UNIVERSITY OF MICHIGAN
DEPARTMENT OF MECHANICAL ENGINEERING

3D Imaging of Microstructure Rotational Micro Platform

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EXECUTIVE SUMMARY

Realizing 3D models of everything around us is becoming an increasingly important practice. The granularity and fidelity of such impressions is a particularly integral characteristic that determines the utility of these models. Finally the ease with which such an impression can be created will ultimately determine whether such techniques are actually utilized in practice.

A brief look is taken at prior benchmark implementations for creating 3D impressions and then our approach is described in software and hardware for automating the process of digitizing small-scale three dimensional objects in a consistent laboratory setting. Our system employs piezoelectric actuation. This method of actuation is capable of achieving infinite resolution which is particularly relevant to micro-scale positioning applications like this one, however a system cannot leverage this fact without incredible precision in manufacturing and this is the primary factor in realizing the full potential of this design approach. In the context of our design time frame we were not able to fully explore this interesting avenue.

Outlined in this paper are the engineering specifications requested of us, namely resolution requirements and the particularly constrained volume requirements that shaped most of our design choices. Following is background information and descriptions of the design iterations we explored throughout a one-semester college design course.

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1. BACKGROUND

It is common to take 2D images of microstructures with microscopes in order to gain information on the grain size and phases of the material [1-2]. It is difficult, however, to get an impression of exact location, spatial extent, and detailed geometry of the microstructure, and unable to produce a 3D model directly from such images [3]. Moreover, 3D images are especially crucial to biomedical purpose, energy study, and microelectronics [4-5]. Therefore, various methods have been developed to produce 3D images of microstructures, and can be classified into two large categories: contact and non-contact 3D scanning. Contact scanner uses a physical touch to evaluate the structure of the subject. One type of contact scanner is CMM (coordinate measuring machine) as shown in Figure 1. Non-contact scanner can further be categorized into two different methods. Active scanners (Figure 2) emit laser beam onto the subject and detect the reflected beam to shape the 3D images, whereas passive scanners (Figure 3) uses visible light to detect the shape of subject and are often done with digital cameras [6].

Figure 1: An example of contact scanner: CMM produced by Coord3 Industries [7].

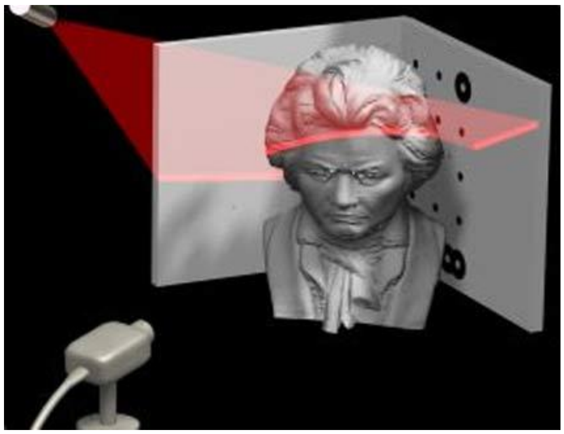


Figure 2: An example of non-contact active scanner using laser beam [8].

Figure 3: An example of non-contact passive scanner: WT-TD350-LCD (SXGA) produced by WaltronTech Electronic Technology [9].

Passive scanning is a viable method for digitizing the structure of microstructures. If the orientation of the microstructure could be changed, then we could use the same microscope camera to take pictures at multiple angles to construct 3D images. A number of microstructure pictures at different angles are required to create a 3D model [10]. Our device will use this passive scanning method by taking pictures of microstructure at multiple angles. We will design and manufacture a mechanism with a platform on which the microstructure will rest, where the platform needs to rotate about both vertical and horizontal axes. Hence, we are designing the device for a predetermined shell to integrate with microscope, and thus our assembly, including actuators, must fit in the shell provided.

2. PROBLEM DESCRIPTION

Most current microscopes attached with a digital camera can provide 2D images of micro objects, without providing any height information. Therefore, a platform for the microstructures rotating along two different axes is required to combine 2D images taken at different angles with a software tool to form a 3D image of the micro world. Our sponsor provided a specific microscope accessory to connect the rotating platform to the microscope, and it constrains the dimensions of our design. Moreover, in order to disregard the generation of static electricity which could interfere with the captured images, the surface of the platform needs to be grounded. Furthermore, the motion of rotation should be remotely controlled so that the mechanism does not need to be detached from the shell after every shot of image.

There are many attempts on the market that can create different views of the microstructures on microscope. There are various types of products and patents including microscale actuators and microscale multi degree of freedom mechanism.

For example, H-811-Miniature Hexapod, Compact 6-Axis Positioning Stage made by Physik Instrumente (PI) provides a possible mechanism that can achieve desired rotation angle about both horizontal and vertical axes (Figure 4) [11]. It uses Parallel-Kinematic Precision Positioning System to generate six degree of freedom motion. However the mechanism is assembled with 6 supporting column structures which are way more complicated and challenging to fit in our micro-scale model. Also, this system does not allow 360 degree in plane rotation.

Figure 4: H-811-Miniature Hexapod, Compact 6-Axis Positioning Stage from Physik Instrumente.

Another mechanism that achieves multiple degrees of freedom is shown in the patent “Multiple Degree of Freedom Micro Electro-mechanical System Positioner and Actuator,” shown in Figure 5 [12]. It uses a semi-conductive layers along with a series of beams to generate motions from relative actuation between individual actuators.

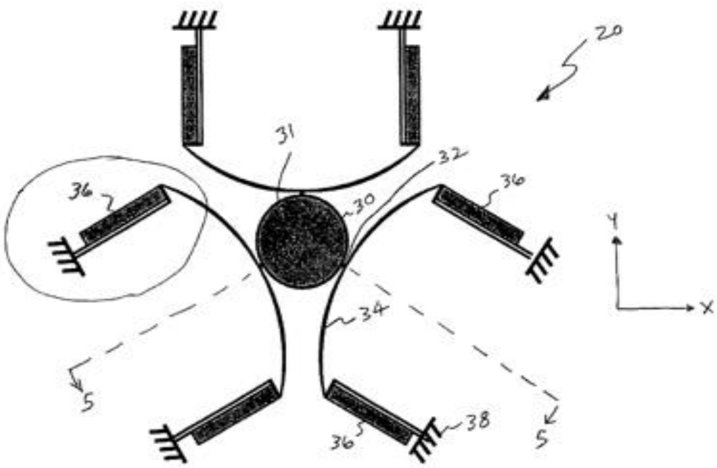


Figure 5: Patent image of “Multiple Degree of Freedom Micro Electro-mechanical System Positioner and Actuator.”

While previous two examples concerns more with the degrees of freedom in motion, the following two patents take accuracy and precision in motion into more consideration [13-14]. The first patent is “Ultra-precision Two-dimensional Moving Apparatus” (Figure 6) [15]. It uses a laser interferometric measurement system which measures the error signal between the measured position and a desired position, correct the position by using piezoelectric actuators and closed loop control.

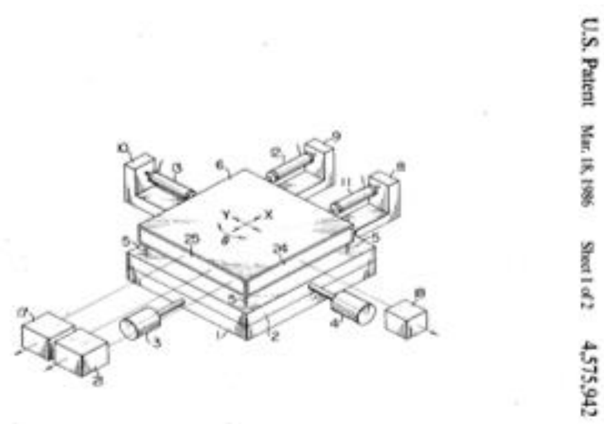


Figure 6: Patent image of “Ultra-precision Two-dimensional Moving Apparatus.”

