Calibration of Microelectronic Five-Hole Probes

Michael D. Gerding

Undergraduate Honors Thesis

Summa Cum Laude

B.S. in Aerospace Engineering

Interdisciplinary Microsystems Group

Spring 2018

Acknowledgements

I would like to thank Dr. Mark Sheplak and Haocheng Zhou for guiding me through this design process. I have learned a lot from my time working in the lab. I would also like to thank David Mills as well as all of the other IC2 members who spent time helping me improve my design during a team review. I wish to thank all of my IMG lab mates for providing a friendly, constructive learning environment. Finally, I would also like to thank all the members of Boeing who spent time aiding with my design.

Abstract

A calibration rig was designed for a microelectronic machine (MEM) based five-hole probe. This probe will give a unique solution to characterizing unknown flows in uncontrolled environments. Five-hole probes are very sturdy pieces of equipment that have been used on mechanisms such as aircraft to calculate both the speed and angularity of the flow along the aircraft through the measurement of the pressures at a number of ports at the tip of the probe. Traditionally five-hole probes have a time delay from when pressures are experienced to when pressures are recorded due to long pneumatic tubes connecting the probe to a pressure transducer. A MEM based five-hole probe eliminates this delay. Previous MEM based five-hole probes have not utilized optical pressure transducers, which allow the port pressures to be measured without compromising the accuracy of the measurements. The calibration rig was to be ran at low Reynolds numbers and step through a series of angular positions ranging from positive to negative ninety degrees in either direction for both rotational axes. The probe tip is to be placed at the center of the two rotational axes. Two Physik Instrumente (PI) rotation stages were utilized as it was desired to have small angular steps of approximately 0.1 to 0.2 degrees for angular positions less than five degrees. As such, a roll and cone angle coordinate system was utilized for the rig as opposed to a pitch and yaw coordinate system so the torque requirements could be minimized, allowing the use of extremely precise and delicate rotation stages. The L-611ASD was selected as the cone angle rotational stage due to its minimal stepping capability of 0.7 μrad. The DT-80 was selected for the roll rotational stage as it had a mass of 0.8kg (compared to the 2.6kg of the L-611ASD) and needed to be supported by a less rigid portion of the rig structure. A calibration rig was designed around these two rotational stages to place the tip of the probe in the middle of an eight inch by eight-inch wind tunnel exit area. The rig was designed to allow the adjustment of leveling feet to better position the probe tip. The deflection of the probe tip resulting from the stiffness of the DT-80's stage was calculated to be 0.0005 degrees, which is an order of magnitude smaller than the innate manufacturing uncertainties present in the product. The L-611ASD has small enough uncertainties to the point that any resulting position error will be less than one percent whereas the DT-80 may have an error on the order of magnitude of 10% depending on the effects of the stage's backlash. As such the DT-80 may be unable to meet the 0.1 to 0.2 degree step specification reliably. Once the motors are received from the supplier in Europe the accuracy of the stage can be verified experimentally.

Contents

Table of Figures

Table of Tables

Introduction and Literature Review

This paper will detail the design of a calibration rig to be used in tandem with a microelectronic machine (MEMS) based five-hole probe. A five-hole probe has one central hole and four evenly spaced periphery holes present on its tip. **Figure 1** shows a visual representation of this layout. Note that the probe being development by IMG will have a hemispherical tip as opposed to a conical tip. The probe is connected to a pressure transducer which will read the pressure at each of the holes. For a given probe orientation relative to the flow and a given speed of the flow, the pressures of the five holes relative to one another should be consistent. For instance, if the probe is pointed directly into the flow, the central hole should have the largest pressure reading while top and bottom holes have equal pressure readings. Moreover, If the bottom hole is perpendicular to the flow it will then have a larger pressure reading than the center hole, which in turn will have a larger pressure reading than the top hole. However, for a probe to be able to determine its angle relative to a flow and the velocity of said flow, it needs a calibration database of example flows at a variety of angles and velocities. At each calibration condition, non-dimensional coefficients of various pressure differences can be recorded and stored for reference in unknown flow conditions [3].

To perform such calibration a rig is needed to step the probe tip through a variety of angles relative to the variable flow speed of a wind tunnel. To do so, the tip of the probe needs to remain at the same point in space. This is done by placing it at the intersection of two axis of rotation. Two coordinate systems can be used in this process; pitch and yaw or roll and cone angle. Either of these coordinate systems can be used effectively and then converted using explicit geometrical relations when convenient [3]. **Figure 1** shows a five-hole probe while labeling rotation axes. Note that the actual five-hole probe will have much smaller holes. **Figure 2** gives an example of a roll and cone angle rig whereas **Figure 3** gives an example of a pitch and yaw rig. Note that there are no studies describing which calibration rigs perform optimally and provide the best positioning accuracy. As such the design presented in this report is an attempt to create a simple yet accurate calibration rig by looking at examples existing in the real world. This design will be automated, which will make it inherently more precise and time efficient than manually operated calibration rigs.

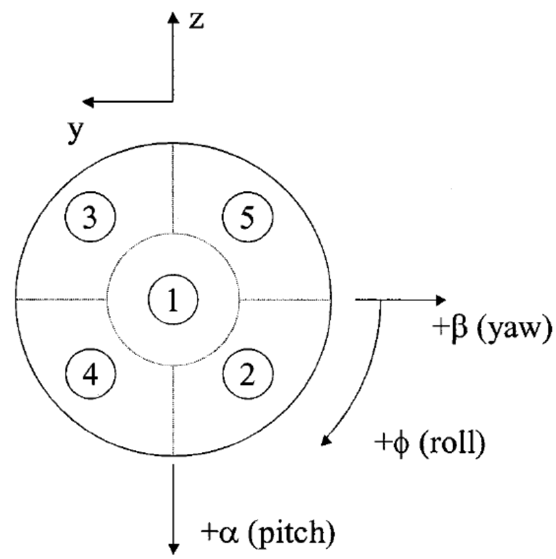

Figure 1: Five-Hole Probe Layout [3]. Note that the nomenclature is not used in this paper.

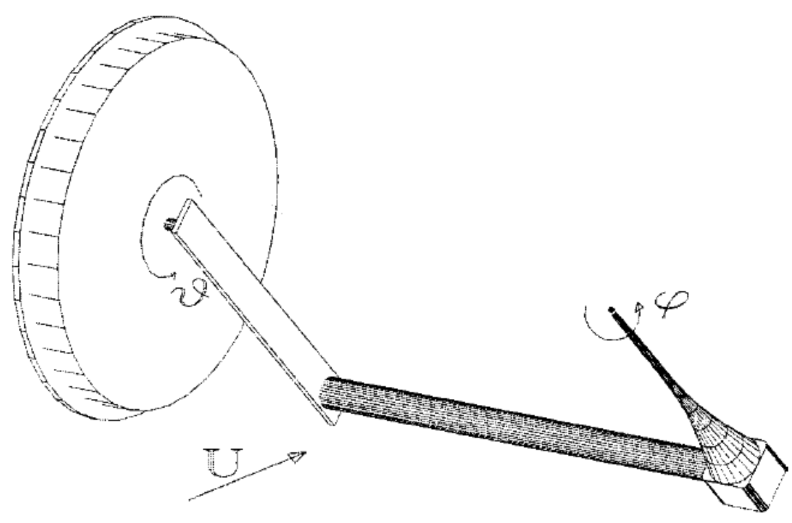

Figure 2: Roll and Cone Angle Rig [3]. Note that the nomenclature is not used in this paper.

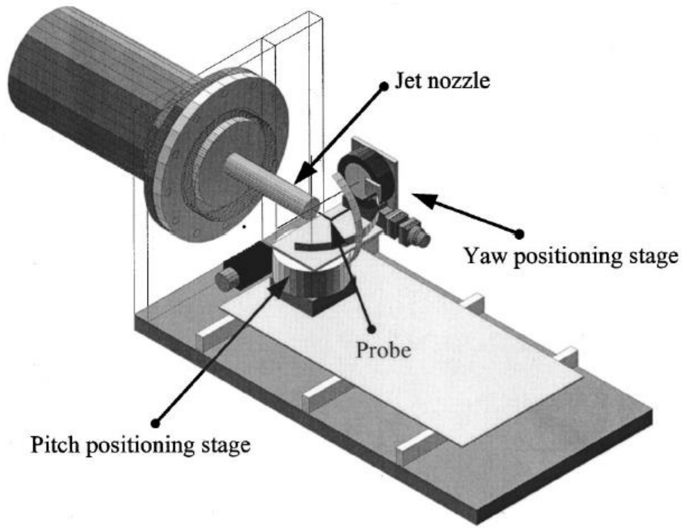

Figure 3: Pitch and Yaw Rig [3]

The purpose of developing a MEM based five-hole probe is to increase the accuracy of readings with respect to time. In traditional probes, air must travel through long pneumatic tubes to reach sensing equipment which can take a significant amount of time when compared to the amount of time taken for the flow to change. A MEM based five-hole probe removes this lag from the process through the use of optical pressure transducers embedded in the tip of the probe. Many past attempts to develop a five-hole probe with a better frequency response have not resulted in the manufacture of a functioning MEM based five-hole probe. One MEM based probe was developed in the past; however, it did not utilize optical pressure transducers. The piezo resistors that were utilized as an alternative caused high heat generation which altered the flow field around the probe compromising the results. Optical pressure transducers will not cause such a problem. Five-hole probes have been used on aircraft, rockets, and in the calibration of wind tunnels. Boeing uses five-hole probes to measure the wake behind a model aircraft in a wind tunnel. This data can be used to calculate accurate drag and lift data [8].

There are several other flow measurement techniques which multi-hole probes compete. One of these is hot-wire anemometry (HWA). This technique places a heated-up wire in the flow and uses the convection heat transfer to measure the flow. Three such wires would be needed to make three dimensional measurements. However, the small size of the wires makes them very vulnerable to breaking when compared to the five-hole probe. Laser Doppler Velocimetry (LDV) uses the doppler effect of lasers to characterize the flow when pointed at particles seeded in the flow. While this method is non-intrusive and does not place a solid object in the flow, this method requires a transparent flow field and could only operate in research facilities. Additionally, LDV requires a relatively expensive and a time-consuming set up process. Particle Imaging Velocimetry (PIV) is another nonintrusive flow characterization technique. In facilities the flow is seeded with particles and pictures can be taken as the particles move downstream allowing velocity measurements to be taken. Again, this method requires transparent fluid and can only take place in a facility. Note that only multi-hole probes also provide pressure information, allowing for more than flow kinematics to be studied. Only the multi-hole probe is suitable for a flight test. Vanes can be used to measure flow angle on flight vehicles, but not the velocity. Additionally, vanes are not mechanically robust and are prone to breaking in unfavorable weather conditions [8].

This project is being mentored by both Boeing and the National Aeronautics and Space Administration (NASA), both of whom have required specifications for the five-hole probe and calibration rig. NASA differentiates small flow angles from large flow angles as being less than five degrees. For small angles NASA requires angular steps of 0.1 to 0.2 degrees from the calibration rig. For large angles, NASA requires angular steps of one to two degrees from the calibration rig. The probe is to be calibrated for angles with the bounds of plus or minus ninety degrees for both axes of rotation. This is assumed to yield a five-hole probe with an angular error of no more than approximately five percent of the flow angle being measured. However, the purpose of this paper is to discuss the design of the calibration rig and not the performance of the five-hole probe. However, the probe will rely heavily on the calibration process to remain accurate. Boeing simply requires angular steps of one to two degrees for all angles. As such, the NASA specifications were pursued to the best of ability assuming that the Boeing specifications would be met regardless. It was desired to be able to control the rig using national instrument's LabVIEW.

