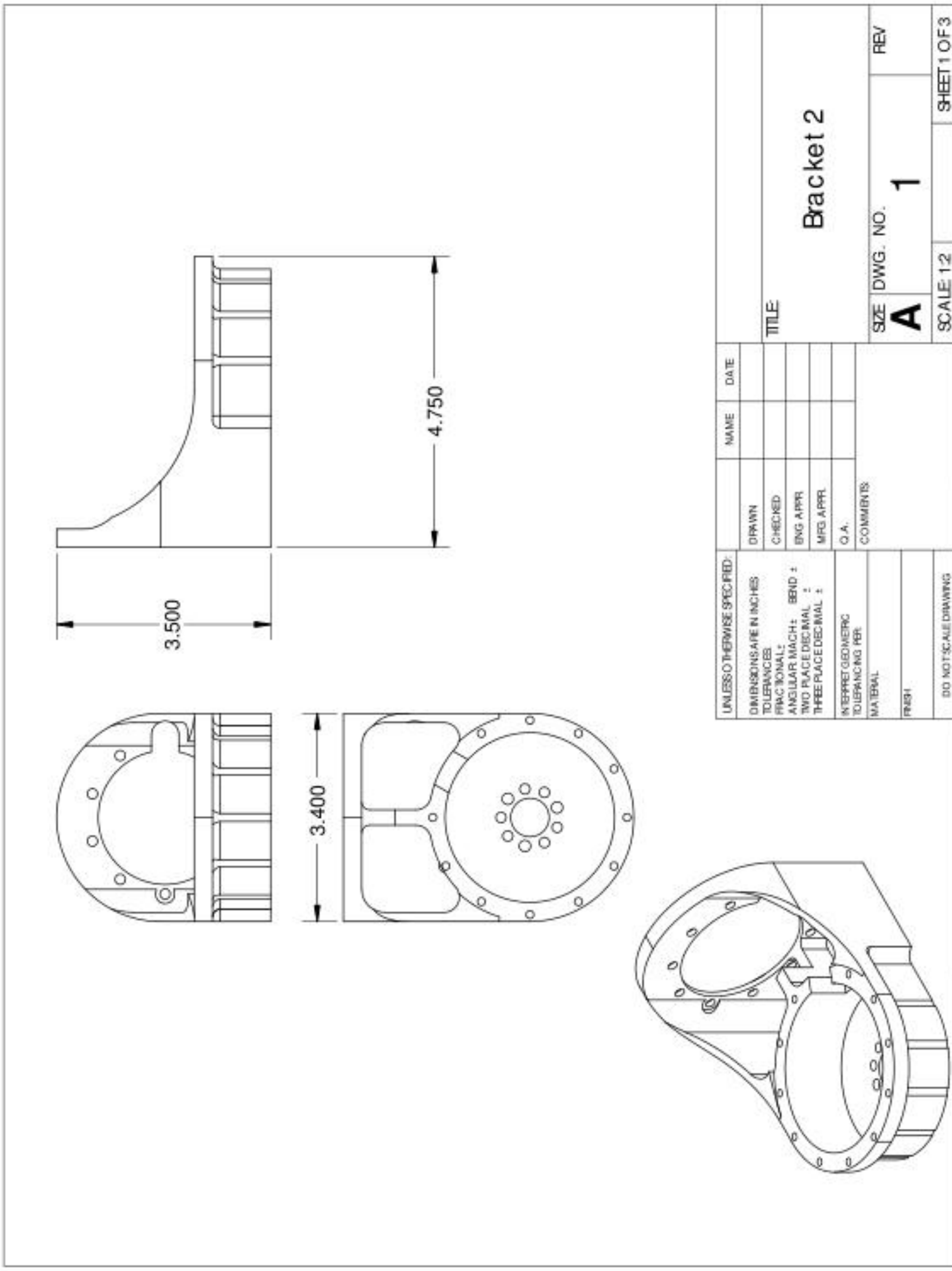
4
5

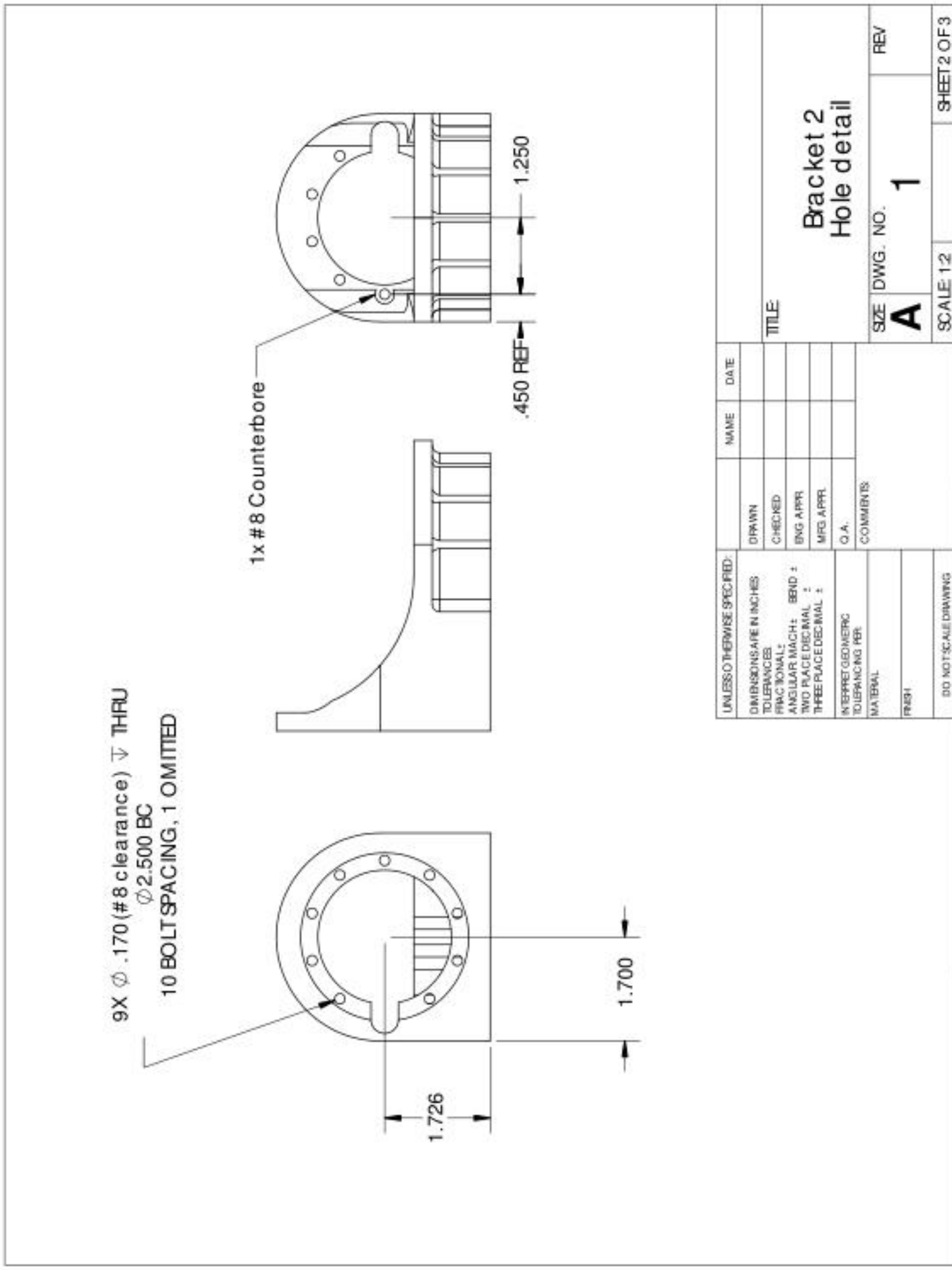
Appendix J: Bracket Drawings



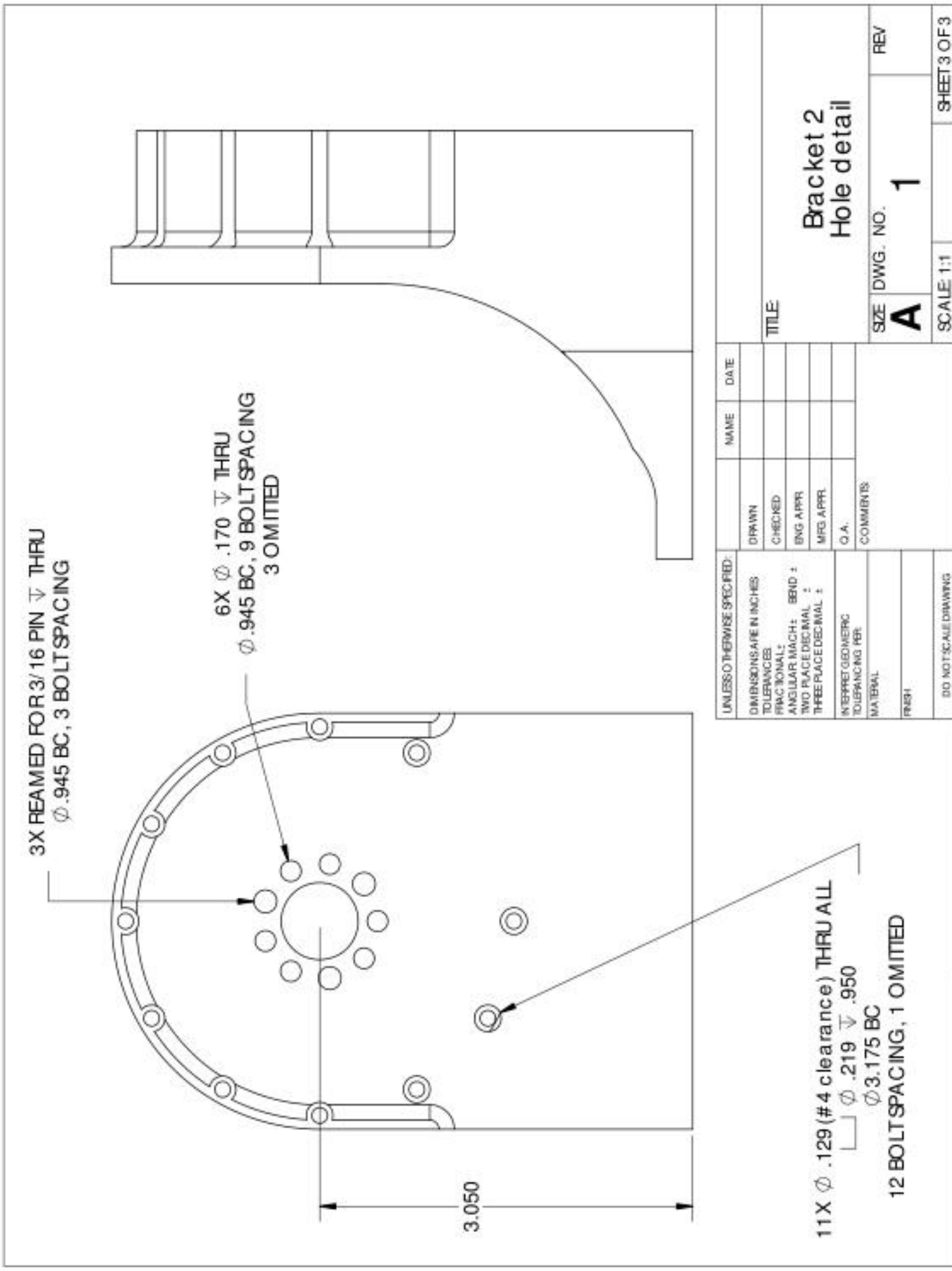

10x Ø.116(#4 clearnace) THRU
Ø3.175 BC, 12 BOLT SPACING
2 OMITTED
1.750
3X REAMED 3/16 ↧ THRU
Ø.945 BC, 3 BOLT SPACING
6X Ø .177 (#8 clearance) ↧ THRU
Ø.945 BC, 9 BOLT SPACING
3 OMITTED
6x #4 COUTERBORE
(Check CB depths)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bracket 1
Hole Detail
SIZE
A
DWG. NO.
1
REV
SCALE: 2:3
SHEET 2 OF 3
1
2
3
4
5

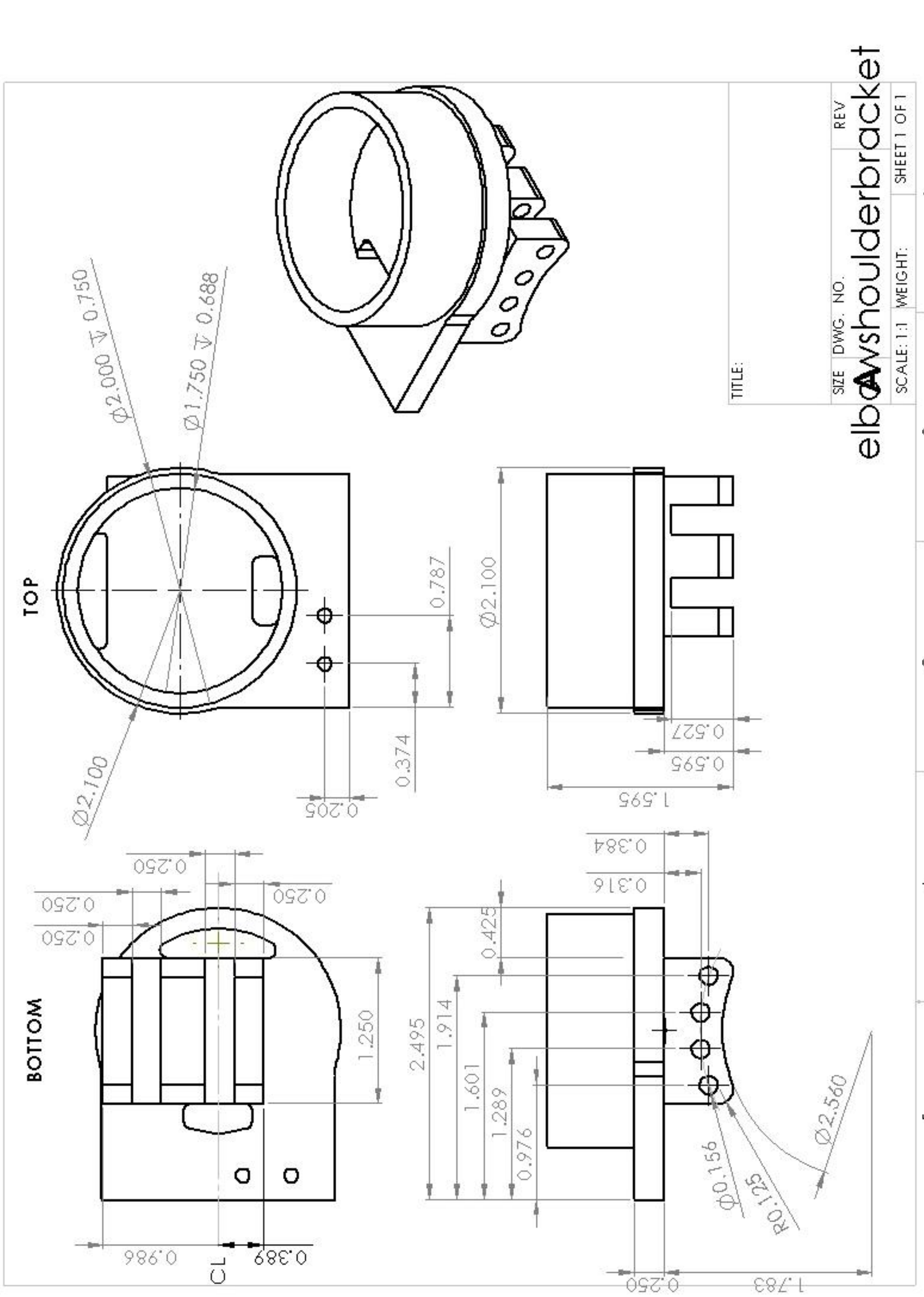

9X ⌀ .177 THRU ALL
⌀2.500 BC, 10 BOLT SPACING
1 OMITTED
2.550
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bracket 1
Hole Detail
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
SHEET 3 OF 3
1
2
3
4
5

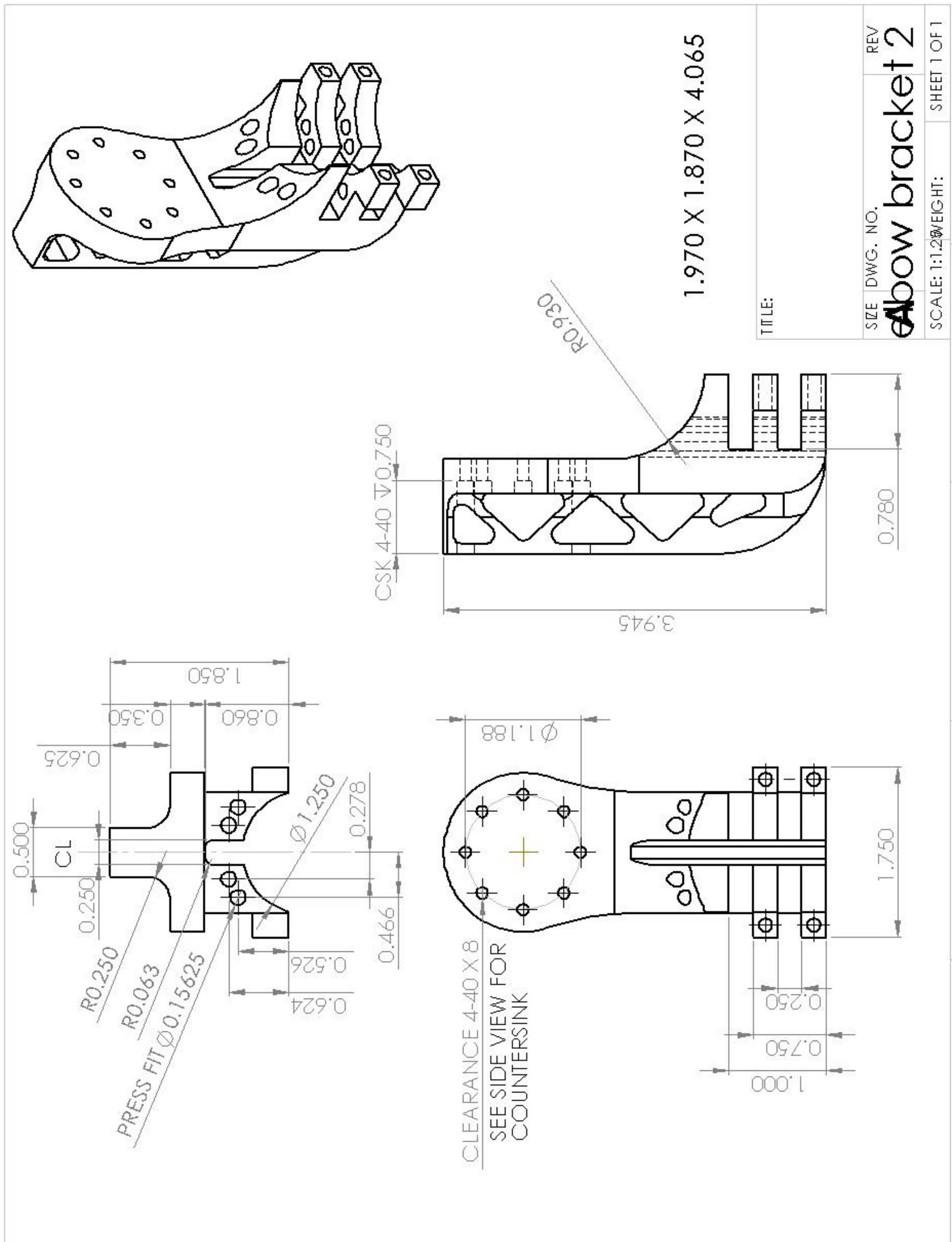

3.500
4.750
3.400
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bracket 2
SIZE
A
DWG. NO.
1
REV
SCALE: 1:2
SHEET 1 OF 3
1
2
3
4
5

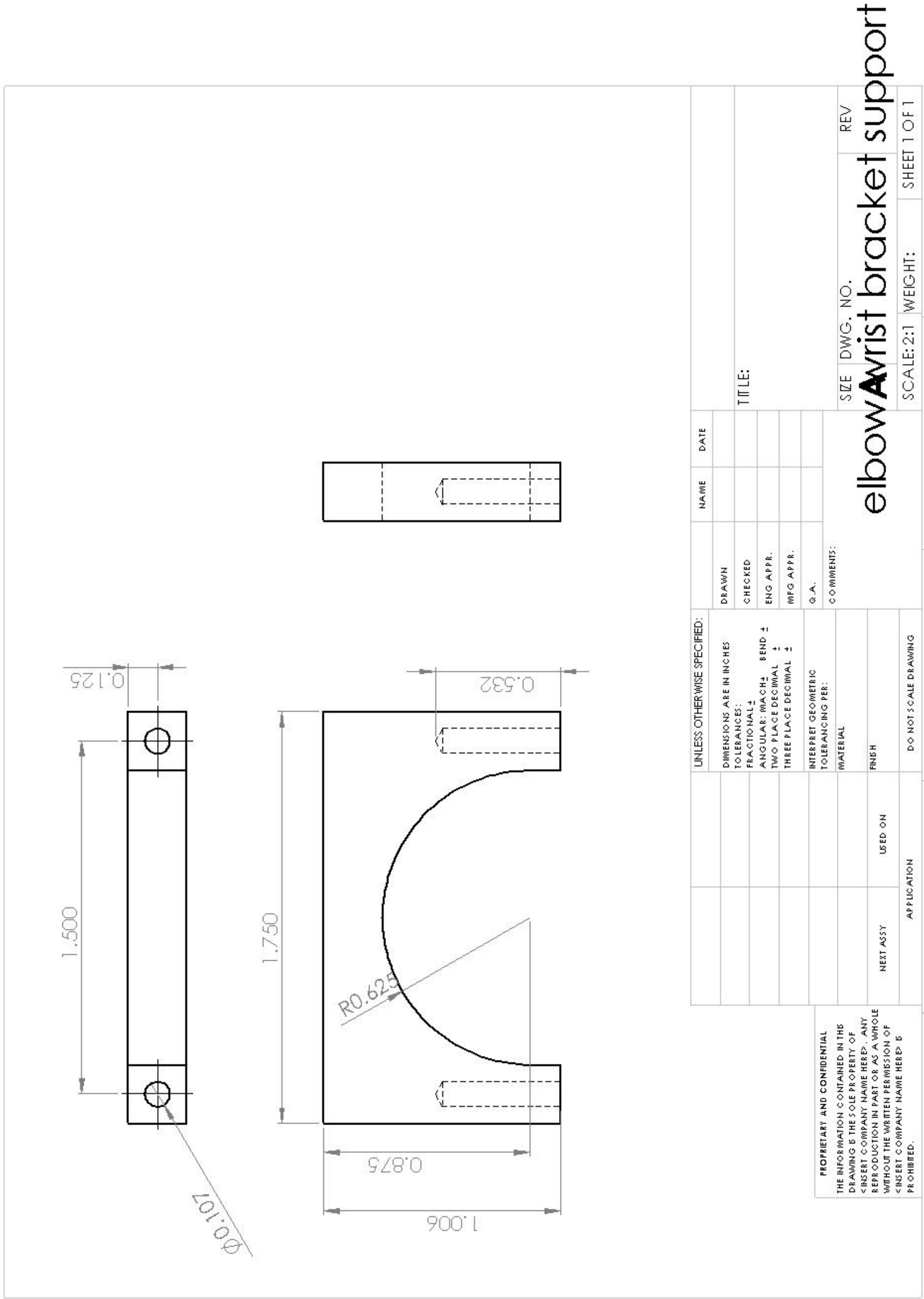


9X ⌀ .170 (#8 clearance) THRU
⌀2.500 BC
10 BOLT SPACING, 1 OMITTED
1x #8 Counterbore
1.250
.450 REF
1.700
1.726
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bracket 2
Hole detail
SIZE
A
DWG. NO.
1
REV
SCALE: 1:2
SHEET 2 OF 3


