Final Design Deliverable

EML 4552C – Senior Design – Spring 2013 - Deliverables

Team #5 – Sensor Ring Test Rig

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Nomenclature

D_{neg} = Sensor displacement at negative extreme position (mm)

D_{pos} = Sensor displacement at positive extreme position (mm)

$LVDT$ = Linear variable differential transformer

S = Sensor ring sensitivity ($\frac{V}{mm}$)

V_{neg} = Sensor voltage at negative displacement extreme position

V_{pos} = Sensor voltage at positive displacement extreme position

Executive Summary

Danfoss Turbocor is currently seeking a way to optimize sensor testing for their compressors. While their current system is able to test these sensors it is not reliable. The fixture has to be calibrated after a certain number of sensor rings have been tested in order to ensure that the measurements are accurate. Danfoss Turbocor has sponsored a senior design project to design and build a new sensor test fixture rig in order to improve quality and production time.

In order to complete this task certain specifications have to be met in the new system. Each direction of measurement has to be independent of each other as to not interfere with the other sensor readings. The displacement only needs to be approximately 400 micrometers with an accuracy of 2 micrometers. The movement needs to have three distinct stopping points to take measurements. It also needs to have minimal backlash. These constraints are all most important and must be taken into consideration of the design of the system. Concept designs are developed and then eliminated until a final design is chosen. This design has been modeled in CAD software with mechanics analysis. While this system may still need more improvements, it does give Danfoss Turbocor a starting point to solve all of their issues. Once the fixture has been assembled testing and calibration of the system will happen, which will help refine any changes that need to be made.

About Danfoss Turbocor

Danfoss Turbocor is a Canadian based company that manufactures large-scale HVAC systems for commercial use. Their compressors are used in buildings such hotels, warehouses, and airports. These compressors are extremely efficient as they operate with extremely low friction on the compressor shaft. The unique aspect of these compressors is that the compressor shaft floats in a magnetic field eliminating contact with bearings.

Surrounding these compressor shafts are two sensor rings that detect any displacement of the compressor shaft from its centered position. These sensors are extremely important as the compressor shafts can spin in excess of 30,000 rotations per minute. If a compressor shaft were to vary from it centered rotational position, serious catastrophic damage could occur to the compressor system.

The sensor rings themselves are made up of three sets of voltage sensors pressed in an aluminum ring. Each sensor set is responsible for monitoring a different axis of movement: X, Y, and Z. These sensor sets are capable of detecting shaft misalignment down to the order of microns.

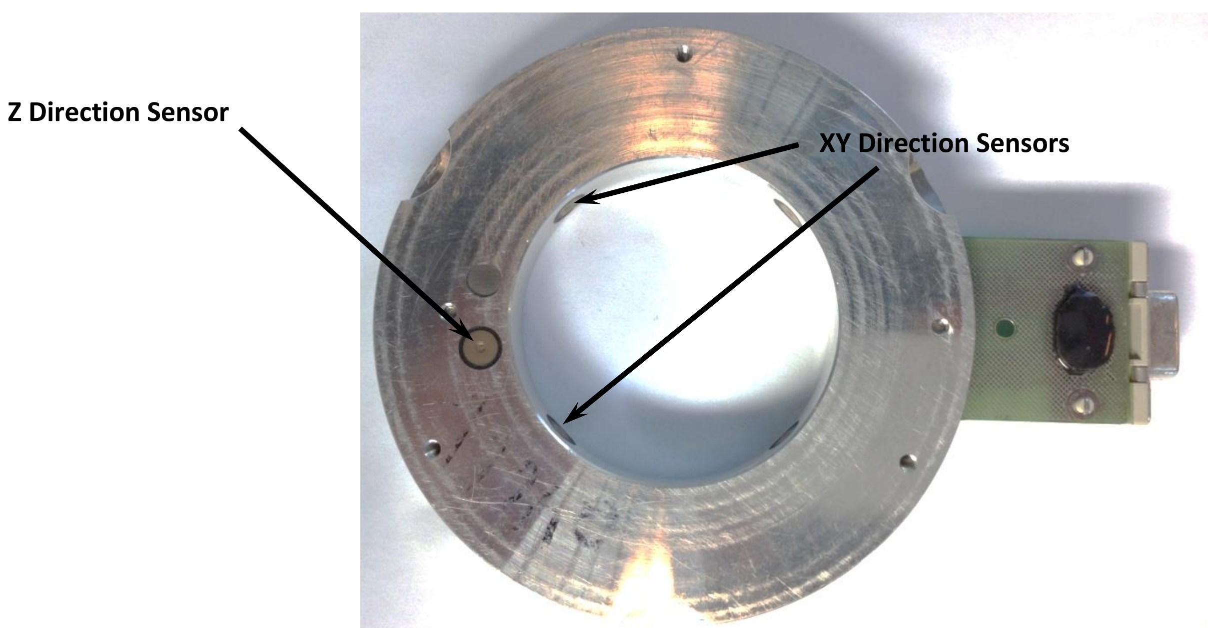


Figure 1: Sensor Ring and Location of Sensors

Current Testing System

Danfoss Turbocor produces compressors for industrial and commercial use in HVAC systems. These compressors are outfitted with two sensor rings that sense any movement from the shaft, this ensures that the shaft is centered and tells the operator if calibration is needed. On the production line a sensor testing rig is used to test the accuracy and precision of these sensors.

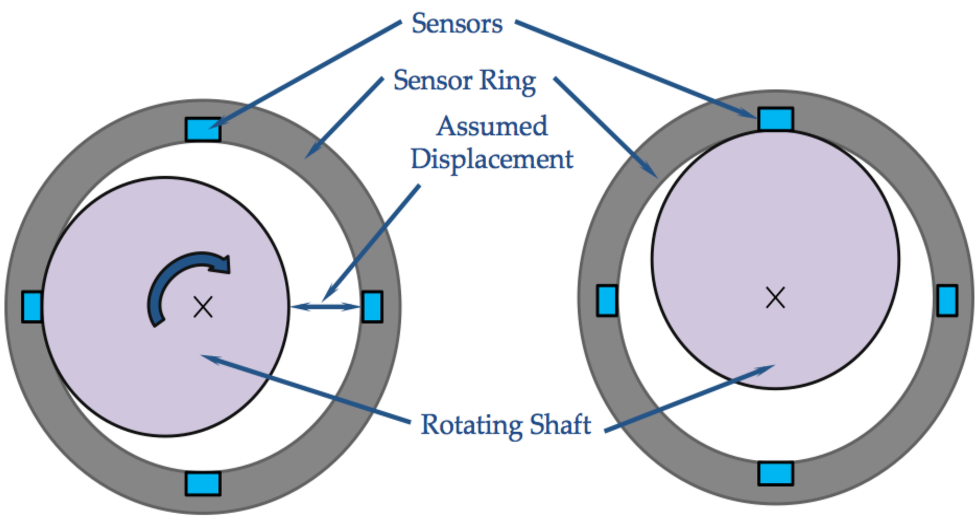


Figure 2: Schematic of Current System

The sensor ring is mounted onto a shaft and it is spring loaded so the sensor ring does not move. The shaft is off center from the sensor rings center so that the edge of the shaft is touching the inner edge of the ring, covering the sensor that reads the X-Direction. This contact that is produced has an assumed displacement of 0 micrometers. The distance from the other side of the shaft to the other side of the sensor ring is measured to be approximately 400 micrometers. From here the shaft is then rotated, using a stepper motor, 90° so that the shaft is now touching the Y-Direction sensor. In the Z-Direction a flange is protruding from the shaft, so as it rotates the flange will cross the Z-Direction sensor and give a reading.

This fixture has quite a few problems, ones that cannot be overlooked. The assumed displacement is a major contributing factor in the constant need to recalibrate the fixture. The distance of 400 micrometers has to be measured repeatedly after a certain number of rings have been tested; this is because the shaft does not line up exactly to the same position on every ring. Furthermore, there is no independent displacement measuring system in place to track the actual motion. The stepper motor also poses a problem. As the motor rotates the shaft and comes to an abrupt stop, the shaft moves forward or backward a miniscule amount. This movement is not negligible simply due to the scale of magnitude of precision that is required. Finally, a better way of measuring displacement in the Z-Direction has to be developed. In the current design only one position measurement can be read, when the flange passes over the sensor.

Problem Statement

The goal of this system is to create a sensor test rig that will ensure that the sensors being produced are up to the quality Danfoss Turbocor's needs. Danfoss Turbocor is currently using a sensor testing platform that requires an assembly worker to mount the sensor ring on to the tester. The tester is then initiated and outputs a reading so that software acquires the data and determines whether the sensors will pass or fail for use in a compressor. The existing mechanism that displaces the sensors ring has backlash, which leads to inaccurate sensor reading, thusly it is unsuitable. The problem that arises is the platform continuously needs to be calibrated after a certain amount of sensors are tested. This slows productions time down and decreases the reliability of the test rig. In order to improve efficiency, a system which reliably tests the sensor is needed.

Constraints

Danfoss Turbocor has a set of requirements that the new system must be able to do. The fixture must be able to test in the XYZ-Directions independently. Unlike the current system where when the X-Direction sensor is tested, the reading given off by the Y-Direction sensor changes, this systems has to be able to measure one sensor without affecting the others. There must also be at least three positions at which the sensors can stop and take readings from. Generally it would be from the two extremes of the sensors and when the shaft is centered in the ring. A resolution of 2 micrometer is required for our displacement measurement, so that the sensors can accurately be compared to it. In total the shaft must be able to move 400 micrometers diametrically, or 200 micrometers radially. Finally, the system has to minimize the backlash so that the known displacements the shaft is moving can be compared to the sensors.

Background

Our team was tasked with developing a production test fixture for testing of the sensor rings that are used inside their extremely efficient compressors. The most important feature being the test fixture must create uniaxial displacement for testing the sensor ring's sensors individually for each direction. Initially the most appealing design was to implement a three-direction linear stage, one that would be designed and fabricated by hand. This proved impractical and not favorable for our time constraints.

So our next concept included using a commercial linear stage to maintain the precise movements, and building a fixture around that. However, this design had its flaws as well. High cost and excessive manual operation requirements halted further development.

The final design has a completely new approach to the testing procedure. A stepper motor is coupled to a drive screw to convert excellent rotational resolution into optimal linear motion of the sensor ring in relation to the compressor shaft. For axial motion, a micrometer is used. This design scheme proves to meet all of the needs of Danfoss Turbocor, creating uniaxial movement that will both be observed and measured by the sensor rings. The advantages of this design far outweighed its downfalls, which still stack up against the previous design concepts.

X/Y Axis Test Stage Drive System

To move the test stage to provide radial displacement between the sensor ring and the mock compressor shaft, a stepper motor was utilized. As the stepper motor spins, it turns a drive screw that is threaded into the test stage. This provides linear motion for the test stage in a fixed direction.

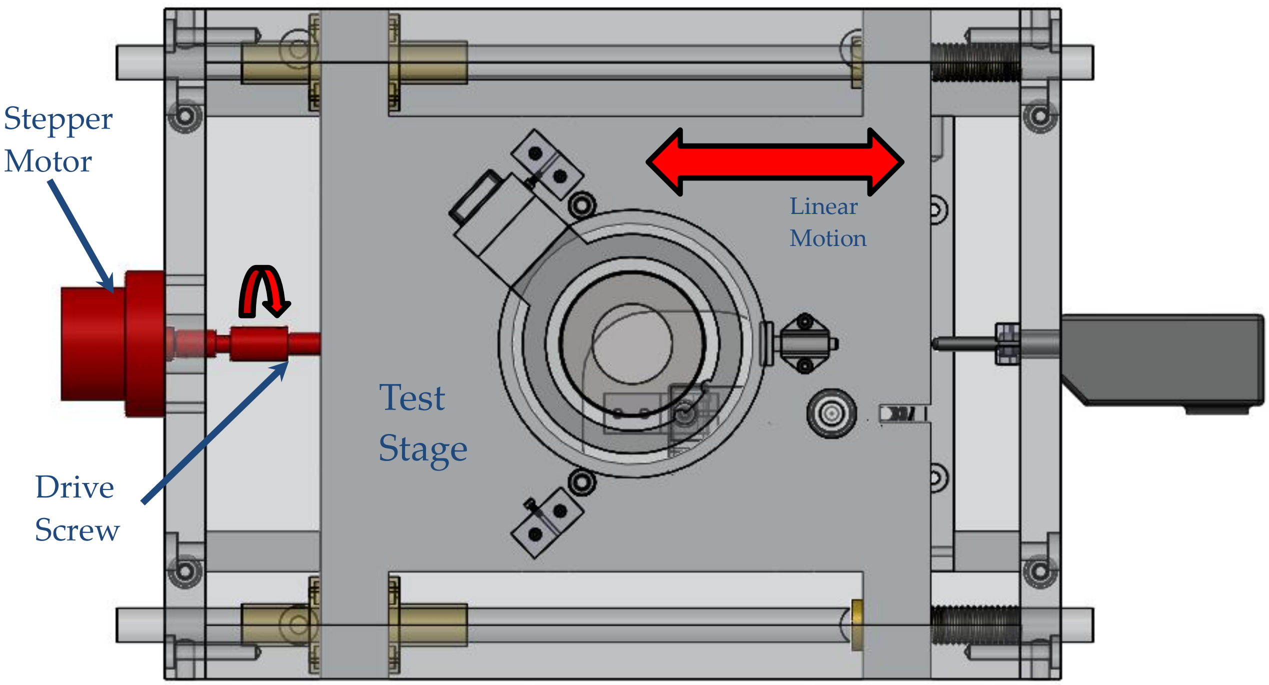


Figure 3: Sensor ring test stage linear drive system (stepper motor and drive screw in red)

The stepper motor chosen for this project is a Portscap™ geared stepper motor that is custom-made for Danfoss Turbocor. It provides 0.25 degrees per step using full-step method. The drive screw chosen has a 3/8" diameter with 24 threads per inch. When this drive screw is coupled to the stepper motor, a resolution of 0.735 micrometers per step is achieved.

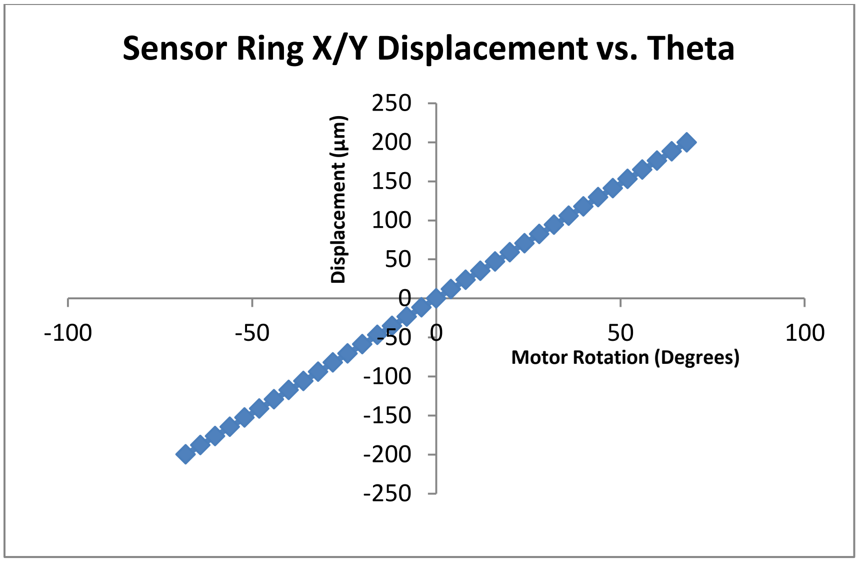


Figure 4: Test stage/sensor ring displacement vs. stepper motor rotation

The stepper motor system is controlled by the HCS-12 Dragonboard. Code Warrior is used to load code onto the Dragonboard. The control board is set up to start the stepper motor and test stage in the centered position. When the code is initialized, by pressing the red initiate button, the test stage moves 200 microns in the positive direction. It then waits for a period of about 8 seconds to leave time for data acquisition. After that, the motor moves the stage in the negative direction 400 microns. After another 8 second wait, the motor moves the stage back to the center position. After the sensor ring is rotated 90 degrees to switch to the next set of sensors, the process can be repeated by again pushing the red "initiate" button mounted to the control board casing.

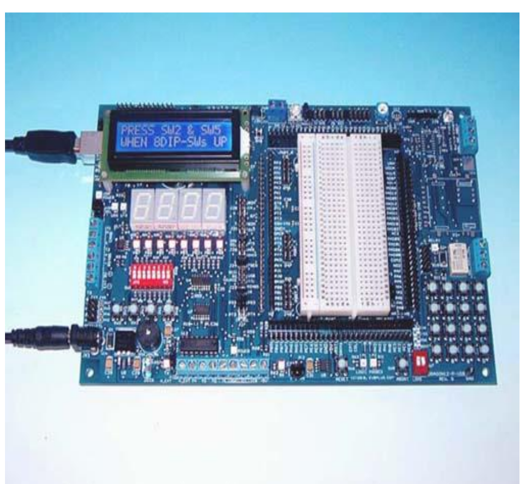


Figure 5: HCS-12 Dragonboard used for stepper motor control

Testing and Calibration

The sensor ring test fixture was tested in various stages as to ensure proper operation and measurements. Once the assembly was completed, a transfer ring was installed to ensure that the test stage and sensor ring were centered with the vertical axis of the cylindrical mock compressor shaft. This was possible due to the design and shape of our transfer ring. The transfer ring is essentially a hollow cylinder with the same exact outside diameter as the sensor rings that are to be tested. The inside diameter is slightly smaller than that of the sensor ring as is designed to fit snuggly over the mock compressor shaft. During the last step of the assembly, the transfer ring was installed while the mock compressor shaft mounting bolts were still slightly loose. Once the transfer ring provided concentricity for the mock compressor shaft and the test stage sensor hole, the mock shaft mounting screws were tightened.