The initial phase of experiments on the five-hole probe will be at low Reynolds numbers using the University of Florida's wind tunnel shown in **Figure 4**. The opening is an eight-inch square cross-section.

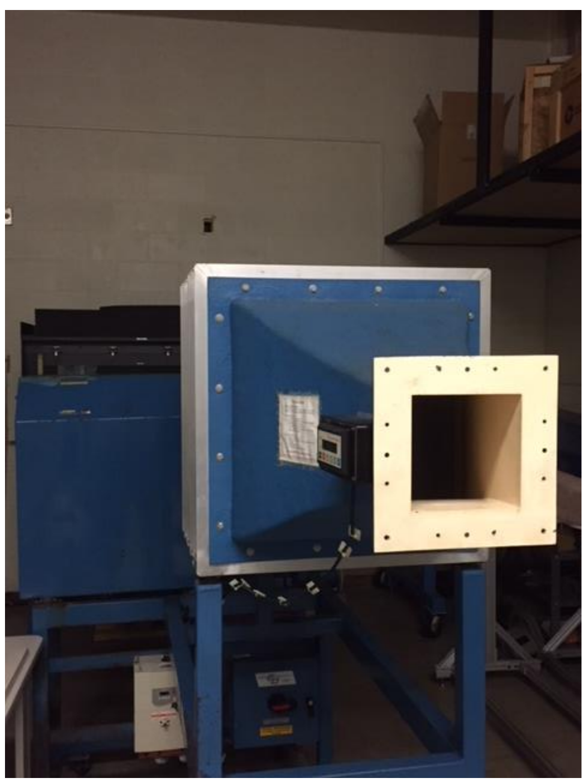

Figure 4: University of Florida's Open Return Wind Tunnel

Design Development

The design was developed around the rotational stages that were to be used to achieve NASA's specifications as they are the most crucial component of the calibration rig. OTS rotational stages were considered to be more precise than a custom made design due to gear trains not being perfectly efficient. Additionally, it was desired to control the calibration rig through the use of LabVIEW. Physik Instrumente (PI) is a unique supplier as it sells rotation stages that are accurate to the scale of µrad. Additionally, it was ascertained that they supply a LabVIEW library for use with their motors which would make any programming task simpler in the future. Since the stages are accurate to such a small increment of motion, they naturally have relative low holding torques when compares to less accurate angular positioning devices. As such a pitch and yaw coordinate system was ruled out as a possibility for the calibration rig, as it will naturally place a larger torque on the pitch rotational stage than would be present if it were a roll rotational stage (see **Figure 6** and **Figure 9**) [2]. Note that the probe being manufactured will not be a hooked probe, thus reinforcing that idea that a pitch and yaw coordinate system is unobtainable. The nature of the calibration rig's operation means that stepper motors would be a natural fit for the application. This would allow the rig to take an incremental step in angular position and pause to take data sequentially for a long period of time. All PI rotational stages that could be driven by a stepper motor either had an unlimited travel range or was limited to ten degrees in either direction. Since ninety degrees of motion is required in either direction, only the stages with unbounded ranges were considered. **Table 1** details the remaining rotation stages (NS means not specified). Of the stages available the L-611ASD had the second smallest minimum incremental motion of 0.35 µrad. Note that PI defines minimum incremental motion as the smallest movement that a stage can execute repeatedly. As will be detailed in the expected performance section, this minimum incremental motion is adequate for the specifications. The PRS-200 was not selected for its minimal motion as this level of precision will unnecessarily increase expenses. Furthermore, the stages are relatively expensive, costing tens of thousands of dollars. As such the L-611ASD was selected as the cone angle rotation stage. The L-611ASD was not selected for the roll rotational stage as it has a significantly higher mass which will put more strain on the cone angle rotational stage and will cause an increased amount of bending in the rig structural components. The DT-34 had the highest minimum incremental motion so it was not considered adequate. 350 µrad is approximately 0.02 degrees. This is ten percent of the maximum step sized desired for the calibration rig at small angles. Thus, the inherent uncertainties in the DT-34 will have a larger effect on the positioning than the other stages. Both the DT-80 and RS-40 are less than a kilogram in mass and are considered lightweight. The DT-80 is considered superior to the RS-40 despite having twice as much mass due to its far lower backlash error. Backlash error is defined as the error incurred when switching directions. However, it is also characteristic of the error incurred when stopped at a new angular position. As will be discussed in the expected performance section, the DT-80 might not be accurate enough to meet NASA's specifications. The DT-80 was justified in being selected as it was the most accurate "lightweight" rotation stage available. "Zero" backlash errors are also discussed in the expected performance section. The DT-80 was selected as the roll rotation stage [6]. **Figure 5** shows the selected motors.

Table 1: PI Rotation Stages [6]

Motor	L-611ASD	DT-80	RS-40	PRS-200	DT-34
Minimum Motion (µrad)	0.7	70	87	0.5	350
Mass (kg)	2.6	0.8	0.4	8	0.15
Backlash Error (µrad)	0	350	1500	0	NS

Figure 5: L-611ASD (left) and DT-80 (right) [6]

Note that the design was restricted by the use of a large wind tunnel as opposed to a smaller nozzle (which many other experiments have favorited as in **Figure 6**) [2]. The torque restrictions of the motors also acted as a design constraint as mentioned before. Thus, a curved design as in **Figure 7** is not realistic [1].

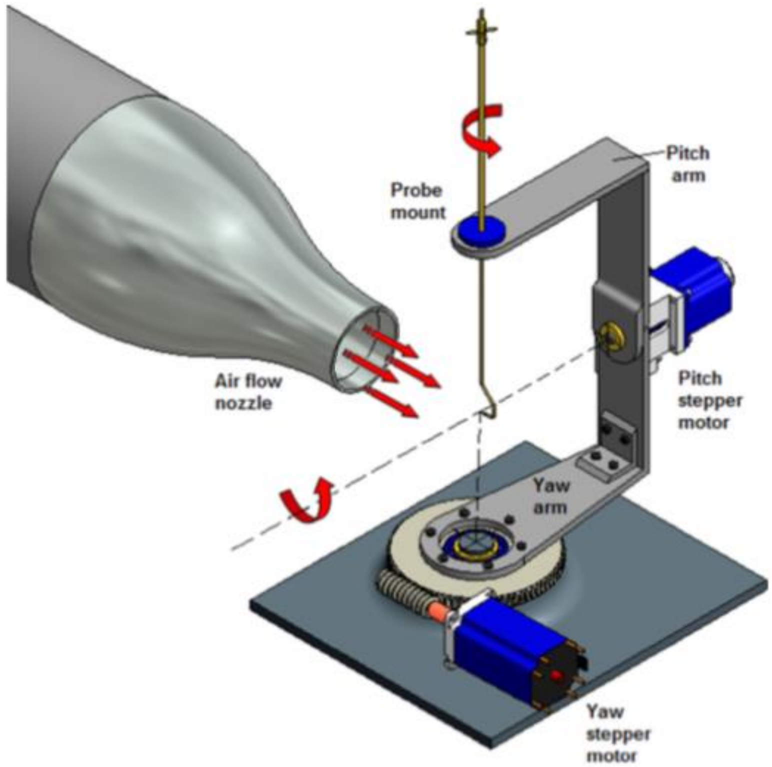

Figure 6: An Experimental Pitch/Yaw Configuration [2]

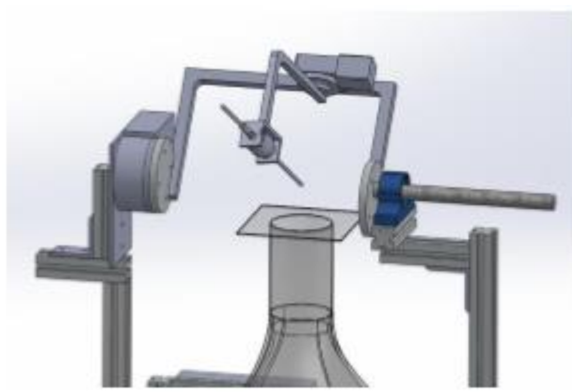

Figure 7: "Arced" Rig Configuration [1]

To provide visual context for the upcoming discussion, **Figure 8** is provided as a view of the designed calibration rig.

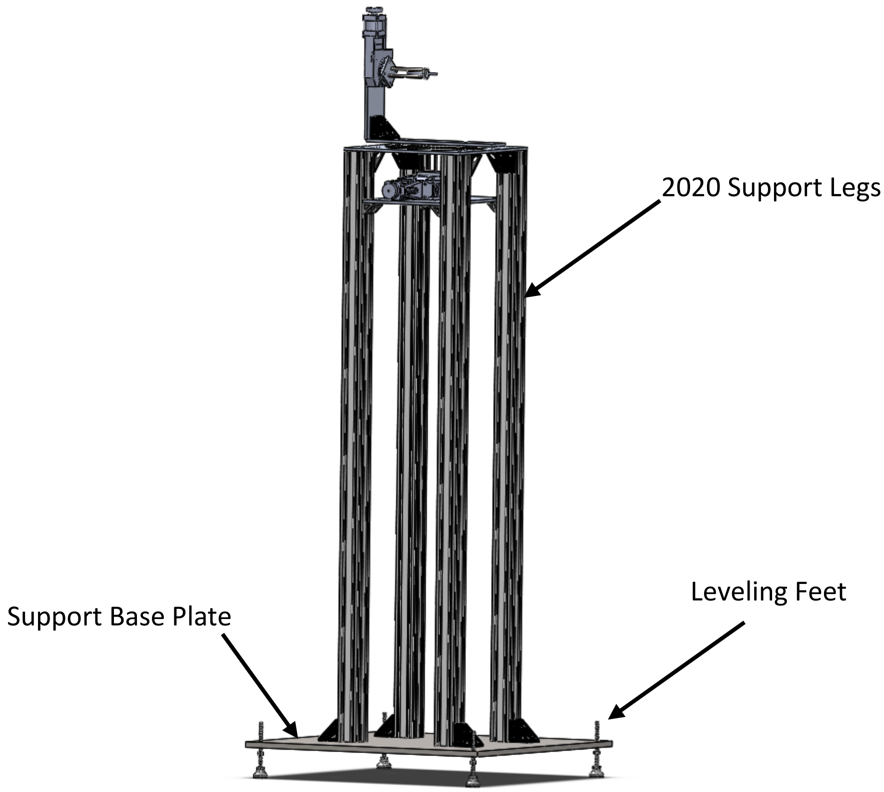

Figure 8: Calibration Rig

The wind tunnel to be used for this project has the bottom of its opening at almost five feet off of the ground. As such a support structure must hold the major rig component up off the ground. 2020 support legs supplied by 80/20 are used to connect all rotating components to the base of the support. These 80/20 legs are connected to a stainless-steel plate that is half an inch thick with a two-foot, square cross-section. This relatively thick plate was made out of steel rather than aluminum to lower the center of mass of the rig. This prevents the rig from tipping over and the expensive rotation stages from being damaged. This concept was used as opposed to an entirely 2020 support system as it would be more expensive. Leveling feet are included with a four-inch threaded length to help make the probe tip perpendicular to an incoming flow. The leveling feet can be adjusted to make the central hole of the pressure probe have the max pressure reading while the pressure readings of the periphery holes are symmetrical per the roll angle of the probe. The leveling feet are rated for 250 lbs each (1000 lbs total) [4]. The probe was to be positioned in the center of the wind tunnel opening. The center of the support base plate was placed at the center of the four-inch threaded length of the leveling feet and the 2020 support legs were then dimensioned accordingly to do so. The tip of the probe is just under seven inches above the highest point of the 2020 legs, making the legs just under 53 inches in length. This gives the rig equal distances of play in either direction for each foot. For a discussion of the top of the calibration rig, **Figure 9** was provided as a visual reference. Note that fasteners are not included in any figures due to time constraints although they have been specified in **Table 5**.