The other patent is “Microscopic Positioning Device and Tool Position/Orientation Compensating Method” (Figure 7) [16]. This design also uses piezoelectric actuators to control the position in nano-order, and allows six degrees of freedom including a full rotation. For our design, small piezoelectric actuators are necessary, and PCB motors would fit into our purpose (Figure 8) [17].

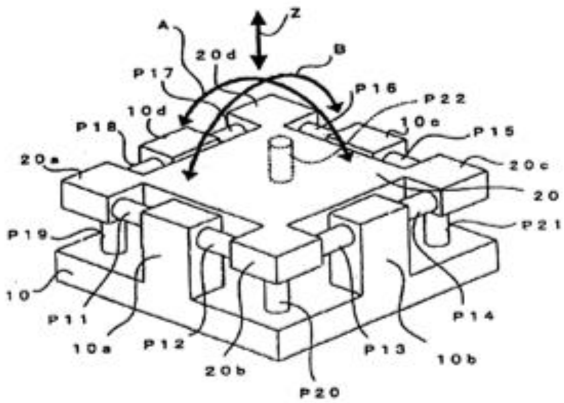


Figure 7: Patent image of "Microscopic Positioning Device and Tool Position/Orientation Compensating Method."

Figure 8: PCB motor using piezoelectric actuator.

There are other types of actuators used for micropositioners as well, such as magnetic, electrostatic, thermal, and electrochemical actuators [18]. These actuators may also be considered as they are small enough to fit into our design and have high precision in motion. For example, the patent "Multiple Degree of Freedom Micro Electro-mechanical System Positioner and Actuator" uses electrochemical actuators for various motion [12].

On the other hand, the patent on "Microscope Stage Moving Mechanism" incorporates microscope with the moving mechanism (Figure 9) [19-20]. Although this is not remotely controlled, it gives an idea of attaching the platform onto the microscope.

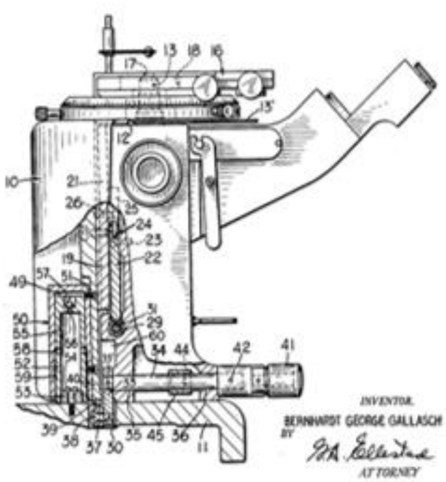


Figure 9: Patent image of "Microscope Stage Moving Mechanism."

Although there are various types of products and patents available, such products usually do not fit inside the constrained dimension of the shell, and/or not provide enough in plane rotation or tilting. Most of the rotary platforms are too large or too small to be used on the microscope. Since our project has strict requirements on dimension of the product, we need to design smaller product to fit sponsor's requirement in dimension. Also, some precise mechanism of current products depends on manual control. We need to make our device remotely controlled. Furthermore, similar products in the market do not provide enough tilt angle and full rotation at the same time. Rotating stages do not tilt, while multi degree of freedom positioning stages does not rotate 360 degrees along one axis.

3. SPONSOR REQUIREMENTS AND ENGINEERING SPECIFICATIONS

3.1. SPONSOR REQUIREMENTS

In order for our designed platform to complete its purpose of reconstructing 3D images of microstructures from multiple 2D images taken at various angles on a microscope, our team set up six user requirements to base our designs. All the user requirements are proposed by our sponsor. Our design should:

1. fit inside a shell to integrate with a microscope,
2. have high accuracy and precision of imaging microstructures with resolution less than 0.1 degrees,
3. have a conductive platform to be grounded,
4. achieve certain rotation angles about horizontal and vertical axes,
5. limit the power input,
6. and adjust for loading conditions.

3.2. ENGINEERING SPECIFICATIONS

3.2.1. Dimension

Our platform is to be attached to a microscope with digital camera, so that the camera can take images of the mounted microstructures. Thus, our design should fit inside a shell which integrates our device with the microscope. Our sponsor provided the dimensions of the shell, and in order for our assembled platform to fit inside, our designed platform should have a diameter less than 25.5 mm and height less than 31 mm. This is the most important criterion for our specification because unless our device is attached to the microscope, the whole mechanism cannot perform properly to capture multiple 2D images and generate 3D images from them.

3.2.2. Resolution Angle

Resolution angle, as defined by our sponsor, is the difference in angle between the original position and the same position after one full rotation. Our sponsor suggested the resolution angle should be less than 0.1 degrees. This is to achieve high accuracy and precision in imaging microstructures. With much difference in this angle, the captured 2D images may cause error while constructing 3D images. Thus, this requirement should be met with carefulness in designing the mechanism, selecting the actuator, and manufacturing the parts.

3.2.3. Conductive Platform

It is important to avoid static electricity to be generated while taking the images of microstructures because it may influence the captured images. Therefore, the platform should be grounded, and thus the material for the platform should be made out of conductive material, or it is required to be coated with conductive material. This specification has high priority.

3.2.4. Angles of Rotation

For this specific purpose of generating 3D images from 2D images of microstructures, various angles of pictures should be taken. In order to achieve this, our mechanism should have tilting along two different axes with the maximum angles of 30 degrees, as suggested by the sponsor. However, because it is much preferred to have multiple pictures at a variety of angles in order to accurately generate 3D images, we would try to achieve the in plane rotation of 360 degrees, along with 30 degree tilting motion along another axis.

3.2.5. Power Input

Our sponsor limited the power input to be less than or equal to 12 V. It is to be compatible with the microscale motors. This specification is easier to meet because small size of our mechanism, limited functioning of rotating along two axes, and light microstructures to be mounted do not require much power.

3.2.6. Loading Mechanism

There are cases when microstructures are under deformation when constructing 3D images. In order to perform this, the sponsor requires us to design a loading mechanism to place on the platform. An additional motor can be used to control force over the microstructures with voltage difference. This is a secondary requirement and our team did not consider achieving this specification in this project.

4. CONCEPT GENERATION

In order to start generating design concepts, our team performed functional decomposition. The major performance required by our sponsor is platform rotation, tilting rotation, and loading mechanism. In this report, loading mechanism is not considered as mentioned by our sponsor. Figure 10, pg. 10, shows the full sketch of our functional decomposition.

As shown from the functional decomposition, major functions of our mechanism for this project are two rotation motions along two different axes with high precision and maintaining its center position within a small constrained dimension so that the microscope can take pictures at various angles and the images can be combined easily to produce 3D model of the microstructure. Therefore, our team mainly focused on generating concept designs to rotate in two degrees of freedom in a small scale, and varied the methods of actuation and force transmission.