Since the test stage is spring loaded, it has a tendency to move to one extreme on the X axis. To ensure that the stage would remain centered when the transfer ring was removed, the LVDT's were turned on a "zeroed" out at the test stage location that the transfer ring provided. Then, the transfer ring was removed. At this step, the test stage did move a considerable amount from the centered position. This movement, however, was noted by the XY LVDT. To adjust the test stage back to the center position, the stepper motor was moved in one-step increments until the test stage was back to the position set by the transfer ring. This process can be repeated periodically to confirm that the test stage has not moved out of the center position while it is not in operation.

Figure 6: Transfer ring for centering the XY test stage

Once the center position was confirmed, the extreme XY positions could be tested. This test was simple as it only involved running the stepper motor repeatedly to see if the same extreme positions were repeatedly achieved. This test revealed that the test structure consistently hit extremes between 193 and 200 microns in both directions from the center position. These values can be considered more than acceptable for sensor ring testing.

As expected, the Z axis motion system moved with great precision and resolution. Since this system is moved by hand using a micrometer, resolution of 1 micron was easily achieved with a range of motion of more than 1 millimeter. A range of motion of only 500 microns is required for sensor ring testing.

Once all of the motion tests were completed, it was time to test some sensor rings from Danfoss Turbocor. The sensor ring sensors measure voltage. The voltage read by the sensor, at each extreme position for each axis, is then divided by the displacement detected by the LVDT systems on the test rig. This yields sensitivity in volts per millimeter. At this point, the sensitivity provided by the sensor ring test is compared to an acceptable range of sensitivities provided by Danfoss Turbocor. As these ranges and values are proprietary information, we will not be discussing them in our report. However, the equation that was used to calculated sensitivity is shown below.

$$S = \frac{V_{pos} - V_{neg}}{D_{pos} - D_{neg}}$$

Equation 1: Sensor ring sensitivity as a function of voltage difference and displacement

Cost Analysis/ Engineering Economics

An in-depth analysis was done on the total project expenditures and expenses that would be considered by Danfoss Turbocor in future sensor test rig builds. For the sake of the senior design class, expenditures that were actually carried out by Turbocor during the design and build were totaled, and a separate total reflects the total expenditures including costs for components that are required for each test rig build.

As a result of filling out and submitting purchase orders with Turbocor, a consolidation of all the purchase order forms was developed to portray the total expenditure paid for by Turbocor, and if not, on site parts were used. Turbocor allotted an upper limit for project budget of $2000. Not including the on site components that were donated at no cost, the total project cost came in just under $1000. The most significant expenditure to Turbocor for the build was the aluminum stock, $300, used for the main structure. Aside from the aluminum, the other components fell well under the cost of building materials.

At the same time, it is important to consider the components that weren’t purchased and instead taken off the production line to use in the build. For example, two LVDT’s were donated to the project, which at $600 each brings the total cost up $1200, but at no cost to Turbocor. Other significant expenses that didn’t affect Turbocor were the stepper motor ($30), machining and storage ($720), and Dragon Board ($170) used for controlling the motor.

A detailed purchase order table can be seen in the following pages. At the very bottom of the table are the donated components of the design and build. The decision to use each and every component that was purchased, either from McMaster-Carr or direct from Mitutoyo, was determined after considering the overall purpose of the component and the required strengths.

The most significant purchase was the aluminum stock for the test fixture structure. Aluminum 6061 series was used due to its high strength and relatively low cost. During operation, the test rig and its structural components are never subjected to any significant loads. However it is important that the structure is as rigid and robust as possible to ensure the test rig maintains a solid outer structure to prevent any discrepancies in testing. At Turbocor Al 6061 is already used for a number of applications on the production line, so this decision was easy.

Another component that was strongly considered was the stainless steel guide rods. For this component, we wanted a material that wouldn't easily flex under the weight of the sensor test stage and its relevant mechanisms. The sensor test stage was machined out of 1" thick Al 6061, hence its relatively heavy weight. The stainless steel guide rails provide high strength and negligible deflection under the load of the sensor test stage.

The testing mechanism for the axial sensor or "Z" sensor was made using a 3/8" in diameter titanium rod. Titanium is used in the compressors on the production line today so the test rig utilizes titanium for the axial sensor. This brings up another significant component, the test shaft.

Originally an aluminum cylinder was purchased to use for the test shaft, however it was brought to our attention late in the design process that aluminum would not work at all in conjunction with the sensors. The most viable solution was to use a scrap compressor shaft that is outfitted with a titanium target sleeve for the sensor ring to sense during operation. This last minute change is not reflected in the total spent, but is should be noted that the aluminum shaft was included in the cost analysis.

The clamp for the LVDT's also proved to be somewhat of a hassle. Initially, specifically designed micro-head clamps were purchased direct from Mitutoyo, the manufacturer of the LVDT's. However the wrong clamps were shipped and could not be used. Instead of shipping the clamps back and ordering the correct ones, the machinist at Turbocor was able to fabricate custom clamps that fit perfectly into our application. This minor set back was taken care of quickly and did not hinder the assembly of the rig. The clamps purchased from Mitutoyo were about $30 each, two were used, and that cost is not reflected in the total expenditures, however should be noted as a possible requirement for future builds.

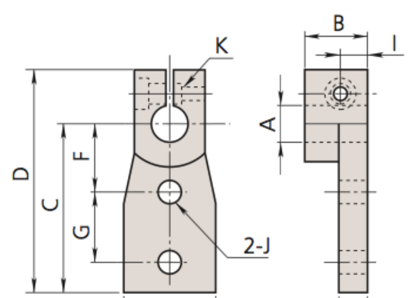


Figure 7: Micro head clamps

An important component to this design was the bearings. On the test stage are 8 linear ball bearings, $31 each. The smooth translation if the test stage is imperative considering we're working on the scale of microns, 10^{-6}, or millionths of a unit. Every error counts. Another type of bearing was used for the axial sensor mechanism, bronze sleeve bearings. There are two, each heat pressed into the bracket holding the titanium test rod.


Figure 8: Linear bearings

For locomotion, the stepper motor is coupled to the test stage using a set of custom-made couplers and a drive screw. Originally a bellows coupler, which accounts for 7 degrees of misalignment, was going to mate the motor and screw, however that did not work out. After receiving the coupler, it was brought to our attention that under lateral load, the coupler stretches and compresses like a spring. Unfortunately this characteristic was not specified in the description. This expense is included in the total ($80); however a more rigid coupler was fabricated and used in place on the final test fixture.

Figure 9: Bellows coupler

Reducing backlash was another significant focus of this design. In order to mitigate any induced backlash, 4 waveform springs, $5.50 each, were incorporated into the design. Two are mounted on the test stage, and two on the axial mechanism. The waveform springs are made specific to fit a shaft of ½" OD. It was also important that the spring rate was not too strong so test stage movement was not hindered.

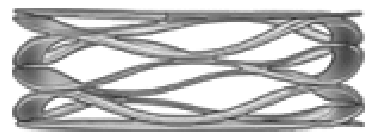


Figure 10: Waveform spring

This covers the more significant components of the test fixture. The remaining parts list reflects various screws and nuts and machining components required for assembly and power supplies. All in all, the total spent on this project build was well under the $2000 budget, coming in at just under $990.

In the case Turbocor wishes to manufacture another of these test fixtures, the total cost would include the LVDT's, stepper motor, and machining hours. This of course assuming that none of these parts are available in the warehouse for immediate use. The only component that will not be required for test stage operation at Turbocor is the Dragon Board. Turbocor has in house control capabilities that are already used for controlling these stepper motors. The total cost for manufacture from the bottom up rounds to just over $3,100. Keep in mind that over a third of this estimate is contributed by the LVDT's at $600 a piece. Below is a complete list of purchased and donated components.

Al 6061 5/8" thick 10" width 6' length	1614T973	1	$237.13	$237.13
Al 6061 1" thick 10" width 1' length	8975K103	1	$86.09	$86.09
303 SS Rod	88915K223	2	$29.34	$58.68
18-8 SS Shoulder Bolts	94731A480	2	$21.19	$42.38
Al 6061 Rod	8974K731	1	$24.62	$24.62
Bellows Shaft Coupler	59925K91	1	$80.28	$80.28
Grade 2 Titanium Rod	89145K169	1	$17.49	$17.49
Micrometer Head	8578A67	1	$72.00	$72.00
Spring Plunger	3351A13	1	$7.94	$7.94
10-24 Set Screws	92158A248	1	$4.82	$4.82
Compression Springs for Axial	9657K317	1	$8.38	$8.38

Linear Bearings	6483K53	8	$30.80	$246.40
AC to DC Converter	70235K96	1	$16.56	$16.56
Sleeve Bearings	9368T58	2	$2.03	$4.06
Springs for stage	9657K22	2	$2.84	$5.68
1/4-20 set screws	92158A417	1	$5.50	$5.50
3/8"-24 Threaded Rod (drive screw)	6516K21	1	$7.90	$7.90
#4-40 set screws	92158A119	1	$3.93	$3.93
1.5" Dowel Pins	97395A510	1	$14.56	$14.56
8-32 cap screws	91251A196	1	$12.48	$12.48
M4 x 0.7 Jam Nuts	93935A325	1	$4.69	$4.69
High load compression springs	1561T34	2	$11.07	$22.14
M3 SHCS screws	91290A124	1	$5.15	$5.15
LVDT	DONATED	2	$600.00	$1,200.00
STEPPER MOTOR	DONATED	1	$28.00	$28.00
MACHINING	DONATED	36	$20.00	$720.00
DRAGON BOARD HCS-12	DONATED	1	$170.00	$170.00
			Subtotal	$988.88
			Total	$3106.88

Table 1- Entire project budget

Safety & Environmental Concerns

1. It is imperative that none of the power supply wires are inserted into the incorrect terminals to avoid destroying the control board and to prevent risk of fire. Always check the wire connections prior to use. A detailed diagram and instructions are provided below.

2. To avoid damage to the motor driver, be sure that the motor is not exceeding 1 ampere during use.

3. To avoid pinching, keep hands and other body parts away from the test fixture while the motor is moving. The LCD display on the control board will indicate when it is safe to touch the fixture.

4. Always be sure that the system is powered down prior to leaving the test fixture unattended to avoid equipment damage and fire hazards.

Motor and Power Supply Wiring to the Control Board

Figure 11 – DragonBoard Power inputs

Motor:

1. Red wire goes to terminal "M1"
2. Grey wire goes to terminal "M2"
3. Yellow wire goes to terminal "M3"
4. Black wire goes to terminal "M4"

Power supply:

1. Positive wire goes to terminal "V_EXT"
2. Negative wire goes to terminal "GND"

Environmental concerns are not a significant issue with this design project, however it is important to touch on how disposal of various components can negatively impact the environment. Proper disposal is always an important aspect and should not be overlooked. Any batteries that become unusable should be disposed of properly following environmental protocol. The use of this test fixture will be indoors, on-site at Turbocor.

The Final Design

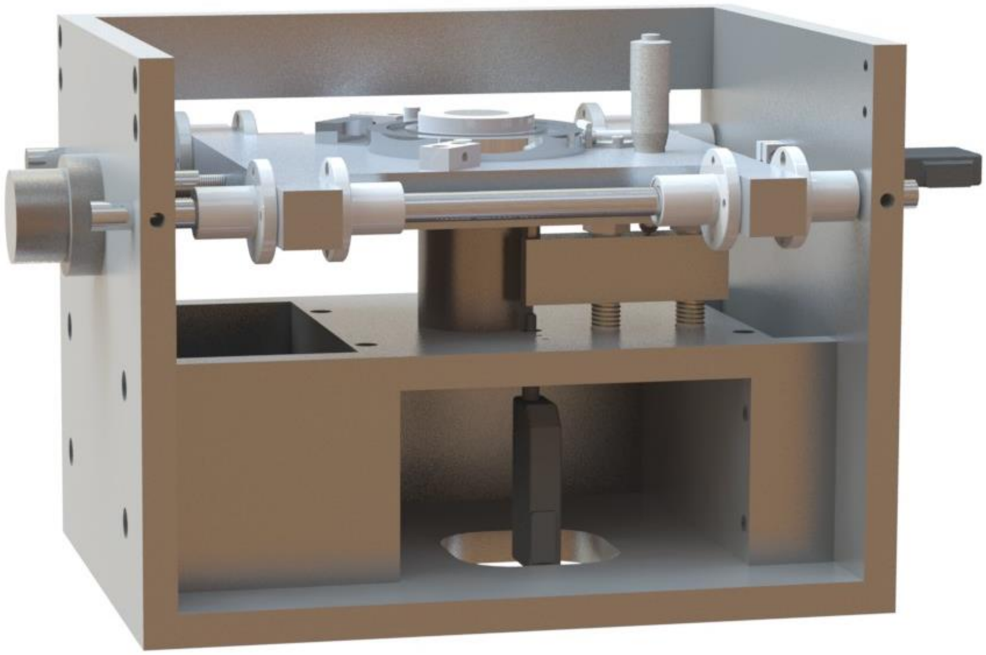


Figure 12: Final Test Stage

Upon many considerations and revision, we were able to develop the final test fixture as seen above. This design utilizes one stepper motor, one micrometer, and two LVDT's as its core mechanisms for displacements and measurements. Similar to our initial concepts the sensor ring will be place upon a platform and the platform will be displace. A mock shaft will also be used; it will be statically place in the center of the sensor rings. There are several sub-systems within the final design. These subsystems are further explained below.

Stepper Motor

First we used the stepper motor to move the sensor platform. The stepper motor is coupled to a drive screw. It is connected to the sensor platform, which have the same thread size. The motor, Portescap™, is specifically made for Danfoss Turbocor. It has 0.25^{o} per step. The screw used has a thread size of 3/8-24. The combinations of the two provide excellent motion resolution of 0.735 µm per step. For 400 µm of lateral displacement, the motor would need to rotate 136^{o}. There are several advantages to this mechanism. One, it has excellent repeatability, almost always displace to the exact positions as measure by the LVDT. It also allow for automated operation because the stepper motor is controlled using a DragonBoard HCS-12. Programming the board with a computer using C code and link it to the board via USB connector. Once the code is on the board, it will stay there until another code is loaded. There were not any disadvantages to this method that we have encounter. Maintenance includes replacing the drive screw and the setscrew with is simple and inexpensive.

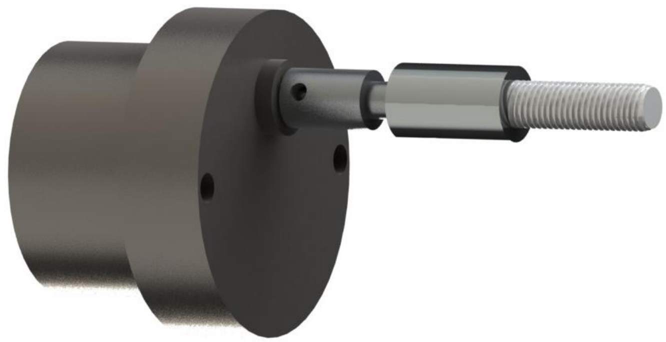


Figure 13: Stepper motor coupled to drive screw

Z-Sensor Mechanism

The z-sensor is tested by the platform depicted in the figure below. We are using a micrometer to displace a rod that is flushed with the z-sensor. The micrometer is mounted to the sensor table; the end of the micrometer has an extension. The extension is machine to have a circular end to reduce the surface contact, consequently to reduce the friction force it will cause while testing the X, and Y sensors. A major setback to this system is being manually operated. There are friction that can cause the X, and Y sensor reading to be inconsistent. While testing the Z-sensor, the X and Y sensor would have to be delay. The micrometer must be returned to the 0 position to allow smooth movement of the platform in order to reduce errors.