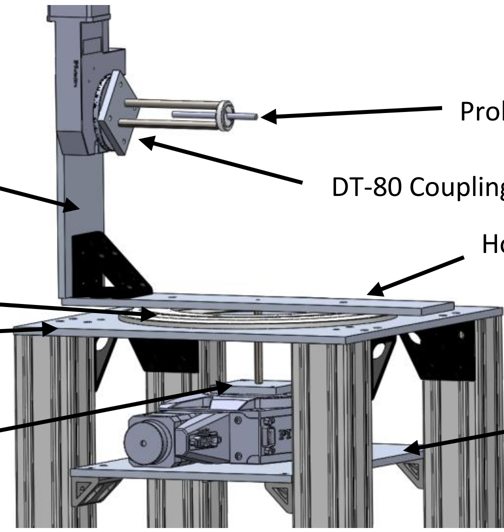

Figure 9: Top of Calibration Rig

Note that the probe is modeled as a three-inch-long cylinder for simplicity. At the time of the writing of the report, the probe has yet to be fully manufactured. The probe is to have a hemispherical tip with a diameter of five millimeters. As such an off the shelf (OTS) five-millimeter aluminum shaft collar was used to hold the probe in place. Probes often increase in thickness after a few inches of distance from their tip. As such a different collar may be needed in the future. An OTS shaft collar was utilized rather than a custom design to ensure a tight grip around the circumference of the probe. Holes had to be made in the collar for it to be fastened to two shafts approximately 3.6 inches long. These shafts might also vary in length depending on the final geometry of the probe and the location along the probe where it is to be gripped. Typically, probes are gripped near the tip to prevent any vibrations while measuring the flow. However, this project will start by testing the probe at low Reynolds numbers, thus minimizing the potential for vibration in the first place. In the current configuration, the probe is being gripped an inch away from the tip. Regardless of where the probe is gripped, the probe tip must be at the center of the axis of rotation of the L-611. Minimizing the effects of components other than the probe altering the flow is also a priority. As such as many components as possible are desired to be kept out of the flow or at least kept at a distance behind the probe tip. The widest five-millimeter shaft collar was selected so that the two 0.25 in shafts have as much clearance as possible with the probe (due to an unknown final geometry). This width was 25 mm, or slightly less than an inch [7]. The DT-80 has an aperture size of forty millimeters and was not a constraining factor for this consideration. The shafts also benefit from being longer rather than shorter by allowing a larger radius of curvature for any cords exiting the rear of the probe. The two shafts are tapped on each end for a 5-40 fastener. These shafts can be ordered with one side already tapped. Thus, they can be cut to length and given a matching tap on the cut end. This will help minimize manufacturing costs. The shafts are composed of 1045 Steel, which will help prevent the shafts from deforming under weight. Both shafts are fastened to a coupling plate made of 6061 Aluminum which mates to the pattern of threaded holes on the surface of the DT-80. The probe is positioned to be precisely at the center of the DT-80's aperture.

The DT-80 is fastened to the vertical arm using both of its tapped holes as well as its bolt holes. The vertical arm is 0.25 in thick, three inches wide (to be able to mate to the DT-80), and 7.25 inches tall while being made out of 6061 Aluminum which is cheaper than stainless steel. The height of the vertical arm was made to both give enough space to mate to the DT-80, as well as place the probe tip at the center of the wind tunnel opening while keeping the remainder of the rig out of the flow entirely. The probe tip is approximately six inches above the bottom most face of the vertical arm. This distance only needs to be four inches to keep the remainder of the rig out of the flow while keeping the probe at the center. Material could be removed from the vertical arm to make it more aerodynamic if deemed necessary in the future; however, this would increase manufacturing costs. The vertical arm is fastened to the horizontal arm at its bottom using an OTS eight-hole, gusseted angle bracket supplied by 80/20. The gusset will make the joint more rigid so that the position of the probe tip is not as affected by the bending of structural components.

The horizontal arm is 0.25 in thick, 2.5 in wide, and thirteen inches long while being made out of 6061 Aluminum. The width of the horizontal arm had to be at least two inches to mate with the angle bracket, yet was made 2.5 in to help improve rigidity as well as leave less of the vertical arm hanging over its edges as the exact center of mass of the DT-80 is unknown. If torsion of the horizontal arm is determined to be a problem, the cross-section can be altered. The connection between the two arms uses fasteners which were verified to fit regardless of the space constraint of the nearby table top. The horizontal arm is connected to a shaft which is also fastened to the L-611 coupling plate, which serves a similar purpose to the DT-80 coupling plate. This shaft is produced in the same manner to those connecting to the DT-80 coupling plate. Both rotational stage coupling plates are made out of 6061 Aluminum to decrease cost. They are also not expected to experience very high forces. The horizontal arm is connected to the shaft at the center of its length. It extends equally far in both directions so that an appropriate counterweight can be placed to generate a similar moment to all the components connected to the upper half of the vertical arm. This counterweight is to be designed after the rig is manufactured initially so that an appropriate position of the center of mass can be determined experimentally. This would minimize any moments on the turntable. The horizontal arm is connected in two places to the 6.18 in bolt circle of the OTS lubricated steel turntable supplied by McMaster-Carr. The turntable is rated for heavy machinery so the amount of weight placed on it should not be an issue [4]. If the bending of the horizontal arm is determined to significantly impact the position of the probe, it could be made out of steel making it more rigid. Such a determination would be made experimentally after the rig is built. The horizontal arm may need to be made longer in the future to provide more space for the geometry and cables of the probe. Note that at the time of the writing of this report, the PI rotational stages have yet to be shipped from Europe. As such, any center of mass determinations have not yet been made.

The table top is a one-foot square plate with a thickness of 0.25 in which connects the turn table to the 2020 legs. This too is made out of 6061 Aluminum. A hole was made for the L-611 shaft to pass through the table top. The table top is connected to the 2020 legs using the same angle bracket as was used on the arms. This same bracket was utilized to connect the 2020 legs to the support base plate. This helps improve the rigidity of the structure. A separate eight inch by one foot by 0.25 in plate made of 6061 Aluminum was used to support the L-611. OTS four-hole, wide, gusseted angle brackets were used in this case to ensure the bolt pattern would not interfere with the positioning of the L-611.

All fastener clearance holes above the top surface of the turn table as well as the connection between the L-611 coupling plate and the L-611 shaft were made to be close fit clearance holes. This helps ensure the accurate positioning of the probe tip at the center of both axes of rotation. All other fastener clearance holes were dimensioned to be free fit clearance hole. As such, the L-611 will be less likely to have torque placed on it as a result of manufacturing imperfections within the tolerances of the designed parts. Fasteners were selected so when they were used with a nut, the fastener were always long enough to reach through the components it was connecting as well as through the entirety of the nut. When fasteners were to be threaded into a hole, it was made sure that the fasteners would always have at least three fully engaged threads.

Expected Performance

This section will estimate the expected performance of the calibration rig's ability to accurately locate the probe tip at the center of two axis of rotation as well as incrementally change its angular position about said point. This will be done entirely using motor specifications and estimated weights of designed parts. Manufacturing tolerances will not be considered as this is best done experimentally which would require the rig to have been assembled, which was not possible at the time this report was written as the rotational stages had yet to be delivered. **Table 2** and **Table 3** summarize the rotational stages' base specifications and uncertainty specifications respectively. In **Table 2** the cost is only of the rotational stage, not any controller or cables required. The minimum motion is that which is capable of being executed repeatedly through the use of a controller that was purchased whereas the step size is that of the stage. The permissible torque refers to that about the rotation axis. "Tilt" specifications refer to that which is perpendicular to the axis of rotation. The design resolution is the theoretical minimum movement of the stage. In **Table 3** tilt stiffness characterizes the tilting of the axis of rotation downwards under weight. Axis deviation is the possible linear distance the axis of rotation can be from the center of the rotational stage. The repeatability is defined as how close the stage can return to a given position after a deviation from that position. The DT-80's repeatability is defines as returning from the same direction whereas the L-611's repeatability is defined as returning from either direction. Returning to the same position from the same direction is negligibly affected by backlash error. As such, backlash error is considered more important as the stages will have to stop rotating frequently to record data. The backlash error is allegedly eliminated from the L-611 through the use of an integrated angle measuring system [6]. This allows the exact position to be measured regardless of backlash.

Table 2: PI Stages Base Specifications [6]

	L-611	DT-80
Total Cost ($)	8,914	2,744
Minimum Motion (deg)	0.00004	0.004
Permissible Torque (Nm)	3	0.1
Mass (kg)	2.6	0.8
Axial Load Capacity (N)	100	20
Tilt Load Capacity (N)	-	10
Permissible Tilt Torque (Nm)	40	5
Step Size (deg)	0.02	0.01
Design Resolution	2.00E-05	0.01

Table 3: PI Stages Uncertainty Specifications [6]

	L-611	DT-80
Tilt Siffness deg/Nm	0.001719	0.00859
Wobble (tilt about rotation axis) (deg)	±0.000859	±0.006
Stage Flatness (µm)	±1	±30
Axis Deviation (µm)	±2.5	±30
Repeatability (accuracy when returning) (deg)	±0.0002	±0.01
Backlash (deg)	0	0.02

To estimate the performance of the calibration rig as well as confirm that the DT-80 could withstand the weight of the probe clamping parts, weight and moment calculations were required. The parts included in this calculation were the DT-80 Coupling Plate, the Parallel Shaft Couplings, the Ruland 5mm aluminum shaft collar, and an estimated probe shape. The probe was approximated as a three-inch-long solid cylinder. All parts were considered solid shapes and fastener were neglected. Despite the parts being various steels and aluminums, all were approximated as Stainless Steel with a density of 8000kg/m^3 as an overestimation [5]. This value provides an overestimation regardless of fasteners being neglected and the change in materials. Note that the Parallel Shaft Couplings are not of definite length as the probe geometry was not certain at the time of this calculation. For the purpose of this calculation, they were estimated to be approximately 3.6 inches in length, so that the probe is gripped an inch away from its tip. All measurements were rounded up so an overestimate would be acquired. Equation (1) details how the weight of each part was calculated whereas (2) shows how the moment arm for each part was calculated. Finally, (3) approximates the moment of each part. ρ is the overestimated density, A is the cross-sectional area of the solid part, l is the length of the part along the rotational axis, m is the minimum distance from the part in question to the rotational stage, W is the weight of a part, M is the moment of a part, g is the acceleration due to gravity ($9.81 m/s^2$), and L is the moment arm of a part. Note that these calculations assume that the rotational axis is perfectly horizontal and that each part is symmetrical about the axis of rotation.

$$W = \rho A l g \tag{1}$$

$$L = \frac{l}{2} + m \tag{2}$$

$$M = WL \tag{3}$$

Table 4 gives the results of the aforementioned calculations.