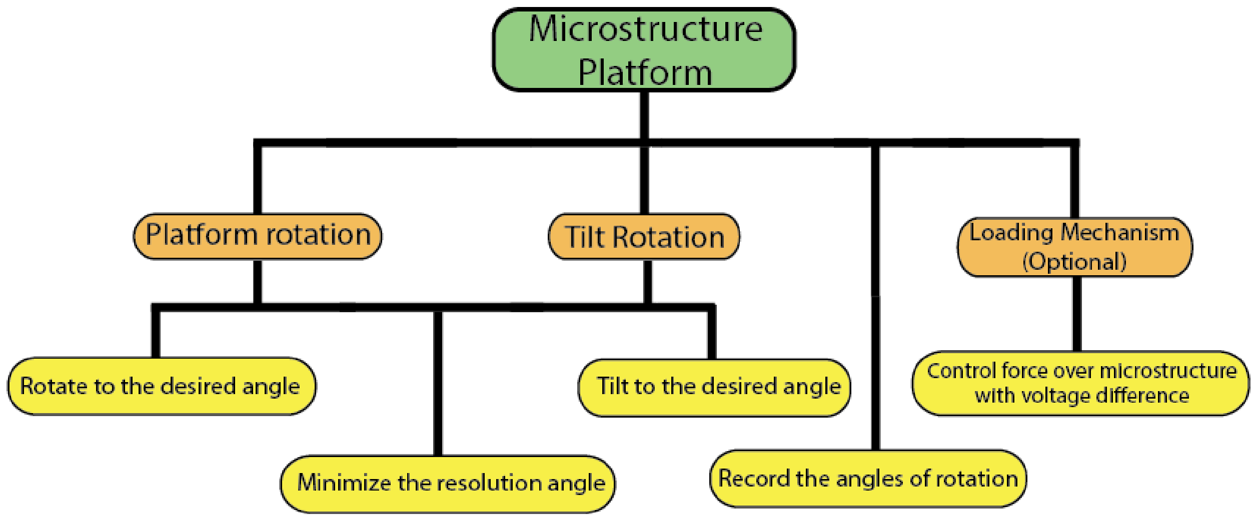


Figure 10: Functional decomposition of our mechanism. It should rotate and tilt to the desired angles, while minimizing the resolution angle less than 0.1 degrees. Also our mechanism needs to record the angles of rotation so that we know at which angle the images are taken. Lastly, it should have additional mechanism to control force over microstructure with voltage difference.

In order to generate multiple and diverse ideas, each member of our team came up with at least four designs on their own, and gathered together as well to come up with new design concepts based on our literature search and brain storming. Afterwards, our team came up with 20 design concepts. Five most competitive and distinct concepts are described in the following paragraphs, and further discussed in Concept Selection to evaluate each design based on Pugh Chart. Other remaining 15 concepts are described in Appendix A.

Our first major design concept is using ordinary two motors to achieve rotation along two different axes (Figure 11). This is the most common design concept that several team members came up with. It requires two motors, each of which rotates the base plate so that the images of the microstructure can be taken at a variety of angles.

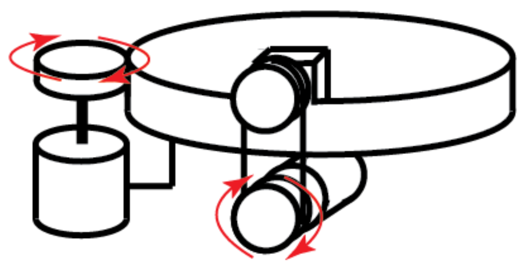


Figure 11: First major design concept using two ordinary motors to rotate along two axes.

Our second major design concept is using three legs to achieve tilting along two different axes (Figure 12). This design is based on the literature search of H-811-Miniature Hexapod, Compact 6-Axis Positioning Stage made by Physik Instrumente (PI) [11]. Instead of using six legs to achieve six degrees of freedom, we simplified the design into three legs. By adjusting the lengths of the legs, the base plate can tilt at various angles.

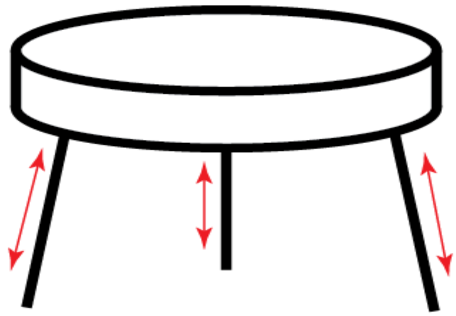


Figure 12: Second major design concept using three legs to tilt at different angles.

Our third major design concept is using a linear actuator to tilt the base plate while using a PCB motor to rotate the base plate (Figure 13). A hinge is placed at the center of the base plate and one end of it is lifted using a linear actuator to create tilting motion. A weight is placed at the end of the plate so that when the linear actuator is shrunk, the base plate can attain its original position. Moreover, a PCB motor is used underneath the base plate so that the microstructure mounted on the plate can rotate while the plate is tilted to take images at various angles.

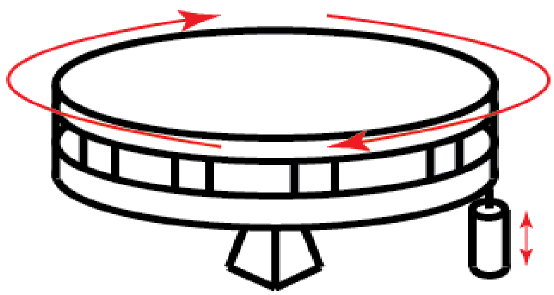


Figure 13: Third major design concept using a linear actuator to tilt and PCB motor to rotate the base plate.

Our fourth major design concept uses two PCB motors to generate in plane rotation and tilt (Figure 14). A tilt rod is attached to one end of the PCB motor at the bottom, so that as the motor rotates, the rod adjusts the tilting angle of the base plate.

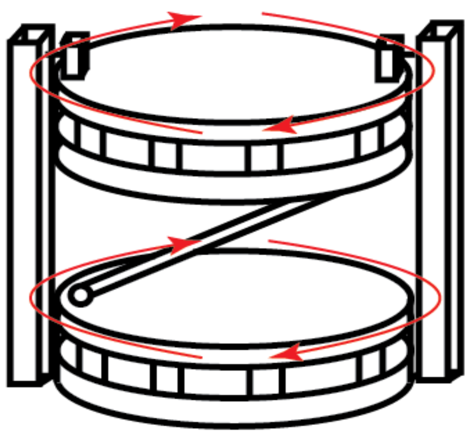


Figure 14: Fourth major design concept using two PCB motors to rotate and tilt the platform.

Our last major design concept is using spiral rotation, so that tilting and in plane rotation can be done using a single actuator. (Figure 15). This design concept allows the combined motion of tilting and rotating, and thus, only one actuator is required. There is a spiral slot along the wall of the mechanism, so that as the base plate rotates, it changes its tilting angles, so that multiple 2D images at different angles can be taken.

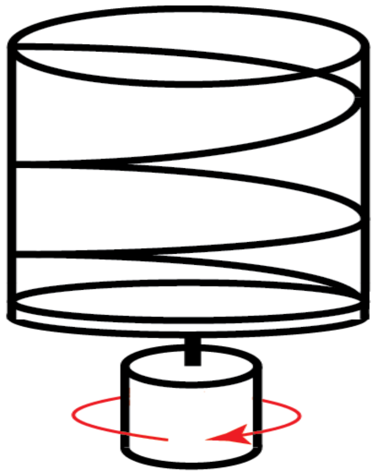


Figure 15: Fifth design concept to achieve tilt and rotation using a single actuator with the help of spiral slots.

5. CONCEPT SELECTION

To determine the most suitable concept for our engineering specifications, we transformed them into several judging criteria. Consider that we should include every detailed requirement from our sponsor, we carefully thought about the financial, temporal, and technical constraints. Finally, we came up with seven criteria that cover all the aspects we should pay attention to and weighed them out of 100 percent.

The first criteria is manufacturability. It takes 15 percent weight in the total score system and it is defined as the easiness and feasibility of manufacturing. Since this project requires us to make a small scale product, we need to consider whether our manufacturing methods and techniques allows us to make its parts with high precision and accuracy.

The second criteria is ease of assembly. It has the same weight as manufacturability. After we have manufactured the parts, we need to assemble them. Considering the small dimension constraint, our parts would be too tiny to assemble using the tools that our team can access. Hence, to make our product user-friendly, we hope that the assemble process would be short and easy which won't cause users' complaint.