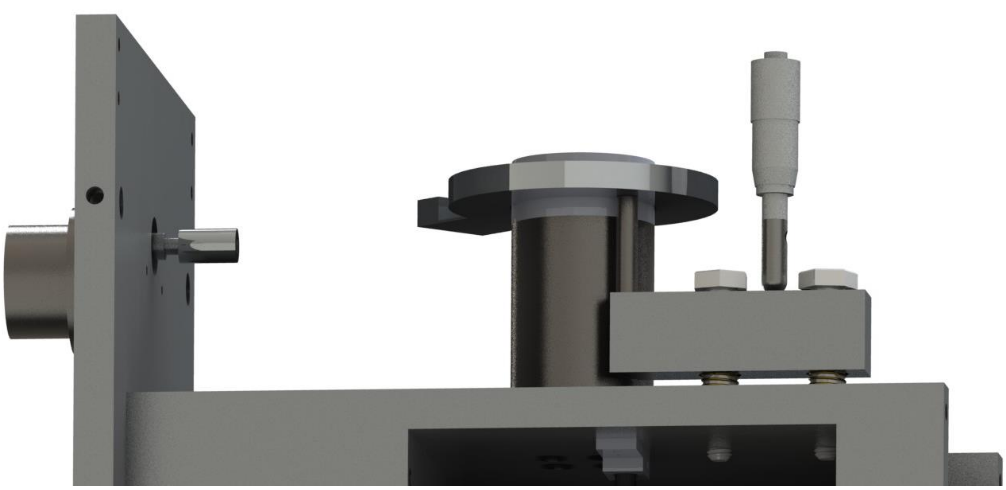


Figure 14: Z-Platform

Linear Bearings

For smooth linear displacement of the sensor platform, we are using a steel rod, which was machined to be smooth and linear. The bearings are excellent for linearity as well as being able to handle the loads of the aluminum table. This was one of the crucial pieces of the fixture that needed much attention while assembly, as will be mention later. The advantage of these bearings is the way they are mounted. The bearings can be bolted on which allows rooms for alignment. While installing the bolts are loosely screw into the platform. After we have aligned the steel rods into the sidewalls, the bolts are tightened. This made it so the table will be align and it does not buck during operations.

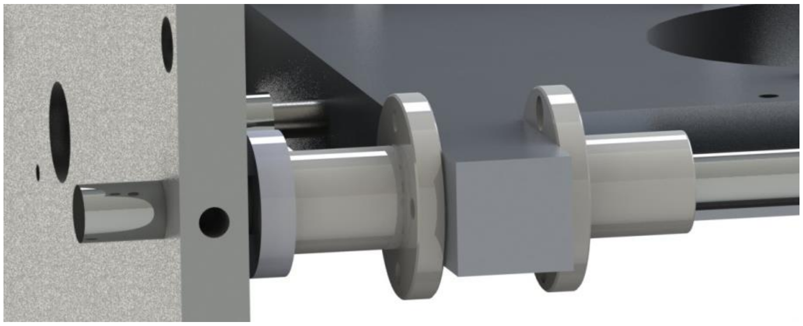


Figure 15: Linear bearings

Sensor Ring Mount

In order for the sensor rings to be correctly in the center of all parts, mounting it requires high precision. We are using two steel dowels; combine with a spring plunger, the sensor ring can be snapped into place. In order to snap the ring into position we use two simple screw stops. Because there is a known voltage when the sensor and the shaft are 200µm away, using this voltage we can adjust the screw and sensor until it is in center position. It is not difficult for maintenance of this mechanism; the steel dowels and the spring plunger can be replaced with ease. The disadvantage of using this method is the manual rotation of the sensor ring 90^o from its initial position to test the second sensor.

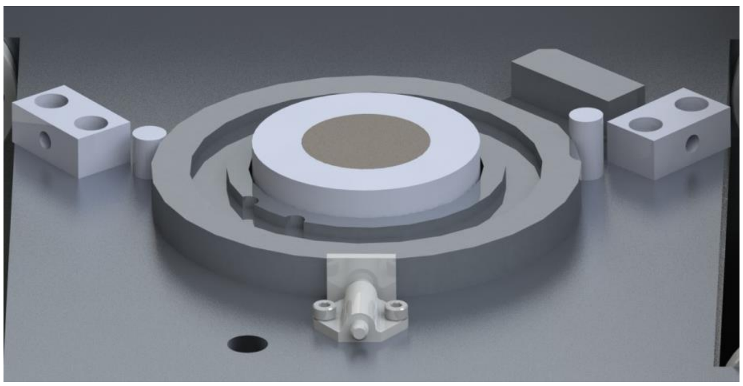


Figure 16: Mounted Sensor Ring

Below we can see a top view of final design. The stepper motor coupled to the drive screw is connected to the table of the left. On the right we can see the LVDT directly centered of the table and in line with the drive screw, which allowed for high precision of measurements. The steel guides are connected to the sensor platform with linear bearings on both sides, allowing smooth and high precision movements. On the platform there are mount blocks, sensor ring, shaft, steel dowels, plunger and micrometer.

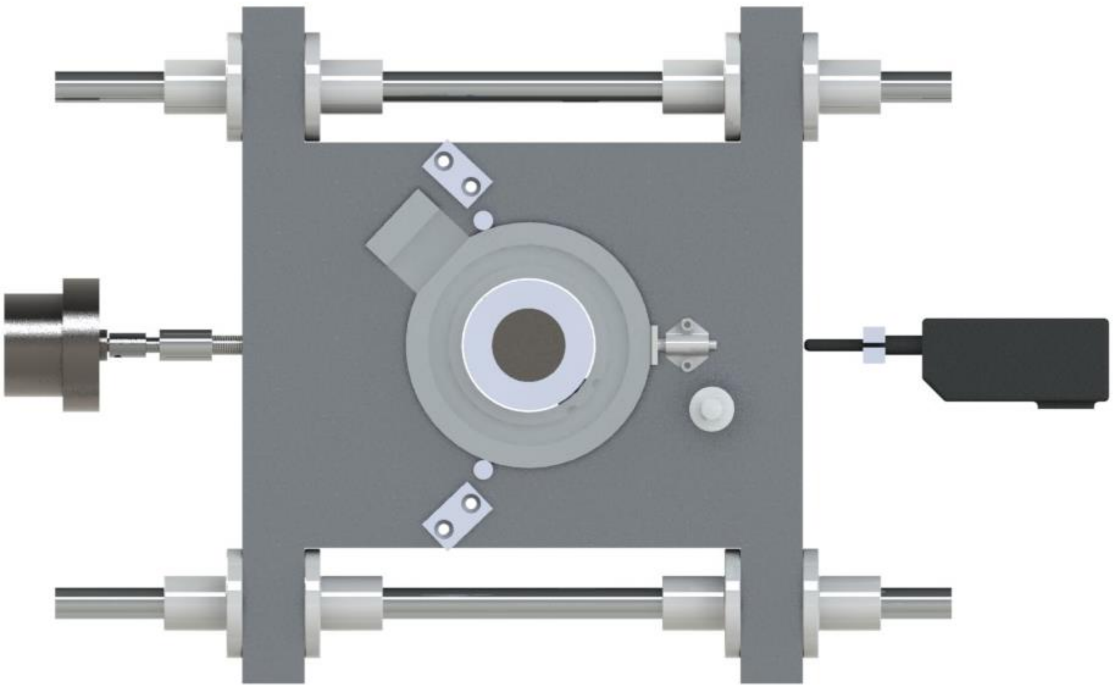


Figure 17: Top view of Test Stage

Results

The sensor ring test was performed using a sensor ring that had passed previous tests with their current test fixture. This same sensor ring had also been used successfully in one of their compressors. The sensitivity calculated using our test fixture fell well within the provided acceptable range of sensitivities provided by Danfoss Turbocor. This test was repeated for a sensor ring that was a known failure. Our test fixture also indicated a bad sensor ring. After this, multiple other sensor rings were tested with results that favored our test fixture.

It should be noted that there was no absolute way to confirm that the test fixture provided better tests than the previous method for testing sensor rings. It can only be assumed that the results acquired were favorable because the displacements being used for calculations were measured with reliable equipment. The previous sensor ring test did not have any independent displacement measuring system to utilize so it is possible that our test fixture is providing more reliable data than the previous test fixture. However, there is no way to know if the results acquired are completely exact since we are at the mercy of using the most reliable equipment available to us.

The sensor ring test fixture designed and constructed in this project was designed to be extremely rugged to withstand the harsh manufacturing environment. The heavy design and solid materials used in construction provide an extremely sturdy fixture. Furthermore, all electronics components were surrounded by a hefty, clear Lexan box. However, due to time constraints, long term tests of this prototype were not performed.

Future Recommendations

Overall the team was able to achieve all the goals that were set forth. This does not necessarily mean that no further improvements can be made to the test rig. In fact some recommendations can be made to help aid any additional interest in the project. The recommendations can be broken down into three categories: increase the automation, decrease the difficultly of calibration, and effects of long-term usage.

As of right now the test rig only has automation in the X & Y lateral directions, whereas the in the Z direction a hand-turned micrometer head is used to displace the distance. Using the same method as for the planar motion, a stepper motor can be mounted with another worm-gear screw in order to drive the Z platform up and down. This allows for accurate step-by-step movements that are reliable and repeatable. Furthermore, it has been noted that the sensor ring is difficult to take on and off the test rig. A solution to this problem is the replace the current spring-plunger system that holds the sensor ring in place with one that does not utilize as much force. The spring applies so much pressure that it requires two hands in order to rotate the ring a full 90°. Another solution that uses the current plunger is to build a lever that attaches to the plunger so that the leverage gained allows for easier retraction of the plunger. Integrating automation would be use another motor that is used to pull the plunger back when the system is finished testing a ring, allowing the worker to easily remove and place the sensor rings.

A problem that has recently occurred is calibration of the sensor table once the transfer ring has been taken off. A code has been written so that the table can be moved in increments of 1 micrometer till it has reached the center position, using the LVDTs as a reference point. This method is cumbersome and takes quite a bit of time to accurately get to the center position. Modifications can be made to the code so that it can take feedback from the LVDTs and determine the number of steps required for the stepper motor to center itself. Due to the time constraints of the project the team was unable to achieve this. Alternatively, if the sensor table has to be centered without the use of the stepper motor, it is possible to do it by placing the transfer ring back on. This requires that the motor be unmounted and unscrewed from the sensor table though. The advantage of this is that the absolute center of the table is found, but it takes more time to disassemble the motor from the rig. A redesign of how the motor is mounted onto the test rig may rectify any issues with centering the table with the transfer ring.

Finally, the system was not able to undergo life cycle testing. The test rig is manufactured out of sturdy, robust material so that the material should not fail or be under any stresses. The main concern is the production life of the test rig because it will be undergoing constant use. This poses a concern for the life cycle because of the small delicate parts associated with the motor and z-mechanism. The setscrews used in the coupling of the motor and drive screw and the setscrews used in holding the titanium rod in the z-platform are small and prone to stripping or breaking, this is pertinent because it affects the movement of the table which may cause it to be misaligned. A recommendation for improvements would be to increase the side of the shaft coupler so that a larger setscrew can be used. As for the Z-platform larger holes can be drilled and tapped to accommodate for the larger setscrew.

Gantt chart

	Week of Feb. 24	Week of Mar. 3	Week of Mar. 10	Week of Mar. 17	Week of Mar. 24	Week of Mar. 31	Week of Apr. 7	Week of Apr. 14
Drawings								
Tolerancing								
Stepper Motor Program								
LVDT Testing								
Machining								
Assembly								
Testing								

The gannt chart shows that there were a few delays over the duration of the senior design project. Working with the machinist at Turbocor drawings took longer than expected to meet their expectations. Because of this it halted the machining and assembly of the test rig. Another factor that caused delays was the acquiring of the wrong bracket that is used for the mounting of the LVDTs to the test rig. This problem took time for us to design and machine our own brackets. The entire test rig was not abled to be fully assembled until the last week of our senior design class. While only having a short limited amount of time to test the test fixture, we were still able to gather test results and make a conclusion based on those results.

Appendix I – Initial and Preliminary Design

Initial Design Concept

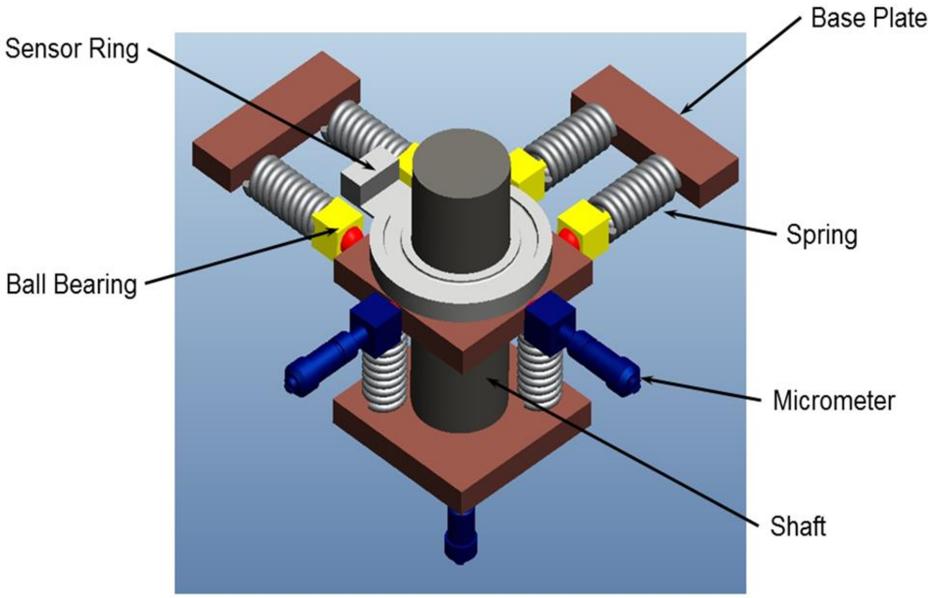


Figure A1 – CAD image of initial design concept

At first glance, the testing stage looked promising. Uniaxial displacement was possible using the micrometer heads for locomotion and ball bearings to limit the displacement to the axis through the micrometer. The third direction would be tested using the assembly on the bottom-side of the stage. The total displacement would never exceed 400 microns (about 4 average human hairs). The displacement is not an issue however with the ball bearings on the sides and bottom of the test stage. When one direction of testing is engaged, the roller bearings let the stage roll effortlessly in the desired direction.

What appealed most about this design was the fact that it does create three measurable positions of displacement, added that all are directionally independent of each other. Also appealing, was the likelihood of a relatively low cost of manufacture. This however is true only because the entire test fixture would have to be machined by hand. Turbocor has imposed a minimum accuracy of 1-3 micrometers, which without expensive machinery, is extremely difficult to accomplish. That being said, the low cost of manufacturing proves to be a downfall of this design. There is no need to reinvent the wheel when there are commercially available linear stages that are more than capable of achieving this magnitude of accuracy. Also adding to the ineffectiveness of this design is that there no solution for backlash that may occur during testing, which is the main reason Turbocor has proposed this design project in the first place. Several changes were implemented to correct these issues.

Corrected Design Concept

During the design phase of the initial design concept, it was clear that a solution was needed to resolve the issue of inaccuracy and backlash. The most apparent cause of the possible backlash and inaccuracy was the construction of the testing stage and its components. Machining these parts to be accurate to 1 micron would be too difficult and time consuming. Therefore the design took a turn towards commercially available linear stages. The stage of interest was the New Focus Gothic-Arch 65-mm Platform Translation Stage, part number 9063-XYZ.

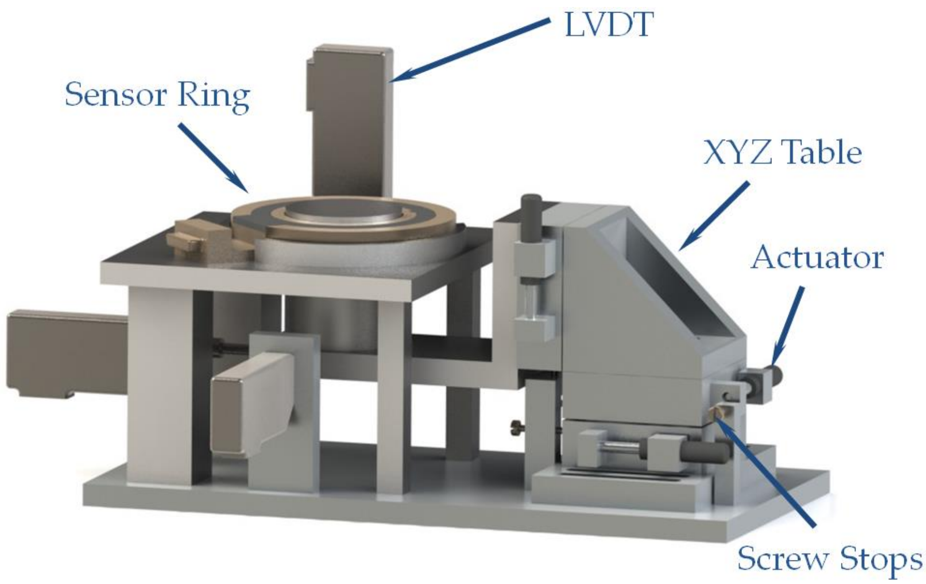


Figure A2 - Corrected linear test fixture CAD

This corrected design features the compounded product from New Focus, which consists of three uniaxial stages mounted on top of one another to create displacement in three directions. Micrometer heads handle the actuation once again, but mechanical stop are shown, and their role was to limit the movement of each platform to the maximum of 400 micrometers. Mounted to the vertical linear stage is the testing fixture that consists of the mock shaft and holding stage for placement of the sensor ring. The vertical stage is mounted using an attachment shown in the image, which shifts directly with the actuation of the micrometer heads. The testing fixture comes off the attached vertical stage and holds the mock shaft. The mock shaft is moved inside the sensor ring to create uniaxial displacement.