Table 4: DT-80 Calculations

Part	L (m)	W (N)	M (Nm)
Probe	0.0910	0.1174	0.01068
Shaft Collar	0.0943	0.231	0.0218
Parallel Shafts	0.0514	0.448	0.0230
Coupling Plate	0.00318	1.286	0.00408
	Sums	2.082	0.0596

It can be seen that the total weight which the DT-80 is experiencing is less than 10N and the "tilt" torque is less than 5Nm. By multiplying the tilt moment by the stiffness given in Table B, the DT-80 axis of rotation will sag at most 0.0005 degrees about the horizontal. Note that since the parts are design to be symmetrical about the axis of rotation, the 0.1Nm of permissible torque about the axis of rotation should not be reached.

Furthermore, the L-611 is considered to operate at its specifications assuming the turntable is properly lubricated. Additionally, all moving parts must be accelerated slow enough so that the resulting inertial forces do not overpower the rotational stages. As such, an angular position error of less than one percent is expected at steps of 0.1 degrees (from the repeatability specification). The DT-80 can expect an angular position error of approximately five to fifteen percent depending on the effects of the backlash error and repeatability error while operating with steps of 0.2 degrees given its specifications in Table B. The exact error will likely be less than fifteen percent as the DT-80 will not be required to completely reverse its direction of rotation. The DT-80 is only required to stop rotating for data collection. This affect can be minimized by having the L-611 rotate as much as possible in lieu of the DT-80. In other words for each position of the DT-80, the L-611 will rotate through all of its positions. As such the DT-80 may be unable to meet NASA specifications at small angles. This would need to be verified by experimentation. However; using a second L-611 might cause other issues with accuracy, such as the rig structure bending more under increased weight. Additionally, this will significantly increase the cost of the rig unnecessarily at such an early stage of the probe design. The effect of the 0.0005 degrees of tilt due to weight simply adds to the effects of the tolerances given in its specifications found in Table B (which are more significant). The effect of the probe tip not being perfectly centered at the two axes of rotation and the axes being tilted are considered to be only verifiable by experiment due to the complexity of the situation. The same is considered for any manufacturing imperfections. Note that an L-611ASD would also bend less than 0.0005 degrees under the weight it would experience as the roll rotation stage.

Moving Forward

At the time this report was written, a bill of materials (BOM), part drawings, and an assembly file have been completed (see appendix). Future work would include adding all fasteners specified in the BOM to the assembly file and creating assembly drawings for the manufacture of the calibration rig. Additionally, the assembly file can be used alongside a finite element analysis simulation to estimate the deflection of the probe tip. However, this would be best done once the exact weight and center of mass of the two rotation stages are known as well as the geometry of the probe. Additionally, the effect of the leveling feet would to be difficult to account for in the simulation. Thus, such a simulation is not a priority as it may be more time efficient to simply account for any deflections experimentally rather than computationally. The calibration LabVIEW code can also be written before the manufacture of the rig utilizing the PI LabVIEW library. This would see the stages incrementally stepped through different angular positions using a for loop with pauses for collecting data. The exact duration of the pauses can be determined once the rig is manufactured by measuring the settling time of preliminary data. Testing procedure may also be formally drafted. For instance, despite the fact that the experiment will be run at a low Reynolds number, testing can be done at a variety of low Reynolds number to see if the calibration changes significantly throughout a given range. It was also postulated that a hot-wire anemometer can be run at the same time as the calibrated probe. This would give another result which can be compared to that of the probe when an unknown flow is characterized. Note that the anemometer will only be able to measure the speed of the flow if only a single wire is utilized. This still can be used to build confidence in the operation of the probe.

Once the rotation stages have been received, much more work can be completed. A counterweight can be developed so that the turntable does not experience a moment. Experiments can be devised to generate angular position uncertainties for the stages through observation rather than reference a data sheet. This will help to better characterize the effects of the backlash error. If necessary, A rotary encoder can be implemented behind the vertical arm to allow for closed loop control of the DT-80 and allowing backlash error to be directly observed. The L-611 already has a sensor for closed loop control. Additionally, the controllers specified in **Table 5** are capable of closed loop control. How level the rig can hold a probe-like object can also be verified. This can be done experimentally by clamping a laser-pointer in the rig and using trigonometry to estimate any deviations while the rotation stages are being turned. The calibration rig could be surrounded by a sort of trifold to record laser point positions on. Note that the leveling feet can also be adjusted to make the rig as level as possible. This could be done in addition to verifying that the top and bottom ports of the probe read the same pressure in a flow field. This would mean the probe is level with the flow. Rolling the probe 180 degrees and observing the same would verify the orientation of the probe.

References

[1] Ciolek, P. et al., “Design and Construction of a Velocity Probe Calibration Rig,” Worcester Polytechnic Institute Qualifying Project Report, 2013, pp. 40.

[2] Georgiou, D., and Milidonis, K., “ Fabrication and Calibration of a Sub-Miniature Five-Hole Probe with Embedded Pressure Sensors for use in Extremely Confined and Complex Flow Areas in Turbomachinery Research Facilities,” Flow Measurement and Instrumentation, 2014, pp. 5.

[3] Johansen, E. et al., “The Compressible Calibration of Miniature Multi-Hole Probes,” ASME Fluids Engineering Digital Collection, vol. 123, 2001; doi: 10.1115/1.1334377.

[4] “McMaster-Carr,” Mc-Master-Carr Supply Company, Available: https://www.mcmaster.com/

[5] “Metals and Alloys-Densities,” The Engineering Toolbox, Available: https://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html

[6] “Product Finder,” Physik Instrumente, Available: https://www.physikinstrumente.com/en/products/productfinder/

[7] “Shaft Collars,” Ruland Manufacturing Company Inc., Available: https://www.ruland.com/shaft-collars.html

[8] Zhou, H., “A MEMS Based Five-Hole Probe with Optical Pressure Transducers,” University of Florida Doctor of Philosophy Proposal, 2017, pp.12-30.

Appendix

Note that parts closer to each other in **Table 5** are closer to each in the physical rig assembly when possible. All figures of part drawings tolerance dimensions that have three decimal places with ±0.005 in. Also note that unnecessary sheet format blocks have not been completed. This is in part because assembly drawings have yet to be finalized.

Table 5: Bill of Materials

Sub Assembly	Part Name	Drawing #	Quantity in Sub Assembly (Total)	Possible Vendor	Vendor Part #	OTS?
Probe Interface	probe	P3	1	-	-	no
	5mm aluminum shaft collar	P2	1	Ruland	ENCL25-5MM-A	no, must be drilled
	M2.5x8 steel hex screw	NA	1	Ruland	ENCL25-5MM-A	yes, comes with collar
	parallel shaft coupling	P1	2	McMaster-Carr	8017T1	no, must cut and tap raw stock
	5-40x0.5'' 316 SS BHS	NA	4 (6)	McMaster-Carr	98164A438	yes
	DT-80 coupling plate	P5	1	-	NA	no
	M4-0.7x10 DIN912 SHS	NA	4	McMaster-Carr	91292A116	yes
	DT-80 rotation stage	NA	1	PI	64439200	yes, comes with DT-80
	M4-0.7 DIN 912 fastener	NA	4	PI	64439200	yes, comes with DT-80
	18-8 SS hex nut M4-0.7	NA	2	McMaster-Carr	91828A231	yes
	vertical arm	P6	1	-	NA	no, must be drilled
	10 series 8 hole al. gusseted corner bracket	NA	1 (9)	80/20 inc	4138	yes
	1/4-20x5/8'' SS BHS	NA	8 (32)	McMaster-Carr	97763A264	yes
	1/4-20-5/32'' hex nut	NA	8	McMaster-Carr	94805A029	yes
	horizontal arm	P4	1	-	NA	no, must be drilled
Table to Interface Connection	5-40x0.5'' 316 SS BHS	NA	1 (6)	McMaster-Carr	98164A438	yes
	1/4-20x9/16'' BHS	NA	2	McMaster-Carr	91255A524	yes
	1/4-20 t-nut	NA	2 (58)	80/20 inc	3382	yes
Probe Table	lubricated turntable	NA	1	McMaster-Carr	1544T2	yes
	10-32x9/16'' BHS	NA	4	McMaster-Carr	91255A027	yes
	10-32 SS hex nut	NA	4	McMaster-Carr	91841A195	yes
	table top	T1	1	McMaster-Carr	89015K137	no, must be drilled
	2020x52.95''	T3	4	80/20 inc	2020-S	maybe, can order to length or cut
	10 series 8 hole al. gusseted corner bracket	NA	4 (9)	80/20 inc	4138	yes

Sub Assembly	Part Name	Drawing #	Quantity in Sub Assembly (Total)	Possible Vendor	Vendor Part #	OTS?
	10 series 4 hole wide gusseted corner bracket	NA	4	80/20 inc	4134	yes
	1/4-20x5/8in SS BHS	NA	24 (32)	McMaster-Carr	97763A264	yes
	1/4-20x5/32in tall hex nut	NA	24 (32)	McMaster-Carr	94805A029	yes
	1/4-20x0.5'' BHCS	NA	24 (40)	80/20 inc	3061	yes
	1/4-20 t-nut	NA	24 (58)	80/20 inc	3382	yes
	L611 shaft emulator	T5	1	McMaster-Carr	8017T1	no, must cut raw stock
	5-40x0.5'' 316 SS BHS	NA	1 (6)	McMaster-Carr	98164A438	yes
	L611 coupling plate	T2	1	McMaster-Carr	NA	no
	M6-1x10mm SS BHS	NA	4	McMaster-Carr	97763A823	yes
	L611 rotation stage	NA	1	PI	L-611.9ASD	yes, included with L-611
	L611 table	T4	1	McMaster-Carr	NA	no
	M6-1x60mm SS BHS	NA	3	McMaster-Carr	92095A254	yes
	DIN 433-6 washers	NA	3	PI	L-611.9ASD	yes, included with L-611
	M6-1 SS hex nut	NA	3	McMaster-Carr	96621A110	yes
Support/Rig interface	1/4-20x0.5'' BHCS	NA	16 (40)	80/20 inc	3061	yes
	1/4-20x7/8'' SS BHS	NA	16	McMaster-Carr	97763A346	yes
	10 series 8 hole al. gusseted corner bracket	NA	4 (9)	80/20 inc	4138	yes
	1/4-20 t-nut	NA	32 (58)	80/20 inc	3382	yes
Support	5/16-18x4'' swivel leveling feet	NA	4	McMaster-Carr	6111K457	yes
	5/16-18 lock nut	NA	4	McMaster-Carr	6111K457	yes, comes with leveling feet
	support base	S1	1	-	NA	no
Other orders	stepper motor controller	NA	2	PI	C-663.12	yes
	stepper motor cable 3m	NA	1	PI	720090000	yes
	L611 to controller converter	NA	1	PI	C-815.AC32-0300	yes