The third criteria is precision. According to the user requirement, the resolution of the rotation should be less than 0.1 degree. Since it is one of the most important requirements, we set it 15 percent of the total weight. To reach such a precision, we have to use encoders on our actuators and the encoders we used have to be precise enough.

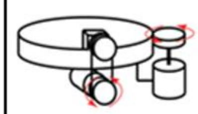
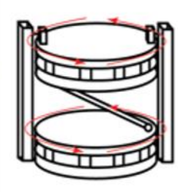
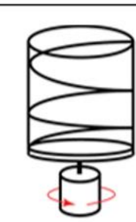
The fourth criteria is achievable angle. According to the engineering specification, the angle range of rotate should be 360 degrees and the angle of tilt should be around 45 degrees (at least 30 degrees). Any concepts that do not reach this angle requirement will lose some scores on this criterion which depend on how large its angle range is. It is also an important criterion, so it takes 15 percent of the total weight.

The fifth criteria is cost. Our funding for this project is about 400 dollars. It is not so important because our project is used in university research lab which should be able to afford the price on a rotational platform. So cost is only 10 percent in our total weight.

The sixth criteria is the ability to maintain center. This requirement is the most important one for our project. Since the purpose of our project is forming 3D images using a microscope, we must assure that the photos we take are available for the relevant software. Thus, when we take pictures, we need the samples always remain in the center of the scenes or at least within the frame. Any displacement may cause unexpected errors.

The last criteria is ease of motion control. During operation, users would want to control the motion of the platform as what they want it to be. In other words, the motion control should be very easy and users can make the object reach any position they like to take photos. We set 10 percent of the total weight for it.

Table 1: Pugh chart showing the concept selection process with five major design concepts.

Description		Ordinary 2 Motor Rotation	3 Leg Tilt	Linear Actuator + PCB	Smart 2 PCB Motors	Spiral Rotation
Sketch						
Criteria	**Weight**	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**
Manufacturability	0.15	2	1	2	7	6
Ease of Assembly	0.15	6	4	6	5	9
Precision	0.15	2	8	6	7	6
Achievable Angle	0.15	10	2	9	8	2
Cost	0.1	7	2	3	6	9
Ability to Maintain Center	0.2	8	10	7	8	1
Ease of Motion Control	0.1	6	3	7	7	6
Net Score		5.75	4.75	5.55	6.85	5.5

Based on these criteria and weight, we assessed all our concepts by assigning points from one through ten so that we can compute the net scores by summing up all the points multiplied by weight of each criterion. Table 1 shows the scoring of the five major concepts introduced in the previous section.

The first concept is Ordinary Two Motor Rotation platform. The idea of this concept comes from our past experience of using two ordinary motors to control two different motions: rotation and tilt. The advantages of this concept are that it can achieve any angles we want and the sample could always remain in the center. However, since we use ordinary motor, the size of motor can hardly fit in our requirements which means that we cannot come up with a workable mechanism to apply this concept. Also, since ordinary motor has large backlash, it will produce large uncertainty and we will not reach the resolution requirement.

The second concept is Three-Leg Tilt mechanism. This concept comes from our benchmark [11]. Net score of this concept is the lowest among the five concepts because: first, we don't have the condition to manufacture such a delicate device; second, since the motion is controlled by three movable legs, the rotate angle is very limited; third, the cost of this concept is very high; and fourth, the motion of legs is complex, so it is not good for motion control. However it also has some advantages. It has extremely high precision because the motion of legs is precisely controlled by computer. Also, this system can easily adjust the position of sample so that it is easy to make it remain in center.

The third concept is Linear Actuator plus PCB motor platform. We use PCB motor for rotation and linear actuator for tilt. This concept scores high in all criteria except for manufacturability and the cost. Since we need an encoder for linear actuator, we should design a mechanism to calculate the length that the actuator changes. After considering all the possibilities, we thought this concept is hard to realize in this small scale project. On the other hand, the price of a micro linear actuator is over 400 dollars which is exceeding our budget.

The fourth one is Smart Two PCB motors platform. This is our final concept design with highest score. We absorbed all the advantages in the concept of linear actuator plus PCB motor platform and replace the linear actuator with another PCB motor. The reason we chose it as our final concept is that this design does not have such weaknesses as we mention in other concepts. To begin with, it is easy to manufacture because all we need is a ball joint linkage. And then, since it has an easy mechanism and satisfy our angle requirement, it would not be difficult to assemble. Furthermore, PCB motor is a high resolution device and we apply two encoders to record the changing angles. Hence, the cost of two PCB motors is reasonable around 300 dollars. Lastly, our mechanism design allows the sample to maintain in the center and the motion control is simple and straight forward.

The last concept is One Motor Spiral Rotation platform. This design is the simplest one. It has the least complex mechanism and it should be easy to be made. In other words, the manufacturability is excellent and the cost is the lowest. But this concept has some deadly weakness. First, since we use only one motor, the rotate motion and tilt motion will happen in the same time, so we cannot adjust any angle we want. Second, the platform will rise which means the height of the sample will change. Thus the ability to maintain in the center is weak.

6. CONCEPT DESCRIPTION

Based on our Pugh chart from DR2, we concluded that the fourth design using two PCB motors and a rod connecting the top and bottom plate meets the engineering specifications and user requirements the best. From this concept, we generated a CAD model using SolidWorks to visually observe the achievable angles and proportions of the dimension. Figures 16 and 17 shows the top and isometric views of the chosen design's CAD model. This design is just to show the mechanism of achieving tilt and rotation motion, and thus is concise. More specified CAD model of this concept is shown in Figure 20 and further described in Final Design and Prototype.

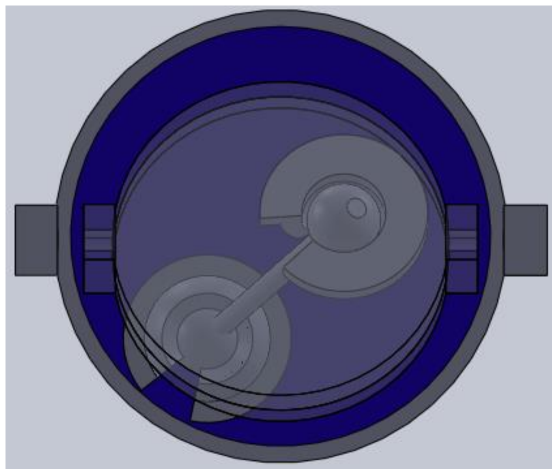


Figure 16: Top view of our chosen design.

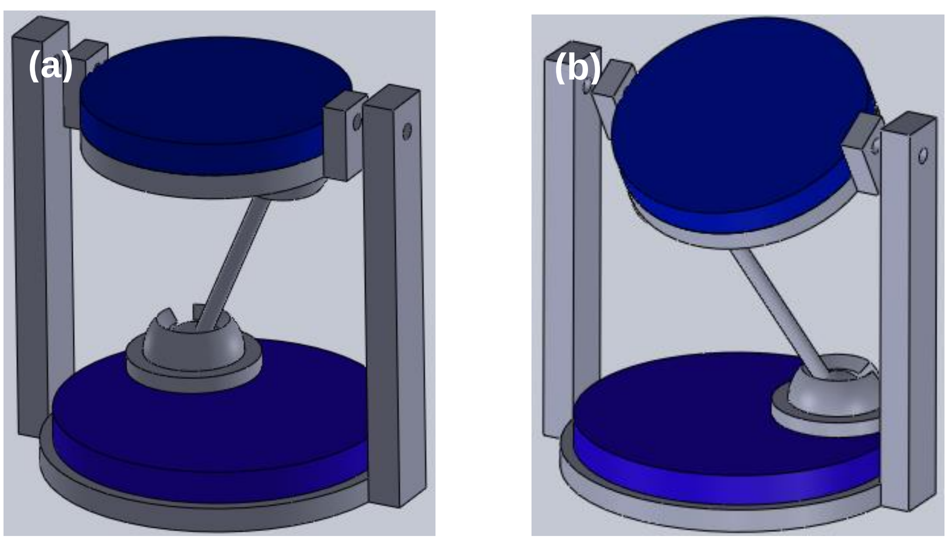


Figure 17: Isometric view of our chosen design at (a) offset position and (b) tilted position.