The three-stage fixture is capable of testing each axis of sensors independently because of its ability to return to the starting position via the spring-loaded platforms. Also seen in the image are LVDT's. This is the solution to the backlash that may occur during testing. When the testing stage is displaced, the LVDT's will very accurately track every step of movement that occurs. The resolution of the LVDT's donated by Turbocor is 0.5 microns. This is more than enough to meet Turbocor's needs of 1-3 microns. On the under-side, an additional piece does the testing for the axial movement sensor.

The accuracy issue is resolved with the commercial linear stage with this corrected design, which leads to the benefits of the design as a whole. Precision in testing the sensor ring is imperative, and this design has the capability of being extremely precise. Linear displacement is once again uniaxial, and any backlash is immediately observed by the LVDT's and errors in measurement are accounted for. However, significant drawbacks still exist in this design. The commercial linear stage brings our estimated cost upwards of $2000, not practical if multiple fixtures are to be built. Also hindering the development of this test fixture design is the fact that all of the testing is still completely manual. Although the commercial linear stage is extremely accurate, automating it is close to impossible without investing in $900 Pico motors for each movement axis.

Design Concept 3

In this concept of the design process the most important task was to seek alternate means of accurately and precisely displacing the testing stage a distance equal to the thickness of 4 human hairs lying next to each other. The solution we discovered was spring steel.

In an effort to drastically reduce the cost of manufacturing the testing fixture, the commercial linear stage needed to be left behind. A completely redesigned testing fixture and sensor ring stage were developed to accompany the new means of movement control. Also with the conversion from commercial linear stage to spring steel test stage, the need for three LVDT's no longer exists. Thusly reducing the cost.

Design concept 3, without commercial stage, is now capable of being fully automated. To do this, air cylinder pistons are to be the primary means of actuation. Again there will be mechanical stops to limit the displacement to the desired amount. The air pistons must be able to provide enough force to overcome the movement restricting force the spring steel has on the test stage. Several test simulations were conducted using Solid Works software to determine the necessary force requirement.

The air pistons provide actuation for testing the sensors in the radial X and Y directions. However, the axial sensor in the Z direction must remain manual. The fixture utilizes a separate mechanism to perform this test. The mechanism is displaced using a micrometer. No LVDT is needed due to the fact the displacement is directly through the micrometer head.

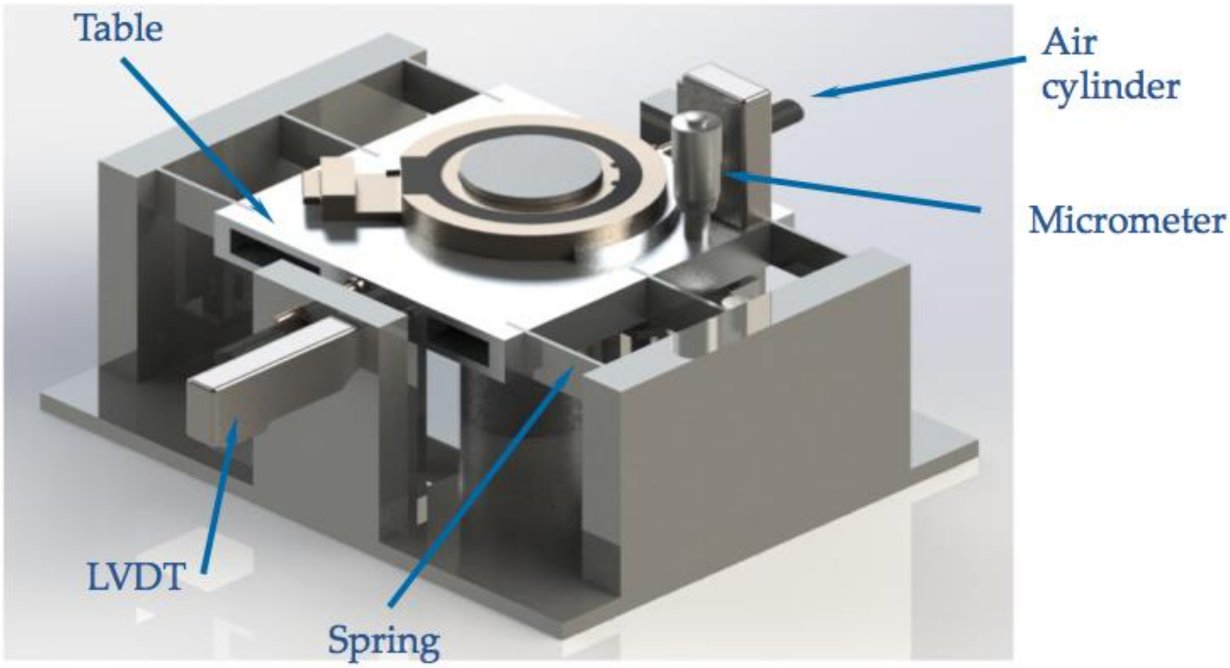
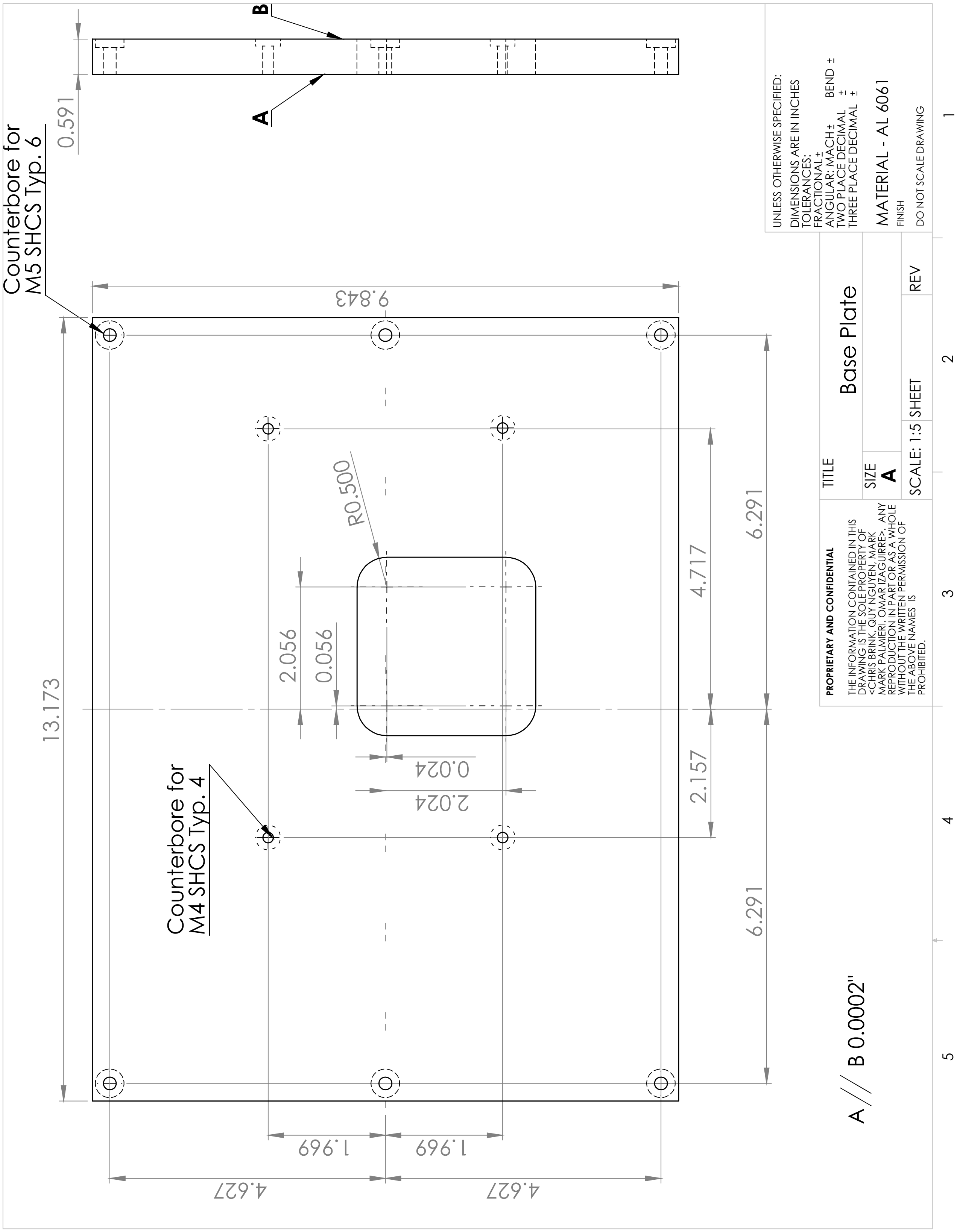


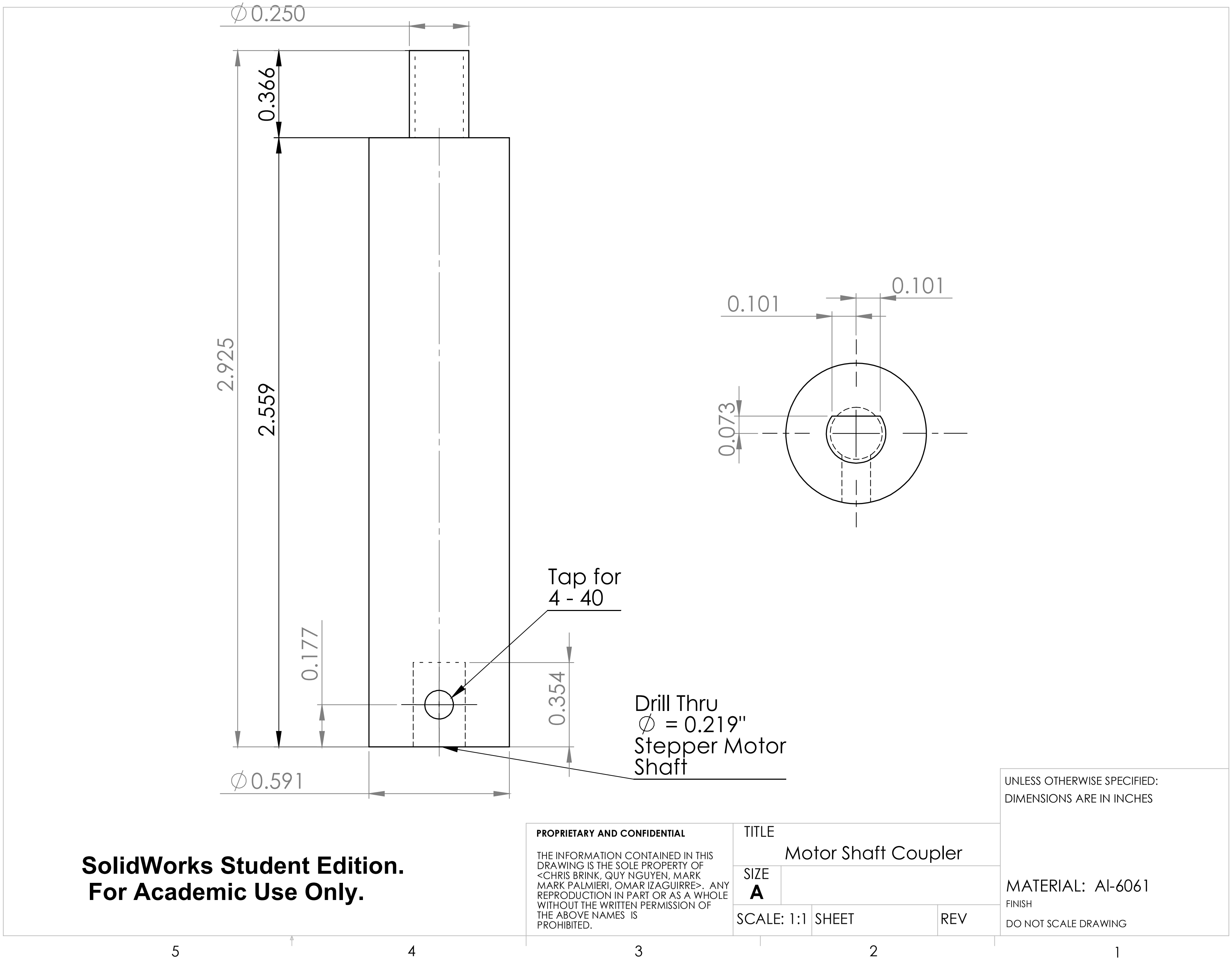
Figure A3 – Fall Final Test Fixture Design

This test fixture design boasts many improvements over the previous designs. The manufacturing cost is extensively reduced without the commercial linear stage. Also reducing the overall cost is the need for only two LVDT's. Turbocor has generously donated two already so there is no longer a need for a third $600 LVDT. Independent linear displacement is also easily executed with this fixture design utilizing the spring steel for movement restriction. And finally, the testing time is greatly reduced by performing the test using the two air cylinder pistons.

However, although this design has many improvements over the previous two it does not show strong promise of the precision and reliability that is required for this test fixture. Simply relying on spring steel to return the stage to the centered position is not sufficient enough. This is when the idea of using a stepper motor first came to thought. This also pushed the design towards the implementation of linear guide rods installed parallel to the axis of motion, thus easing the design and analysis of the systems' accuracy and precision. Because of these reasons the final design was born, and successfully delivered the prescribed motion while maintaining the micron accuracy needed.

Appendix II- Component Drawings





∅0.250
0.366
2.925
2.559
0.177
0.354
∅0.591
Tap for 4 - 40
Drill Thru ∅ = 0.219" Stepper Motor Shaft
0.101
0.101
0.073
SolidWorks Student Edition. For Academic Use Only.
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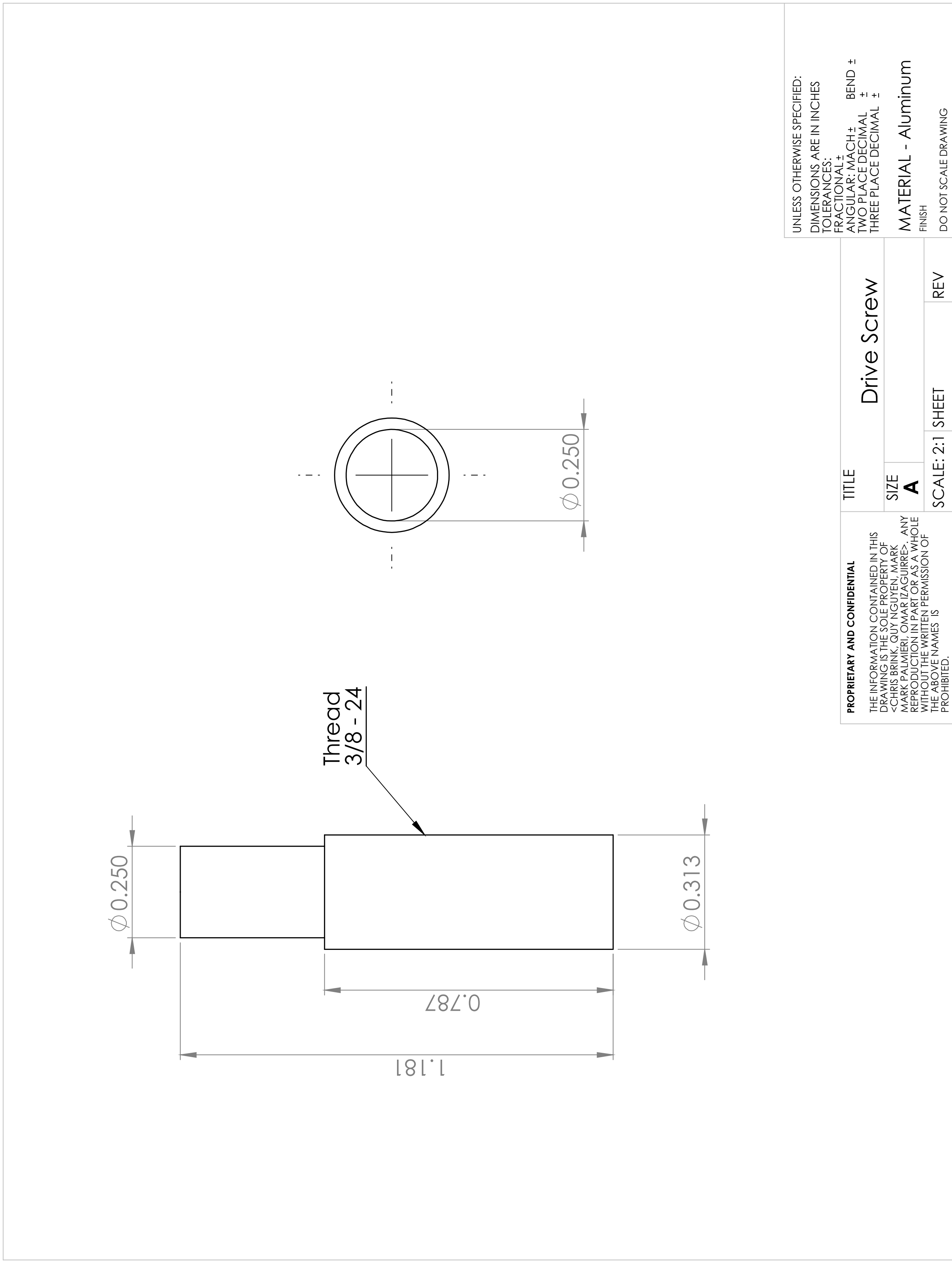
TITLE
Motor Shaft Coupler
SIZE
A
SCALE: 1:1
SHEET
REV
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
MATERIAL: Al-6061
FINISH
DO NOT SCALE DRAWING
5
4
3
2
1