3X REAMED FOR 3/16 PIN ↧ THRU
Ø.945 BC, 3 BOLT SPACING
6X Ø .170 ↧ THRU
Ø.945 BC, 9 BOLT SPACING
3 OMITTED
11X Ø .129 (#4 clearance) THRU ALL
⌴ Ø .219 ↧ .950
Ø3.175 BC
12 BOLT SPACING, 1 OMITTED
3.050
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bracket 2
Hole detail
SIZE
A
DWG. NO.
1
REV
SCALE: 1:1
SHEET 3 OF 3


TOP
BOTTOM
TITLE:
SIZE
A
DWG. NO.
elbowshoulderbracket
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
Ø2.000 ⌵ 0.750
Ø1.750 ⌵ 0.688
Ø2.100
Ø2.100
0.787
0.374
0.205
0.527
0.595
1.595
0.250
0.250
0.250
0.250
1.250
0.986
CL
0.389
2.495
1.914
1.601
1.289
0.976
0.425
0.316
0.384
Ø0.156
R0.125
Ø2.560
0.250
1.783


1.970 X 1.870 X 4.065
TITLE:
SIZE
A
DWG. NO.
elbow bracket 2
REV
SCALE: 1:1.25
WEIGHT:
SHEET 1 OF 1
R0.930
CSK 4-40 ⊽0.750
0.780
3.945
1.850
0.350
0.860
0.625
0.500
CL
0.250
R0.250
R0.063
PRESS FIT Ø0.15625
Ø1.250
0.278
0.466
0.526
0.624
Ø1.188
CLEARANCE 4-40 X 8
SEE SIDE VIEW FOR
COUNTERSINK
1.750
0.250
0.750
1.000


0.125
1.500
1.750
0.532
R0.625
0.875
1.006
Ø0.107
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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SIZE
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elbow wrist bracket support
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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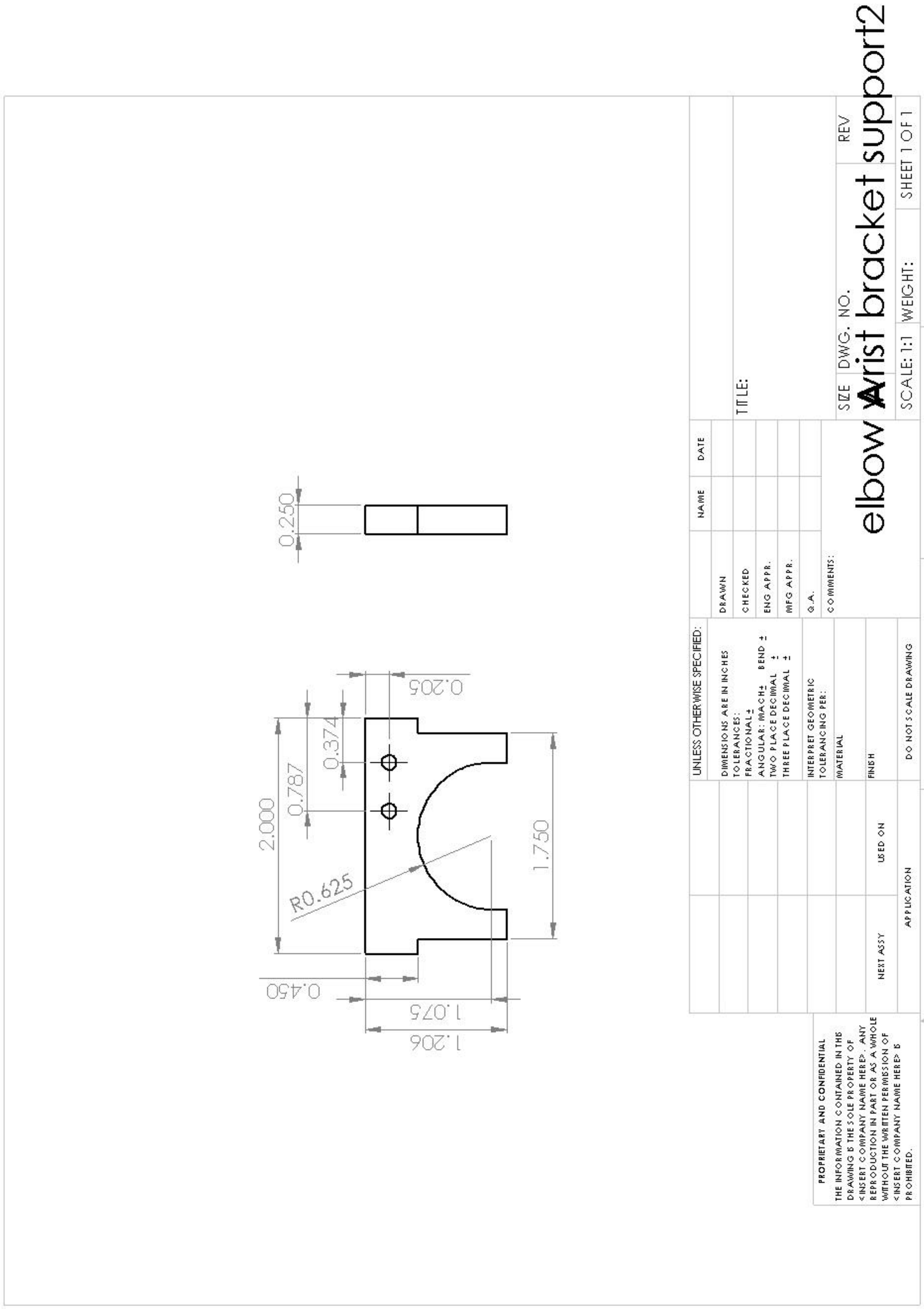
0.250
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
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elbow wrist bracket support2
SCALE: 1:1
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SHEET 1 OF 1
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Appendix K: Bill of Materials

A: Shoulder Joint Parts

BILL OF MATERIALS: SHOULDER JOINTS (3 TOTAL)			
Part Description	**Drawing Name / Part Number**	**Producer**	**Quantity**
Shoulder Motor Housing	Outer Housing	Machined Part	3
Stator Removal Sleeve	Stator Removal Sleeve	Machined Part	3
Rotor Shaft	Rotor Shaft	Machined Part	3
Rotor Disassembly Ring	Rotor Disassembly Shaft	Machined Part	3
Oldham Coupler Rotor	Oldham Coupler Rotor Side	Machined Part	3
X Bearing Clamp	X Bearing Clamp	Machined Part	3
Quick Disconnect Nut	Connecting Nut	Machined Part	3
Oldham Coupler Center	Oldham Coupler	Machined Part	3
Oldham Coupler WG	Oldham Coupler WG end	Machined Part	3
Encoder Wheel Clamp	Rotor Encoder Clamp	Machined Part	3
Shoulder HD Housing	HD Side Housing	Machined Part	3
Output Bearing Retainer	Bearing Retainer	Machined Part	3
Output Bearing Housing	Bearing Housing	Machined Part	3
Output Spacer	Output Blank Spacer	Machined Part	3
Carbon Tube Output	Carbon Tube Output	Machined Part	1
AC Bearing Shim	Bearing Shim	Machined Part	3
Shoulder Motor	HT02000	Emoteq	3
Shoulder Harmonic Drive	CSD-20-100	Harmonic Drive Inc.	3
Shoulder Encoder Disk	DISK-2-2500-1000-I	US Digital	3
Shoulder Encoder Reader	EM1-2-2500	US Digital	3
X Bearing	KAA10XL0	Motion Ind. Kaydon	3
Rotor Bearing	SSRI-1634	Alpine Bearing	3
AC Bearings	KA025AR0	Motion Ind. Kaydon	6
Quick Disconnect	HR10A-7R-5S	Digikey	3

B: Elbow Joint Parts

BILL OF MATERIALS: ELBOW JOINT			
Part Description	**Drawing Name / Part Number**	**Producer**	**Quantity**
Top Bearing / Encoder Cap	Cap	Machined Part	1
Elbow Motor Housing	Elbow Case Top	Machined Part	1
X Bearing Housing	Motor Bearing Ring	Machined Part	1
Top X Bearing Compressor	Motor Bearing Compressor 2	Machined Part	1
Lower X Bearing Compressor	Motor Bearing Compressor	Machined Part	1
Rotor Shaft	Oldham Rotor	Machined Part	1
Oldham Coupler Center	Coupler	Machined Part	1
Oldham Coupler WG	Oldham Coupler WG side	Machined Part	1
Output Bearing Compressor	Bearing Compressor	Machined Part	1
Elbow HD Housing	Elbow Bottom	Machined Part	1
Output Top	Output Top	Machined Part	1
Output Spacer	Output Bottom	Machined Part	1
AC Bearing Shim	Shim	Machined Part	1
Elbow Motor	HT01500	Emoteq	1
Elbow Harmonic Drive	CSD-17-100	Harmonic Drive Inc.	1
Elbow Encoder	E4-360-188-D-D-D-B	US Digital	1
X Bearing	KAA10XL0	Motion Ind. Kaydon	1
Rotor Bearing	6455K100	McMaster	1
AC Bearings	KAA15G0	Motion Ind. Kaydon	2

C: Wrist Joint Parts

BILL OF MATERIALS: WRIST JOINT			
Part Description	**Drawing Name / Part Number**	**Producer**	**Quantity**
Top Bearing/Encoder Cap	Wrist Top	Machined Part	1
Wrist Motor Housing	Wrist Top Case	Machined Part	1
Upper Rotor Bearing Ring	Shaft Upper Bearing Compression Ring	Machined Part	1
Lower Rotor Bearing Holder	Inside Shaft Bearing Holder	Machined Part	1
Lower Rotor Bearing Ring	Lower Shaft Bearing Compression Ring	Machined Part	
Rotor Shaft	Motor Coupler Top	Machined Part	1
Oldham Coupler Center	Middle Coupler	Machined Part	1
Oldham Coupler WG	Bottom Part of Coupler	Machined Part	1
Wrist HD Housing	Bottom Case	Machined Part	1
AC Bearing Compression Ring	Outer Bearing Compression Ring	Machined Part	1
Output Bottom	Output Section	Machined Part	1
Output Carbon Tube Mount	Inner Bearing Compression Ring…	Machined Part	1
AC Bearing Shim	Angular Contact Shim	Machined Part	1
Wrist Motor	HT01000	Emoteq	1
Wrist Harmonic Drive	CSD-14-100	Harmonic Drive Inc.	1
Wrist Encoder	E4-360-156-D-D-D-B	US Digital	1
Lower Rotor Bearing	SSRI-1458	Alpine Bearing	1
Upper Rotor Bearing	SSRI-5532	Alpine Bearing	1
AC Bearings	KAA10AG0	Kaydon	2

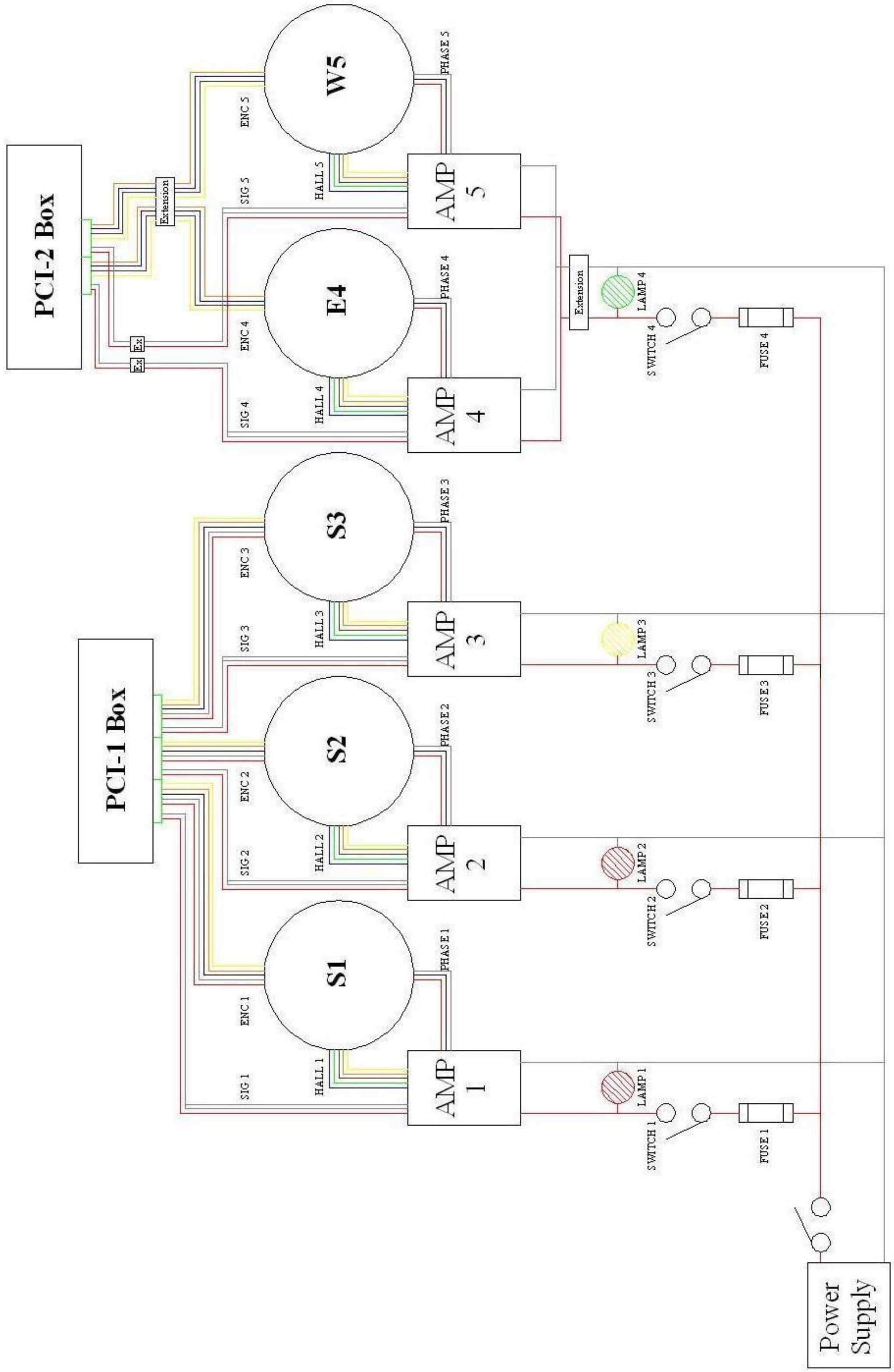
D: Bracket Parts

BILL OF MATERIALS: BRACKETS			
Part Description	Drawing Name / Part Number	Producer	Quantity
Shoulder Bracket 1	Bracket 1	Machined Part	1
Shoulder Bracket 2	Bracket 2	Machined Part	1
Shoulder to Elbow Bracket	Elbow Shoulder Bracket	Machined Part	1
Elbow to Wrist Bracket	Elbow Bracket 2	Machined Part	1
Wrist Bracket Support/Amp Holder	Elbow Wrist Bracket Support 2	Machined Part	1
Wrist Bracket Support	Elbow Wrist Bracket Support	Machined Part	1
1” x 24” Carbon Tube	Braided Carbon Fiber Tube	dragonplate.com	1
2” x 24” Carbon Tube	Braided Carbon Fiber Tube	dragonplate.com	1

E: Electronic Parts

BILL OF MATERIALS: CONTROLS			
Part Description	Drawing Name / Part Number	Producer	Quantity
Motor Controller - PCI	PR9258420CP24IOAD8R	PMD Corp	2
Interconnect Module	IM-1000	PMD Corp	2
3' 100 Pos. Round Shielded Cable	Cable-1003	PMD Corp	2
Motor Controller - PC-104	PR8258420CP2.4IOAD8.R	PMD Corp	2
3' 50 Pos. Cable for PC104	Cable-2003	PMD Corp	3
RS232 Serial Cable	Cable-4203	PMD Corp	1
Amplifiers	AZBE20AB	Servos-2-Go	5
Elbow/Wrist Enc Connectors	CA-MIC4-W4-NC	US Digital	2
Amp Connector - 10 Pos Crimp 5x2	609-2374-ND	Digikey	5
Amp Connector - 12 Pos Crimp 6x2	609-2373-ND	Digikey	5
Amp Connector - 3 Pos Crimp 3x1	609-2340-ND	Digikey	5
Amp Connector - 3 Pos Crimp 5x1	609-2338-ND	Digikey	5

Appendix L: BHRA Wiring Diagram



Appendix M: Motor Control C Code

```
// MotorTest.cpp : Defines the exported functions for the DLL application.
//
#include
"stdafx.h"
#include
"c-motion.h"
#include
"PMDutil.h"
#include
"PMDpci.h"
#include
"PMDconio.h"
#include
"PMDMotorSetup_Magellan.h"
#include
"PMDMB.h"
#include
<jni.h>
#include
<stdlib.h>
#include
<stdio.h>
#include
"MotorTest.h"
PMDAxisHandle hAxis1,hAxis2,hAxis3,hAxis4;
JNIEXPORT jint JNICALL
Java_MotorTest_setup (JNIEnv *, jobject)
{
// TODO insert setup functions here
printf(
"Setup \n");
PMDuint8 ui8major, ui8minor;
PMDuint16 generation, motorType, numberAxes, special, custom, major, minor;
PMDuint16 status;
//PMDint32 position;
if (PMD_NOERROR != PMDSetupAxisInterface_PCI( &hAxis1, PMDAxis1, 1 ))
{
PMDprintf(
"Board initialization failed\n");
return 1;
}
// use the same transport for Axis#2 because it resides on the same chip
```

```
// so must use the same interface
PMDCopyAxisInterface( &hAxis2, &hAxis1, PMDAxis2 );
PMDCopyAxisInterface( &hAxis3, &hAxis1, PMDAxis3 );
PMDCopyAxisInterface( &hAxis4, &hAxis1, PMDAxis4 );
if (PMD_NOERROR != PMDChipsetReset( &hAxis1 ))
{
free( hAxis1.transport_data );
PMDprintf(
"Reset failed\n");
return 1;
}
PMDGetCMotionVersion( &ui8major, &ui8minor );
PMDprintf(
"C-Motion Version %d.%d \n", ui8major, ui8minor);
// just do some easy gets to make sure comms are working
PMDGetVersion(&hAxis1, &generation, &motorType, &numberAxes, &special,
&custom, &major, &minor);
PMDprintf(
"MC%d%d%d%d Version %d.%d\n\n", generation, motorType, numberAxes, custom,
major, minor);
PMDGetEventStatus(&hAxis1, &status);
PMDprintf(
"Axis#1 Event Status: %4X\n",status);
PMDGetEventStatus(&hAxis2, &status);
PMDprintf(
"Axis#2 Event Status: %4X\n",status);
// enable DAC output if output mode is DAC
PMDMBSetDACOutputEnable(&hAxis1, 1);
PMDSetOutputMode(&hAxis1, 0);
// PID controller
==============================================================
========
PMDSetPositionLoop (&hAxis1, PMDPositionLoopProportionalGain, 10);
//Max. 32767 // KP
PMDSetPositionLoop (&hAxis1, PMDPositionLoopIntegratorGain, 10);
//Max. 32767 // KI
PMDSetPositionLoop (&hAxis1, PMDPositionLoopIntegratorLimit, 1000);
//Max 2^31 // Ilimit
PMDSetPositionLoop (&hAxis1, PMDPositionLoopDerivativeGain, 10);
//Max. 32767 // KD
PMDSetPositionLoop (&hAxis1, PMDPositionLoopDerivativeTime, 10);
//Max. 32767 // Derivative Time
PMDSetPositionLoop (&hAxis1, PMDPositionLoopOutputGain, 32767);
// Kout
```

```
// operation mode
=====================================================================
=========
PMDSetOperatingMode (&hAxis1, 0x0033);
//To enable all the option for this product.
// tracking
=====================================================================
===============
PMDSetPositionErrorLimit( &hAxis1, 65535);
// Should probably use a real position limit value
PMDUpdate(&hAxis1);
// ENCODER INVERSION
//PMDSetSignalSense(&hAxis1, (PMDuint16) 1);
PMDUpdate(&hAxis1);
printf(
"motor should be servo'd. \n");
return 0;
}
JNIEXPORT
void JNICALL
Java_MotorTest_move (JNIEnv *, jobject, jint)
{
// TODO insert motion controls here
printf(
"move \n");
PMDSetProfileMode( &hAxis1, PMDTrapezoidalProfile );
PMDResetEventStatus( &hAxis1, (PMDuint16)~PMDEventMotionCompleteMask );
SetupTrace(&hAxis1, 100);
//bufsize = 100
PMDSetVelocity( &hAxis1, 256000 );
PMDSetAcceleration( &hAxis1, 1000 );
while (1) {
puts(
"please input a position and velocity: (pos vel) \n");
int pos, vel;
scanf(
"%d%d", &pos, &vel);
puts(
"Moving to: ");
printf(
"%d \n", pos);
if (pos == 1) {
return;
}
```

```
PMDSetVelocity( &hAxis1, vel );
PMDSetPosition( &hAxis1, pos );
PMDUpdate(&hAxis1);
WaitForEvent( &hAxis1, PMDEventMotionCompleteMask );
}
}
JNIEXPORT
void JNICALL
Java_MotorTest_close (JNIEnv *, jobject)
{
// TODO insert close function here
printf(
"close \n");
PMDHardReset(&hAxis1);
// release motor from servoing
PMDCloseAxisInterface(&hAxis1);
printf(
"Program Terminated. \n");
}
void
InterruptExample(PMDAxisHandle* hAxis)
{
DWORD rc;
PMDResetEventStatus(hAxis, 0);
PMDClearInterrupt(hAxis);
PMDSetInterruptMask(hAxis, PMDEventMotionCompleteMask);
PMDPCI_SetInterruptEvent(hAxis);
PMDSetAcceleration(hAxis, 1000);
PMDSetVelocity(hAxis, 10000);
PMDSetPosition(hAxis, 1000);
PMDUpdate(hAxis);
PMDprintf(
"Waiting for interrupt...\n");
// interrupt should occur once motion is complete
rc = PMDPCI_WaitForInterruptEvent(hAxis, 10000);
// 10sec timeout
switch (rc)
{
case PMD_ERR_OK:
// Interrupt occurred
PMDprintf(
"*Interrupt Received*\n");
break;
case PMD_ERR_Timeout:
```

```
// ERROR - Timeout waiting for Interrupt Event
PMDprintf(
"*Timeout waiting for interrupt*\n");
break;
case PMD_ERR_Cancelled:
// ERROR - Failed while waiting for interrupt
PMDprintf(
"*ERROR* - Failed while waiting for interrupt\n");
break;
}
}
```