As can be seen from the side view of the design, there is one PCB motor installed at the base and the one on the upper plate.

The base PCB motor actuates a 3D printed rod, constrained by 3D printed casters. This motion causes the upper platform to tilt. Not pictured above are the encoders. There will be one for each motor. The encoders are used to give feedback to the microcontroller corresponding to what angles the rotor has achieved.

At the present time we are planning on realizing the design by repurposing an evaluation kit provided to us by *PCBmotor*. We have been in consultation with the CEO of *PCBmotor*. We will be able to disassemble the components of the Eval. Kit, which includes two rotors and stators, and the driver. Disassembling the kit will require us to fill in a few mechanical and electrical dependencies. This includes all of the wiring out to the driver/microcontroller and the mounting mechanism for the stators. Additionally we will need to implement a 'casting' mechanism to keep the rotors aligned. This is an important property for our application and will be one of the more challenging bits to implement.

7. ENGINEERING ANALYSIS

In order to determine important features of our mechanism, key design drivers were considered. For this project, our team regards the constrained dimension, and achievable limit of tilting angle to be the major design drivers to consider for our final design. Therefore, analysis to determine the exact dimensions of our key parts for the mechanism, and corresponding tilting angle according to the bottom PCB motor were performed using theoretical modeling method.

7.1. KEY DESIGN DRIVERS

One of the most important sponsor's requirement is that our mechanism should fit inside the predetermined size of a shell; and thus, all parts of mechanism must be assembled in a small space of a cylinder with diameter of 31 mm and height of 25.5 mm. To achieve this goal, we need to choose one kind of mechanism that could save space as much as possible since we need to make sure to leave enough space for rotating mechanism to operate in a certain degree of freedom. Another concern for this design drive is that we need to choose the design as simple as possible because in such small space, the later on assembling and error detection processes would be challenging.

Regarding the motion, platform must achieve both tilt and rotation motion. The tilt angle must achieve at least 30 degrees and the rotation angle must achieve 360 degrees. This requirement of functionality of this mechanism also becomes a major design driver for our project. The mechanism must be such performance without too many complex components because of the limited space.

Since for our project, the tilt motion will be achieved by the rod connecting to bottom PCB motor and the upper level platform. Such connection must be carefully calibrated since it is not a direct control, the error of each part would cause accumulated error for final result. Also, with micro-scale operation with those parts, it is highly possible the human error could cause the damage to the parts that human eye could not detect which could cause potential failure for the whole mechanism.

7.2. THEORETICAL MODELING OF TILT ANGLES

Theoretical model was developed in order to figure out the required angle of rotation of the bottom PCB motor to achieve at least 30 degrees of tilt angle, which is required by the sponsor. This mode of analysis was chosen to mathematically calculate the relationship between the bottom motor rotation angles and tilting for any given dimensions of the design. First, illustrated model, using R and L respectively for radius of the top and bottom plates and length rod and ball caster assembly, was generated as shown in Figure 18.

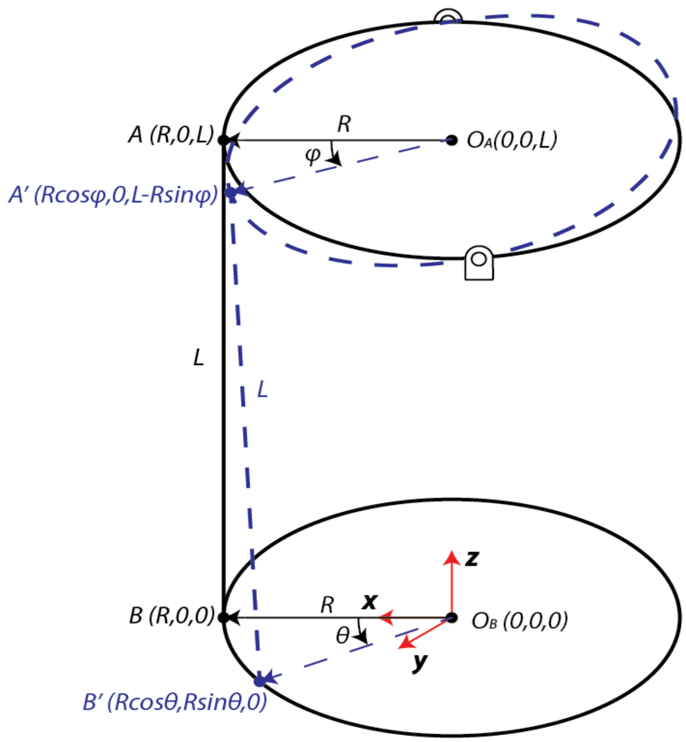


Figure 18: Illustrated model of the chosen design to calculate the relationship between the bottom PCB motor rotation and tilting angle. Black solid lines represent the mechanism at offset position, and blue dotted lines represent the mechanism at tilted position with rotation angle θ and tilting angle φ.

Based on Figure 18, using Pythagorean Theorem for $\overline{A'B'}$, theoretical model for calculating tilt angles can be derived with equation 1.

$$R(1 - \cos\varphi \cos\theta) = L \sin\varphi \qquad \text{(Eq. 1.)}$$

Then, R = 15.5 mm and L = 29.4 mm (values from final prototype, Figure 21) are substituted in equation 1 to find out the achievable tilting angles for the final prototype as plotted in Figure 19.

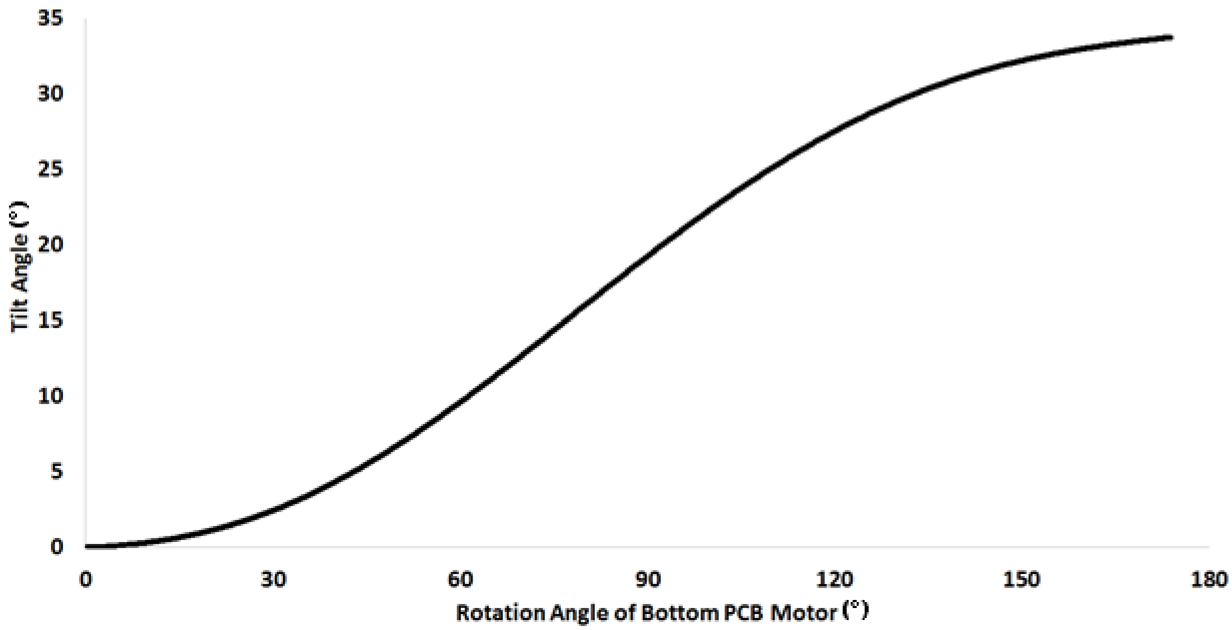


Figure 19: Tilt angle vs. rotation angle of bottom PCB motor. The maximum tilt angle of 34 degrees can be achieved with the encoder count of 180.