Thread
3/8 - 24
Ø0.250
Ø0.313
0.787
1.181
Ø0.250
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - Aluminum
FINISH
DO NOT SCALE DRAWING
TITLE
Drive Screw
SIZE
A
SCALE: 2:1
SHEET
REV
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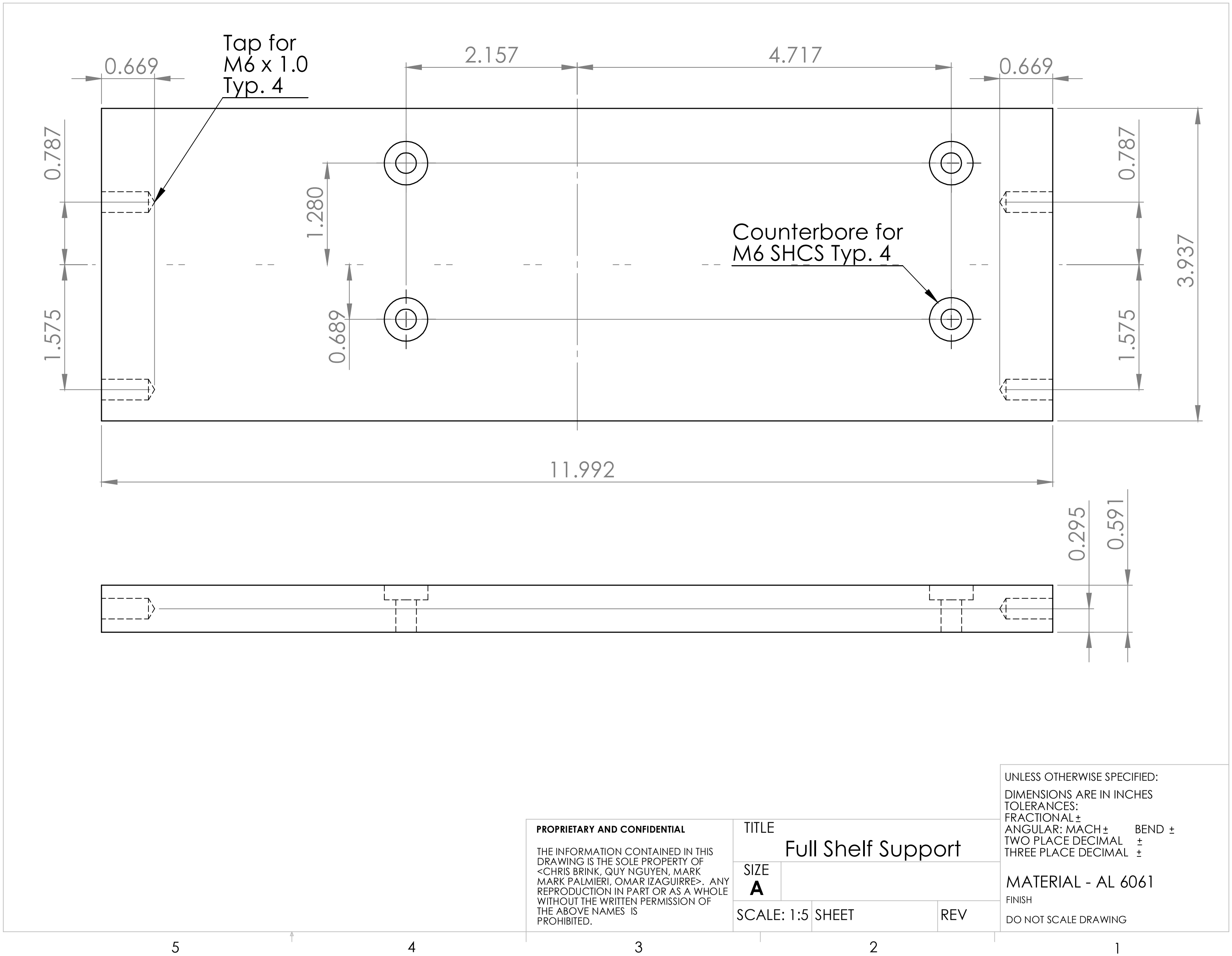
1
2
3
4
5


Tap for
M6 x 1.0
Typ. 4
0.669
2.157
4.717
0.669
0.787
1.575
1.280
0.689
Counterbore for
M6 SHCS Typ. 4
0.787
1.575
3.937
11.992
0.295
0.591
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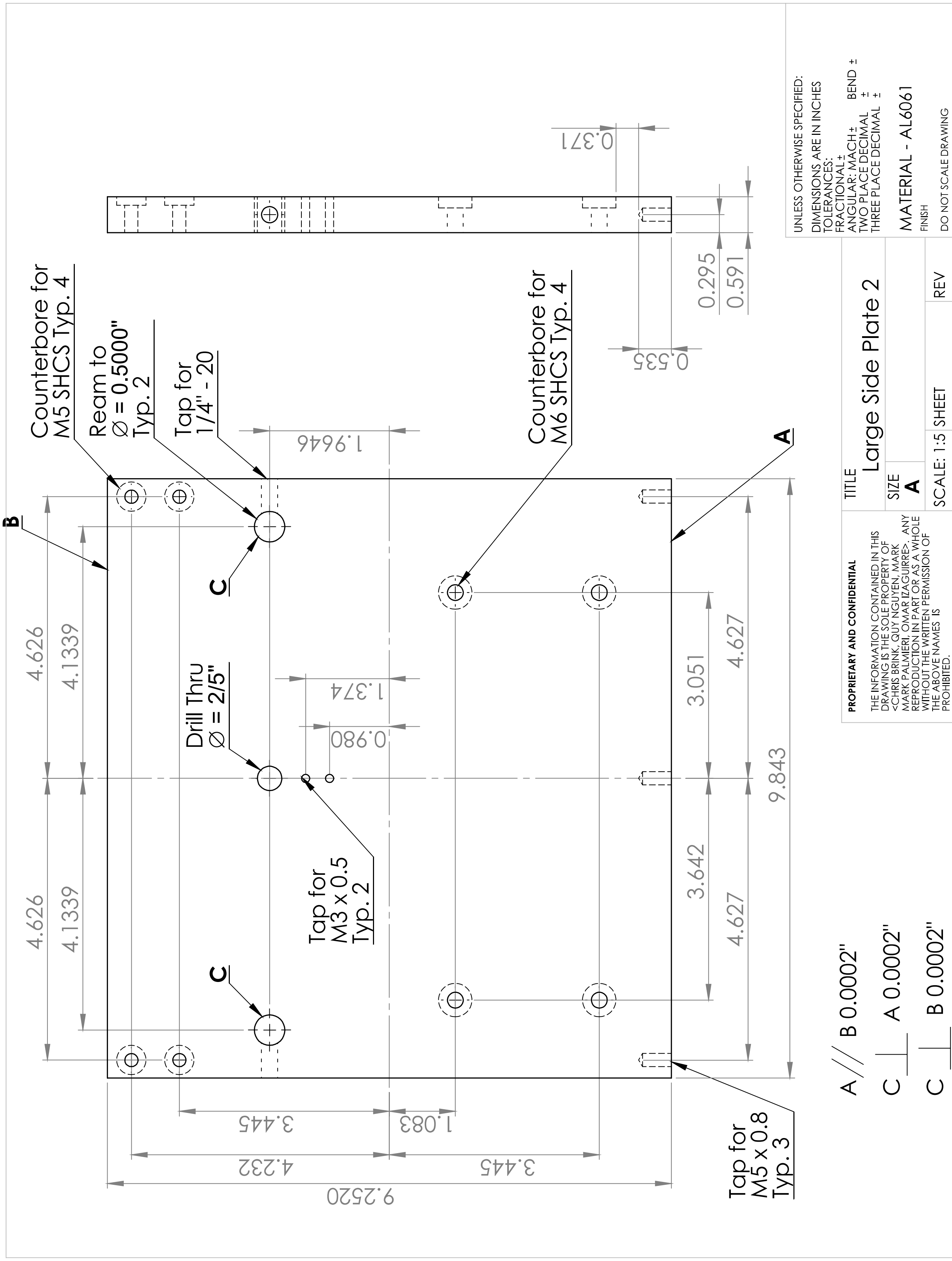
TITLE
Full Shelf Support
SIZE
A
SCALE: 1:5
SHEET
REV
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL 6061
FINISH
DO NOT SCALE DRAWING
5
4
3
2
1



Counterbore for M5 SHCS Typ. 4
Ream to ∅ = 0.5000" Typ. 2
Tap for 1/4" - 20
Counterbore for M6 SHCS Typ. 4
Drill Thru ∅ = 2/5"
Tap for M3 x 0.5 Typ. 2
Tap for M5 x 0.8 Typ. 3
A
B
C
C
A // B 0.0002"
C ⊥ A 0.0002"
C ⊥ B 0.0002"
0.371
0.295
0.591
0.535
1.9646
1.374
0.980
4.626
4.1339
4.626
4.1339
3.051
4.627
3.642
4.627
9.843
3.445
1.083
4.232
3.445
9.2520
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL6061
FINISH
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
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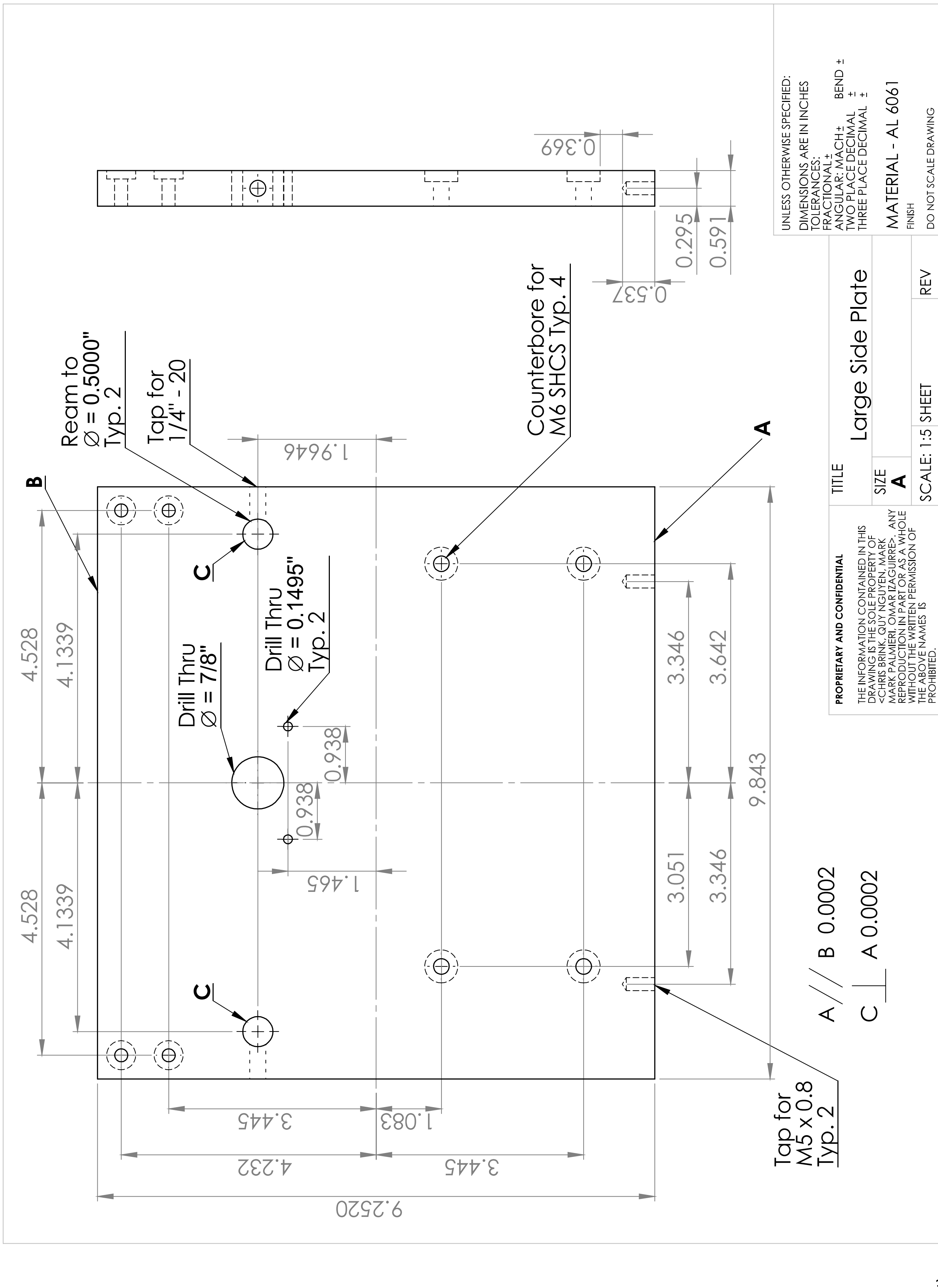
TITLE
Large Side Plate 2
SIZE
A
REV
SCALE: 1:5 SHEET
1
2
3
4
5


Large Side Plate
TITLE
SIZE A
SCALE: 1:5 SHEET
REV
MATERIAL - AL 6061
FINISH
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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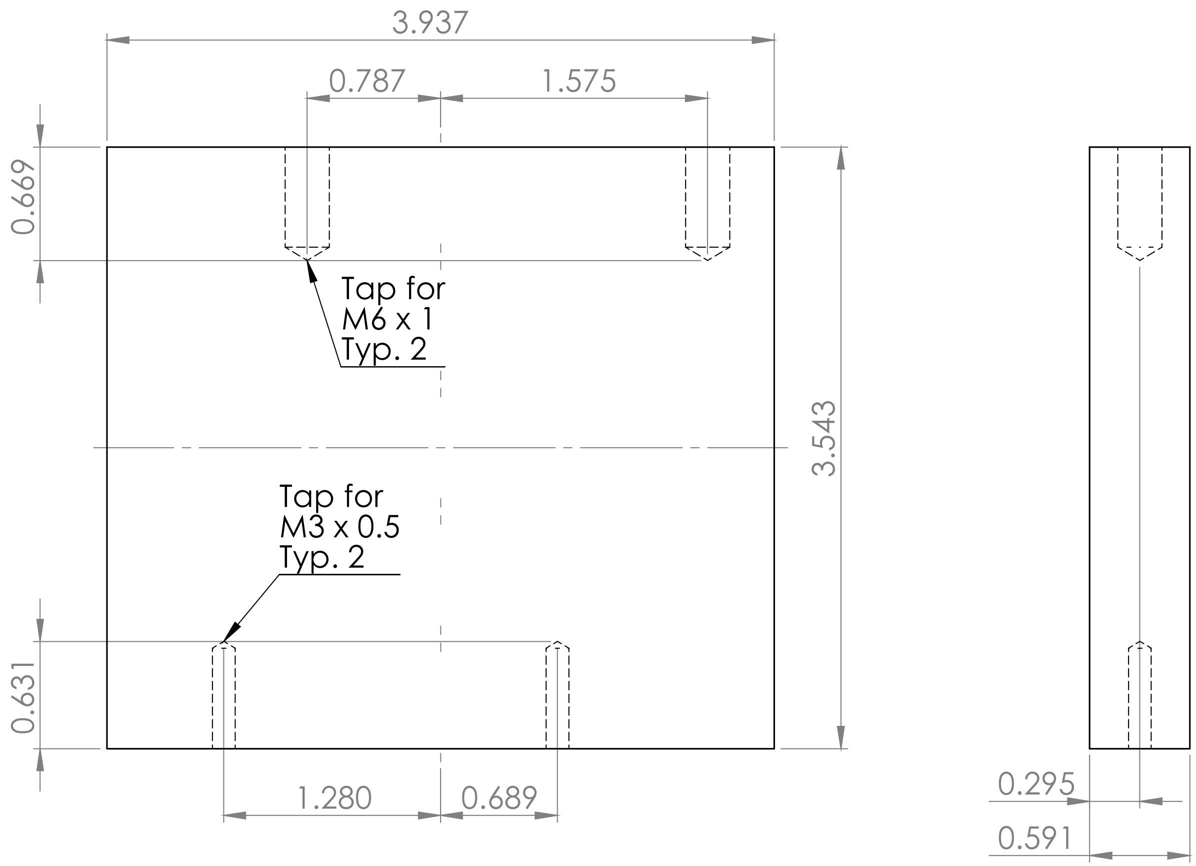
Ream to ∅ = 0.5000" Typ. 2
Tap for 1/4" - 20
Counterbore for M6 SHCS Typ. 4
Drill Thru ∅ = 7/8"
Drill Thru ∅ = 0.1495" Typ. 2
Tap for M5 x 0.8 Typ. 2
A // B 0.0002
C ⊥ A 0.0002
A
B
C
C
4.528
4.1339
4.528
4.1339
1.9646
0.938
0.938
1.465
3.346
3.642
3.051
3.346
9.843
3.445
1.083
4.232
3.445
9.2520
0.369
0.537
0.295
0.591
1
2
3
4
5