Appendix N: DLL Compiled C Code

A: motor_ArmMotor

```
/* DO NOT EDIT THIS FILE - it is machine generated */
#include <jni.h>
/* Header for class motor_ArmMotor */

#ifndef _Included_motor_ArmMotor
#define _Included_motor_ArmMotor
#ifdef __cplusplus
extern "C" {
#endif
/*
 * Class:     motor_ArmMotor
 * Method:    moveNative
 * Signature: (IIII)V
 */
JNIEXPORT void JNICALL Java_motor_ArmMotor_moveNative
  (JNIEnv *, jobject, jint, jint, jint, jint);

/*
 * Class:     motor_ArmMotor
 * Method:    setPosNative
 * Signature: (II)I
 */
JNIEXPORT jint JNICALL Java_motor_ArmMotor_setPosNative
  (JNIEnv *, jobject, jint, jint);

/*
 * Class:     motor_ArmMotor
 * Method:    setVelNative
 * Signature: (II)I
 */
JNIEXPORT jint JNICALL Java_motor_ArmMotor_setVelNative
  (JNIEnv *, jobject, jint, jint);

/*
 * Class:     motor_ArmMotor
 * Method:    setAccelNative
 * Signature: (II)I
 */
JNIEXPORT jint JNICALL Java_motor_ArmMotor_setAccelNative
  (JNIEnv *, jobject, jint, jint);

/*
 * Class:     motor_ArmMotor
 * Method:    setKinematicsNative
```

```
 * Signature: (IIIIIII)V
 */
JNIEXPORT void JNICALL Java_motor_ArmMotor_setKinematicsNative
  (JNIEnv *, jobject, jint, jint, jint, jint, jint, jint, jint);

/*
 * Class:     motor_ArmMotor
 * Method:    encoderInversionNative
 * Signature: (I)V
 */
JNIEXPORT void JNICALL Java_motor_ArmMotor_encoderInversionNative
  (JNIEnv *, jobject, jint);

/*
 * Class:     motor_ArmMotor
 * Method:    homeMotorNative
 * Signature: (II[I)[I
 */
JNIEXPORT jintArray JNICALL Java_motor_ArmMotor_homeMotorNative
  (JNIEnv *, jobject, jint, jint, jintArray);

#ifdef __cplusplus
}
#endif
#endif
```

B: motor_ArmMotorController

```
/* DO NOT EDIT THIS FILE - it is machine generated */
#include <jni.h>
/* Header for class motor_ArmMotorController */
```

```
#ifndef _Included_motor_ArmMotorController
#define _Included_motor_ArmMotorController
#ifdef __cplusplus
extern "C" {
#endif
/*
 * Class:     motor_ArmMotorController
 * Method:    init
 * Signature: ()I
 */
JNIEXPORT jint JNICALL Java_motor_ArmMotorController_init
  (JNIEnv *, jobject);

/*
 * Class:     motor_ArmMotorController
 * Method:    close
 * Signature: ()V
 */
JNIEXPORT void JNICALL Java_motor_ArmMotorController_close
  (JNIEnv *, jobject);

#ifdef __cplusplus
}
#endif
#endif
```

Appendix O: Java and Yobotics SCS Control Code

A: MoveArm

```
/**
 * Philip Diefenderfer
```

```
 * Bucknell University
 *
 * Jun 21, 2011, 10:09:34 AM
 * Project: Arm3
 * MoveArm.java
 *
 */
package testing;

import java.util.InputMismatchException;
import java.util.NoSuchElementException;
import java.util.Scanner;

import motor.ArmMotor;
import motor.ArmMotorController;
import armstuff.Kinematics;

/**
 * Moves the arm to a position hard coded into the program to test the use of
 * the DLL, Kinematics object, and general motion of the arm.
 *
 * @author Philip Diefenderfer
 */
@SuppressWarnings("unused")
public class MoveArm {
	/**
	 * Shoulder 1 of the arm, axis 1
	 */
	private static ArmMotor motor1;
	/**
	 * Shoulder 2 of the arm, axis 2
	 */
	private static ArmMotor motor2;
	/**
	 * Shoulder 3 of the arm, axis 3
	 */
	private static ArmMotor motor3;
	/**
	 * Shoulder 4 of the arm, axis 4
	 */
	private static ArmMotor motor4;
	/**
	 * Shoulder 5 of the arm, axis 5
	 */
```

```
private static ArmMotor motor5;
/**
 * Initializes the motor controllers, sets up the PID controller for each
 * motor and then sends the arm to a position.
 *
 * @param args
 *            Unused
 */
public static void main(String[] args) {
	if (MoveArm.initControls() != 0) {
		System.err.println("Exiting program");
		System.exit(-1);
	}
	MoveArm.initMotors();
	// Scanner keyboard = new Scanner(System.in);
	//
	// boolean flag = false;
	//
	// while (true) {
	// System.out.println("Please Press Enter to Continue...");
	// if (keyboard.nextInt() == 0) {
	// break;
	// } else {
	// if (flag) {
	// MoveArm.gotoEncPos(-90000, 90000, 50000, 20000);
	// flag = false;
	// } else {
	// MoveArm.gotoEncPos(0, 0, 0, 0);
	// flag = true;
	// }
	// }
	// }
	// MoveArm.gotoPos(0, 0, 0);
	// MoveArm.getAndGo();
	// Scanner keyboard = new Scanner(System.in);
	// keyboard.next();
	//
	// motor5.setPos(30000);
	pourDrink();
	System.out.println("Program complete");
}
/**
 * Initializes the PCI control boards for the arm.
 *
```

```
 * @return -1 if the initialization failed
 */
private static int initControls() {
	ArmMotorController PCI = new ArmMotorController();
	if (PCI.init() != 0) {
		System.err.println("System initialization failed");
		return -1;
	}
	return 0;
}
/**
 * Initializes the motors with the characteristics of each and sets up the
 * PID controls for the motors on the arm, then sets the velocity and
 * acceleration for each motor.
 */
private static void initMotors() {
	motor1 = new ArmMotor(1, "shoulder1", 1000000, false);
	motor2 = new ArmMotor(2, "shoulder2", 1000000, false);
	motor3 = new ArmMotor(3, "shoulder3", 1000000, false);
	motor4 = new ArmMotor(7, "elbow", 144000, true);
	motor5 = new ArmMotor(8, "wrist", 144000, true);

	motor1.setKinematics(20, 26, 500, 16, 10, 10);
	motor2.setKinematics(20, 26, 500, 16, 10, 10);
	motor3.setKinematics(20, 26, 500, 16, 10, 10);
	motor4.setKinematics(10, 10, 1000, 10, 10, 100);
	motor5.setKinematics(10, 10, 1000, 10, 10, 100);

	motor1.setAccel(15000000);
	motor1.setVel(1250000);

	motor2.setAccel(15000000);
	motor2.setVel(1250000);

	motor3.setAccel(15000000);
	motor3.setVel(1250000);

	motor4.setAccel(216000);
	motor4.setVel(180000);

	motor5.setAccel(216000);
	motor5.setVel(180000);
}
/**
```

```
 * Sends the robot arm to the position given in the parameters by
 * calculating the angle each motor needs to achieve in order to reach the
 * position then sends the motors to their respective positions.
 *
 * @param x
 *          the x coordinate of the position for the arm to go to
 * @param y
 *          the y coordinate of the position for the arm to go to
 * @param z
 *          the z coordinate of the position for the arm to go to
 */
private static void gotoPos(double x, double y, double z) {
        Kinematics arm = new Kinematics();
        double[] thetas = arm.getThetas(x, y, z);

        motor1.setAngle(thetas[0]);
        motor2.setAngle(thetas[1]);
        motor3.setAngle(thetas[2]);
        motor4.setAngle(thetas[3]);
}
private static void gotoEncPos(int e1, int e2, int e3, int e4, int e5) {
        motor1.setPos(e1);
        motor2.setPos(e2);
        motor3.setPos(e3);
        motor4.setPos(e4);
        motor5.setPos(e5);
}
private static void getAndGo() {
        Scanner keyboard = new Scanner(System.in);
        int num = 0;
        int pos = 0;

        try {
                while (true) {
                        System.out.println("Please enter motor number: ");
                        num = keyboard.nextInt();
                        if (num < 1 || num > 5) {
                                break;
                        }
                        System.out.println("Please enter motor position: ");
                        pos = keyboard.nextInt();

                        if (num == 1) {
                                motor1.setPos(pos);
```

```
				} else if (num == 2) {
					motor2.setPos(pos);
				} else if (num == 3) {
					motor3.setPos(pos);
				} else if (num == 4) {
					motor4.setPos(pos);
				} else if (num == 5) {
					motor5.setPos(pos);
				} else {
					break;
				}
			}
		} catch (InputMismatchException e) {
			System.exit(0);
		} catch (NoSuchElementException e) {
			System.exit(0);
		}
	}
	private static void pourDrink() {
		try {
			int pos = 0;
			Scanner keyboard = new Scanner(System.in);
			while (true) {
				System.out.println("{Please enter a position");
				pos = keyboard.nextInt();

				if (pos == 1) {
					gotoEncPos(-90000, 90000, 50000, 30000, 0);
				} else if (pos == 2) {
					gotoEncPos(0, 0, 0, 35000, 0);
				} else if (pos == 3) {
					gotoEncPos(-20000, 40000, 0, 30000, -5000);
				} else if (pos == 4) {
					gotoEncPos(-20000, 40000, 0, 30000, 35000);
				} else {
					gotoEncPos(0, 0, 0, 0, 0);
				}
			}
		} catch (Exception e) {
			return;
		}
	}
}
```

B: ArmMotor

```
package motor;
/**
 * Urban Robotics Arm Controller
 * Created: 4/5/2011
 *
```

```
 * ArmMotor.java
 *
 * Brent Noll
 * Philip Diefenderfer
 */
/**
 * Controls the individual motors for the arm and allows for the motor to have
 * its position, angle, velocity and acceleration set.
 *
 * @author Philip Diefenderfer
 */
public class ArmMotor {
	private String motorName;
	private int ticksPerRev;
	private int axisNumber;
	private int positiveLimit = 10000000;
	private int negativeLimit = -10000000;
	private int home;

	static {
		System.loadLibrary("ArmMotor");
	}
	/**
	 * Creates a Motor with the name for the motor, the number of
	 * ticks/revolution for the motor, and whether or not one of the encoders on
	 * the motor needs to be inverted to function properly.
	 *
	 * @param motorName
	 * @param ticksPerRev
	 */
	public ArmMotor(int axisNumber, String motorName, int ticksPerRev,
			boolean encoderInvert) {
		this.axisNumber = axisNumber;
		this.motorName = motorName;
		this.ticksPerRev = ticksPerRev;

		if (encoderInvert) {
			this.encoderInversion();
		}
	}
	/**
	 * Moves the motor to the parameter angle (in radians). Converts the angle
	 * to ticks then calls the setPos() Method, same motion restrictions that
	 * apply to the setPos method apply to the setAngle method.
```

```
 * @param angle
 *          angle to move to in radians
 * @return the final angle in radians
 */
public int setAngle(double angle) {
	int ticks = (int) (angle / (2 * Math.PI) * ticksPerRev);
	return (int) (this.setPos(ticks) / ticksPerRev * (2 * Math.PI));
}
/*
 * (non-Javadoc)
 *
 * @see java.lang.Object#toString()
 */
/**
 * Gets the name of the motor, which should be set to the location of the
 * motor on the arm
 *
 * @return the motor's Name
 */
public String toString() {
	return motorName;
}
/**
 * Move the motor to the parameter position at the parameter velocity and
 * acceleration.
 *
 * @param pos
 *          the position to move the motor to in encoder ticks
 * @param vel
 *          the velocity to move the motor at in ticks/sec
 * @param accel
 *          the acceleration of the motor (ticks^2/sec)
 */
public void move(int pos, int vel, int accel) {
	pos = this.checkLimit(pos);
	this.moveNative(pos, vel, accel, this.axisNumber);
}
/**
 * Moves the motor to the parameter position and if the position commanded
 * is outside of the possible range the motor will go to the edge of its
 * range closest to the position.
 *
 * @param pos
 *          the position in ticks to move the motor to
```

```
 * @return the position the motor moved to
 */
public int setPos(int pos) {
        pos = this.checkLimit(pos);
        return this.setPosNative(pos, this.axisNumber);
}

/**
 * Sets the velocity of the motor to the commanded value or less if a limit
 * exists.
 *
 * @param vel
 *          the velocity
 * @return the velocity the motor was set at, the limit if the commanded
 *        velocity was beyond the limit
 */
public int setVel(int vel) {
        return this.setVelNative(vel, this.axisNumber);
}

/**
 * Sets the acceleration of the motor to the parameter value; will only set
 * the motor to the max acceleration at most if a limit on the acceleration
 * exists
 *
 * @param acc
 *          the commanded acceleration
 * @return the acceleration the motor was set to
 */
public int setAccel(int acc) {
        return this.setAccelNative(acc, this.axisNumber);
}

/**
 * @param kP
 * @param kI
 * @param iLimit
 * @param kD
 * @param dTIme
 * @param kOut
 *          PID Output Gain (enter %)
 */
public void setKinematics(int kP, int kI, int iLimit, int kD, int dTIme,
                int kOut) {
```

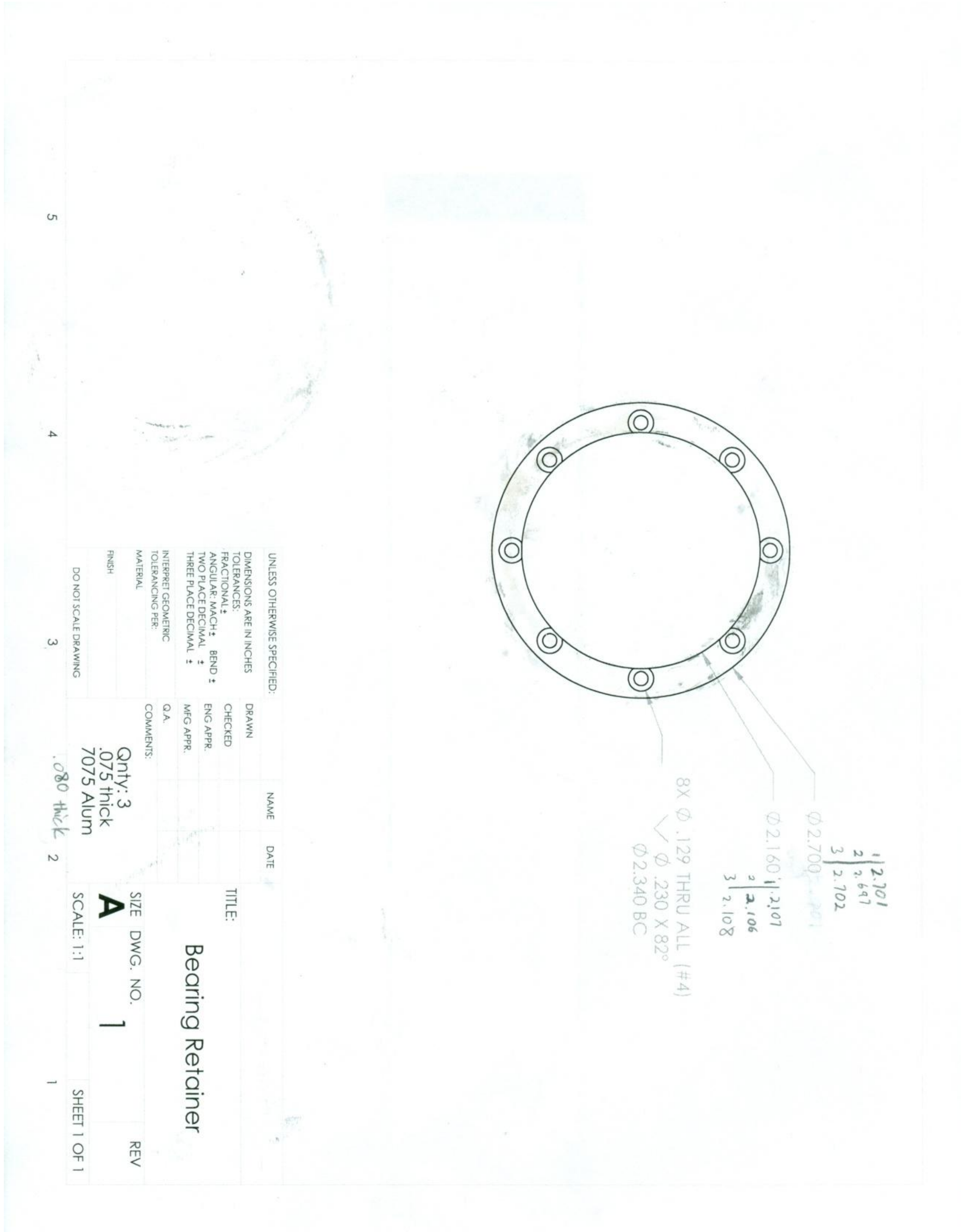
```
		int KOut = (int) (kOut * 65535 / 100);
		this.setKinematicsNative(kP, kI, iLimit, kD, dTIme, KOut,
				this.axisNumber);
	}
	/**
	 * Homes the motor by finding the end points of rotation then goes to the
	 * middle and sets the middle as the zero location.
	 */
	public void homeMotor() {
		int[] positions = new int[3];
		positions[0] = 0;
		positions[1] = 0;
		positions[2] = 0;

		positions = this.homeMotorNative(this.axisNumber, this.ticksPerRev,
				positions);
		this.home = positions[1];

		this.negativeLimit = positions[0] - this.home;
		this.positiveLimit = positions[2] - this.home;
		this.home = 0;

		// System.out.println("Home now at:		: " + this.home);
		// System.out.println("Positive Limit now at: " + this.posLimit);
		// System.out.println("Negative Limit now at: " + this.negLimit + "\n");
	}
	/**
	 * Gets the positive limit of the motor
	 *
	 * @return the positiveLimit
	 */
	public int getPositiveLimit() {
		return this.positiveLimit;
	}
	/**
	 * Gets the negitive limit of the motor
	 *
	 * @return the negativeLimit
	 */
	public int getNegativeLimit() {
		return this.negativeLimit;
	}

	/**
```

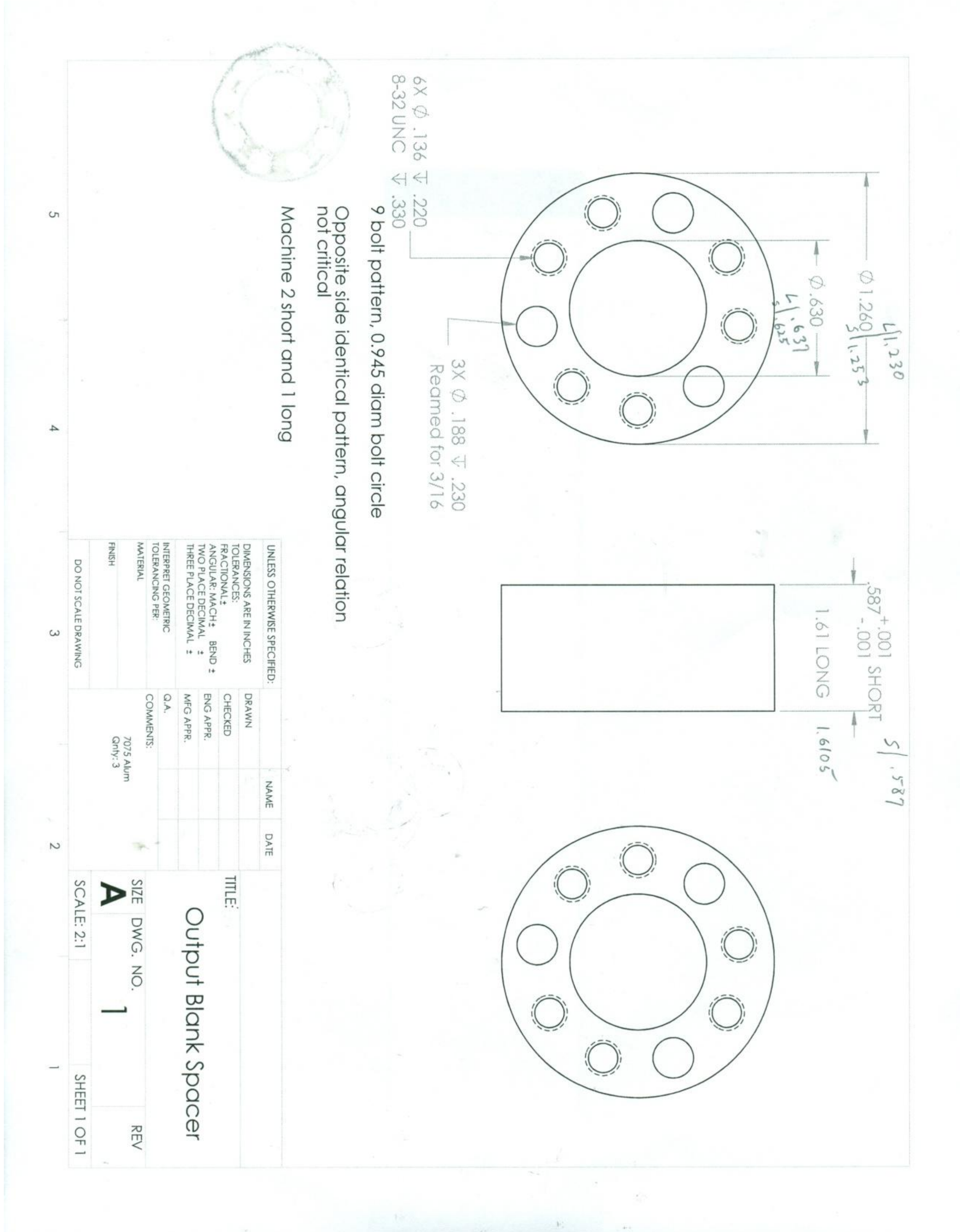
```
	 * Gets the home position of the motor, should be 0.
	 *
	 * @return the home position
	 */
	public int getHome() {
		return this.home;
	}

	/**
	 * Inverts one of the encoders on the motor to allow for motors with
	 * different encoder types to be used.
	 */
	private void encoderInversion() {
		this.encoderInversionNative(this.axisNumber);
	}
	/**
	 * Checks the position passed to the motor against the Limits found during
	 * homing, if the position is greater than the positive limit, the positive
	 * limit is returned, if the position is less than the negative limit, then
	 * the negative limit is returned, else it returns the position passed.
	 *
	 * @param pos
	 *            the position to check against the limits
	 * @return the nearest possible position
	 */
	private int checkLimit(int pos) {
		if (pos > this.positiveLimit) {
			pos = this.positiveLimit;
			System.err.println("Commanded motor position out of range.  "
					+ "Moving to nearest Limit");
		} else if (pos < this.negativeLimit) {
			pos = this.negativeLimit;
			System.err.println("Commanded motor position out of range.  "
					+ "Moving to nearest Limit");
		}
		return pos;
	}
	// Native Methods in dll
=====================================================
	/**
	 * Moves the motor the the position passed in the parameters at the velocity
	 * and acceleration that the arguments specified.
	 *
	 * @param pos
```

```
 *          the position (in ticks) to move the motor to
 * @param vel
 *          the velocity (in ticks/sec) to move the motor at
 * @param acc
 *          the acceleration for the motor (ticks/sec^2)
 * @param axisNum
 */
private native void moveNative(int pos, int vel, int acc, int axisNum);
/**
 * Moves the motor to the parameter position. If motor is stopped by an
 * interrupt or hits a limit and is stopped, this method will return the
 * final position of the robot, else it will return the final position that
 * is equal to the parameter.
 *
 * @param pos
 *          the position (in ticks) to move the motor to
 * @param axisNum
 * @return the position the motor was moved to
 */
private native int setPosNative(int pos, int axisNum);
/**
 * Sets the velocity of the motor. If the velocity has an upper limit set
 * and the velocity is attempted to be set to a higher velocity, this method
 * will set the velocity to the upper limit
 *
 * @param vel
 *          the velocity to set the motor to
 * @param axisNum
 * @return the velocity the motor was set to.
 */
private native int setVelNative(int vel, int axisNum);
/**
 * Sets the acceleration of the motor to the parameter. If an upper limit is
 * set on the acceleration and the user attempts to set the acceleration
 * higher than the limit, this method will set the acceleration to the upper
 * limit.
 *
 * @param acc
 *          the acceleration to set the motor to
 * @param axisNum
 * @return the acceleration the motor was set to.
 */
private native int setAccelNative(int acc, int axisNum);
/**
```