Based on this model, we concluded that our determined dimension can achieve the required tilting motion. Hence, because the motor rotates more than the platform actually tilts, we can possible reduce the resolution angle of tilting. At 180 degree motor rotation, the platform can tilt 34 degrees and the intermediate angles can be determined in terms of the motor rotation angle using Figure 19.

This is very detailed analysis without any assumption. However, poor manufacturing and assembling skills can cause slight difference in the dimensions of the parts, and this experimental data may be incorrect. Yet, in such case, we will be able to adjust the relationship between the two angles by substituting different values for R and L, and generate another plot similar to Figure 19. The goal of this analysis was to see if our mechanism can in fact achieve the desired tilt angle with predetermined dimension.

8. FMEA ANALYSIS

FMEA analysis was performed to express the degree of risk for each sub function in numerical values. Considering the recommended actions to decrease the severity, occurrence, and detection of each risk, our team could figure out several methods to minimize potential failure modes. The complete table of the FMEA analysis is included in Appendix B. Paragraphs below explain about two functions of our mechanism and its modes of failure to show the significance of scoring for severity, occurrence, detection, and RPN.

8.1. FUNCTION 1: TILT-ROD

The tilt rod component is the component with the highest risk of failure. There are two potential modes of failure stemming from this one function, with varying degrees of risk priority based on the likelihood of severity, occurrence, and detectability.

8.1.1. Tilt-rod: Mode 1

The ball caster has too much friction but the motor still actuates.

Effect: The rotor, held still by the rod and the friction at each of the ends, stays in place while the motor actuates, and we lose any degree of resolution that we could have gained by micro stepping and interpolating between the divisions of the encoder.

The **severity** is fairly high because even with a good recalibration procedure (*excerpt 1 below*). This failure mode would be hugely annoying for the user. (Score: 7)

If there is a lot of friction this might **occur** quite often. (Score: 5)

Detection: This is really perhaps the most challenging bit. If the rotor slipped only slightly this may be nearly impossible to account for. That being said because we will be looking for this it will be likely we can recognize it before releasing a final version of our device. (Score: 2)

Final RPN: 70

This mode of failure is caused by the lack of a sturdy mate between the piezo chips on the actuator and the rotor. This can be remedied by carefully designing the mate.

8.1.2. Tilt-rod: Mode 2

The ball caster has too much friction, the motor actuates, and causes the rod itself to bend or otherwise fail structurally.

Severity is very high because the device will not be operable after this fails. (Score: 8)

Occurrence: we don't think that this is terribly likely. (Score: 3)

We will certainly **detect** if this happens. (Score: 2)

Final RPN: 48

Bending of the rod is caused by lack of structural integrity in the rod, and can be remedied by reprinting the rod with better structural integrity properties.

Excerpt 1
If the rotor slipping on the stator is a common mode of failure, we will implement a recalibration procedure as follows. Upon a slip: step rotor back to nearest encoder division, and begin stepping forward again.

8.2. FUNCTION 2: ALIGNMENT

Perhaps the most imminent a threat to our design is the risk that the rotors come out of alignment during operation. If this happens our microstructure will be out of the frame of vision where we take photos for the final reconstruction.

8.2.1. Failure mode

The parts are not perfectly aligned during manufacturing.

Effect: The rotor is out of alignment and ultimately the microstructure can't be properly viewed.

The **severity** is high because it's more than an annoyance to realign the structure. It may be entirely prohibitive to the use case. (Score: 6)

Occurrence in this situation is black and white. Either it's occurring or it isn't. (Score: 5)

Detection: detection is tough in this situation because it may be slightly out of alignment when we ship, but worse it may continue to get more out of alignment. Additionally because our final users may be operating the device far more than we could possible spend time on testing in the use case, it may be something that doesn't become terribly apparent until our users have been using the device for some time. (Score: 8)

Final RPN: 240

The cause here lies in any lack of precision during manufacturing. The solution is to carefully consider our manufacturing processes to a high tolerance for precision and robustness.

9. FINAL DESIGN AND PROTOTYPE

9.1. FINAL DESIGN

Our team has gone through multiple amendments to the designs of our concepts. All changes are listed under Appendix C (Initial Design) and Appendix D (Changes to design after DR4). For the final design, our team managed to meet all the required engineering specifications. This is the ideal design. Top PCB stator board is fixed by four screws on the top cup, which constrains the stator assembly fixed at one position to properly transfer the resonance onto the platform. Bottom PCB stator is also fixed by four screws to the base in order to maximize the performance of the motor with stability. The top and the bottom assemblies are linked by a rod with ball casters so that the rotation of the bottom PCB motor can be transferred into tilting of the platform. Hence, using two pin joints on the wall, the platform can maintain its center position even when it is tilted.

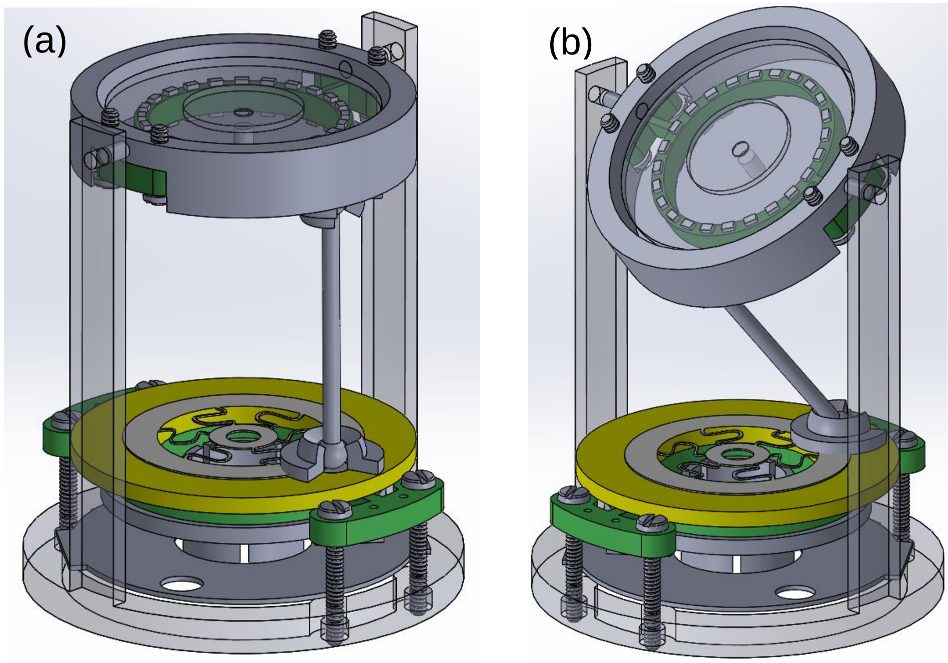


Figure 20: Final Design with optimized stator board at (a) offset position and (b) at tilted position. It fits inside the shell provided by the sponsor, and achieves maximum tilt angle of 37 degrees as shown from (b).

9.2. FINAL PROTOTYPE

Ultimately we could not implement the optimal design as described in the prior section. This was due to the fact that we could not have the custom layout for the stators built in time for the expo. We were then forced to order standard evaluation 13mm stators to utilize in the final design. We had already experienced from our attempts with the 20mm stators that cutting out the stators in order to refactor to a smaller size was a delicate procedure and was highly prone to failure.