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TITLE
Left Side Brace

SIZE A

SCALE: 1:2 SHEET REV

UNLESS OTHERWISE SPECIFIED:

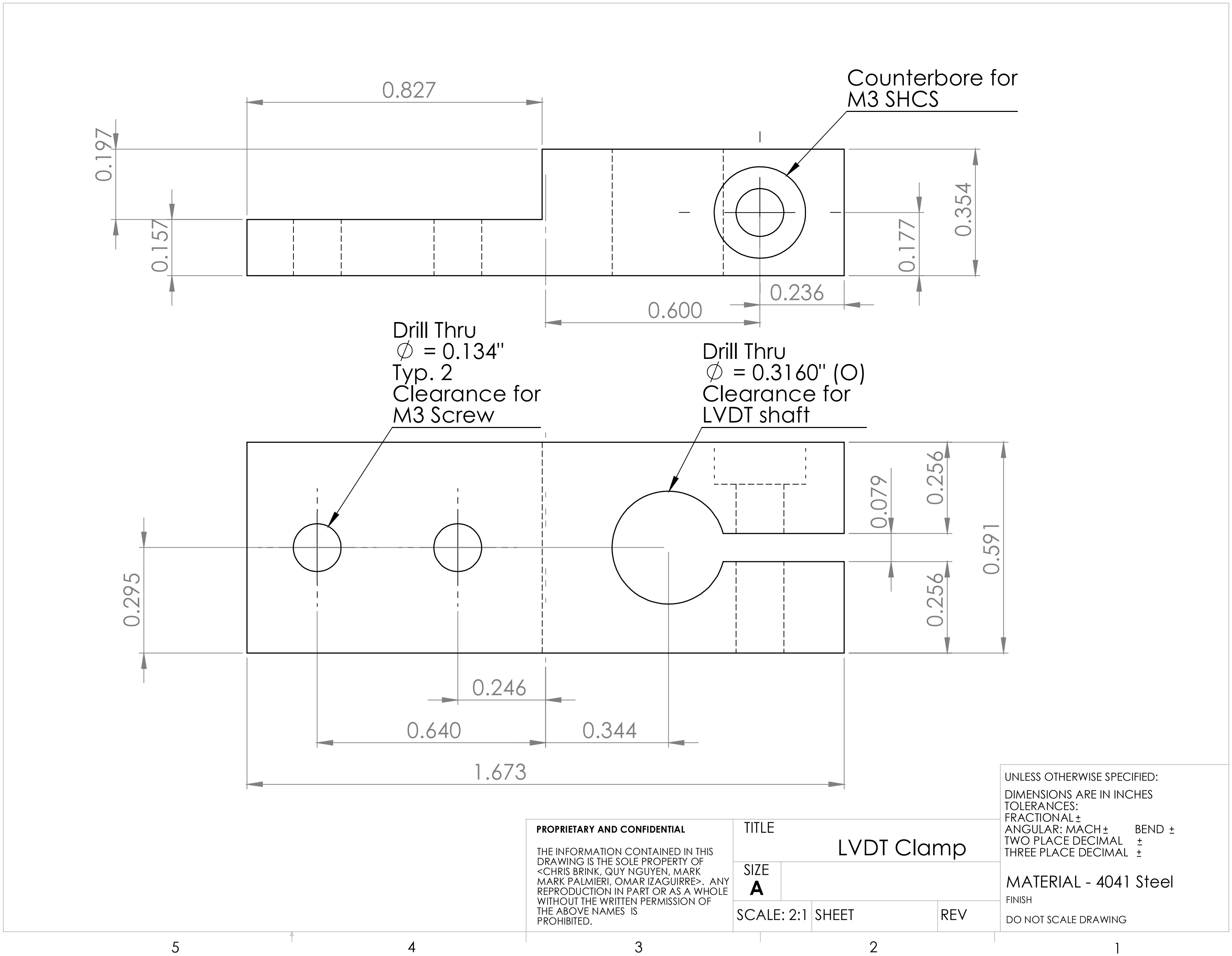
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL - AL 6061

FINISH

DO NOT SCALE DRAWING

5 4 3 2 1



Counterbore for M3 SHCS
0.827
0.197
0.157
0.177
0.354
0.236
0.600
Drill Thru ∅ = 0.134" Typ. 2 Clearance for M3 Screw
Drill Thru ∅ = 0.3160" (O) Clearance for LVDT shaft
0.079
0.256
0.256
0.591
0.295
0.246
0.640
0.344
1.673
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TITLE
LVDT Clamp
SIZE
A
SCALE: 2:1
SHEET
REV
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - 4041 Steel
FINISH
DO NOT SCALE DRAWING
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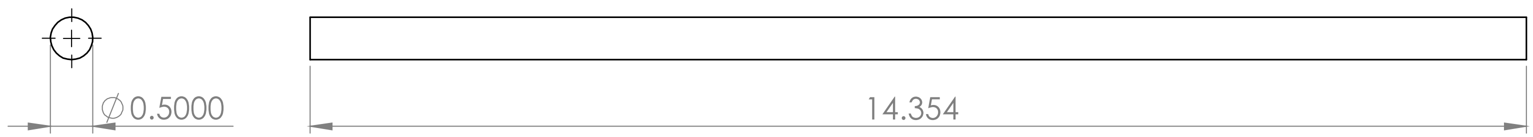
4
3
2
1



Quantity: 2

PROPRIETARY AND CONFIDENTIAL

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TITLE
Guide Rods

SIZE
A

SCALE: 1:5 SHEET

REV

UNLESS OTHERWISE SPECIFIED:

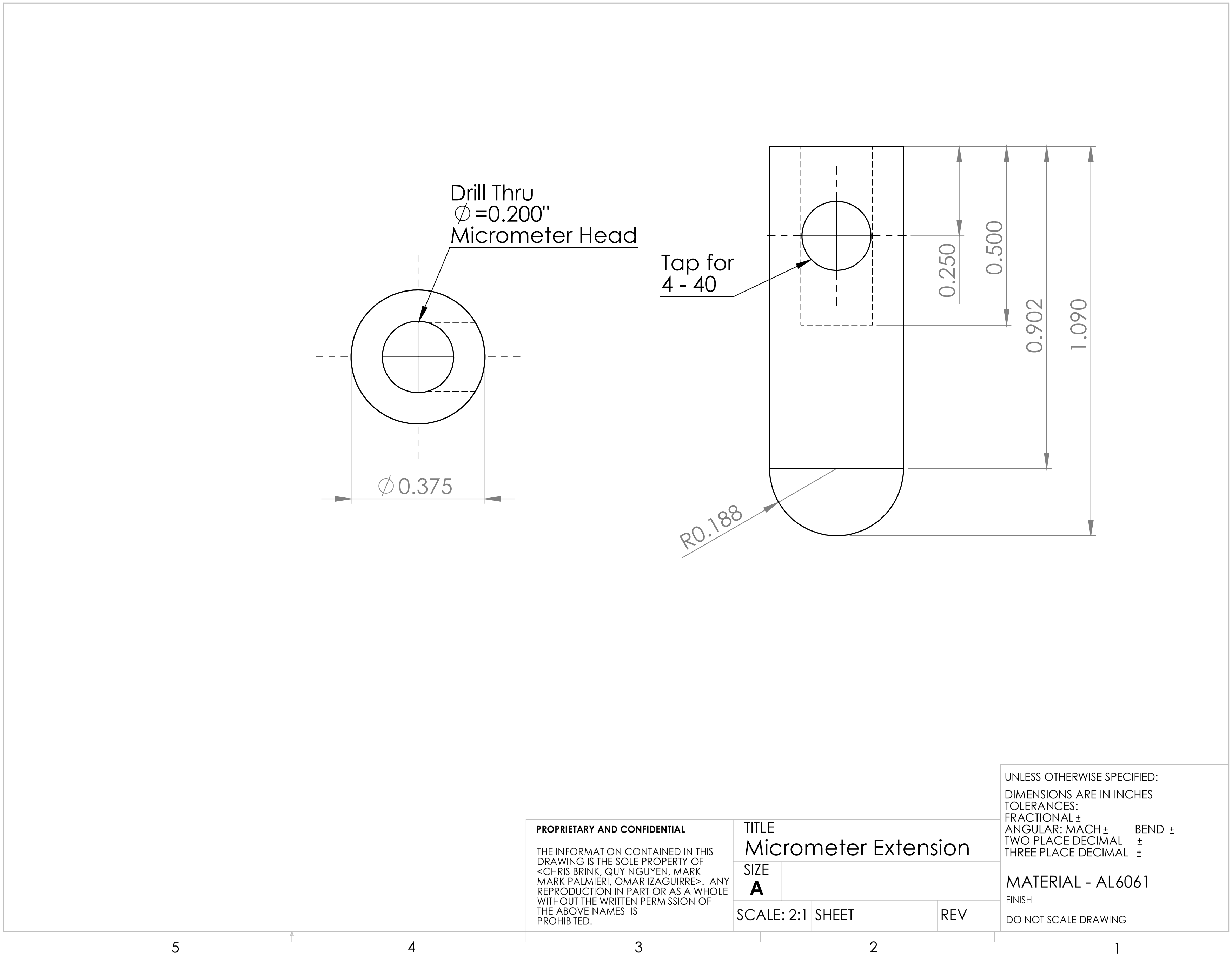
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL - SS303

FINISH

DO NOT SCALE DRAWING

5 4 3 2 1


Drill Thru
∅ =0.200"
Micrometer Head
∅0.375
Tap for
4 - 40
0.250
0.500
0.902
1.090
R0.188
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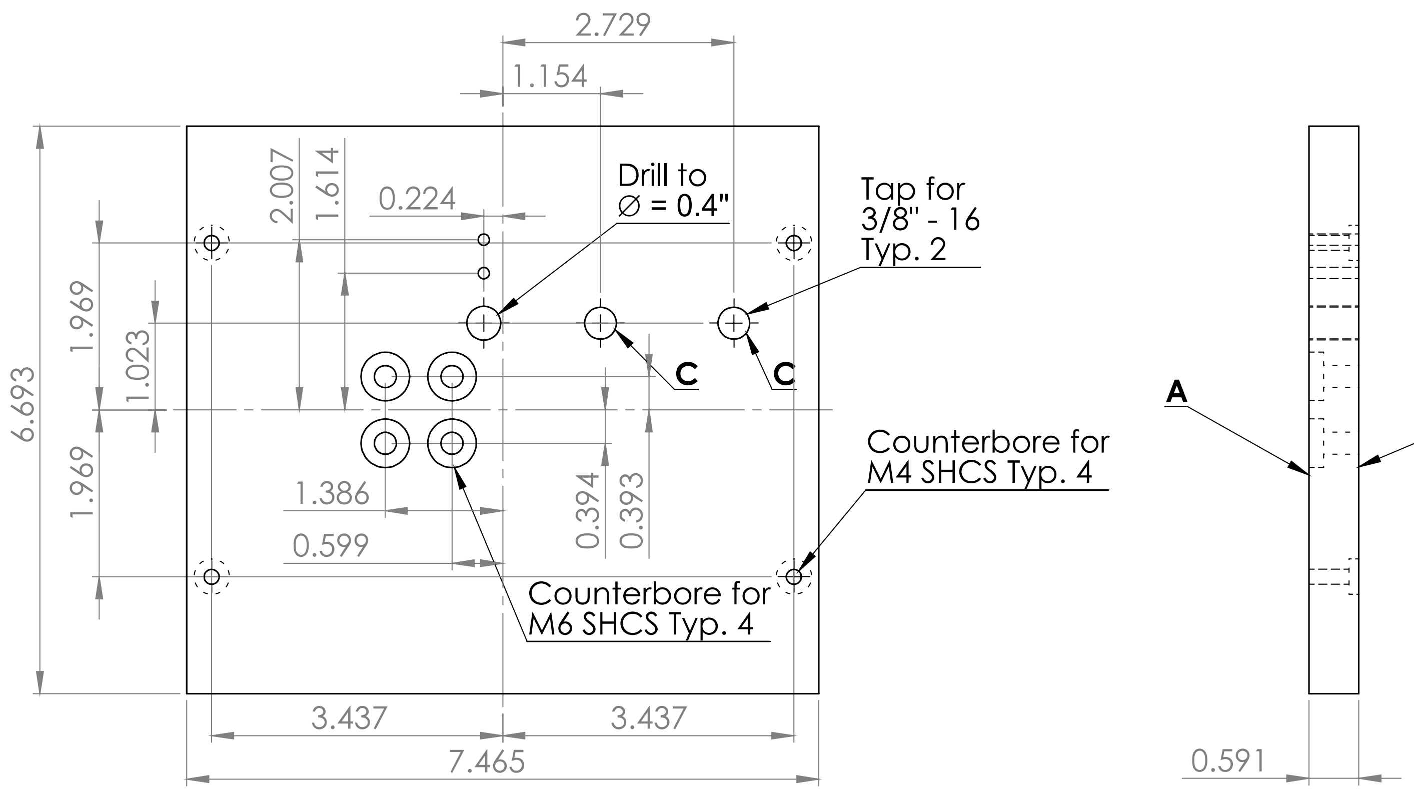
TITLE
Micrometer Extension
SIZE
A
SCALE: 2:1
SHEET
REV
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL6061
FINISH
DO NOT SCALE DRAWING
5
4
3
2
1



A // B 0.0002"

A ⊥ C 0.0002"

B ⊥ C 0.0002"

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TITLE	Middle Plate
SIZE	**A**
SCALE: 1:5	SHEET
REV	

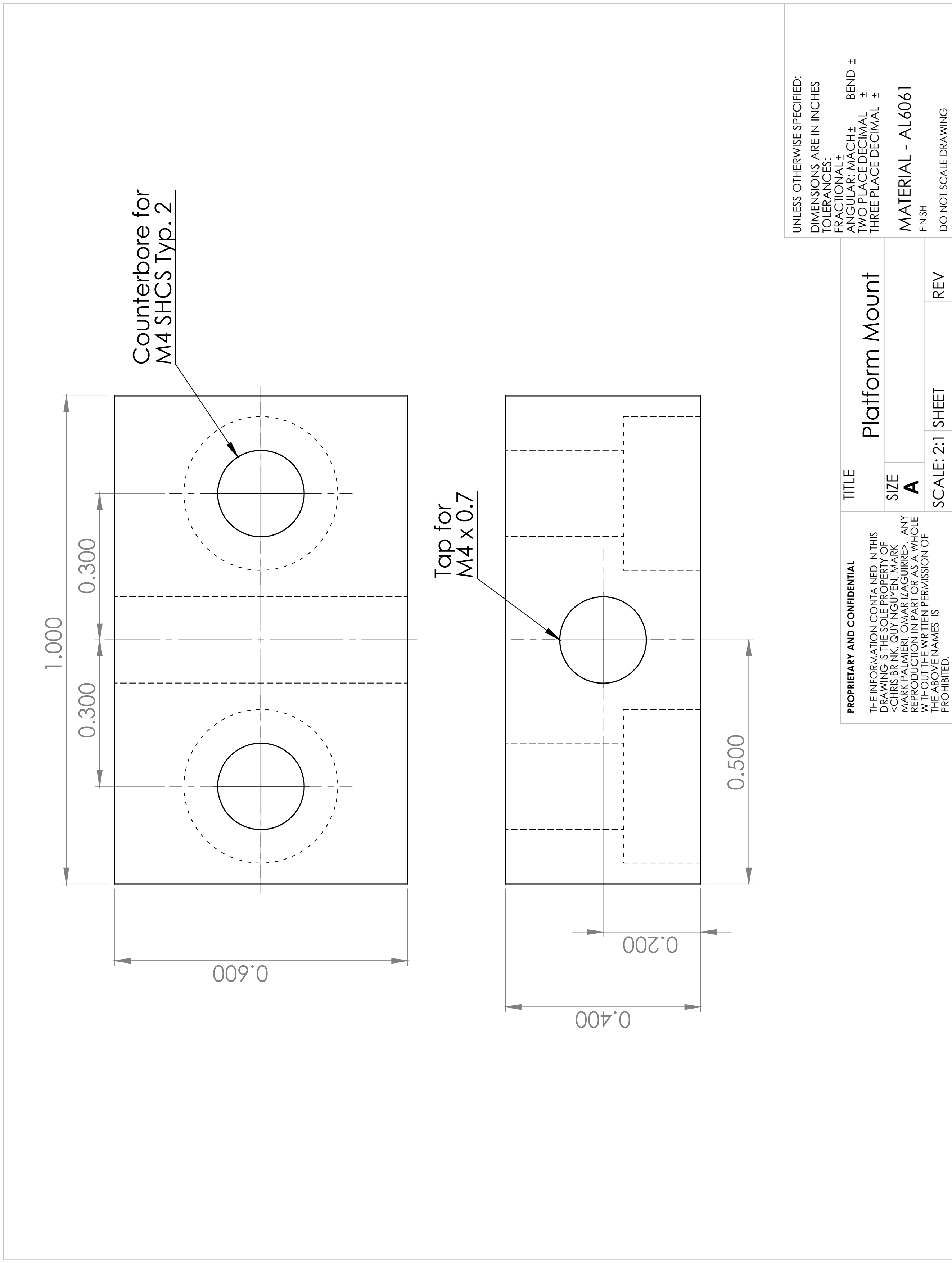
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL - AL6061