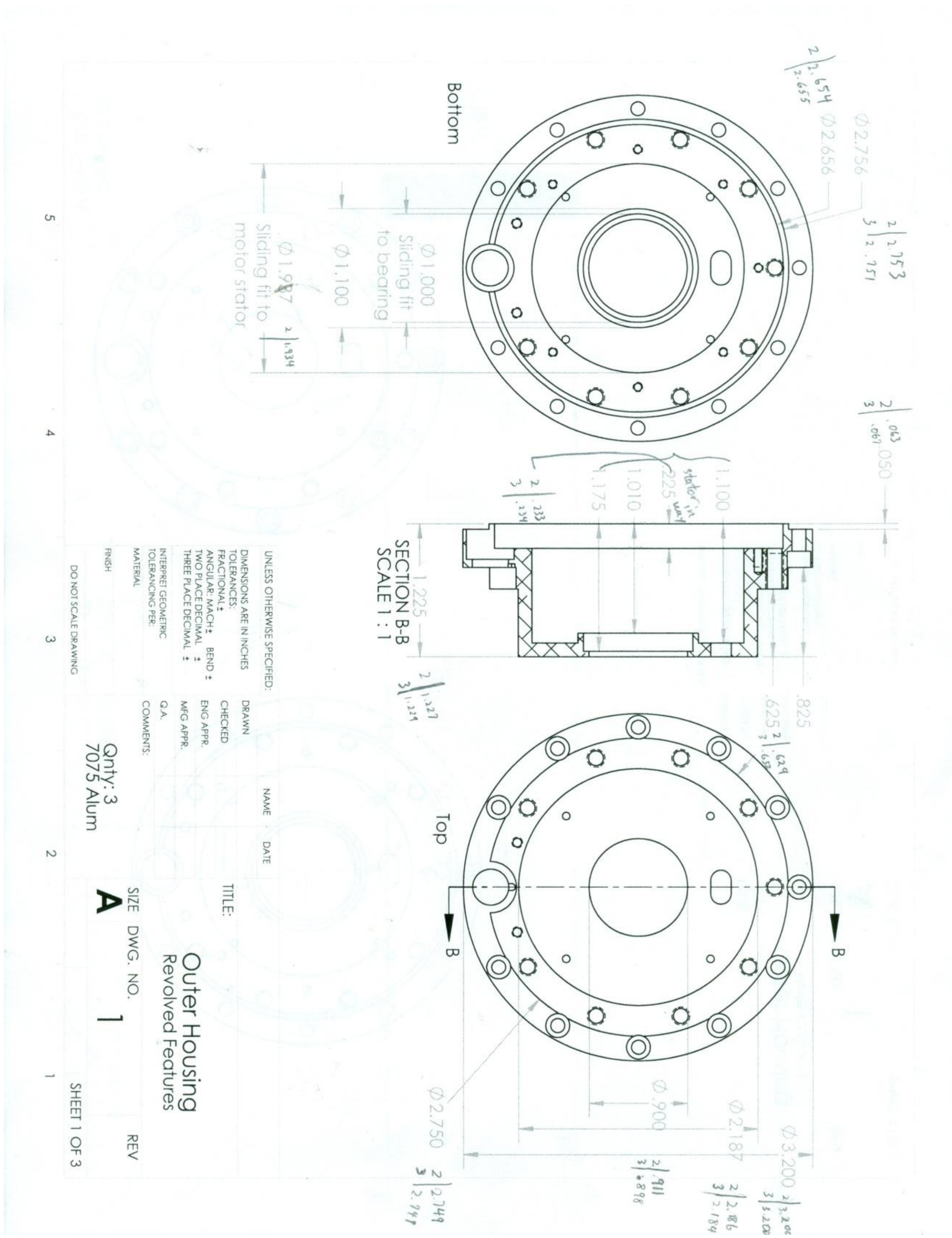
```
	 * Sets the values for the Kinematic equations of the Arm.
	 *
	 * @param kP
	 * @param kI
	 * @param iLimit
	 * @param kD
	 * @param dTIme
	 * @param kOut
	 * @param axisNum
	 */
	private native void setKinematicsNative(int kP, int kI, int iLimit, int kD,
			int dTIme, int kOut, int axisNum);
	/**
	 * Inverts one of the encoders on the motor. Only use this method if one of
	 * the encoders needs to be inverted.
	 *
	 * @param axisNum
	 *            the axis Number of the motor.
	 */
	private native void encoderInversionNative(int axisNum);
	/**
	 * Homes the motor to its center pocition and resets the encoder count so
	 * home is set to the zero mark.
	 *
	 * @param axisNum
	 *            the axis number of the motor
	 */
	private native int[] homeMotorNative(int axisNum, int ticksPerRev,
			int[] positions);
}
```

Appendix P: Blue Printed Shoulder Drawings

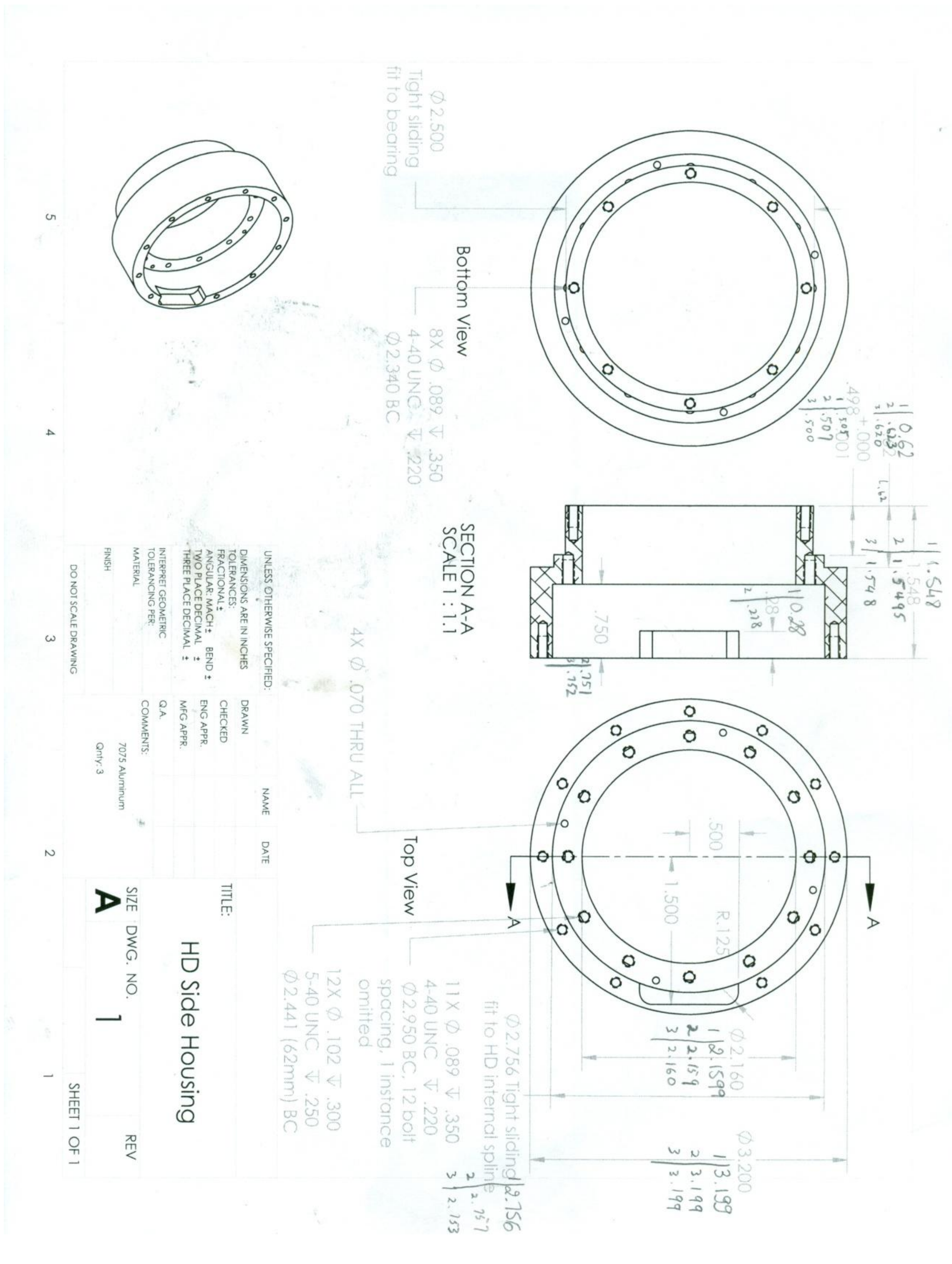




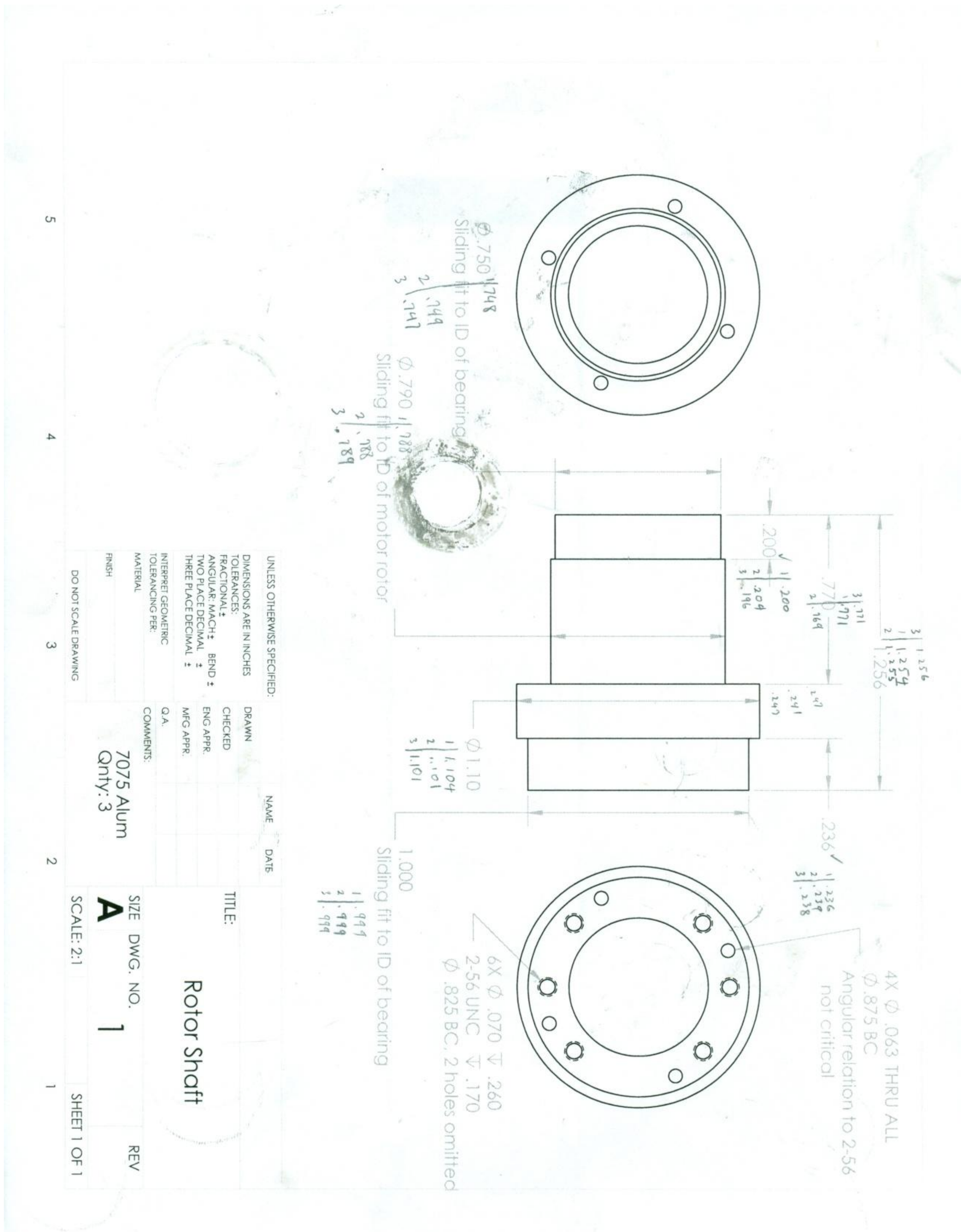
L 1.230
S 1.253
Ø1.260
Ø.630
L .637
S .625
6X Ø .136 ↧ .220
8-32 UNC ↧ .330
3X Ø .188 ↧ .230
Reamed for 3/16
9 bolt pattern, 0.945 diam bolt circle
Opposite side identical pattern, angular relation not critical
Machine 2 short and 1 long
.587 +.001 -.001 SHORT
1.61 LONG
1.6105
S .587
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Output Blank Spacer
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1



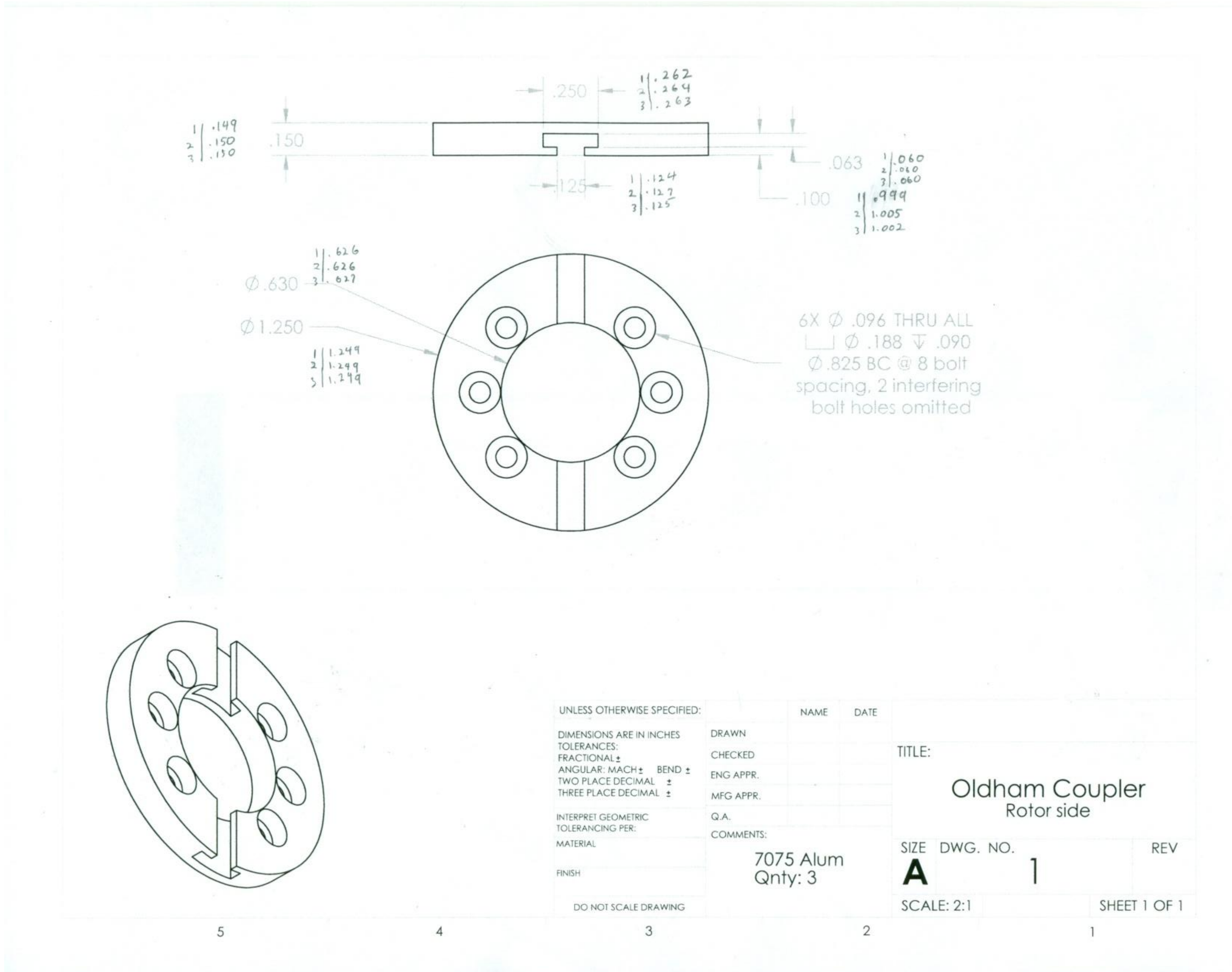
Bottom
Ø2.756
Ø2.656
2 | 2.654
2.655
2 | 2.753
3 | 2.751
2 | .063
3 | .067
.050
1.100
stator in way
.225
1.010
1.175
2 | .233
3 | .234
.825
.625
2 | .629
3 | .65?
1.225
2 | 1.227
3 | 1.229
SECTION B-B
SCALE 1 : 1
Top
B
B
Ø3.200
2 | 3.200
3 | 3.200
Ø2.187
2 | 2.186
3 | 2.184
Ø.900
2 | .911
3 | .898
Ø2.750
2 | 2.749
3 | 2.748
Ø1.000
Sliding fit
to bearing
Ø1.100
Ø1.937
2 | 1.934
Sliding fit to
motor stator
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Qnty: 3
7075 Alum
TITLE:
Outer Housing
Revolved Features
SIZE
A
DWG. NO.
1
REV
SHEET 1 OF 3
5
4
3
2
1

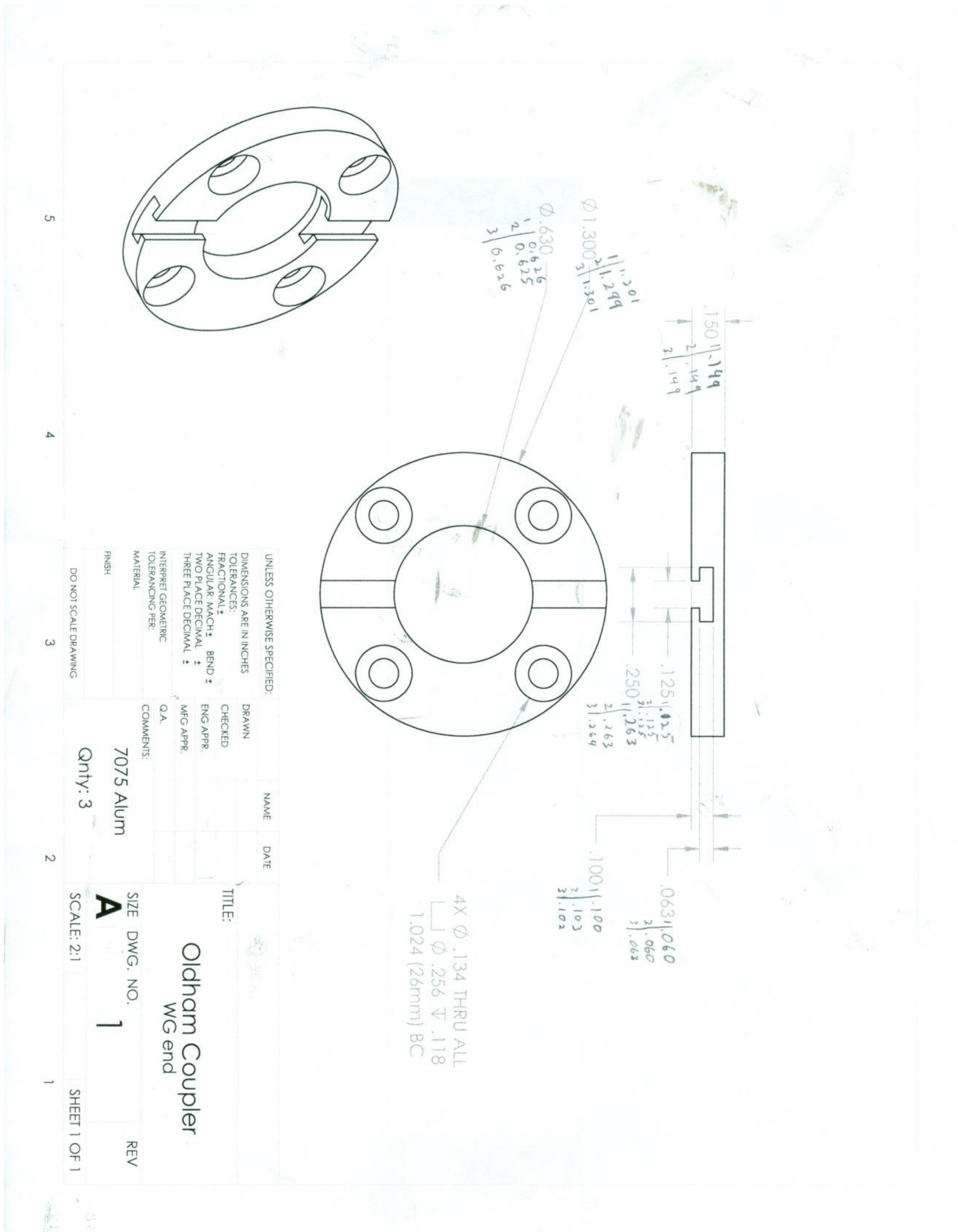


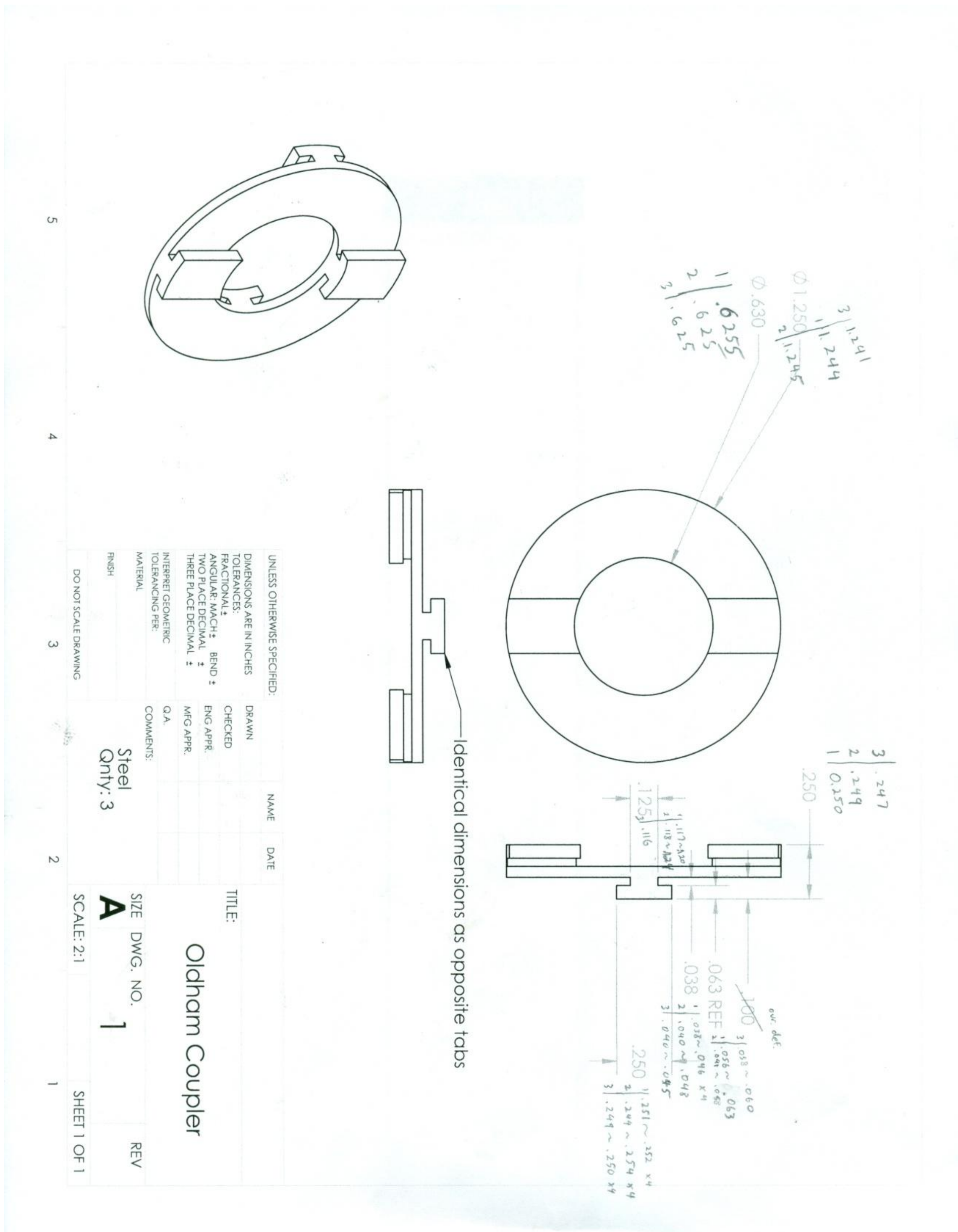
Ø2.500
Tight sliding
fit to bearing
Bottom View
8X Ø .089 ⊽ .350
4-40 UNC ⊽ .220
Ø2.340 BC
SECTION A-A
SCALE 1 : 1.1
.750
4X Ø .070 THRU ALL
Top View
.500
1.500
R.125
Ø2.160
Ø3.200
Ø2.756 Tight sliding
fit to HD internal spline
11X Ø .089 ⊽ .350
4-40 UNC ⊽ .220
Ø2.950 BC. 12 bolt
spacing, 1 instance
omitted
12X Ø .102 ⊽ .300
5-40 UNC ⊽ .250
Ø2.441 (62mm) BC
A
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Aluminum
Qnty: 3
NAME
DATE
TITLE:
HD Side Housing
SIZE
A
DWG. NO.
1
REV
SHEET 1 OF 1