Because of this prior experience and because of the need to accomplish some implementation for the final Expo (for validation sake) we decided to refactor our CAD model for the outer support structure once again. The CAD was laid out such that we could simply bolt the entire PCB to the structure as shown in Figure 21 below. Moreover, limitations in manufacturing methods available to our team would not allow us to safely manufacture something more analogous (and true to actual size scale) to what is shown in Figure 20 above.

Its size is scaled up by a factor of approximately 1.6 compared to the final design. It can achieve maximum tilt angle of 32 degrees as validated from experiment (See Appendix F).

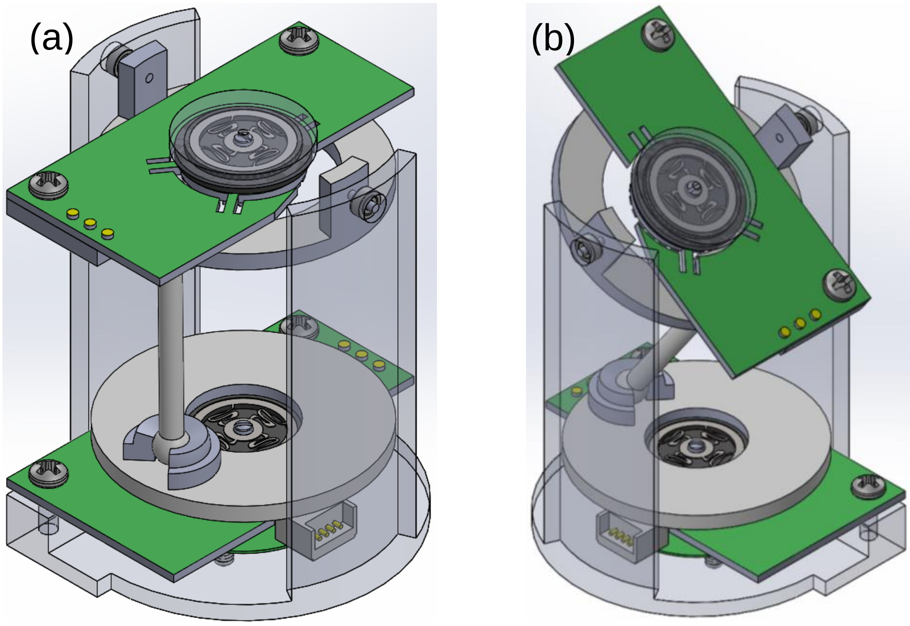


Figure 21: CAD model of Final Prototype at (a) offset position and (b) at tilted position.

The stators are in rectangular shape because our team did not want to take risk of customizing the stator board. With limited techniques and equipment in cutting and re-soldering the minute piezo chips, we were not confident in achieving the shape of the final design. Therefore, the sizes should have been increased proportionally. All parts are manufactured using 3D printer and ABS plastic materials. M1.6 screws and nuts were used to mount stator boards and encoder board on the top and bottom plates. In the CAD, 1/8 in ball bearings were used for pin joints on the wall. Therefore, it requires lathing an aluminum rod into a diameter of 1mm (inner diameter of the bearings) and milling it into a length of 3 mm, which is severely unachievable. Therefore, a wire is placed for pin joint instead of using the bearings as shown in Figure 22.

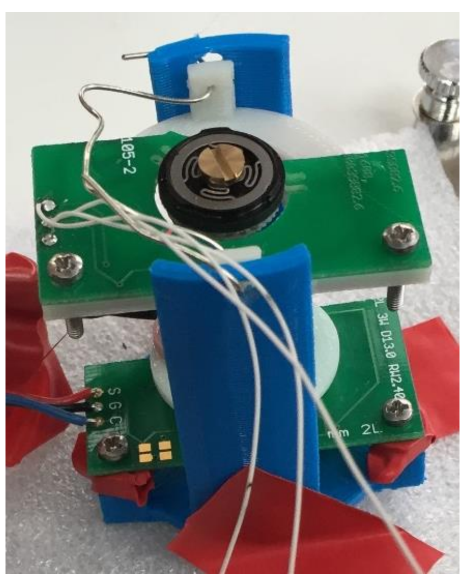


Figure 22: Final prototype built for Design Expo.

9.3. ELECTRICAL SCHEME

Generally, we use a Bluetooth module board to remote control the function of platform that we can set up a goal angle or simply just make the platform rotate. Also, Bluetooth module board can receive digital feedback signal from encoder circuit board which is at the bottom of platform and that will help us track the position of the tilt platform. After that, Bluetooth module board will send a serial signal to the driving board to make PCB motor rotate. When platform reach the tilt angle we need, Bluetooth module board will let motor stop rotating and remain at an exact position.

In Figure 23, our final prototype setup is shown. We connected the camera (AmScope MT500) that embedded in the microscope by using a USB wire to a laptop on the left side. As you can see in the figure, the top platform image is shown on the screen so that we can take photos for microstructure from different tilt angles.

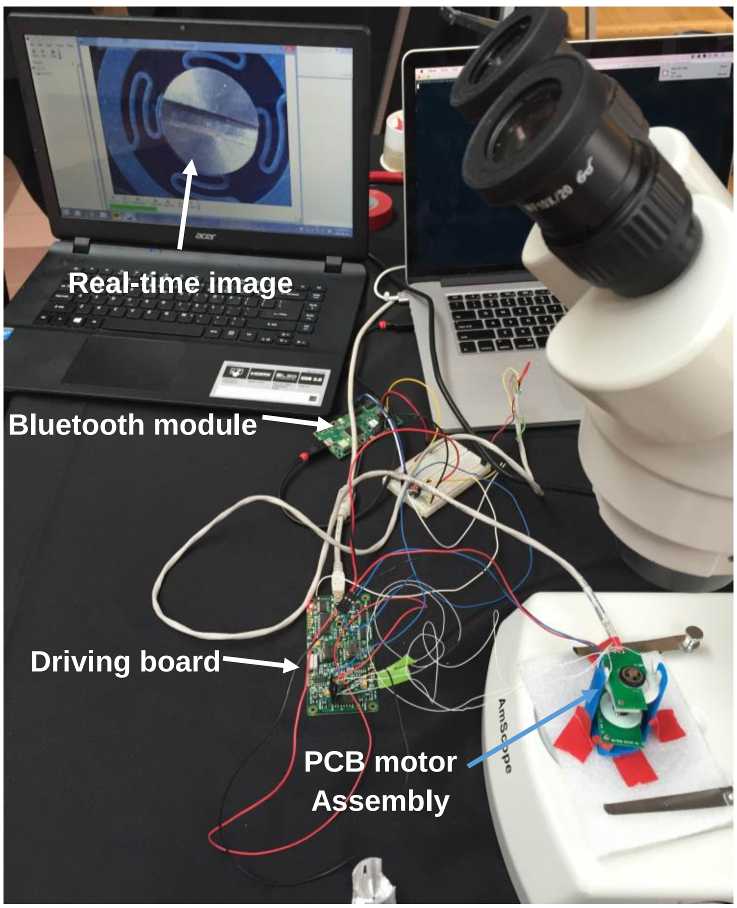


Figure 23: Final setup for Design Expo. Final prototype is mounted on the microscope and image is captured using digital camera.