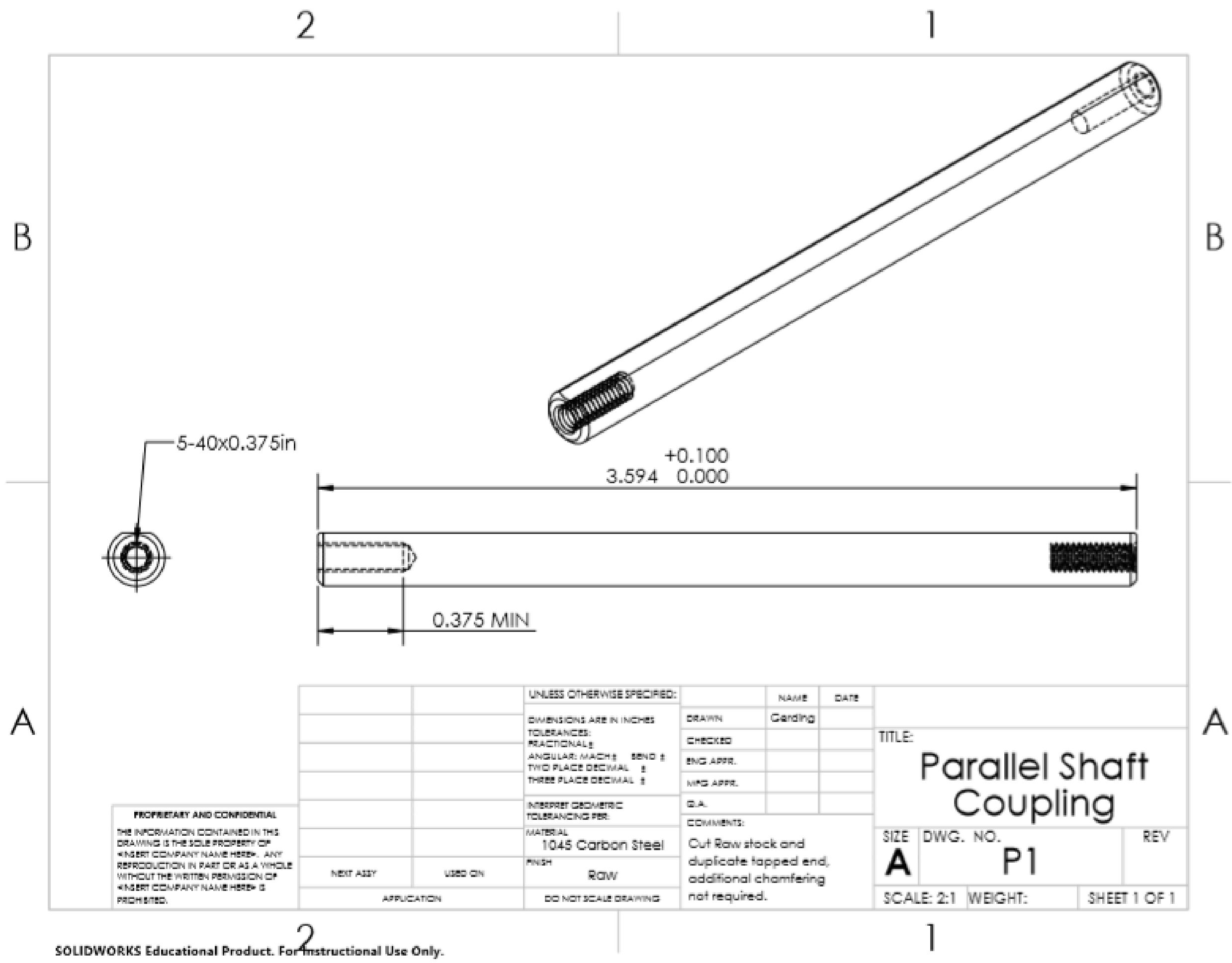

Figure 10: Parallel Shaft Coupling

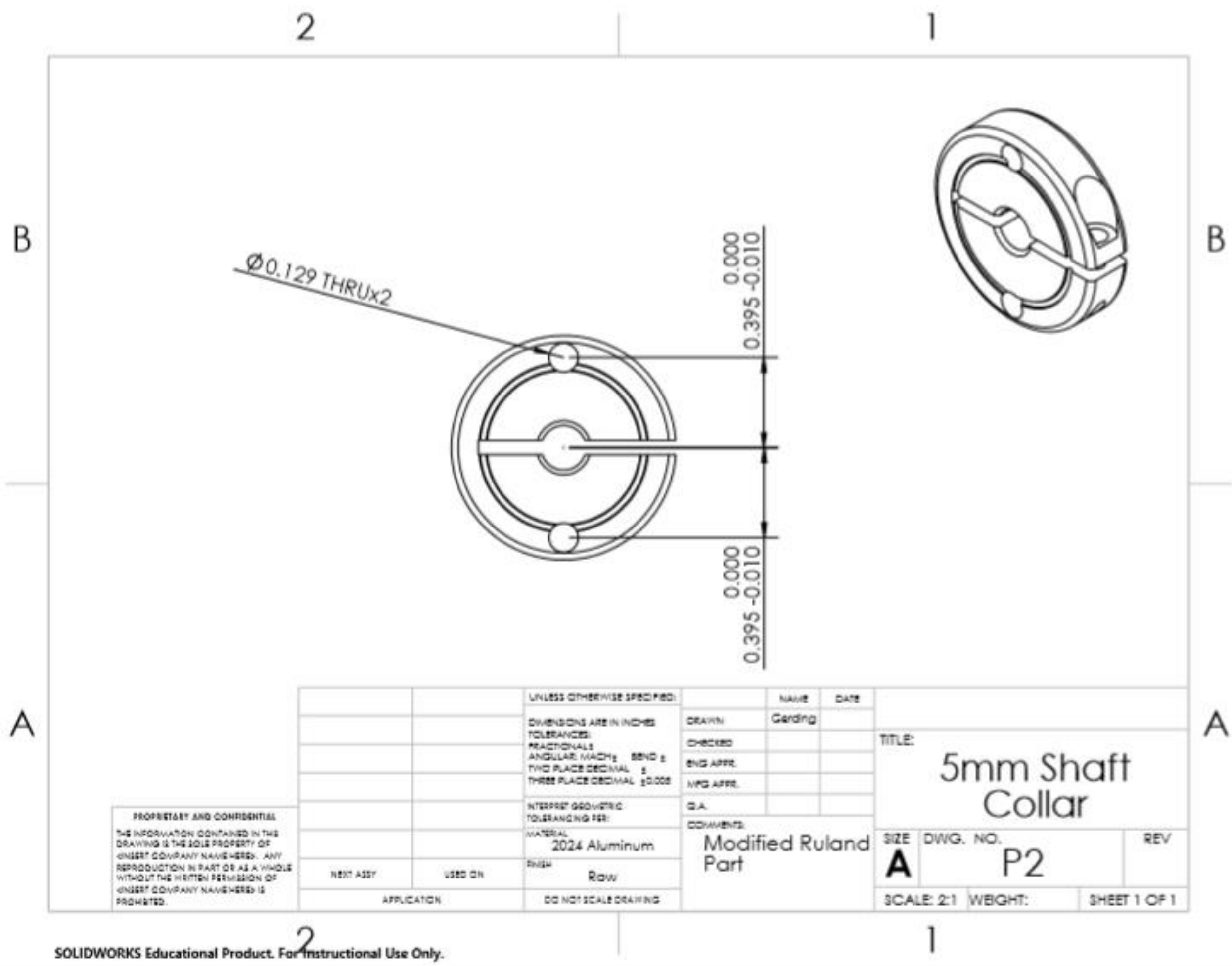

Figure 11: Shaft Collar

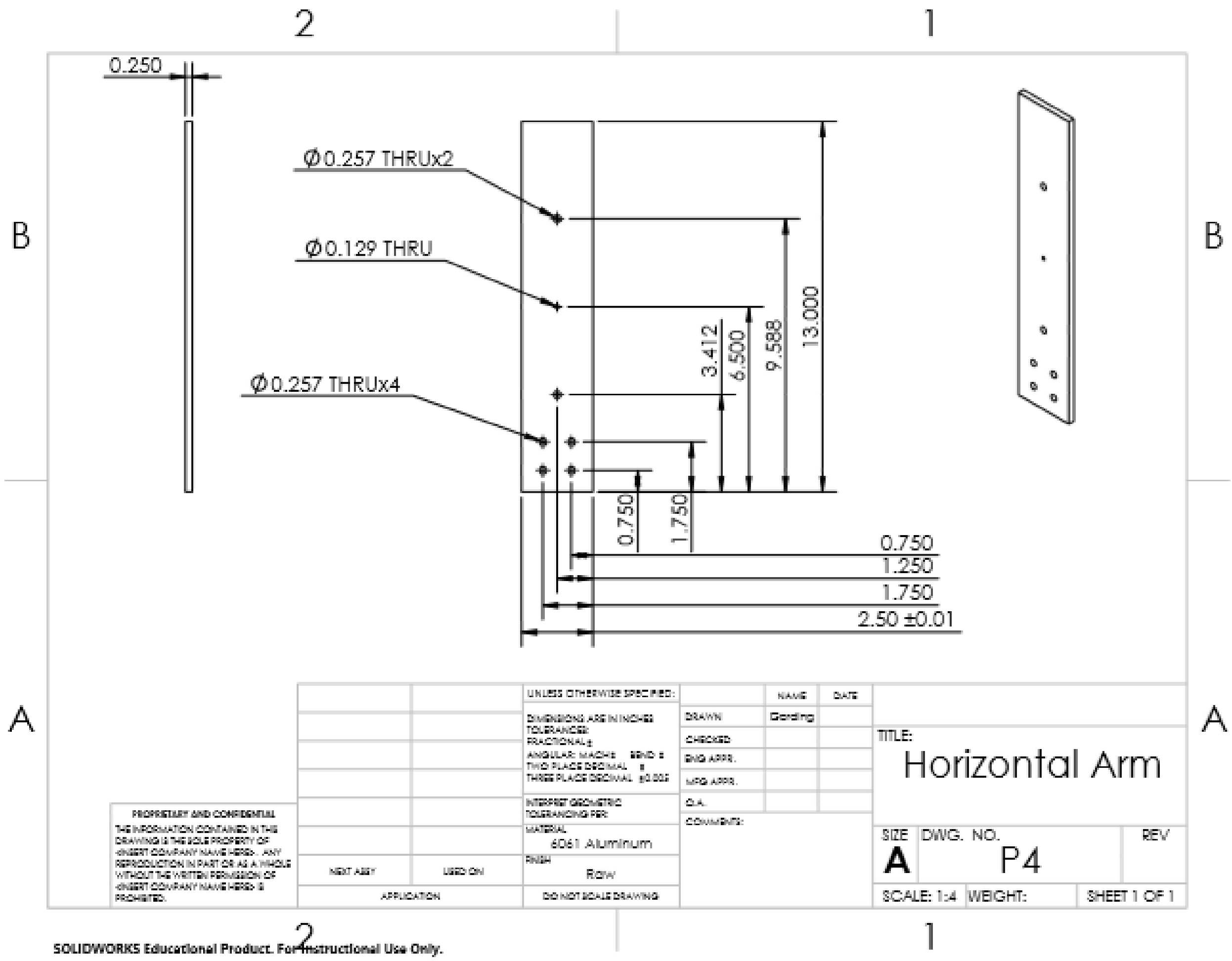

Figure 12: Horizontal Arm