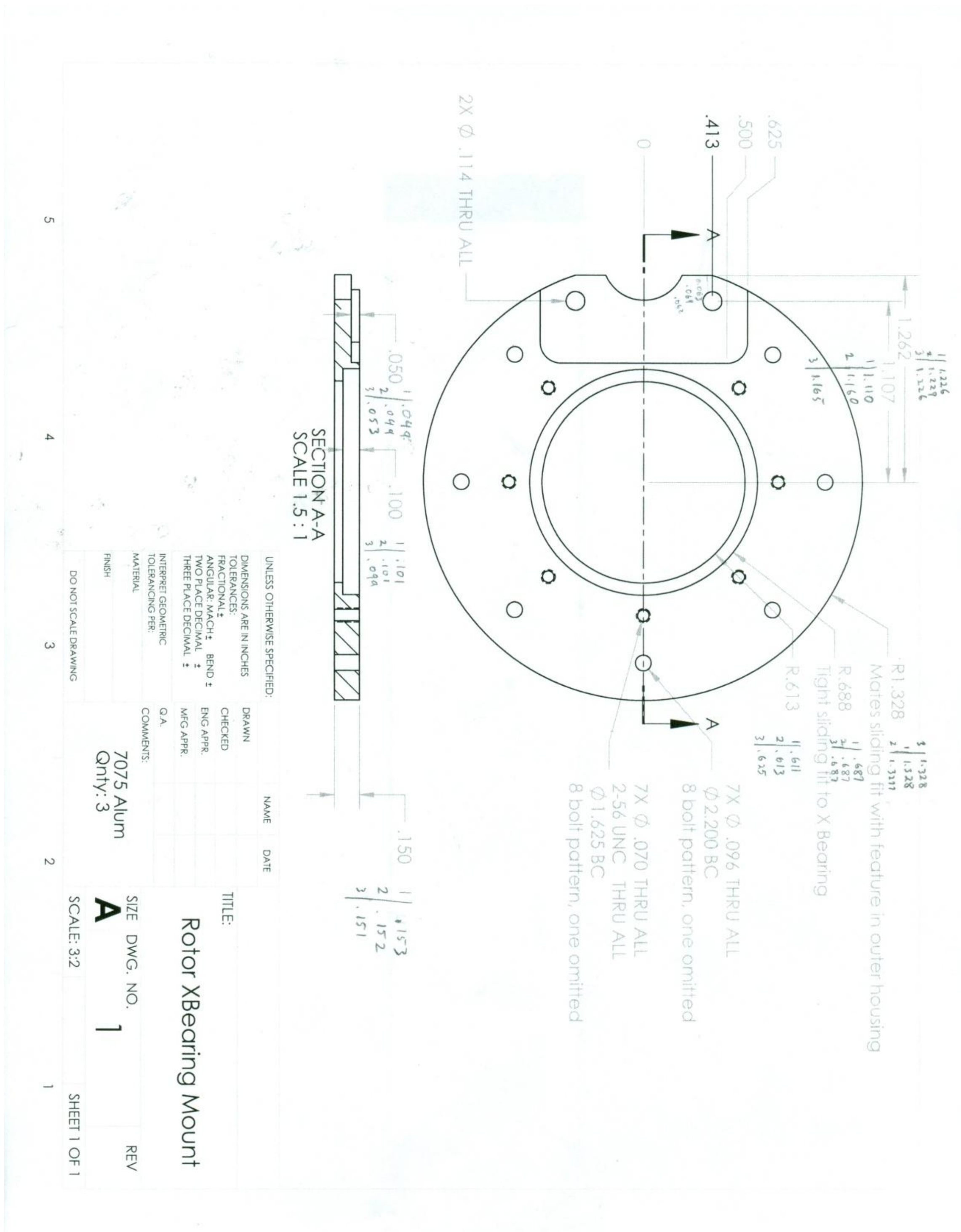


Ø.750 1|.748 2|.749 3|.747
Sliding fit to ID of bearing
Ø.790 1|.788 2|.788 3|.789
Sliding fit to ID of motor rotor
.200 ✓ 1|.200 2|.204 3|.196
.770 1|.771 2|.769 3|.771
1.256 1|1.254 2|1.255 3|1.256
Ø1.10 1|1.104 2|1.101 3|1.101
.236 ✓ 1|.236 2|.239 3|.238
1.000 1|.999 2|.999 3|.999
Sliding fit to ID of bearing
4X Ø.063 THRU ALL
Ø.875 BC
Angular relation to 2-56 not critical
6X Ø.070 ↧ .260
2-56 UNC ↧ .170
Ø.825 BC, 2 holes omitted
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Rotor Shaft
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
5
4
3
2
1

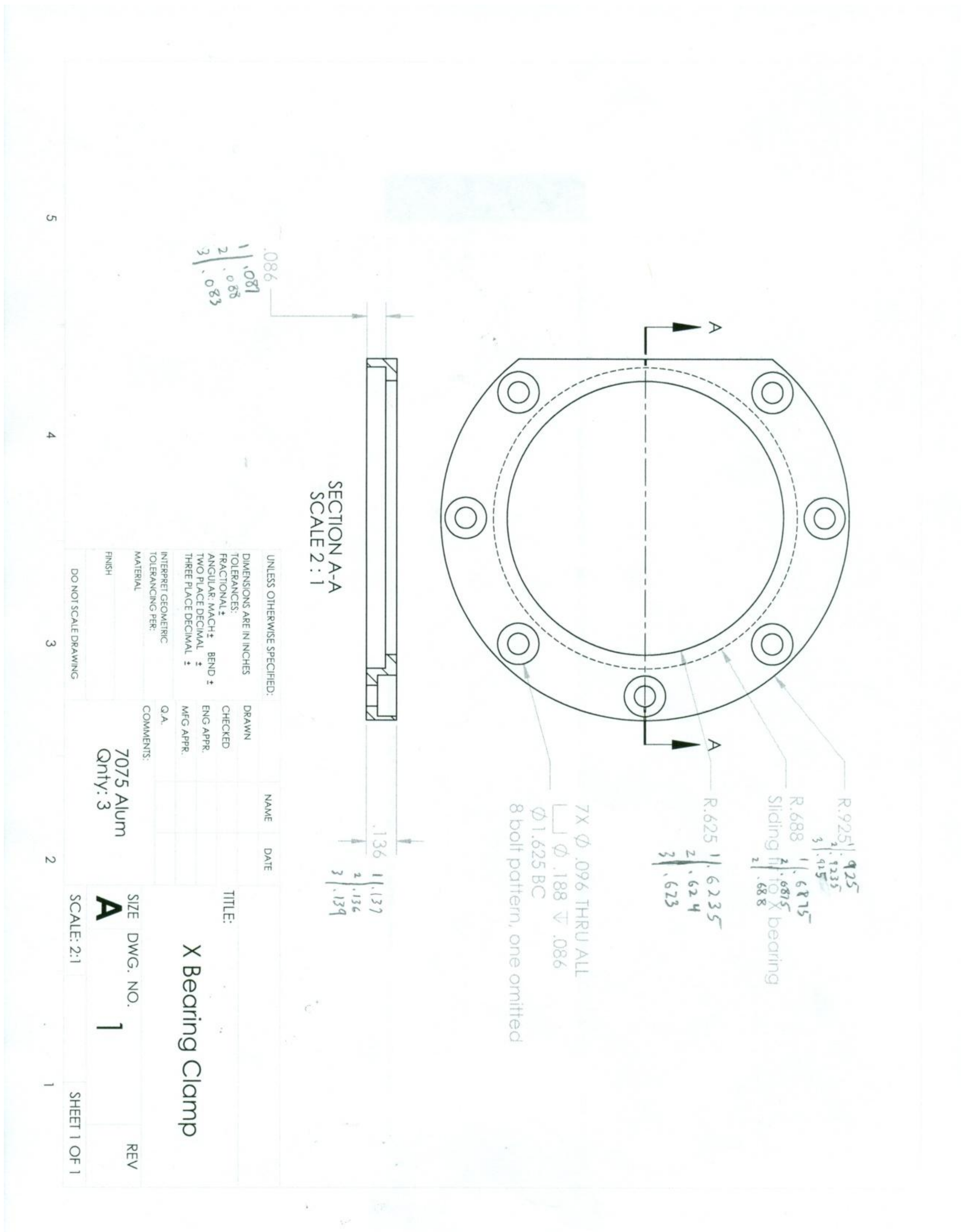

.250
1|.262
2|.264
3|.263
1|.149
2|.150
3|.150
.150
.063
1|.060
2|.060
3|.060
.125
1|.124
2|.127
3|.125
.100
1|.999
2|1.005
3|1.002
1|.626
2|.626
3|.627
Ø.630
Ø1.250
1|1.249
2|1.249
3|1.249
6X Ø .096 THRU ALL
⌴ Ø .188 ↧ .090
Ø .825 BC @ 8 bolt
spacing, 2 interfering
bolt holes omitted
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
7075 Alum
Qnty: 3
DO NOT SCALE DRAWING
TITLE:
Oldham Coupler
Rotor side
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
5
4
3
2
1


Ø1.300
Ø.630
.150
.125
.250
.100
.063
4X Ø .134 THRU ALL
⌴ Ø .256 ↧ .118
1.024 (26mm) BC
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
NAME
DATE
TITLE:
Oldham Coupler
WG end
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1

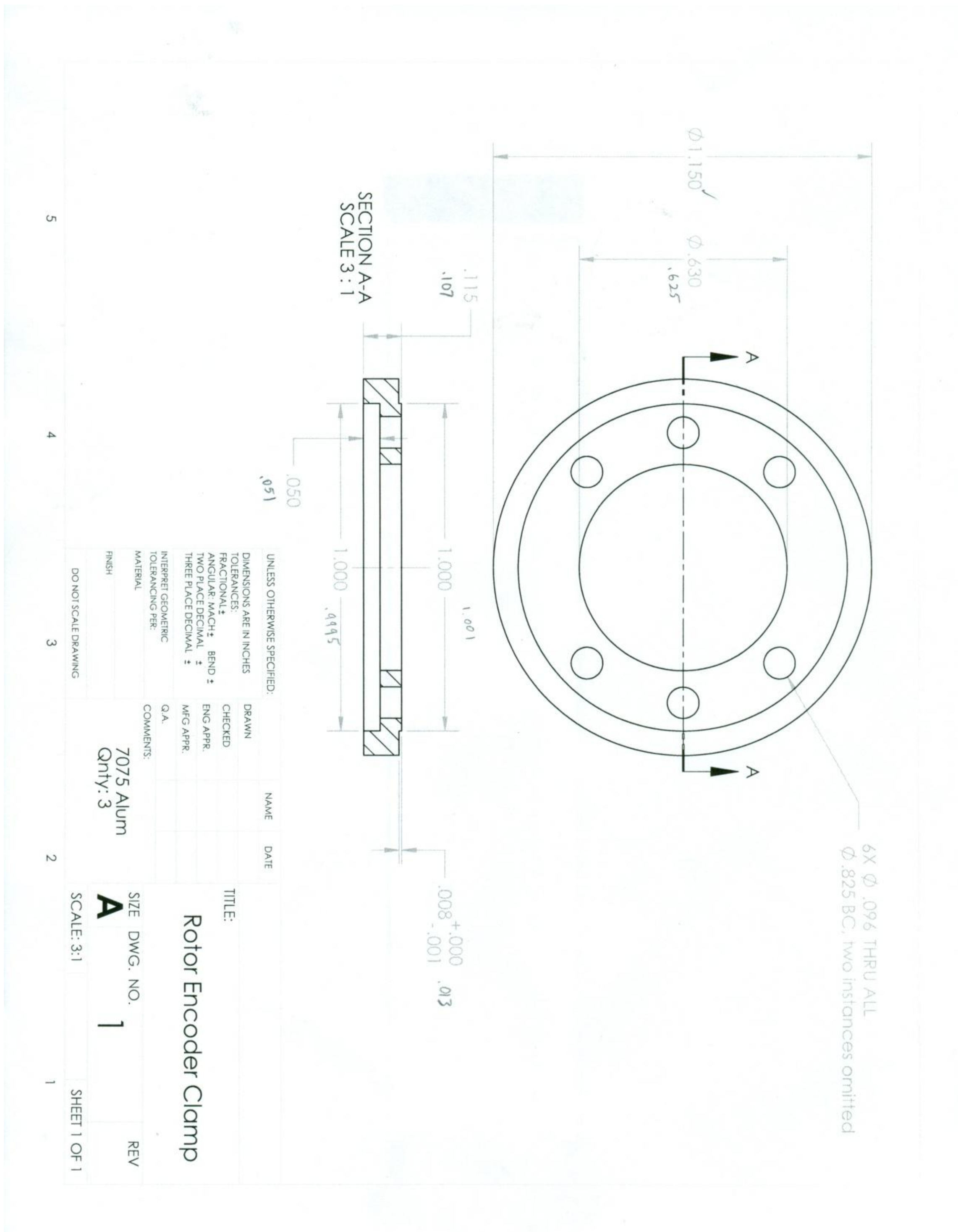

Identical dimensions as opposite tabs
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
Steel
Qnty: 3
TITLE:
Oldham Coupler
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
Ø1.250
Ø.630
.250
.125
.063 REF
.038
.250



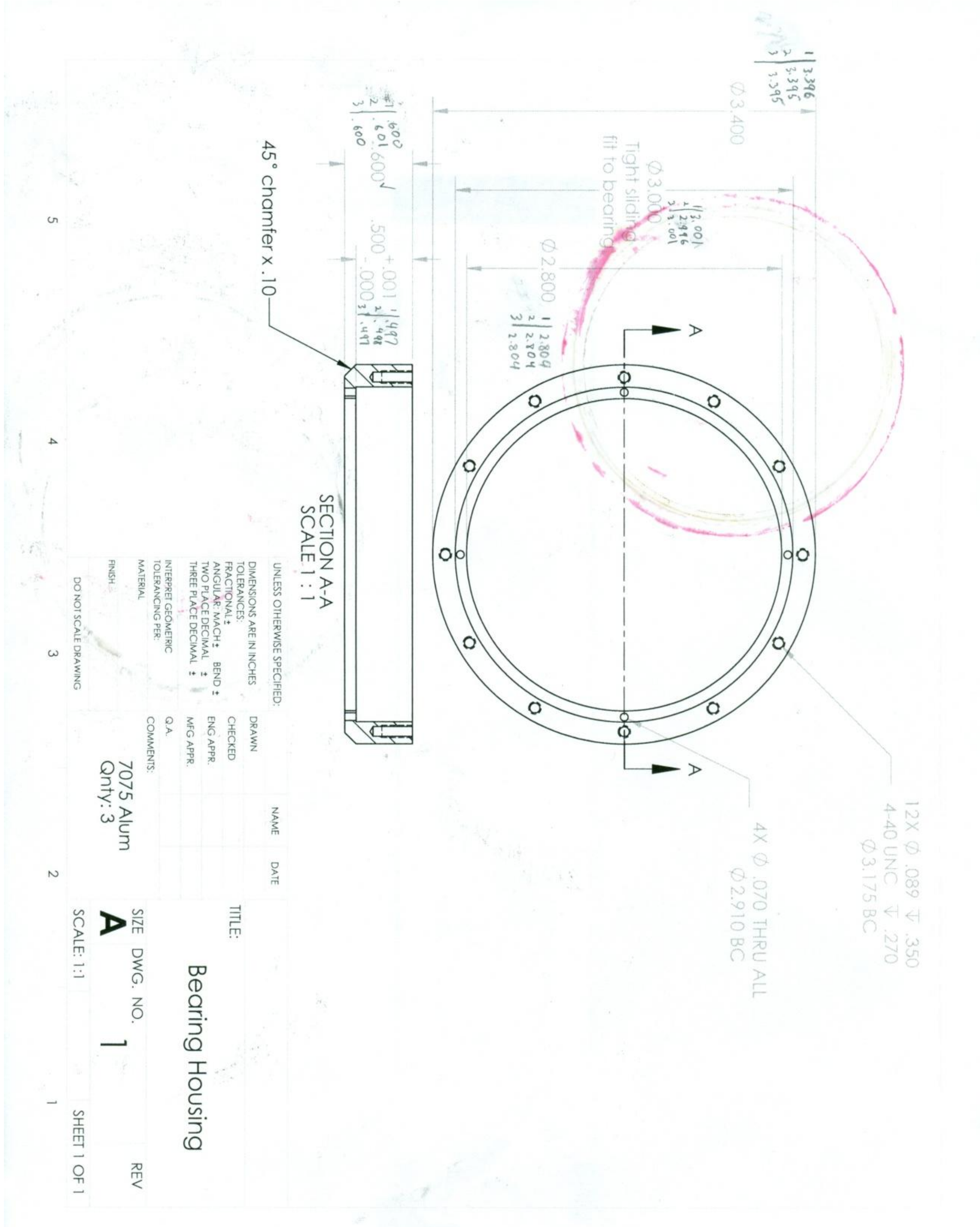
1.262
1.107
.625
.500
.413
0
A
A
R1.328
Mates sliding fit with feature in outer housing
R.688
Tight sliding fit to X Bearing
R.613
7X Ø .096 THRU ALL
Ø 2.200 BC
8 bolt pattern, one omitted
7X Ø .070 THRU ALL
2-56 UNC THRU ALL
Ø 1.625 BC
8 bolt pattern, one omitted
2X Ø .114 THRU ALL
.050
.100
.150
SECTION A-A
SCALE 1.5 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Rotor XBearing Mount
SIZE
A
DWG. NO.
1
REV
SCALE: 3:2
SHEET 1 OF 1
5
4
3
2
1



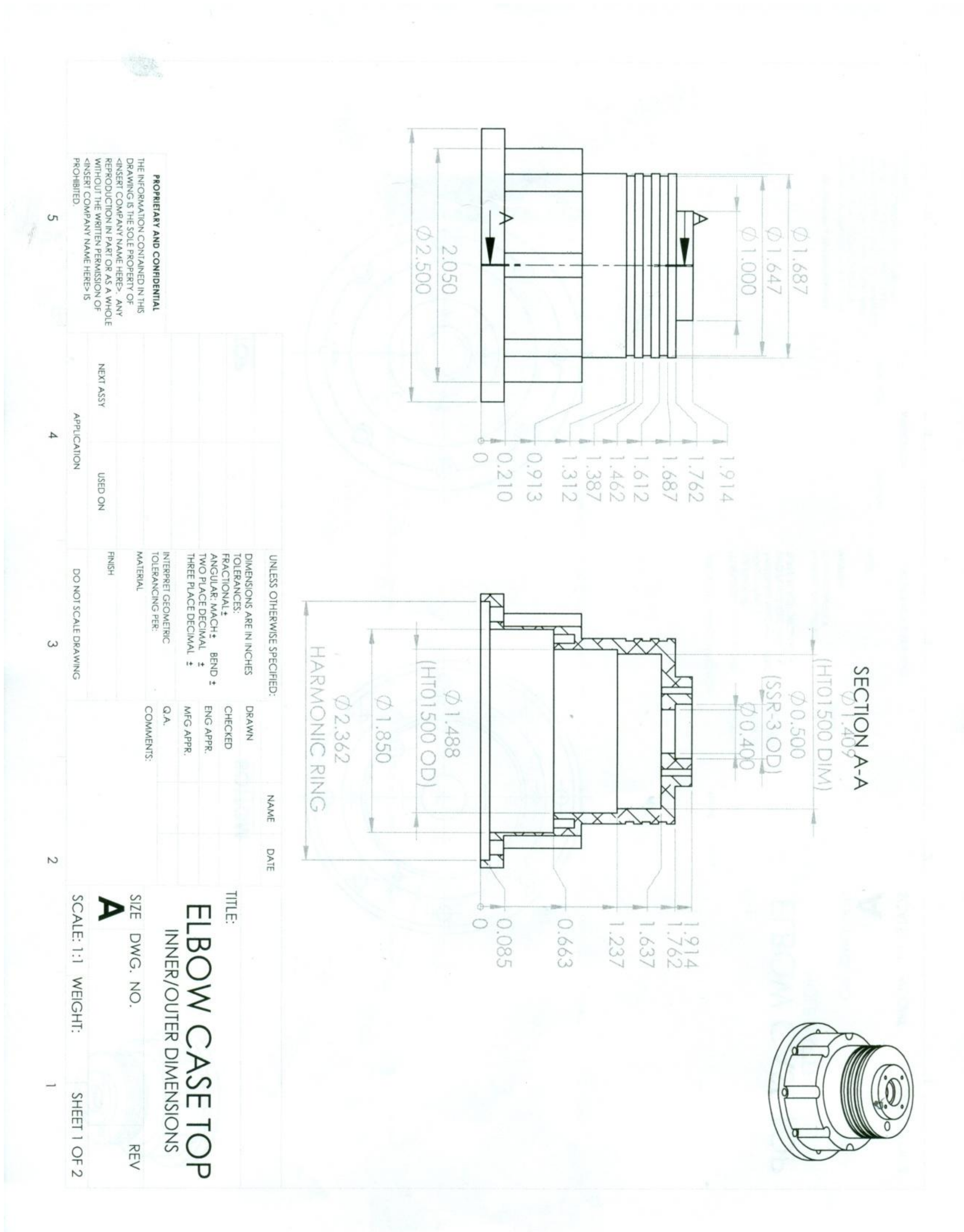
R.925 1|.925 2|.9235 3|.925
R.688 1|.6875 2|.6875 2|.688
Sliding fit to X bearing
R.625 1|.6235 2|.624 3|.623
7X Ø .096 THRU ALL
⌴ Ø .188 ↧ .086
Ø1.625 BC
8 bolt pattern, one omitted
A
A
.086 1|.087 2|.088 3|.083
.136 1|.137 2|.136 3|.139
SECTION A-A
SCALE 2 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
X Bearing Clamp
SIZE
A
DWG. NO.
1
REV
SCALE: 2:1
SHEET 1 OF 1
1
2
3
4
5