FINISH

DO NOT SCALE DRAWING

5 4 3 2 1


Counterbore for
M4 SHCS Typ. 2
Tap for
M4 x 0.7
1.000
0.300
0.300
0.500
0.600
0.200
0.400
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL6061
FINISH
DO NOT SCALE DRAWING
TITLE
Platform Mount
SIZE
A
SCALE: 2:1
SHEET
REV
PROPRIETARY AND CONFIDENTIAL
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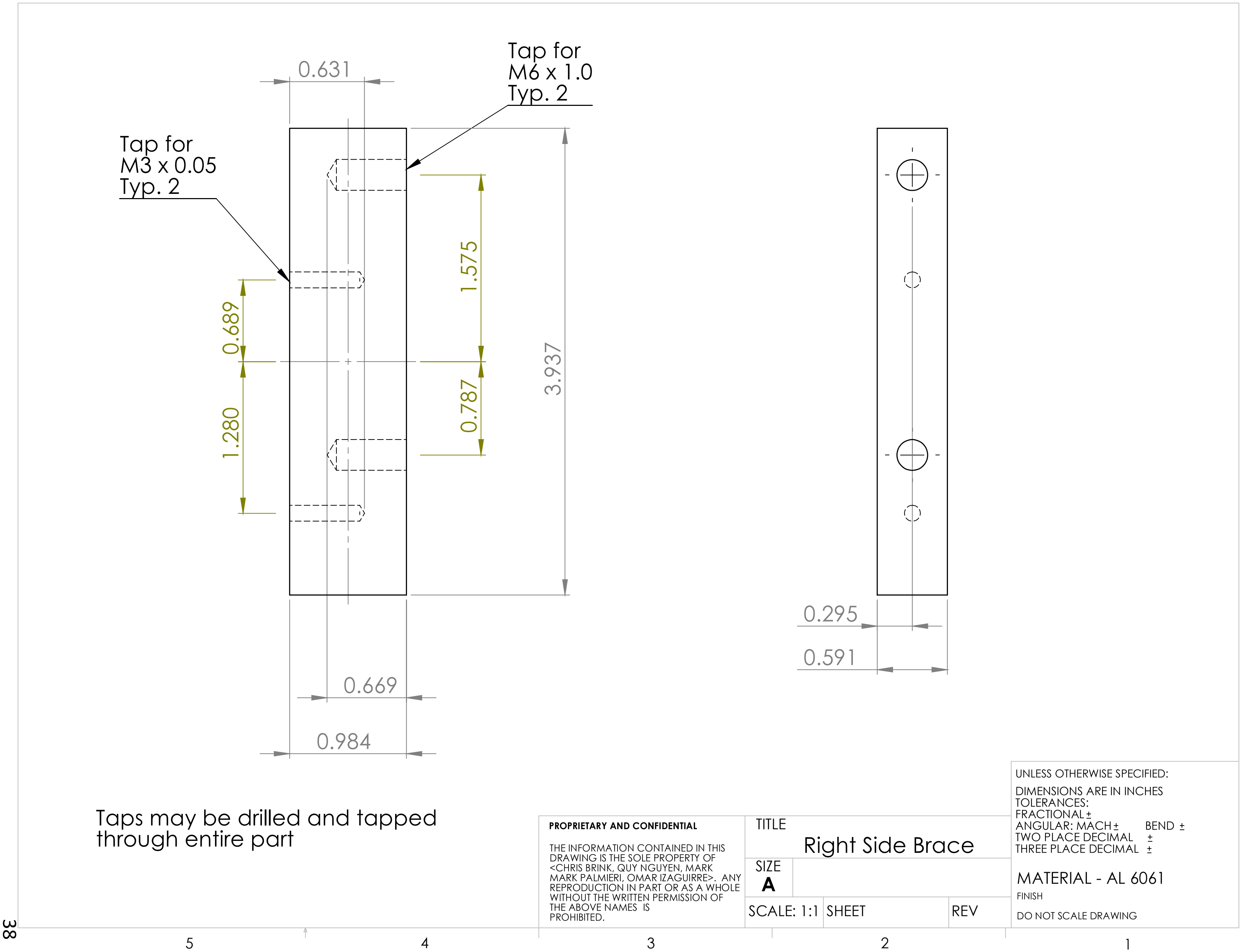
1
2
3
4
5


Tap for
M3 x 0.05
Typ. 2
Tap for
M6 x 1.0
Typ. 2
0.631
0.689
1.280
1.575
0.787
3.937
0.669
0.984
0.295
0.591
Taps may be drilled and tapped through entire part
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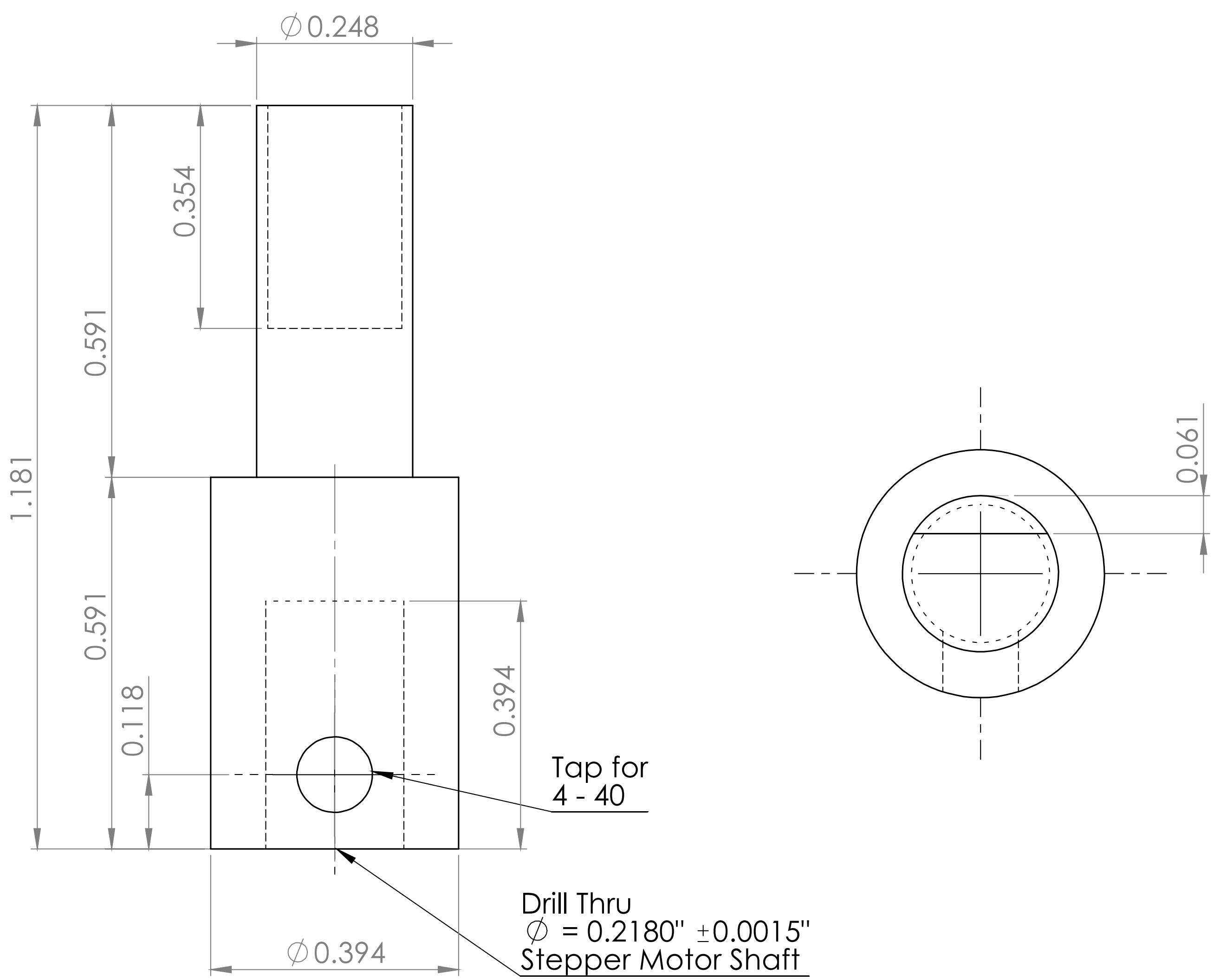
TITLE
Right Side Brace
SIZE
A
SCALE: 1:1
SHEET
REV
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL 6061
FINISH
DO NOT SCALE DRAWING
5
4
3
2
1



PROPRIETARY AND CONFIDENTIAL

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TITLE
Motor Shaft Coupler

SIZE
A

SCALE: 2:1 SHEET REV

UNLESS OTHERWISE SPECIFIED:

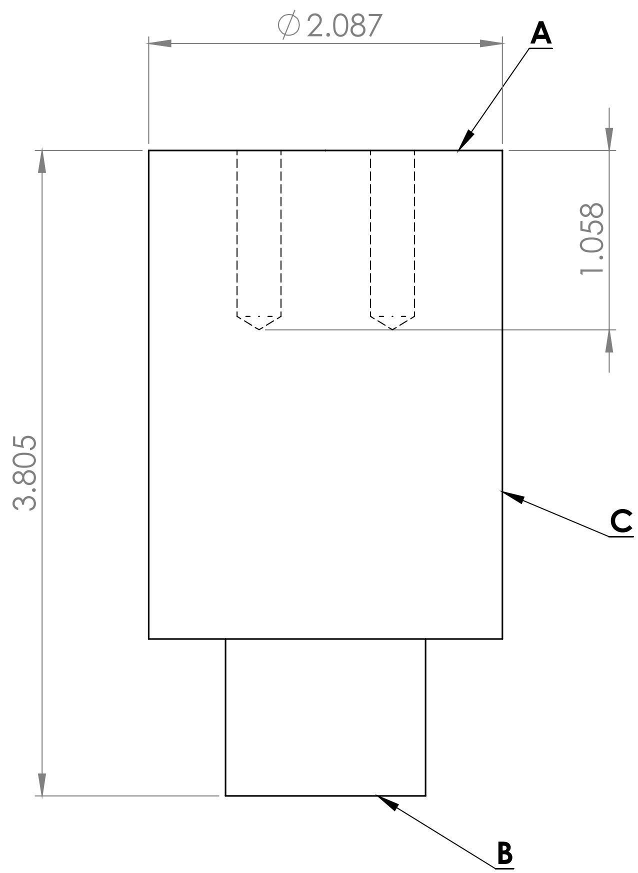
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

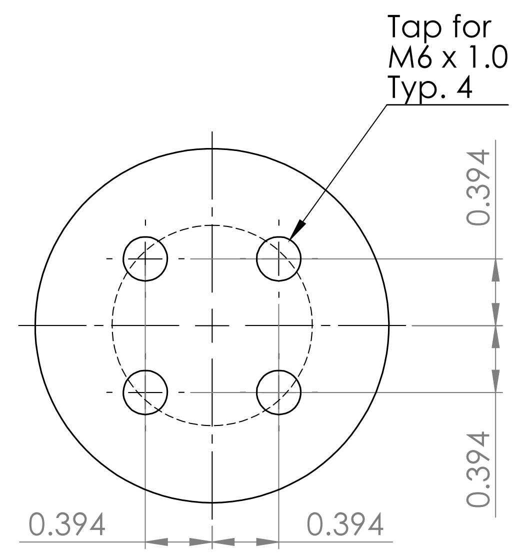
MATERIAL - AL6061

FINISH

DO NOT SCALE DRAWING

Note: This drawing is to be used solely for length of shaft and placement of screws. Real compressor shaft is going to be used





A // B 0.0002''

A ⊥ C 0.0002''

A ⊥ B 0.0002''

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TITLE: Shaft

SIZE: A

SCALE: 1:2 | SHEET | REV

UNLESS OTHERWISE SPECIFIED:

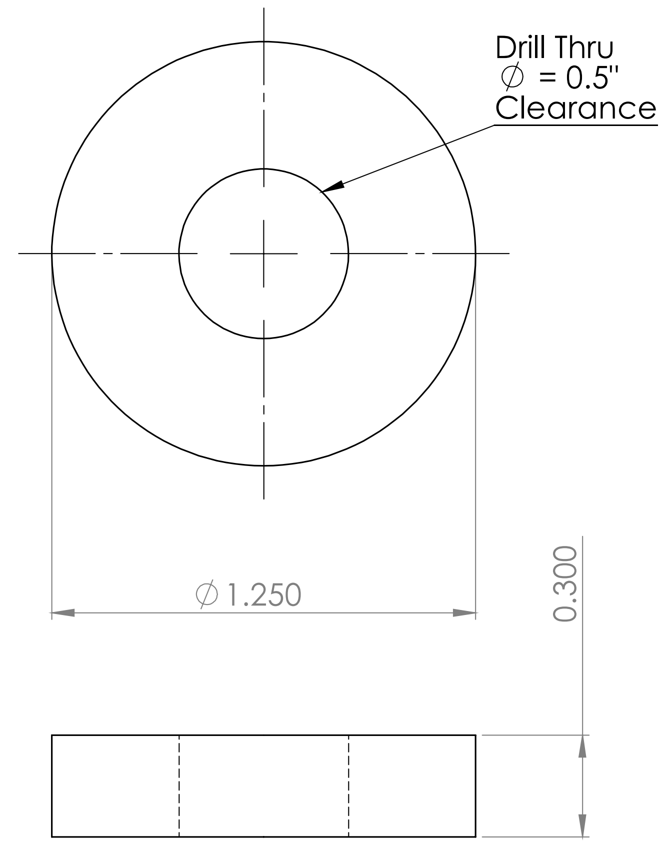
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL - REAL SHAFT