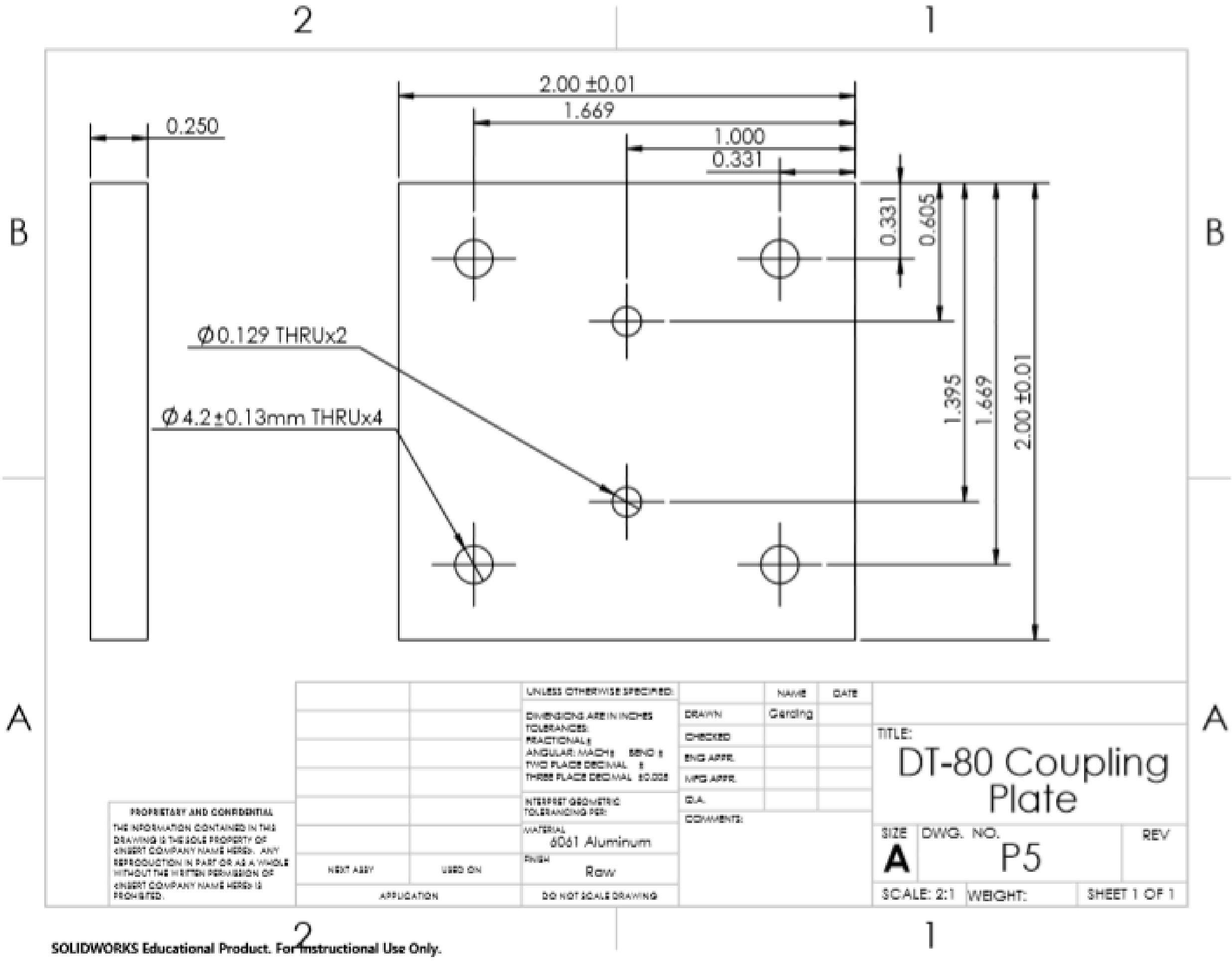

Figure 13: DT-80 Coupling Plate

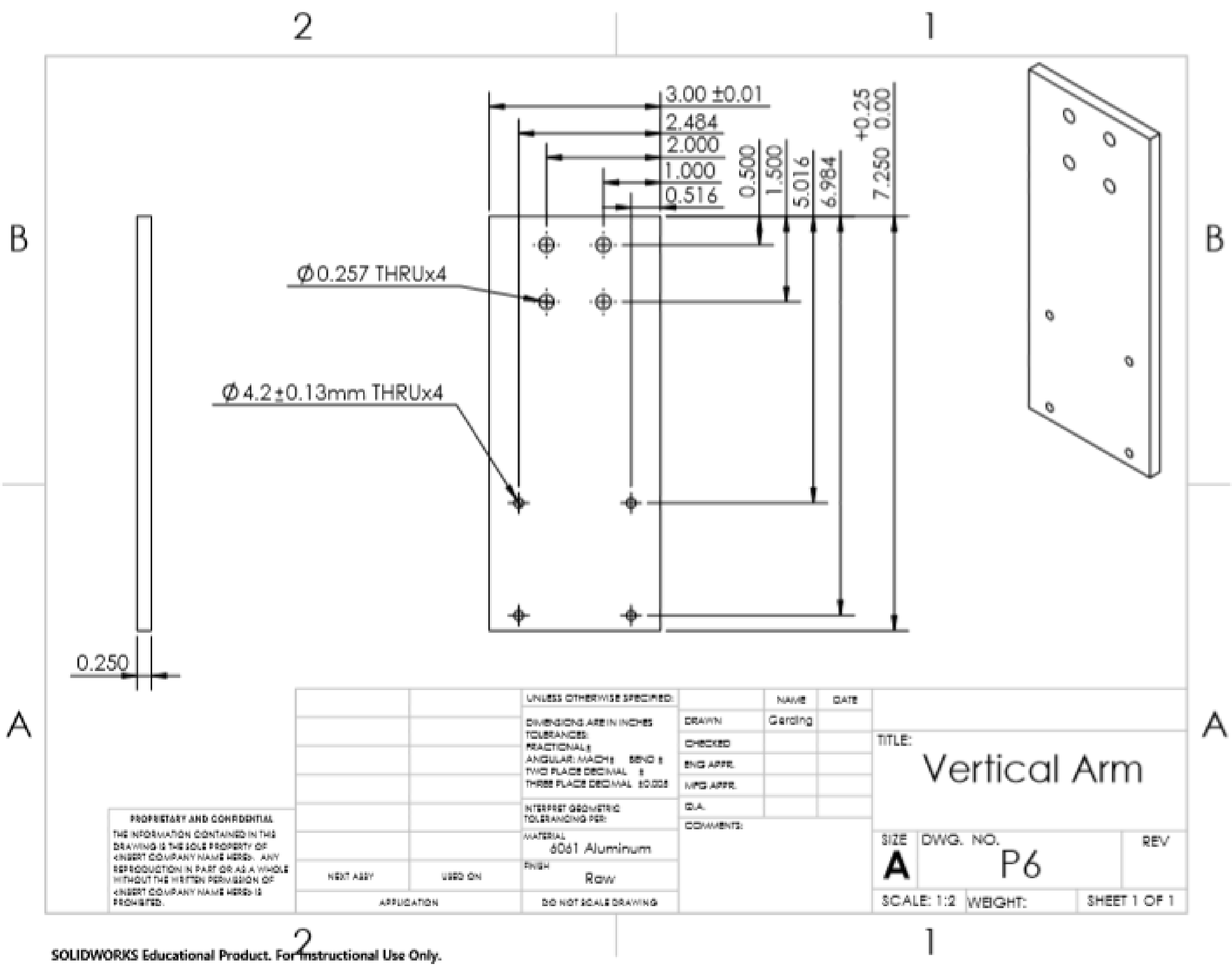

Figure 14: Vertical Arm

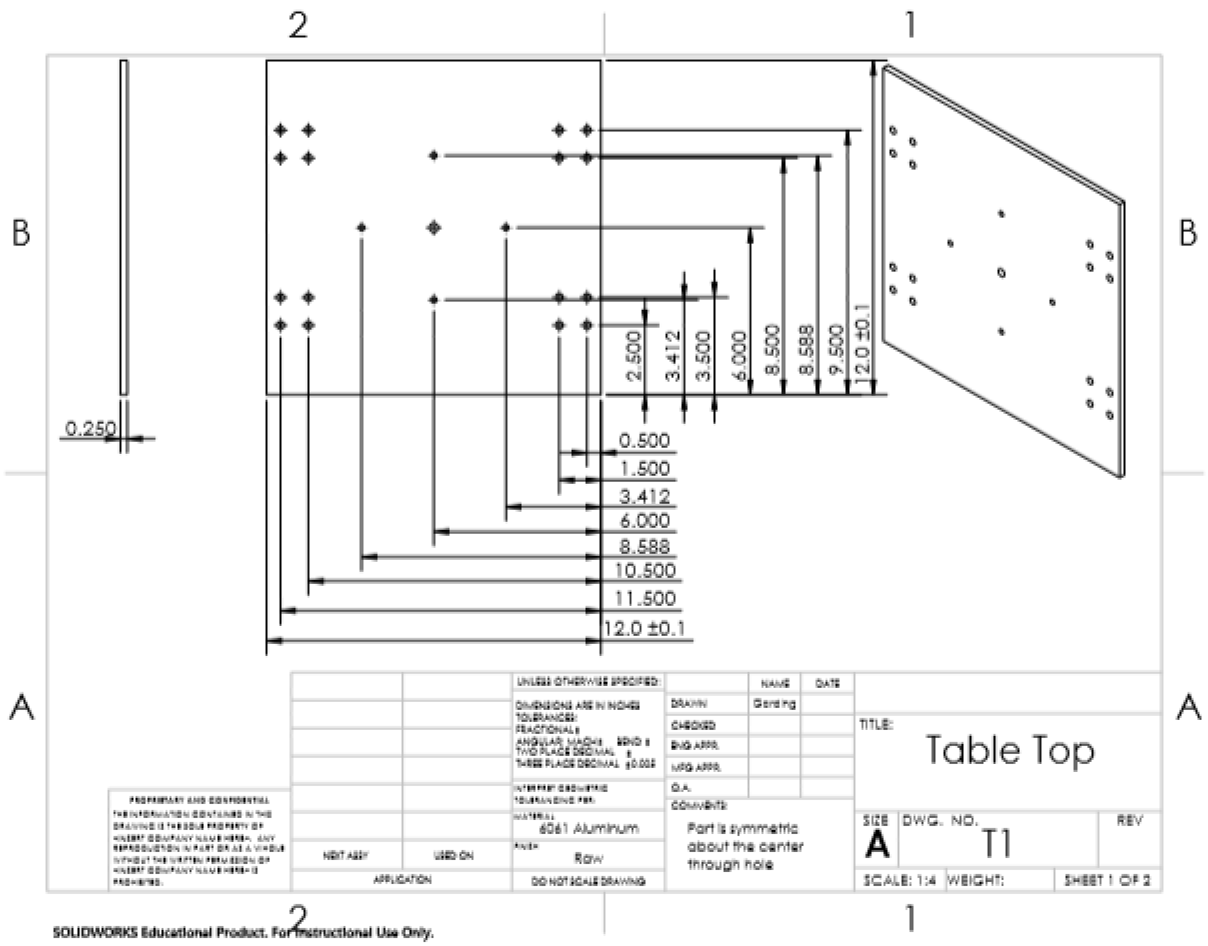

Figure 15: Table Top Sheet 1