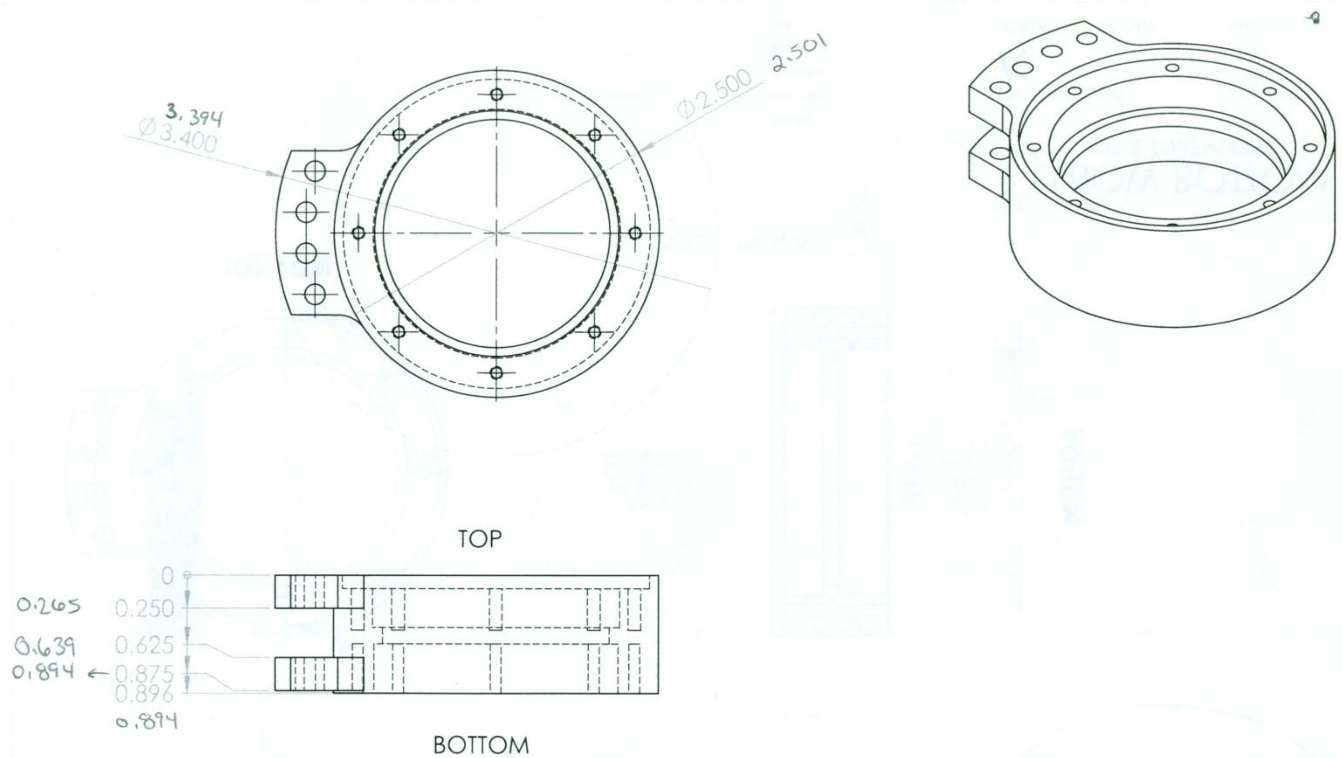


Ø1.150
Ø.630
.625
.115
.107
SECTION A-A
SCALE 3 : 1
.050
.051
1.000
.9995
1.000
1.001
A
A
6X Ø .096 THRU ALL
Ø .825 BC, two instances omitted
.008 +.000 -.001
.013
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
NAME
DATE
TITLE:
Rotor Encoder Clamp
SIZE
A
DWG. NO.
1
REV
SCALE: 3:1
SHEET 1 OF 1
5
4
3
2
1


Ø3.400
Ø3.000
Tight sliding fit to bearing
Ø2.800
.600
.500 +.001 -.000
45° chamfer x .10
A
A
12X Ø .089 ↧ .350
4-40 UNC ↧ .270
Ø3.175 BC
4X Ø .070 THRU ALL
Ø2.910 BC
SECTION A-A
SCALE 1 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
7075 Alum
Qnty: 3
TITLE:
Bearing Housing
SIZE
DWG. NO.
REV
A
1
SCALE: 1:1
SHEET 1 OF 1

Appendix Q: Blue Printed Elbow Drawings





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

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

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TITLE:

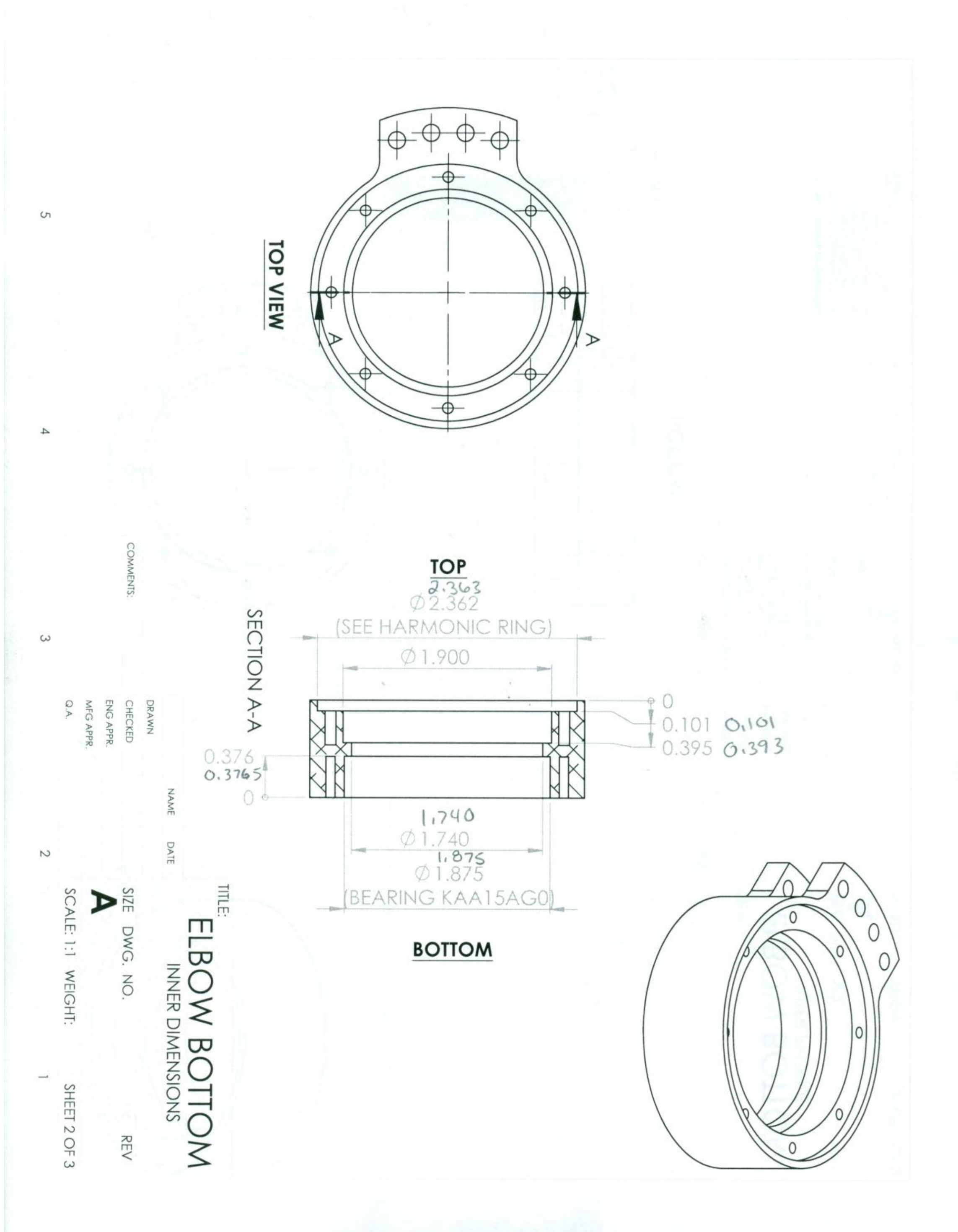
ELBOW BOTTOM

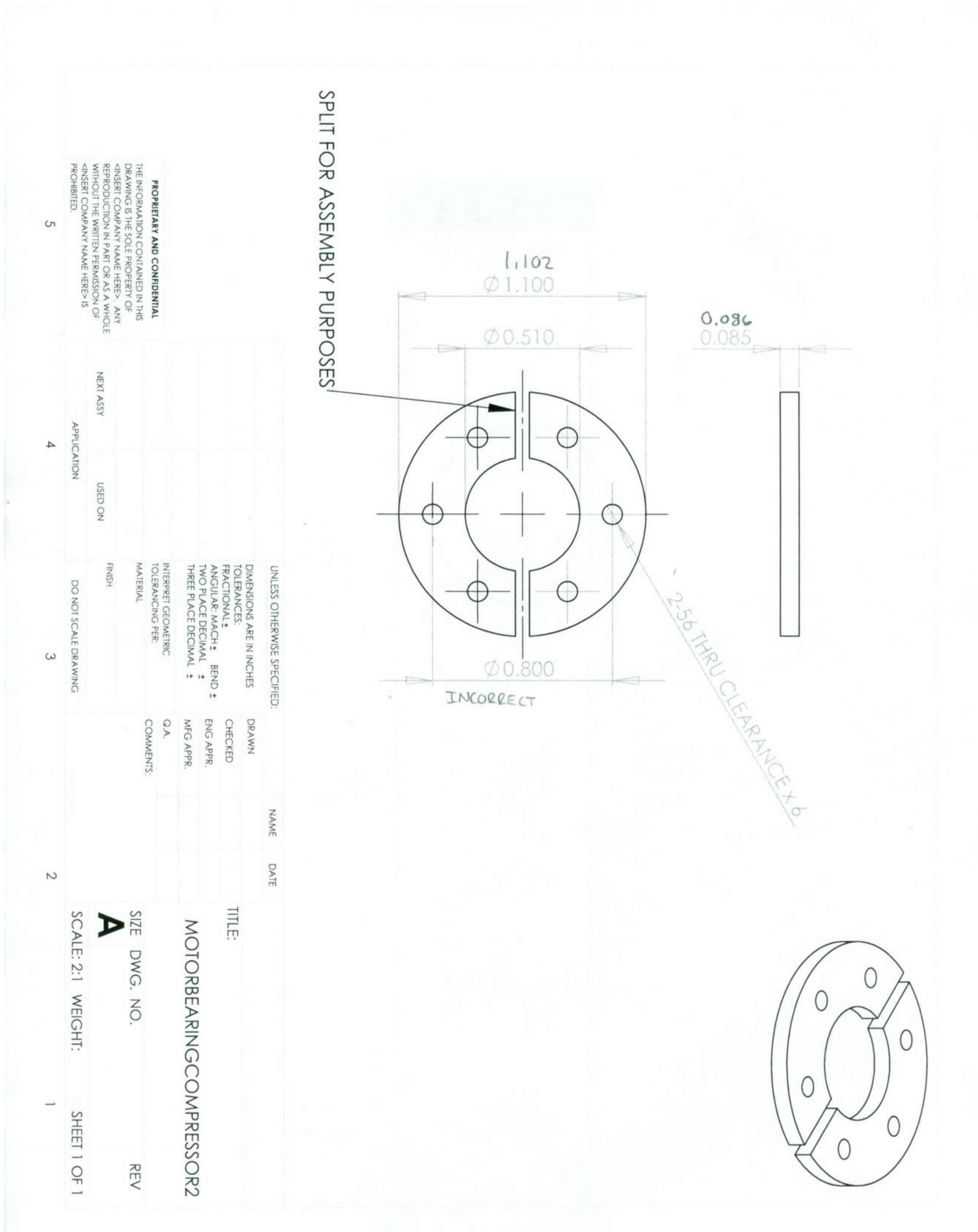
OUTER PROFILE

SIZE A DWG. NO. REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 3

5 4 3 2 1


TOP VIEW
A
A
SECTION A-A
TOP
2.363
Ø2.362
(SEE HARMONIC RING)
Ø1.900
0
0.101 0.101
0.395 0.393
0.376
0.3765
0
1.740
Ø1.740
1.875
Ø1.875
(BEARING KAA15AG0)
BOTTOM
COMMENTS:
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
NAME
DATE
TITLE:
ELBOW BOTTOM
INNER DIMENSIONS
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 2 OF 3
5
4
3
2
1


SPLIT FOR ASSEMBLY PURPOSES
1.102
Ø1.100
Ø0.510
0.086
0.085
Ø0.800
INCORRECT
2-56 THRU CLEARANCE x6
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
MOTORBEARINGCOMPRESSOR2
SIZE
DWG. NO.
REV
A
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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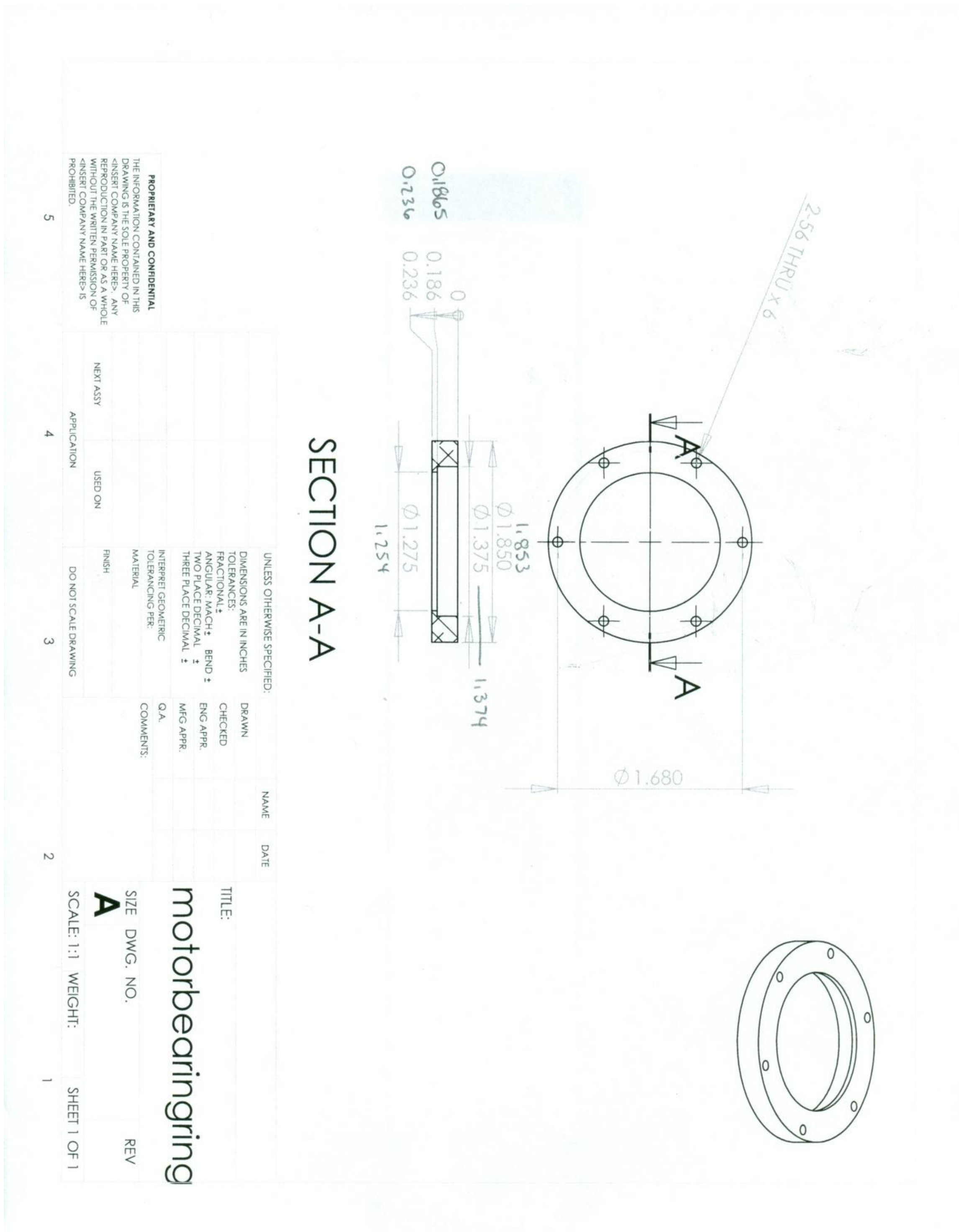
5
4
3
2
1



2-56 THRU x 6
A
A
Ø1.680
1.853
Ø1.850
Ø1.375
1.374
0
0.186
0.236
0.1865
0.236
Ø1.275
1.254
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
TITLE:
motorbearingring
SIZE DWG. NO.
A
REV
SCALE: 1:1 WEIGHT:
SHEET 1 OF 1
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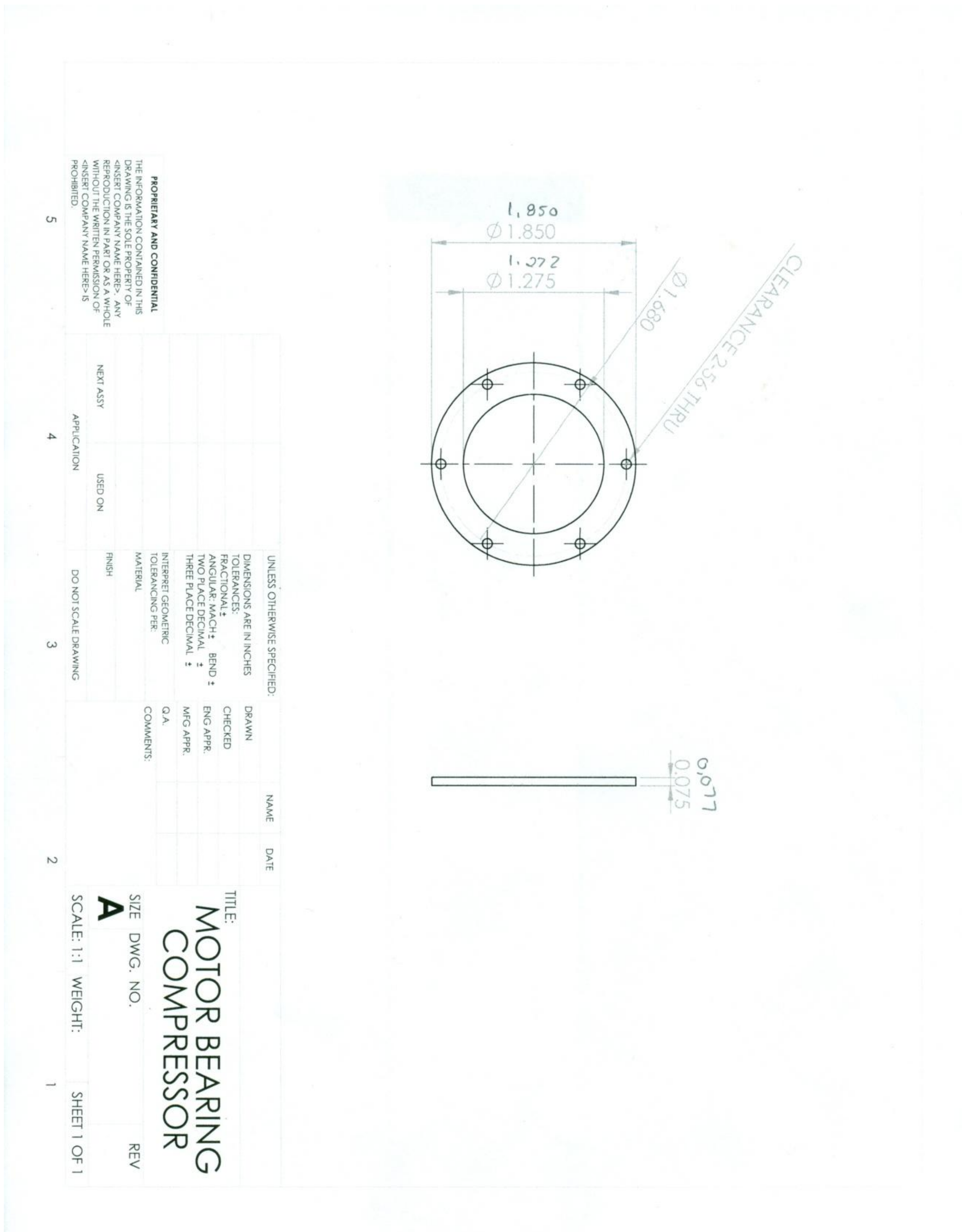
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
5
4
3
2
1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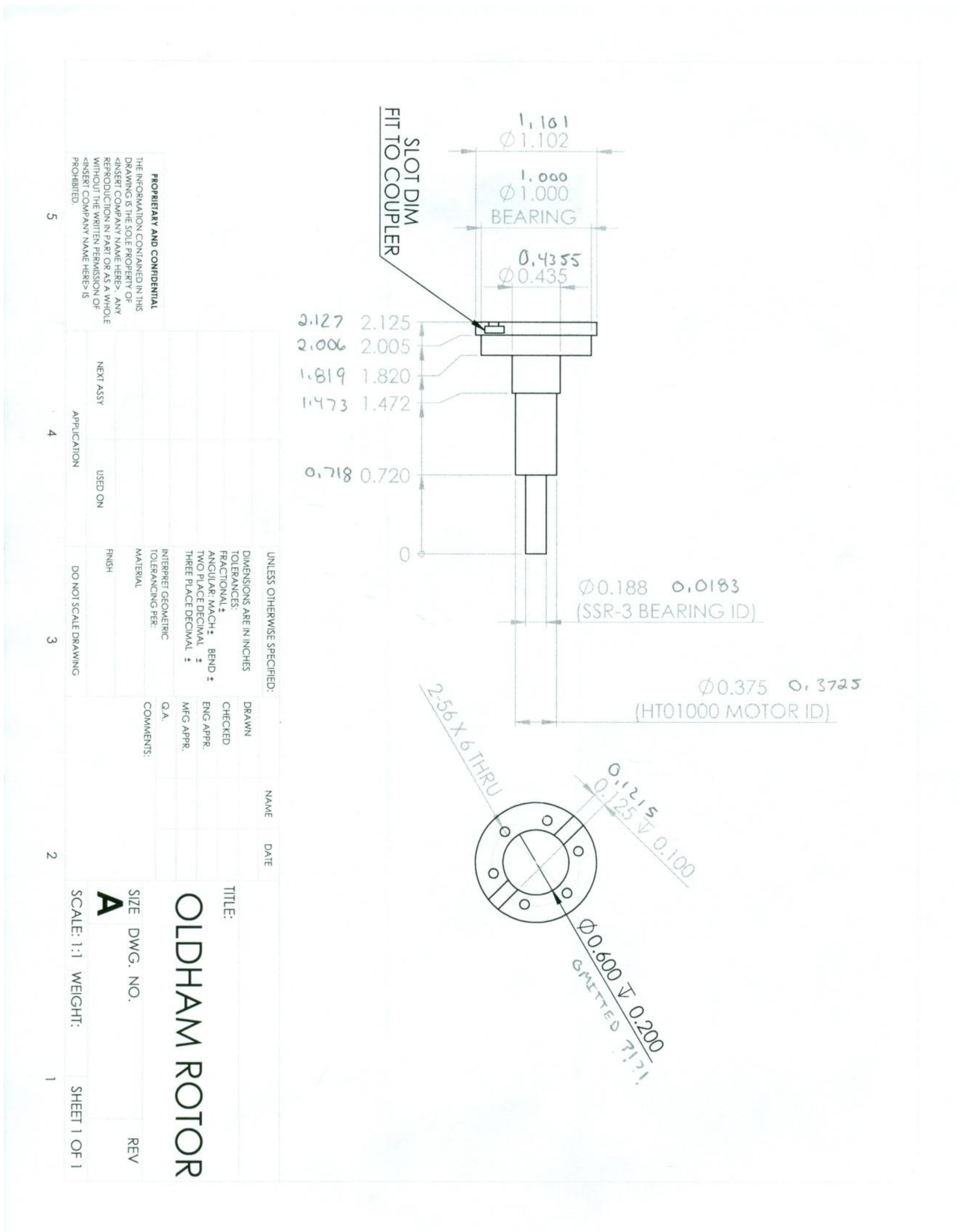
1.850
Ø1.850
1.272
Ø1.275
Ø1.680
CLEARANCE 2-56 THRU
0.077
0.075
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
MOTOR BEARING COMPRESSOR
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