FINISH

DO NOT SCALE DRAWING

5 4 3 2 1



Quantitiy: 4

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TITLE Spacer

SIZE **A**

SCALE: 2:1 SHEET REV

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL - AL6061

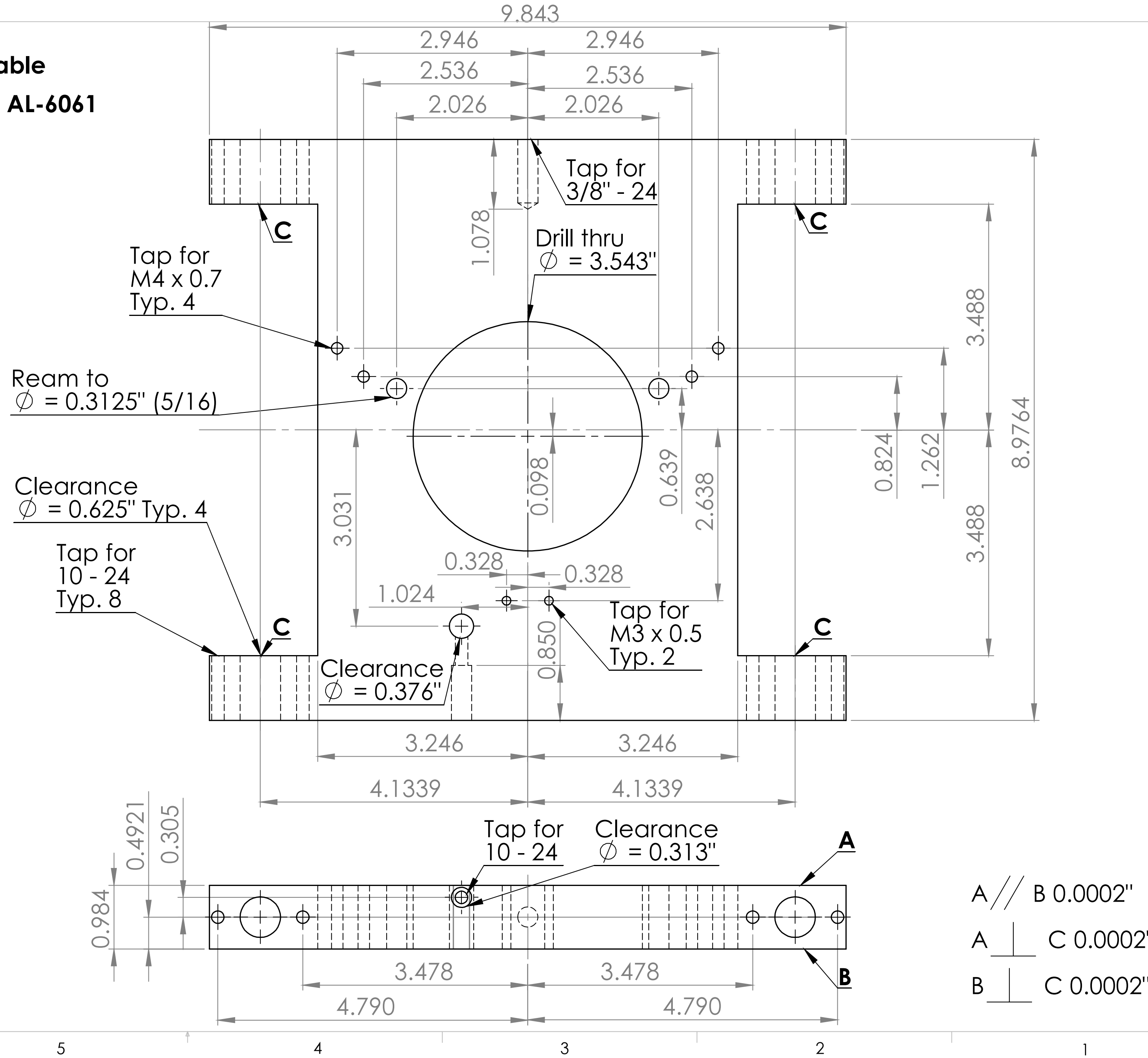
FINISH

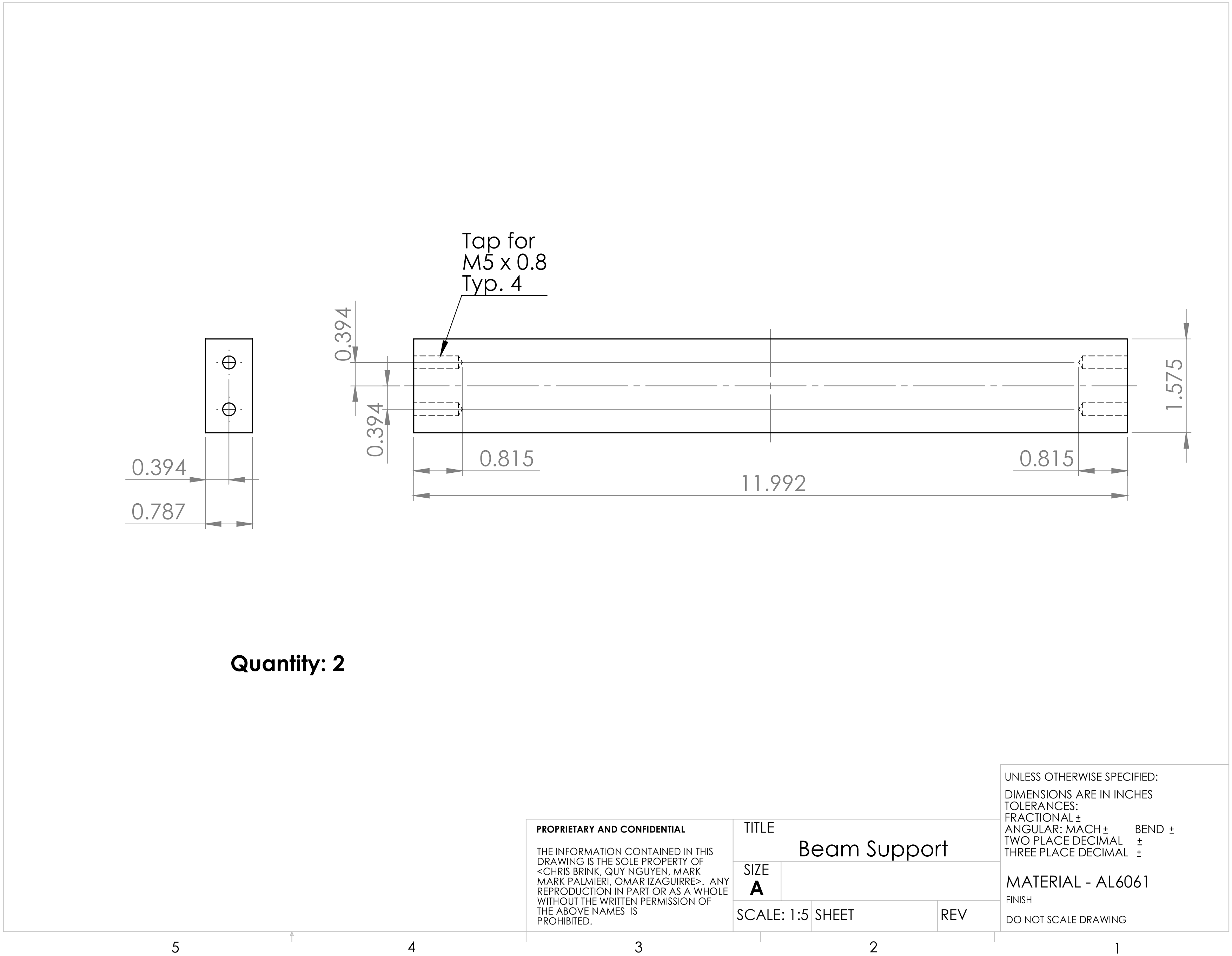
DO NOT SCALE DRAWING

5 4 3 2 1

Sensor Table

Material: AL-6061




Tap for
M5 x 0.8
Typ. 4
0.394
0.394
0.394
0.787
0.815
0.815
11.992
1.575
Quantity: 2
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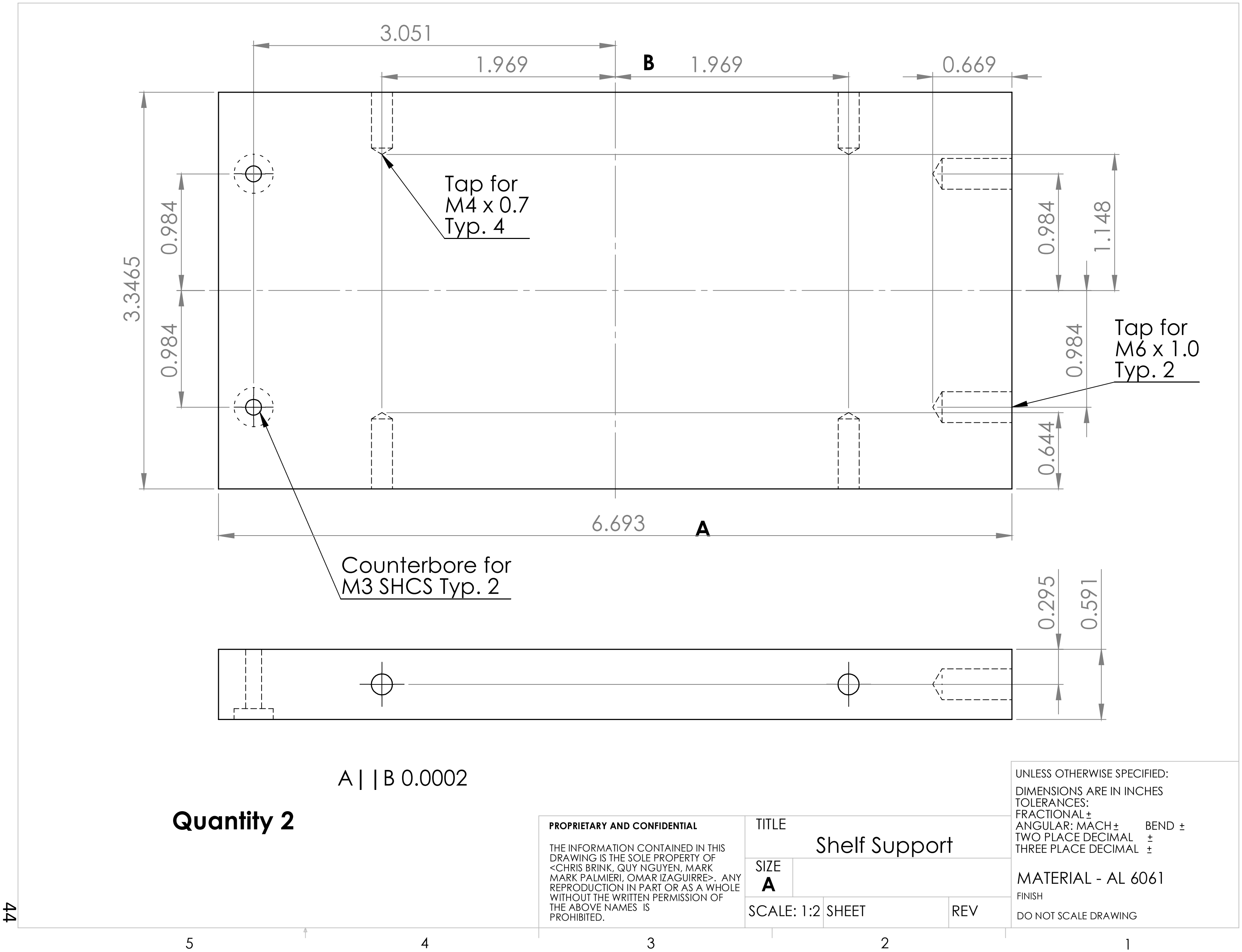
TITLE
Beam Support
SIZE
A
SCALE: 1:5
SHEET
REV
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL6061
FINISH
DO NOT SCALE DRAWING
5
4
3
2
1


3.051
1.969
B
1.969
0.669
Tap for
M4 x 0.7
Typ. 4
0.984
1.148
3.3465
0.984
0.984
Tap for
M6 x 1.0
Typ. 2
0.984
0.644
6.693
A
Counterbore for
M3 SHCS Typ. 2
0.295
0.591
A | | B 0.0002
Quantity 2
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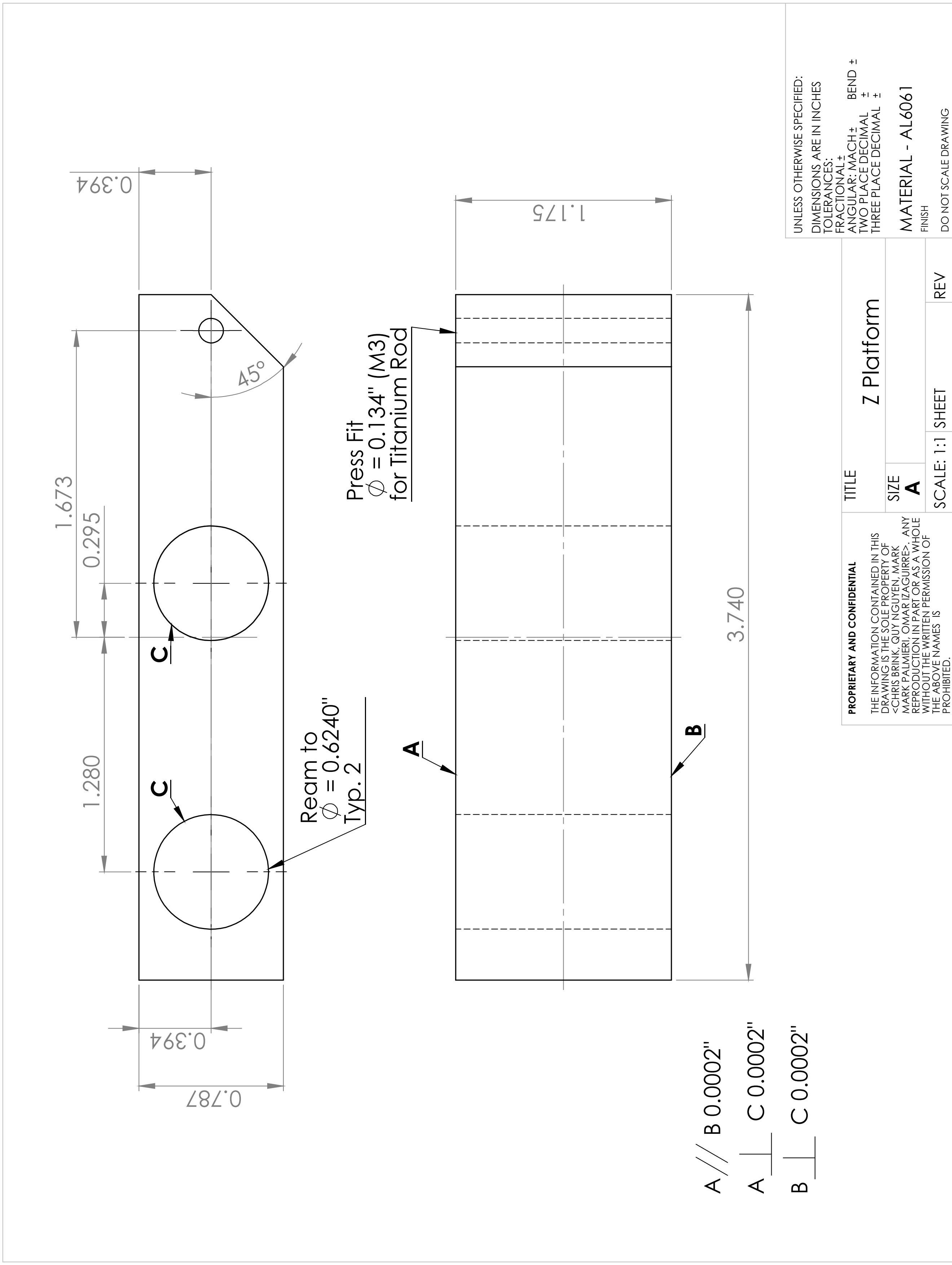
TITLE
Shelf Support
SIZE
A
SCALE: 1:2
SHEET
REV
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL 6061
FINISH
DO NOT SCALE DRAWING
5
4
3
2
1



0.394
1.175
1.673
0.295
45°
1.280
C
C
Ream to
∅ = 0.6240"
Typ. 2
Press Fit
∅ = 0.134" (M3)
for Titanium Rod
A
B
3.740
0.394
0.787
A // B 0.0002"
A ⊥ C 0.0002"
B ⊥ C 0.0002"
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL - AL6061
FINISH
DO NOT SCALE DRAWING
TITLE
Z Platform
SIZE
A
SCALE: 1:1
SHEET
REV
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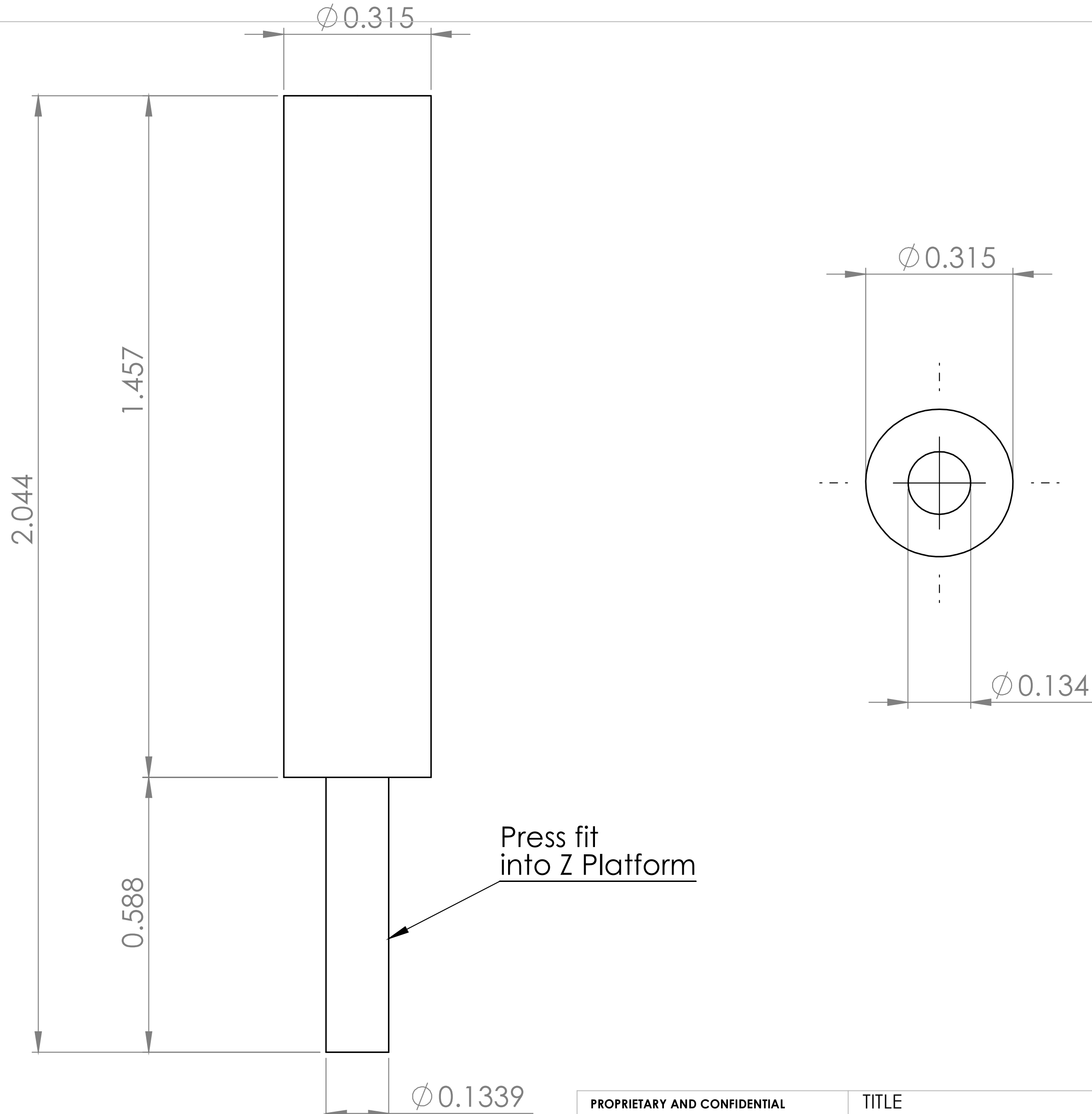
1
2
3
4
5



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TITLE

Z Axis Rod

SIZE **A**

SCALE: 2:1 SHEET REV

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL - Titanium

FINISH

DO NOT SCALE DRAWING

5 4 3 2 1