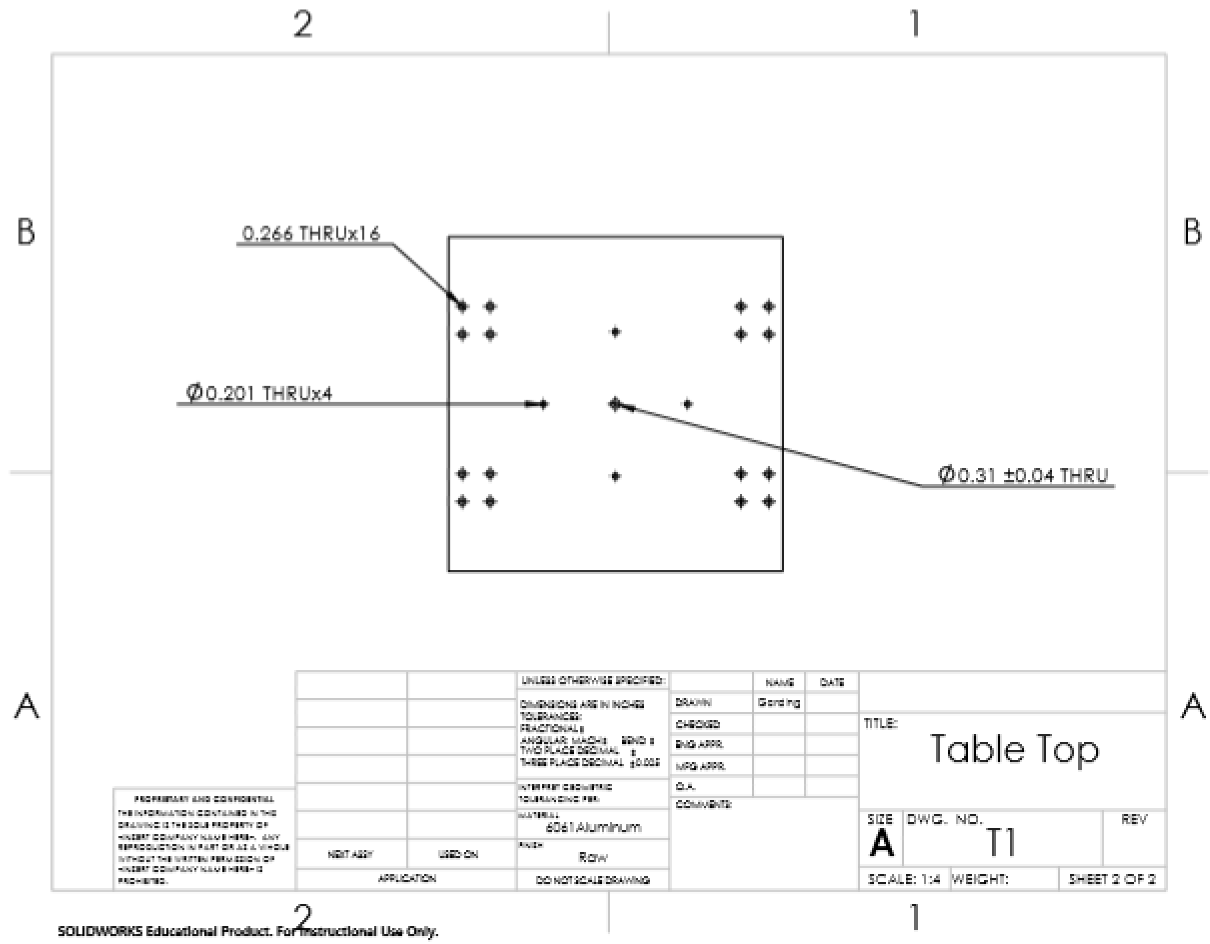

Figure 16: Table Top Sheet 2

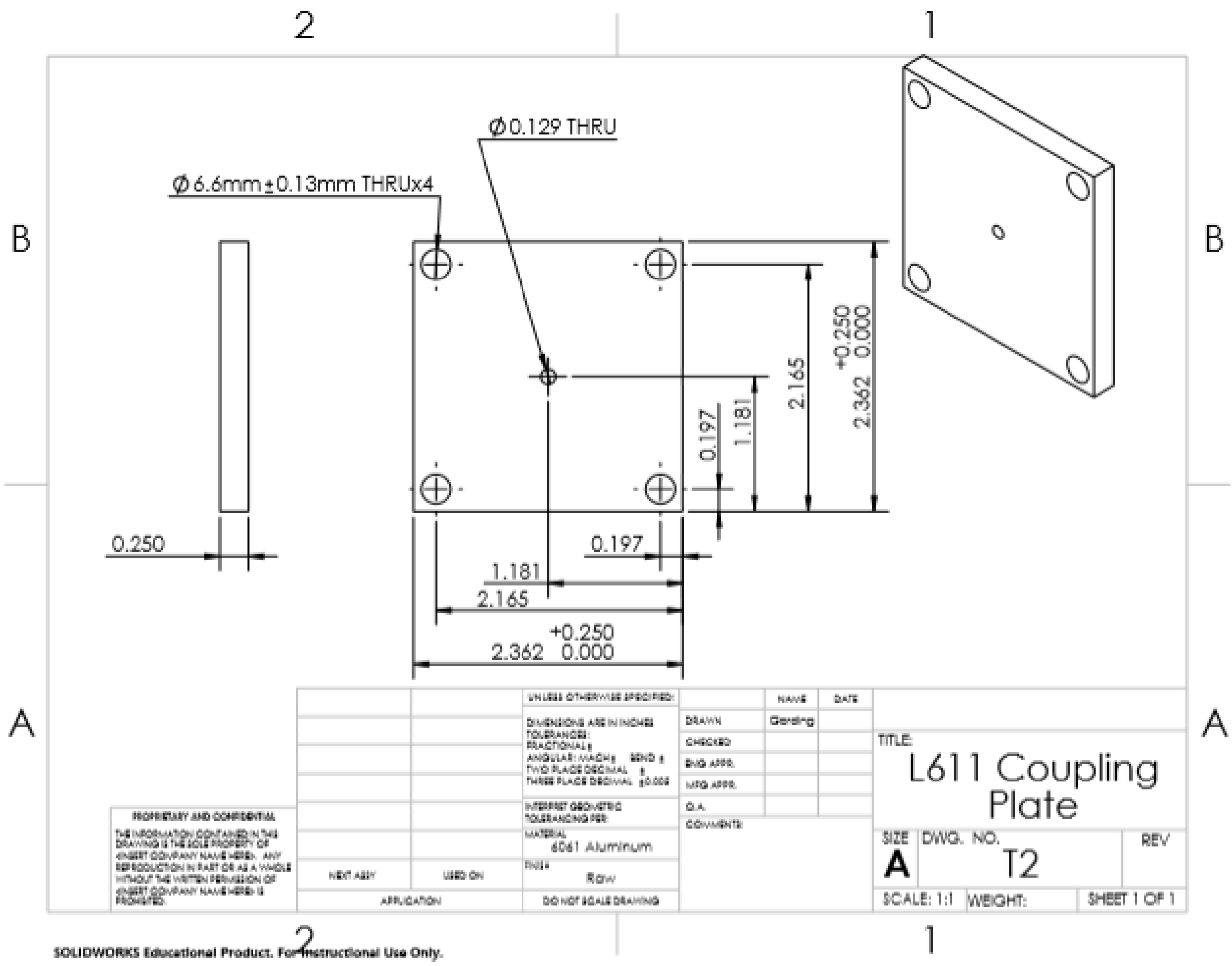

Figure 17: L-611 Coupling Plate

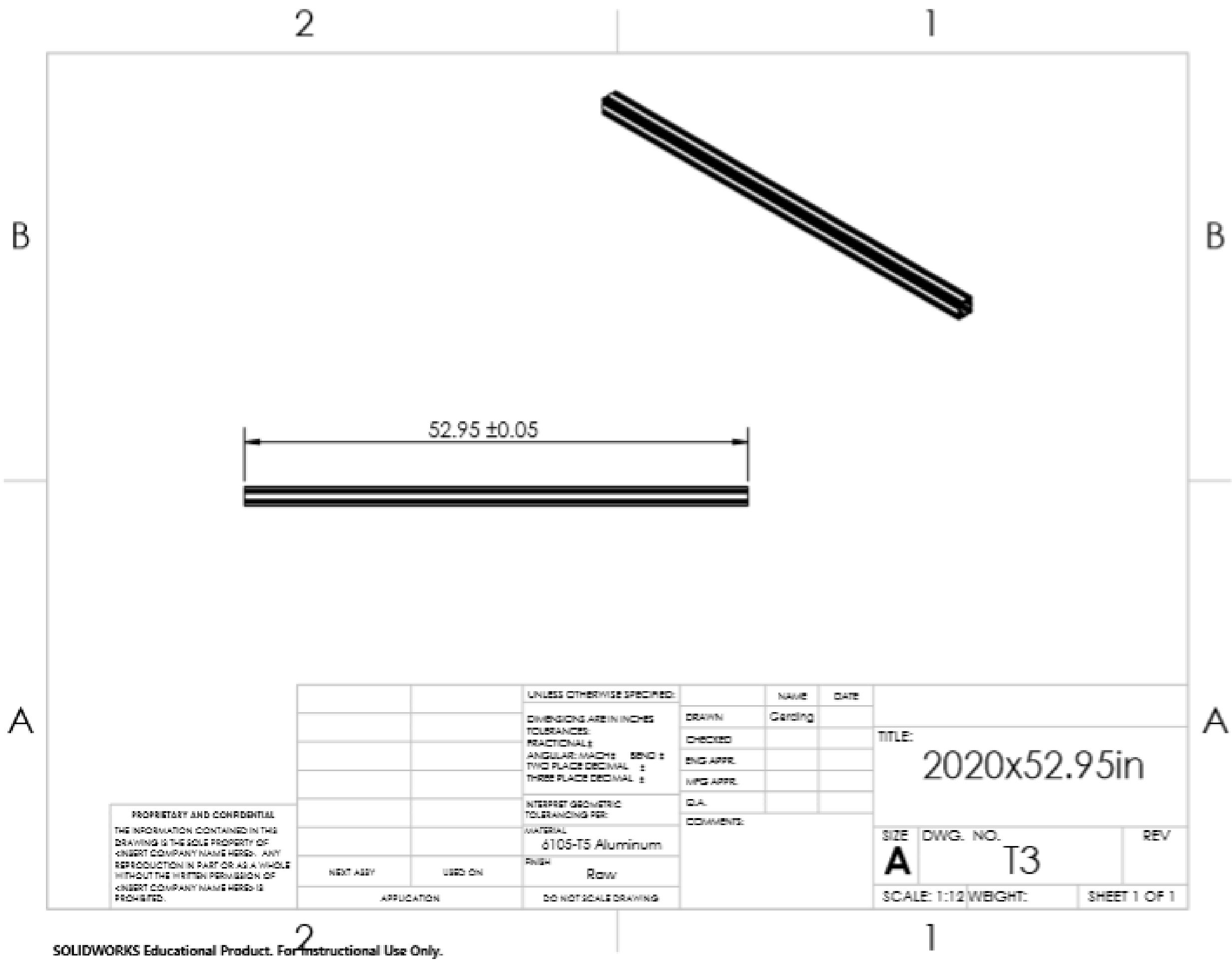