SLOT DIM
FIT TO COUPLER
1.101
Ø1.102
1.000
Ø1.000
BEARING
0.4355
Ø0.435
2.127 2.125
2.006 2.005
1.819 1.820
1.473 1.472
0.718 0.720
0
Ø0.188 0.0183
(SSR-3 BEARING ID)
Ø0.375 0.3725
(HT01000 MOTOR ID)
2-56 X 6 THRU
0.1215
Ø.125 ↧ 0.100
Ø0.600 ↧ 0.200
OMITTED 7/2/1
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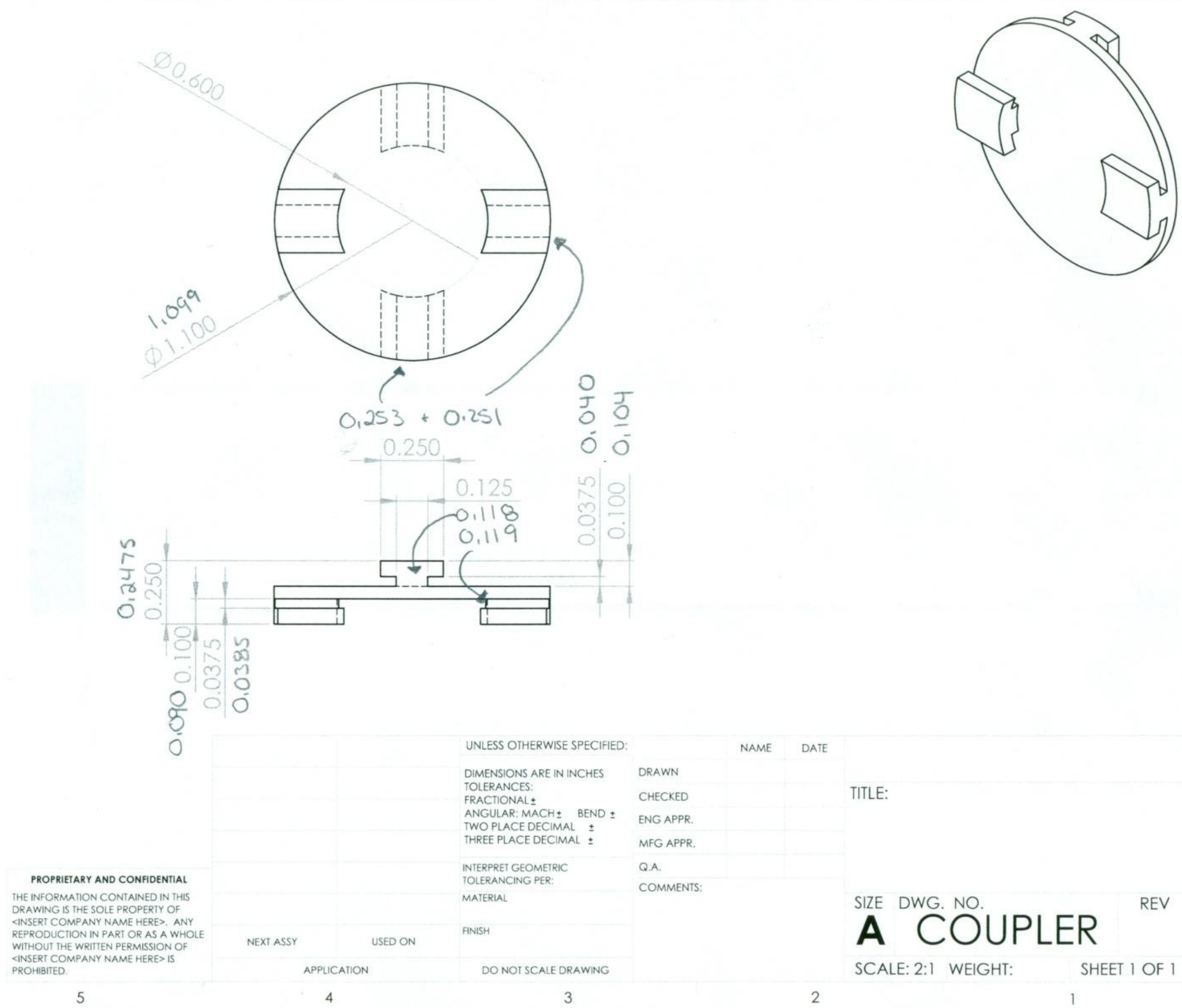
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
OLDHAM ROTOR
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Ø0.600
1.099
Ø1.100
0.253 + 0.251
0.250
0.125
0.118
0.119
0.040
0.104
0.0375
0.100
0.2475
0.250
0.090
0.100
0.0375
0.0385
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
COUPLER
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
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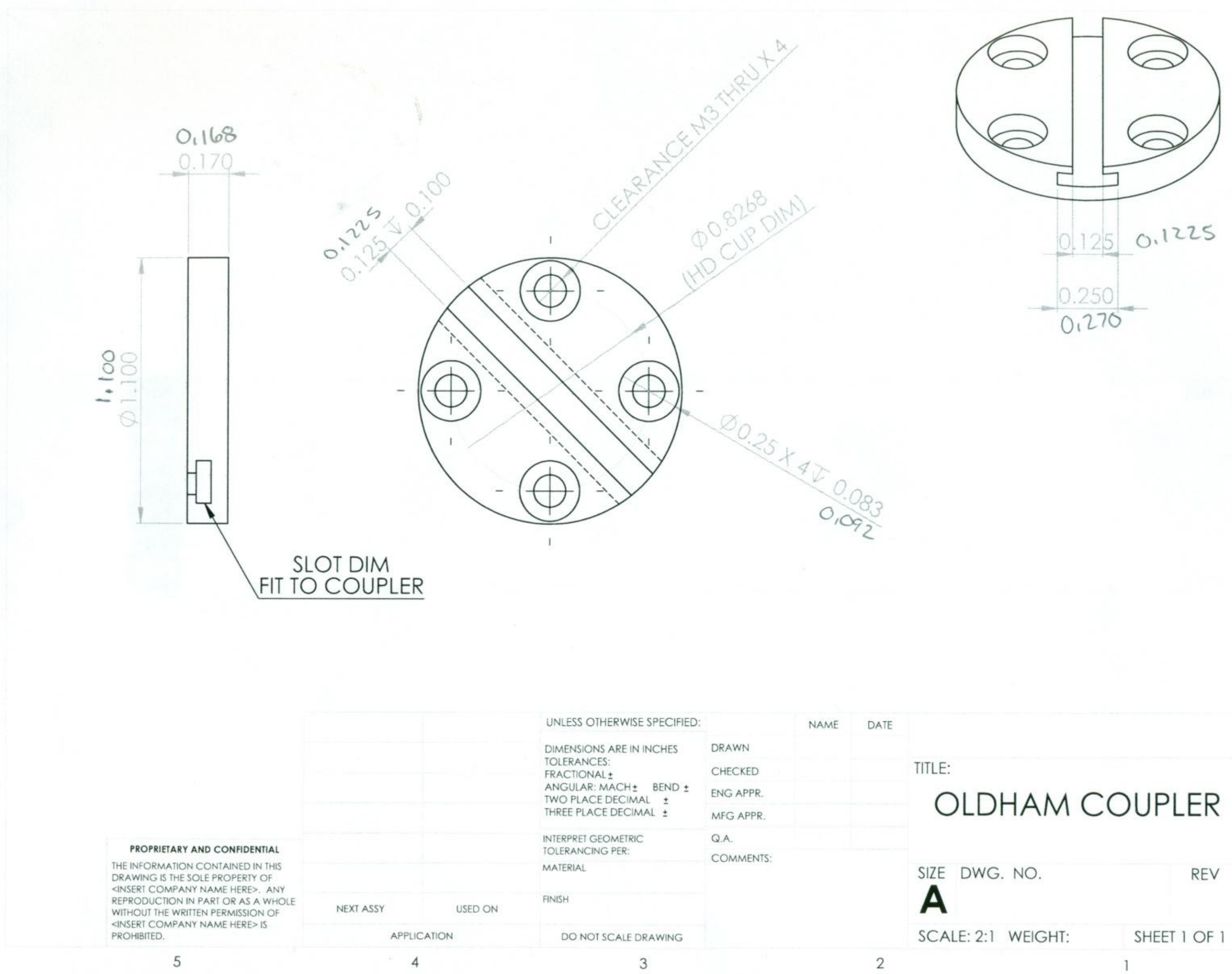
5
4
3
2
1


0.168
0.170
1.100
Ø1.100
SLOT DIM
FIT TO COUPLER
0.1225
0.125 ⊽ 0.100
CLEARANCE M3 THRU X 4
Ø0.8268
(HD CUP DIM)
Ø0.25 X 4 ⊽ 0.083
0.092
0.125
0.1225
0.250
0.270
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
OLDHAM COUPLER
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
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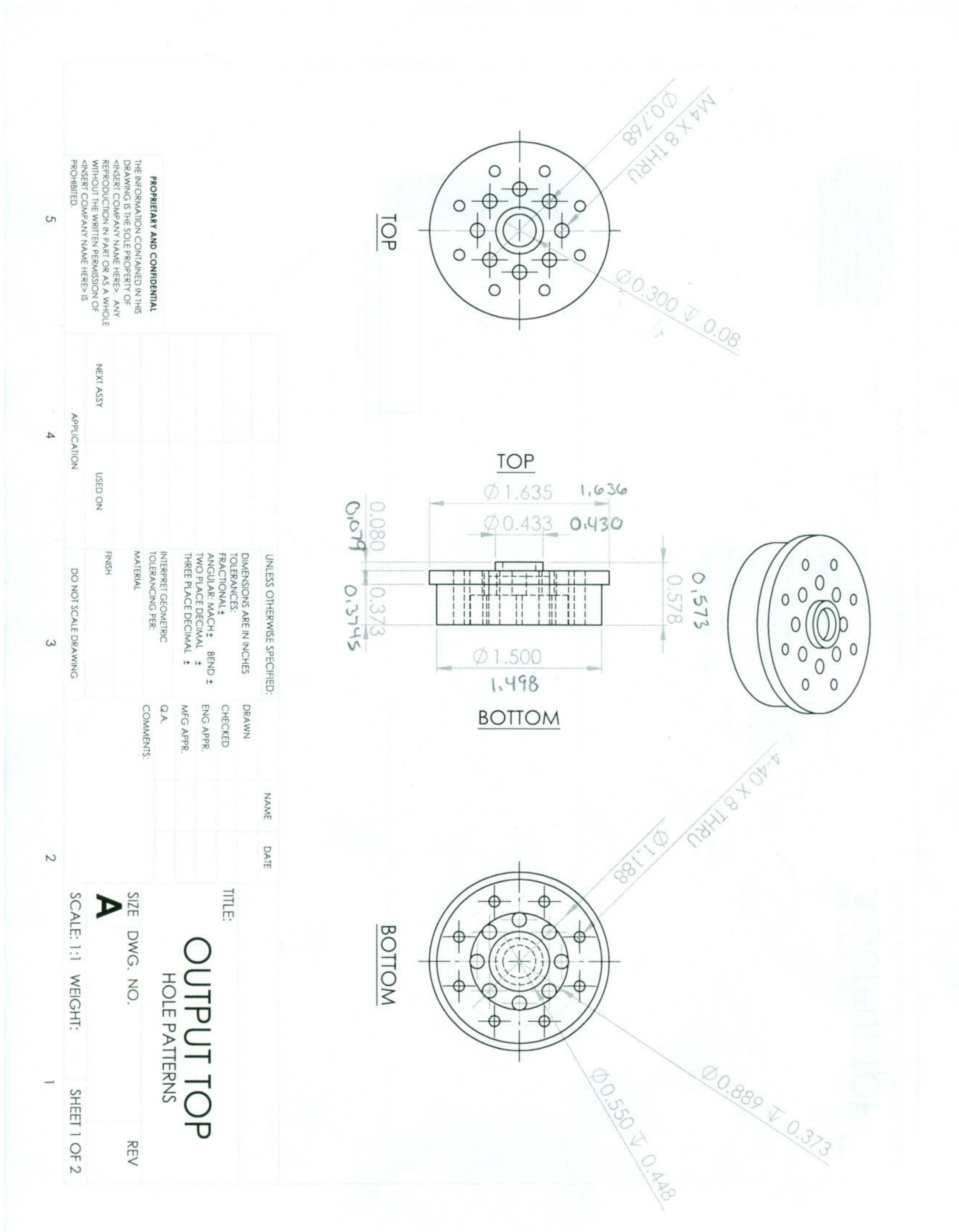
NEXT ASSY
USED ON
APPLICATION
5
4
3
2
1


TOP
Ø0.768
M4 X 8 THRU
Ø0.300 ⊽ 0.08
TOP
Ø1.635
1.636
Ø0.433
0.430
0.080
0.079
0.373
0.345
0.578
0.573
Ø1.500
1.498
BOTTOM
4-40 X 8 THRU
Ø1.188
Ø0.889 ⊽ 0.373
Ø0.550 ⊽ 0.448
BOTTOM
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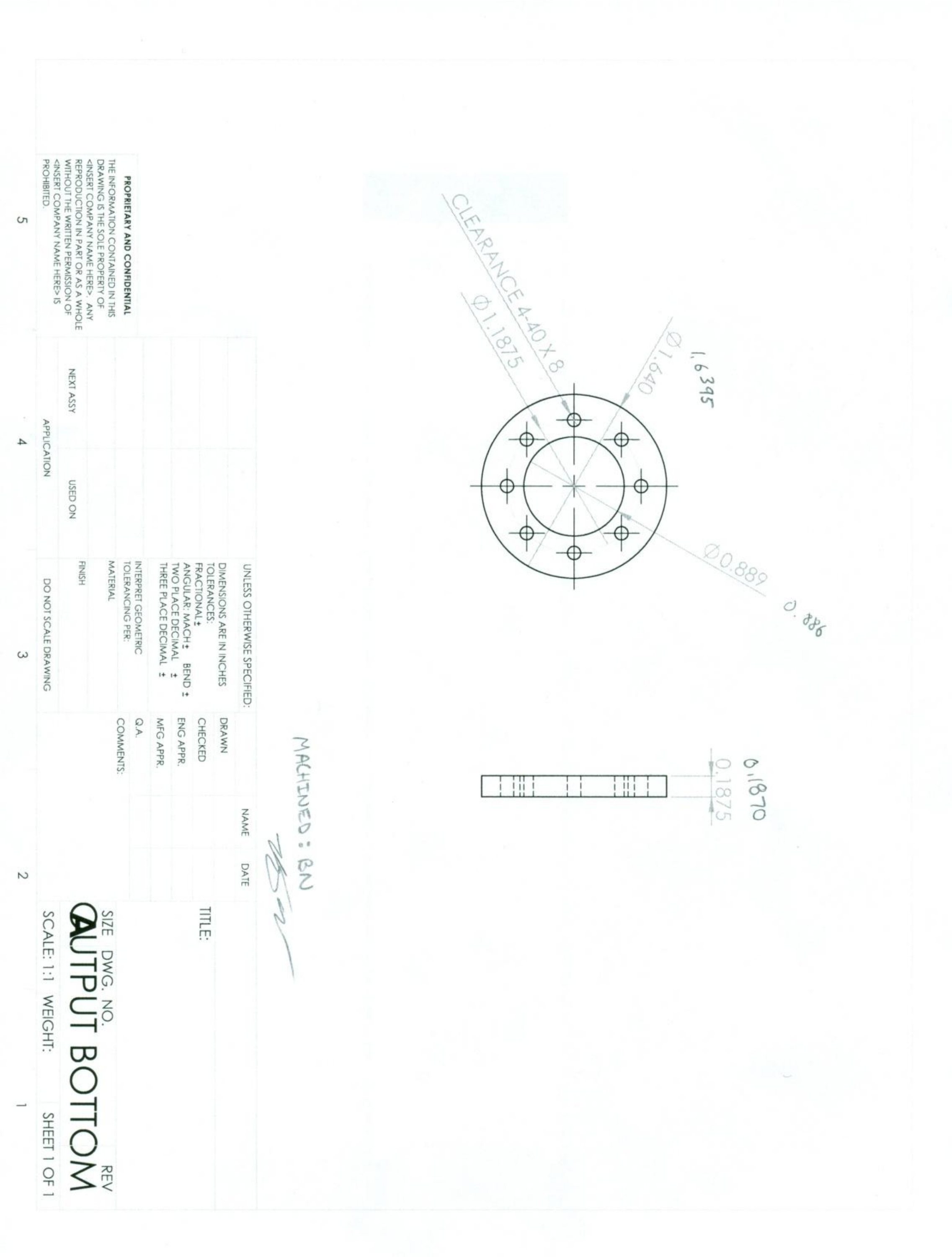
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
OUTPUT TOP
HOLE PATTERNS
SIZE DWG. NO.
A
REV
SCALE: 1:1 WEIGHT:
SHEET 1 OF 2
5
4
3
2
1


CLEARANCE 4-40 X 8
Ø1.1875
Ø1.640
1.6395
Ø0.889
0.886
0.1870
0.1875
MACHINED: BN
PROPRIETARY AND CONFIDENTIAL
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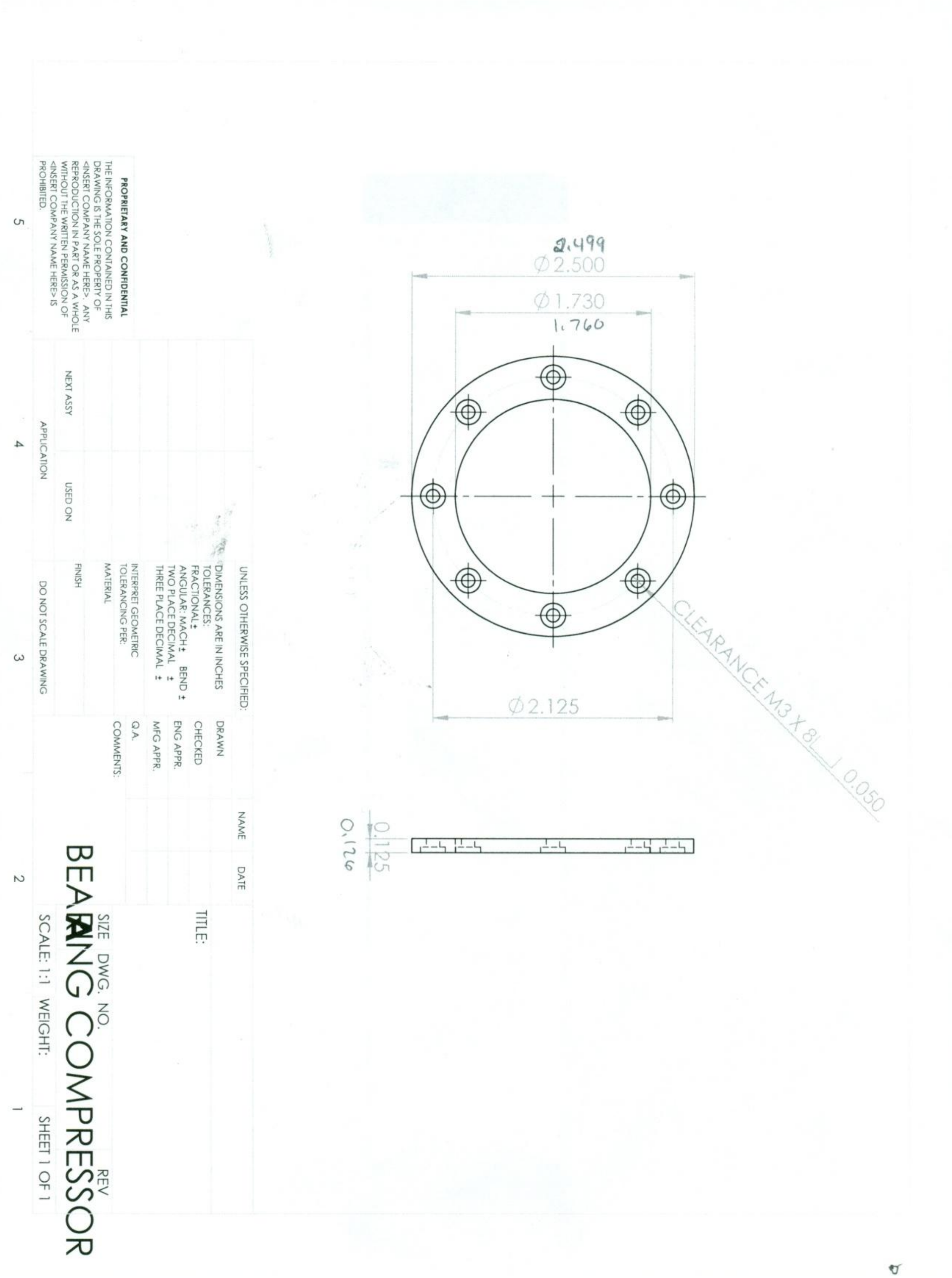
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
A
OUTPUT BOTTOM
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