Figure 18: 2020x52.95in

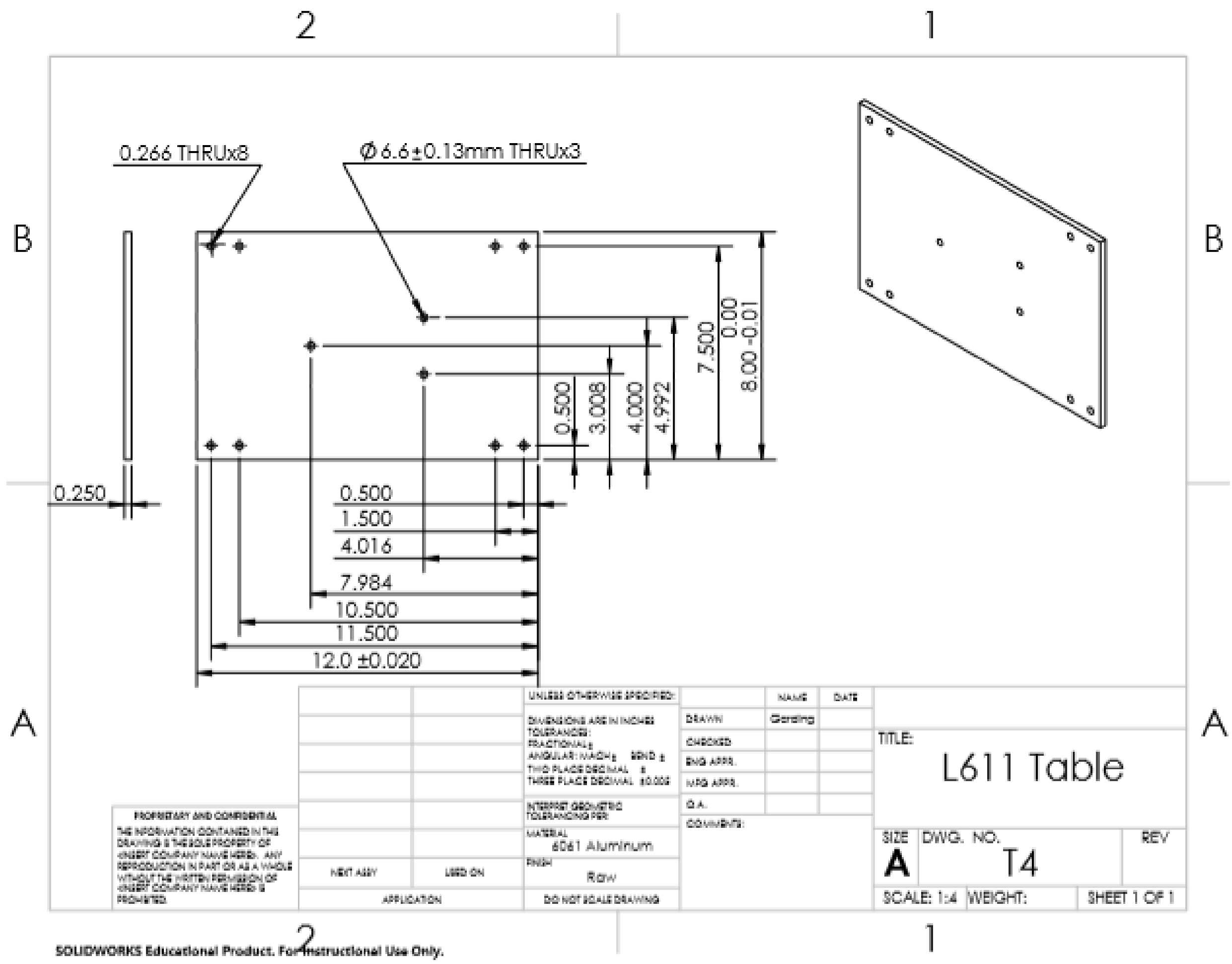

Figure 19: L-611 Table

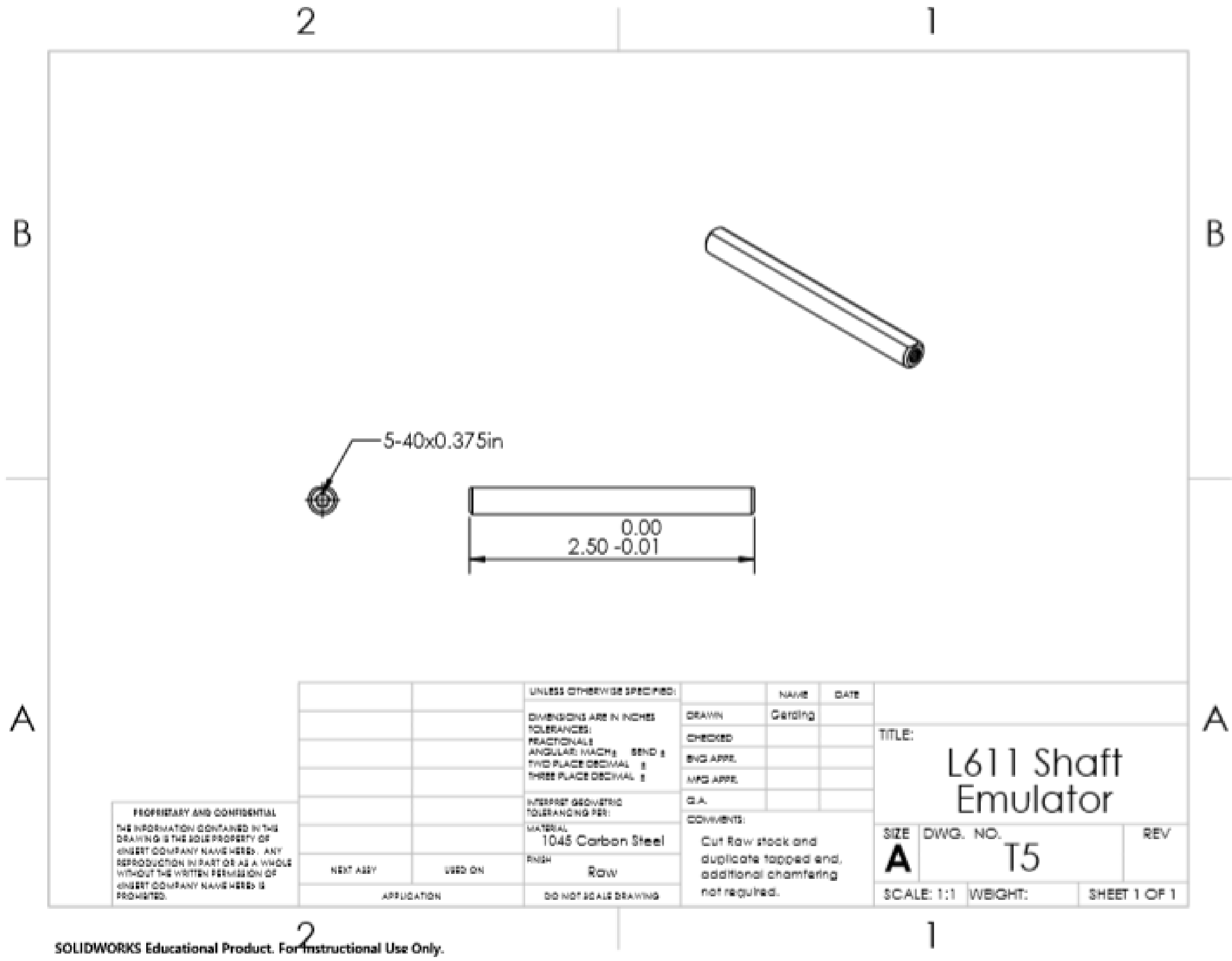

Figure 20: L-611 Shaft

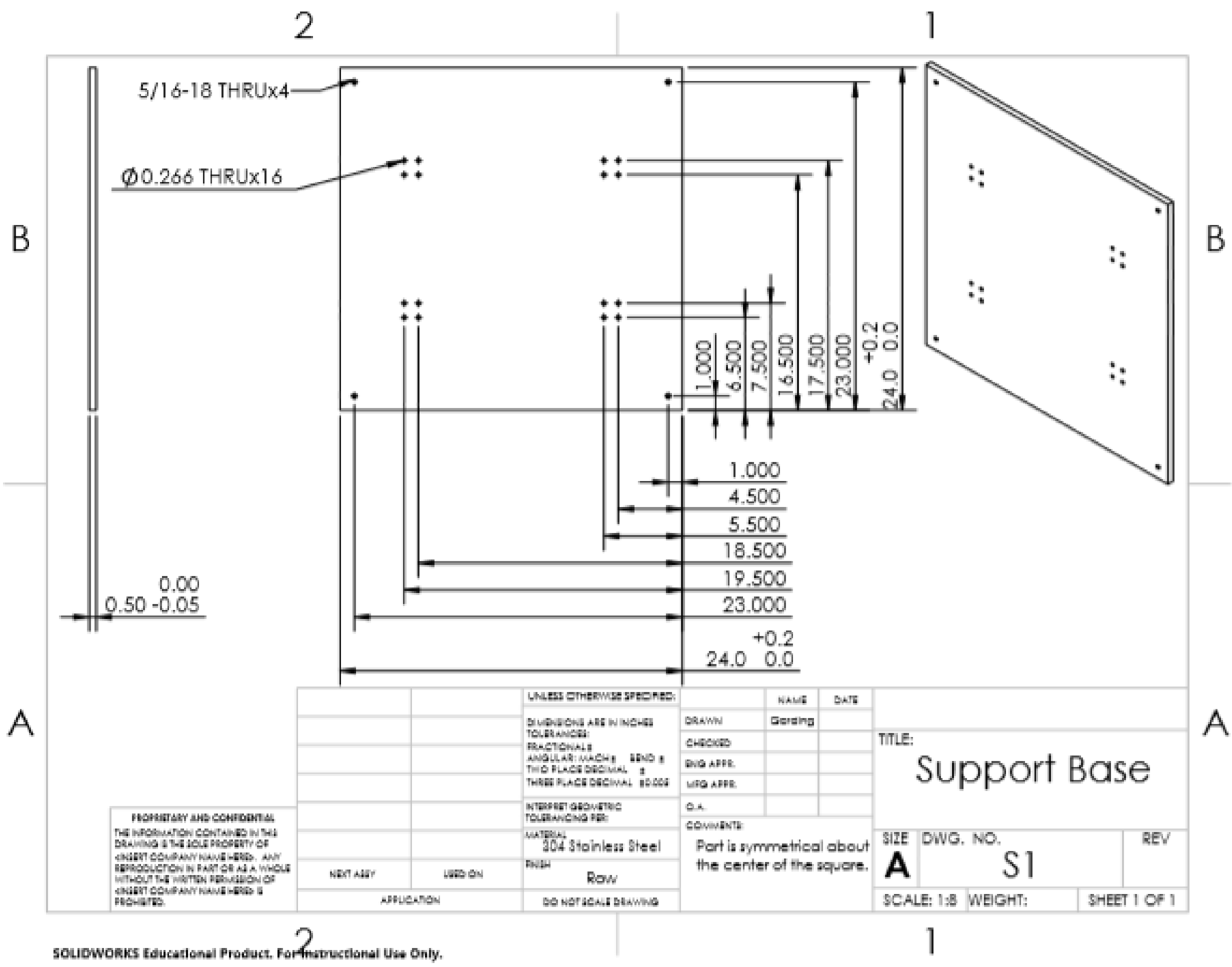

Figure 21: Support Base