2.499
Ø2.500
Ø1.730
1.760
Ø2.125
CLEARANCE M3 X 8L ⊥ 0.050
0.125
0.126
PROPRIETARY AND CONFIDENTIAL
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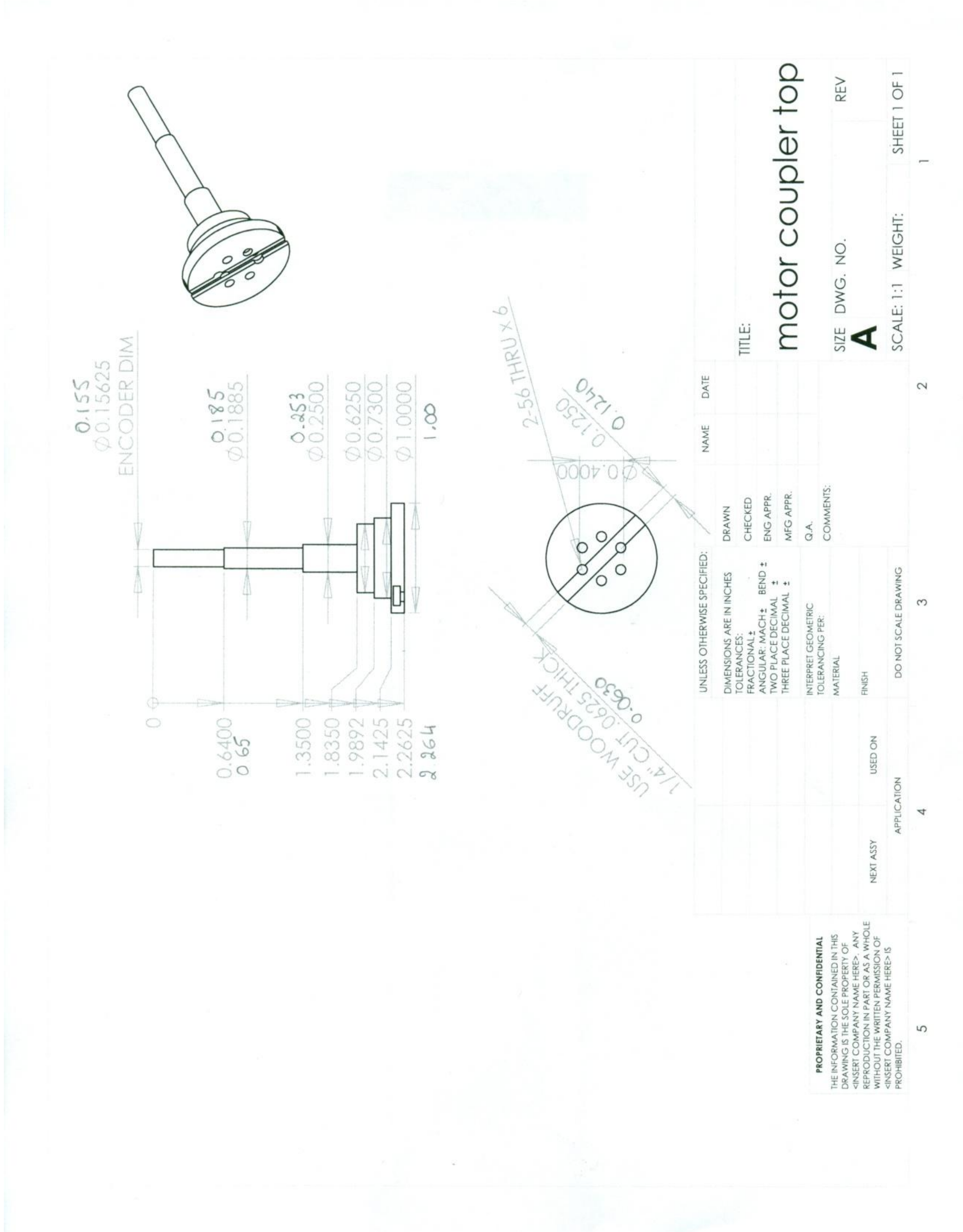
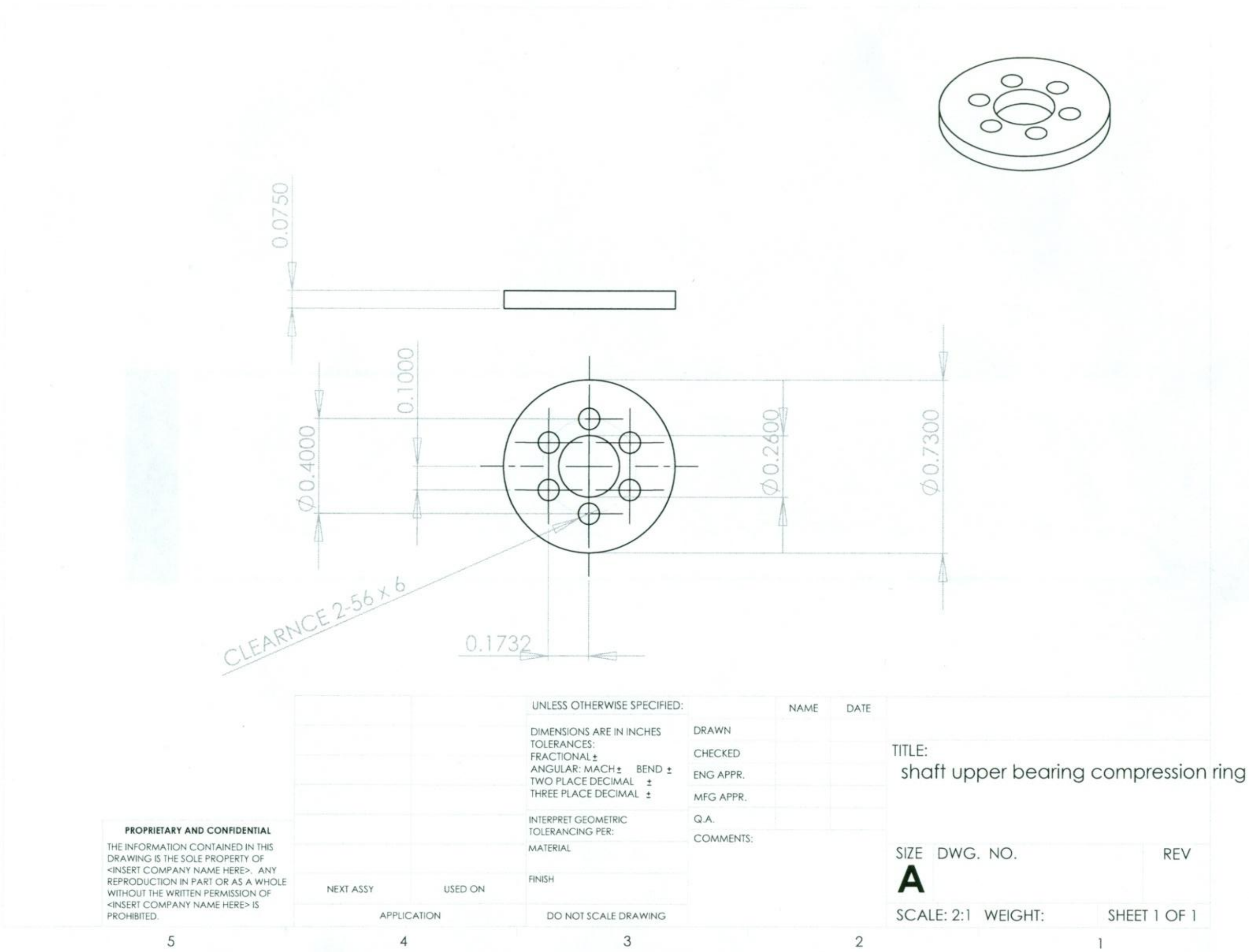
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
REV
BEARING COMPRESSOR
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1

Appendix R: Blue Printed Wrist Drawings




0.0750
0.1000
Ø0.4000
Ø0.2600
Ø0.7300
CLEARNCE 2-56 x 6
0.1732
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
TITLE:
shaft upper bearing compression ring
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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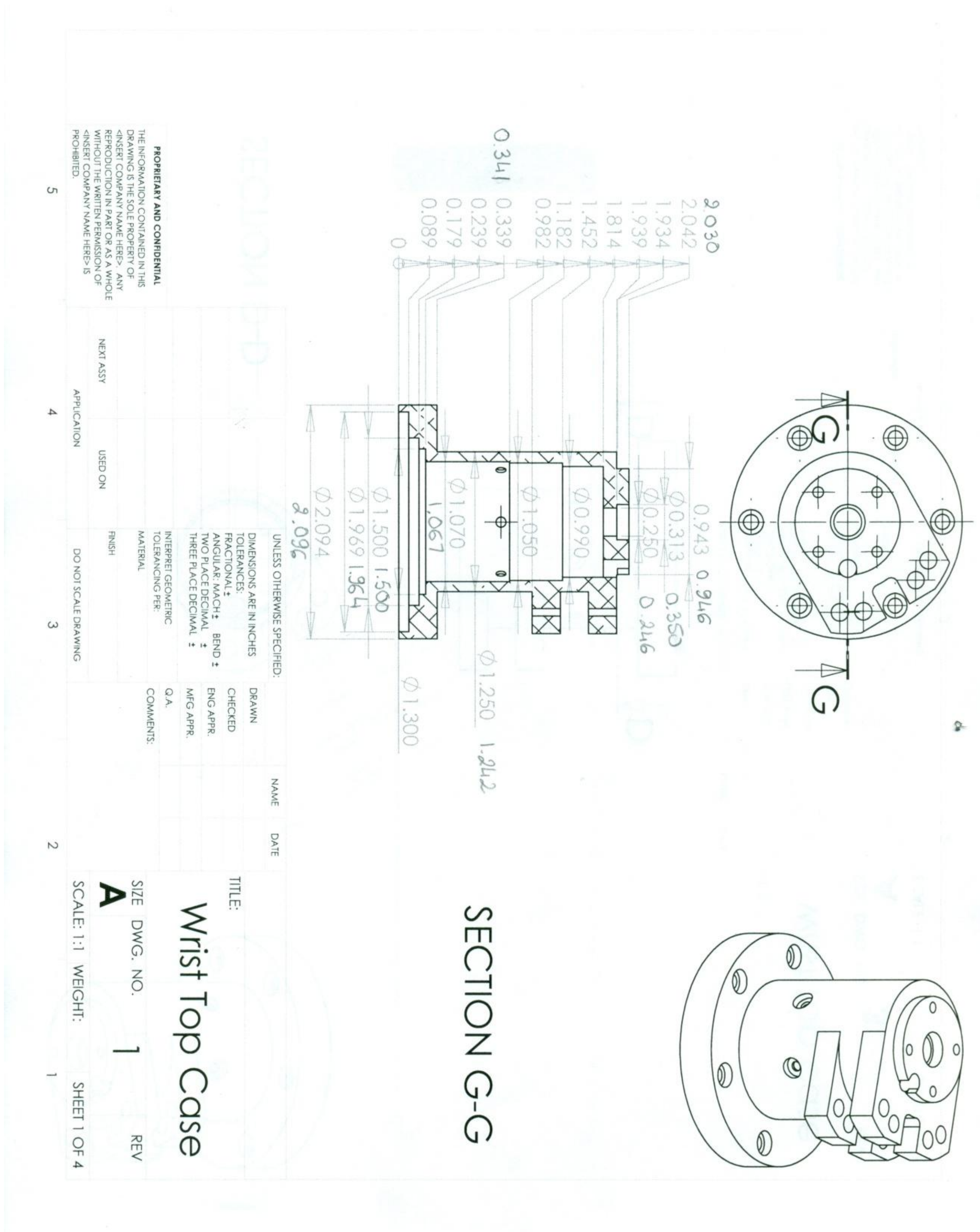
5
4
3
2
1


SECTION G-G
G
G
2.030
2.042
1.934
1.939
1.814
1.452
1.182
0.982
0.339
0.239
0.179
0.089
0
0.341
Ø0.313
Ø0.250
Ø0.990
Ø1.050
Ø1.070
Ø1.500
Ø1.969
Ø2.094
Ø1.250
Ø1.300
0.943 0.946
0.350
0.246
1.067
1.500
1.964
2.096
1.242
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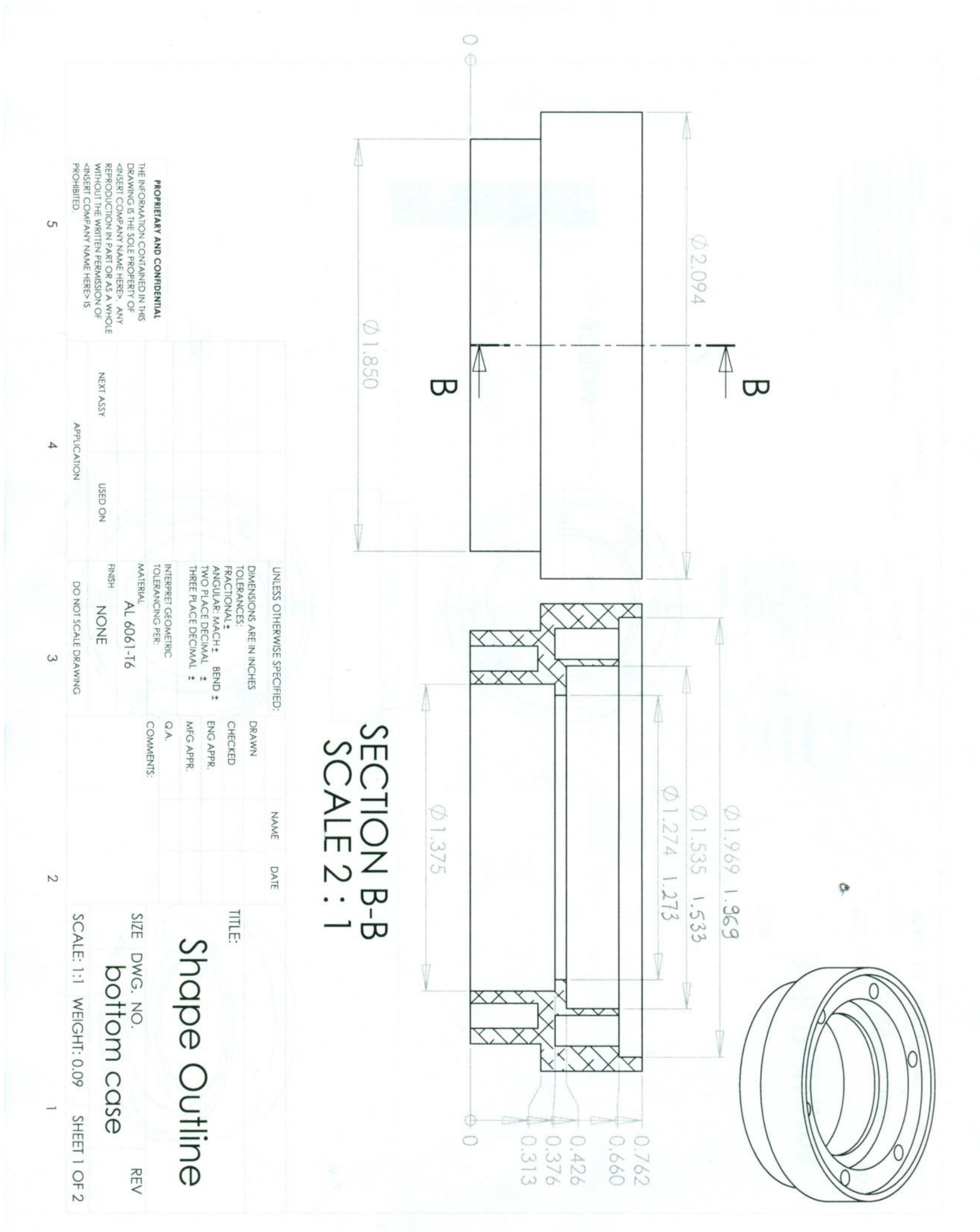
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
Wrist Top Case
SIZE
DWG. NO.
REV
A
1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 4
5
4
3
2
1


Ø2.094
Ø1.850
B
B
SECTION B-B
SCALE 2 : 1
Ø1.969 1.969
Ø1.535 1.533
Ø1.274 1.273
Ø1.375
0
0.762
0.660
0.426
0.376
0.313
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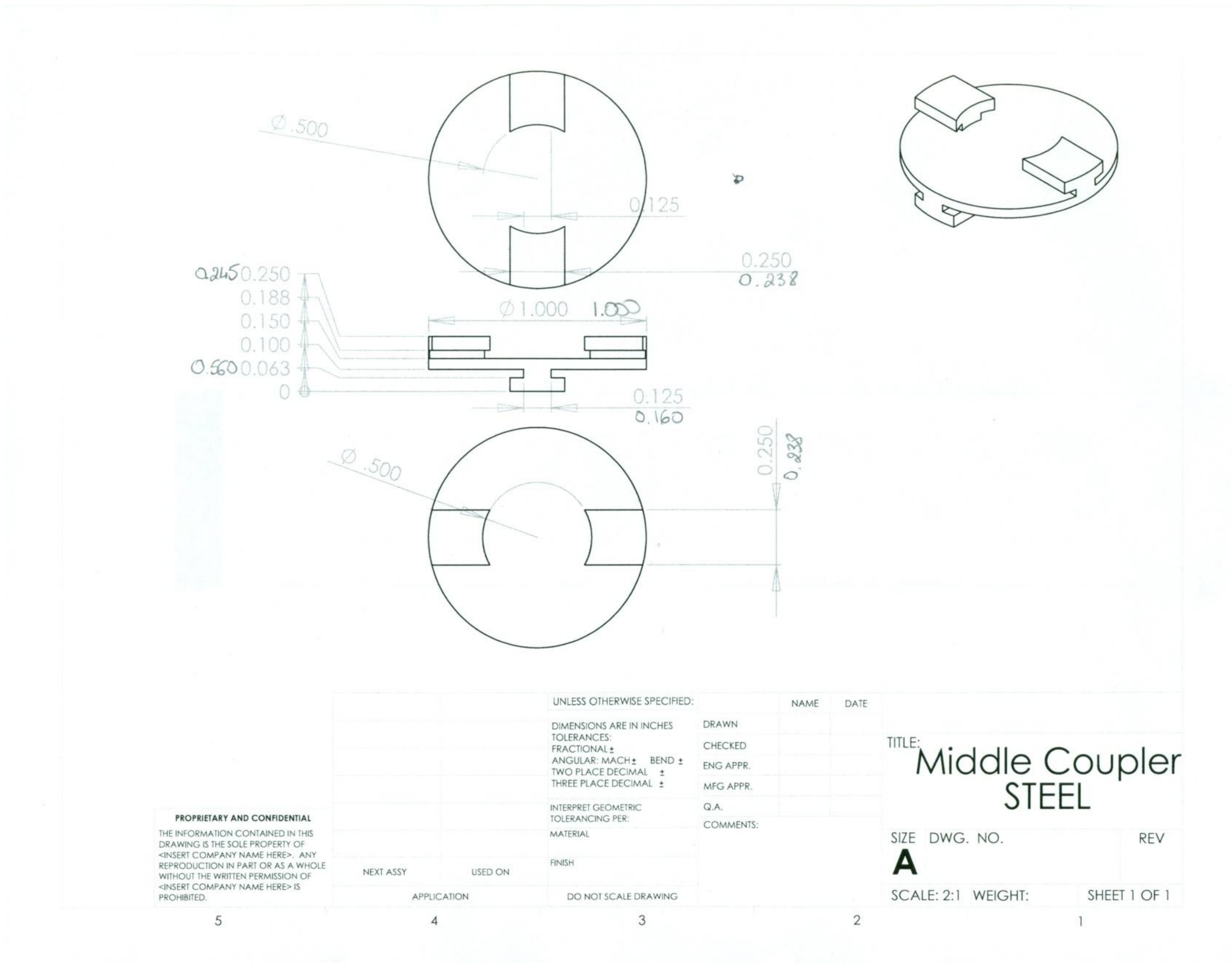
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
AL 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
Shape Outline
SIZE
DWG. NO.
bottom case
REV
SCALE: 1:1
WEIGHT: 0.09
SHEET 1 OF 2
5
4
3
2
1


Ø .500
0.125
0.250
0.238
0.245
0.250
0.188
0.150
0.100
0.560
0.063
0
Ø 1.000
1.000
0.125
0.160
Ø .500
0.250
0.238
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
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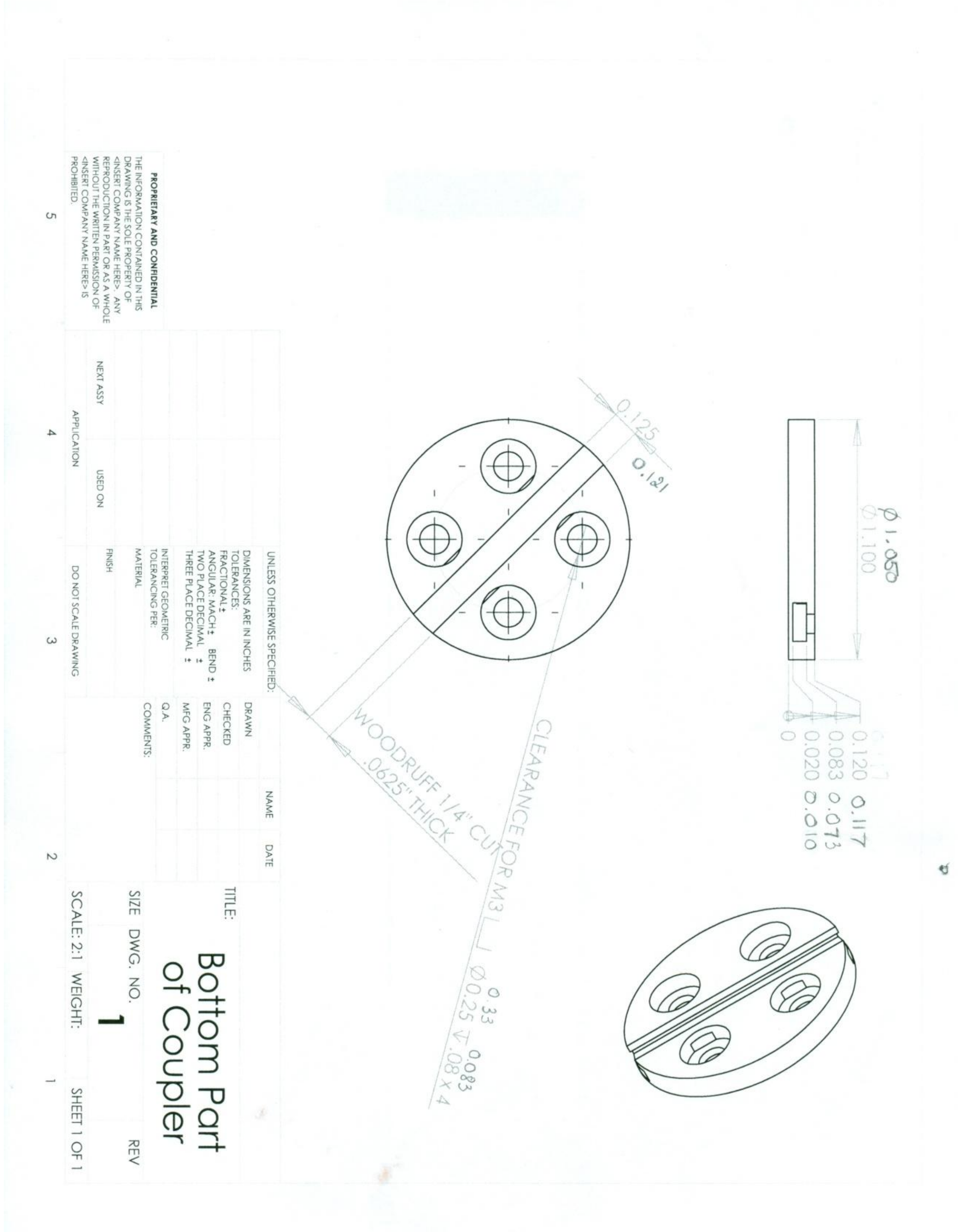
TITLE:
Middle Coupler
STEEL
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Ø 1.050
Ø 1.100
0.120 0.117
0.083 0.073
0.020 0.010
0
0.125
0.121
CLEARANCE FOR M3 ⌴ 0.33 Ø0.25 ↧ 0.083 .08 x 4
WOODRUFF 1/4" CUT .0625" THICK
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bottom Part of Coupler
SIZE
DWG. NO.
1
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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5
4
3
2
1