10. DISCUSSION

10.1. DESIGN CRITIQUE

We were presented with a particularly challenging design, primarily due to the small size scale for implementation. We decided to take a novel design approach (utilizing piezo actuation) which inherently had many benefits, and at the same time many challenges. Although theoretically our design would achieve incredible resolution and control it was difficult to implement in the time frame of this course. The fact of the matter is quite simple. We were not able to mechanically constrain this piezo based actuation technology to function properly in the small size scale. Further work is needed in order to properly layout the components in the allotted volume. To be frank this is as simple as having the time to manufacture a custom layout for the PCB element to be properly placed and constrained, and furthermore to manufacture a customized setup for the rotors to engage the stator properly. If this is possible then it is very reasonable that the ball and caster method we designed for could work effectively. But to further explore *what might have been*, implementations which convert the rotational motion of the bottom rotor to tilt motion of the upper module without off-axis load to the bottom rotor would indeed have been the most effective implementation and a prime consideration for future work on this design.

10.2. FUTURE WORK

The PCB motor lends itself nicely to volume constrained applications like this one. As discussed in the primary Design Concept section there are a number of factors which need to be taken into account when integrating this technology. Both the stator (the stationary PCB piece with piezo elements) and rotors need to be properly affixed and mechanically constrained to function smoothly. We had been working with evaluation stators provided by *PCBmotor* which were not meant for any particular purpose, and struggled to refactor them to our use case.

With *application specific* consideration of the physical layout of the stators and rotors this technology could be integrated quite elegantly into an effective solution. Figure 20 illustrates what our final design might look like if we had time to customize the PCB layout (with screw holes and electrical via in appropriate locations). Additionally the process of translating the rotation of the bottom rotor into tilt of the upper platform needs to be carefully considered for future iterations of the design. It is possible that a method other than the ‘tilt-rod’ technique would prove more effective.

APPENDIX A: CONCEPTS GENERATED

In this section, the design concepts generated by our team based on the functional decomposition are listed with each figures. There are 15 design concepts which were not discussed in the Concept Generation section.

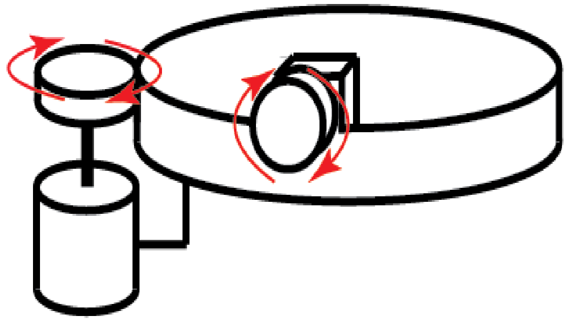


Figure A.1: Ordinary two motor platform. One motor controls the platform rotation, and the other controls the tilt rotation.

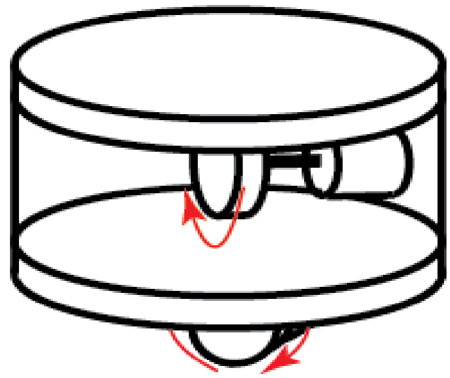


Figure A.2: Tilt only platform, using two ordinary micromotors. One of them control tilt motion at X-axis, and the other controls tilt motion at Y-axis.

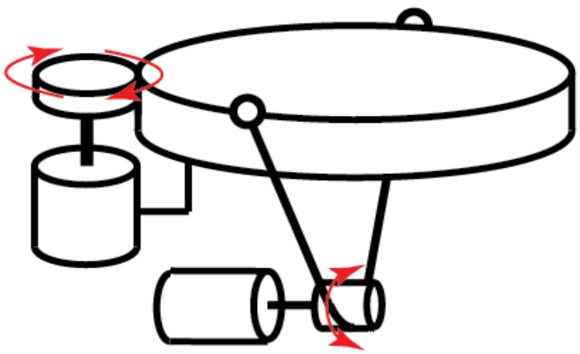


Figure A.3: Typical two motor-driven mechanism. One motor on the side rotate the platform in plane, and the other motor uses belt as transmission to create certain degrees of tilt motion for the platform.

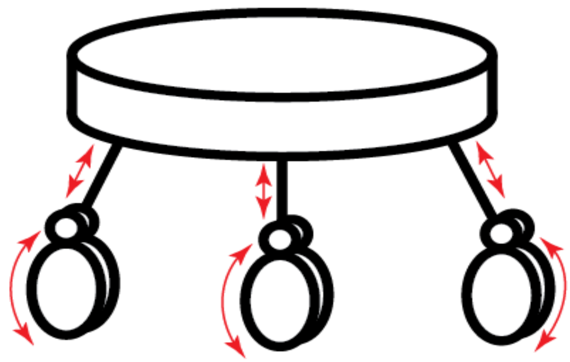


Figure A.4: Three-leg mechanism with elliptical shape transmission. As the ellipse rotates, the length of each legs can either elongate or shrink to create tilting motion along two axes using the difference in the lengths of the legs.

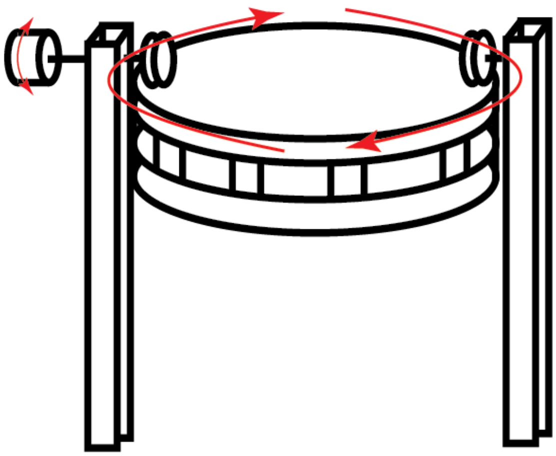


Figure A.5: One motor plus PCB motor platform. The micromotor rotates the platform to create tilt rotation, and the PCB motor attached below the surface of the platform rotates the whole platform in plane.

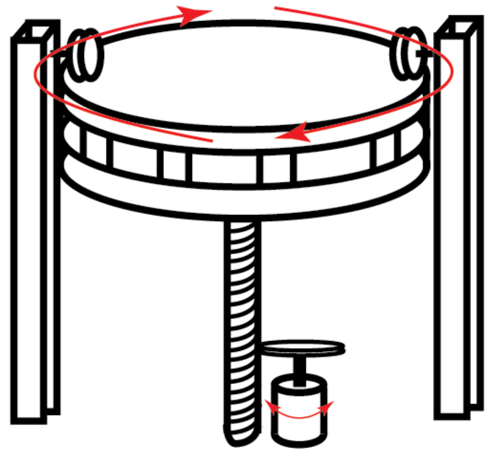


Figure A.6: Similar mechanism to the previous design shown in Figure A.5, but this mechanism creates a tilt motion using two meshing gears rotating in the x-y plane.

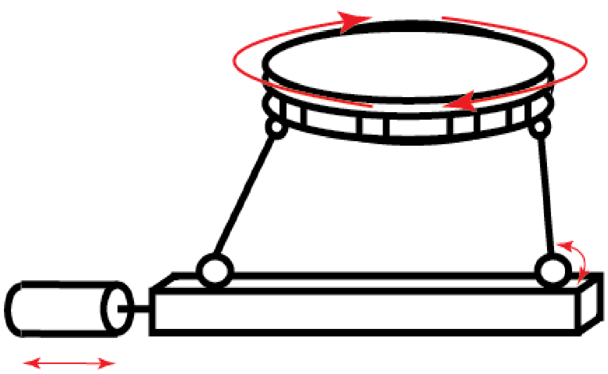


Figure A.7: Four bar linkage platform to achieve tilting motion. However, because the center of the microstructure may go off the frame of the camera, there is additional linear motor used to adjust the horizontal position. Hence, it uses a PCB motor to rotate the platform.

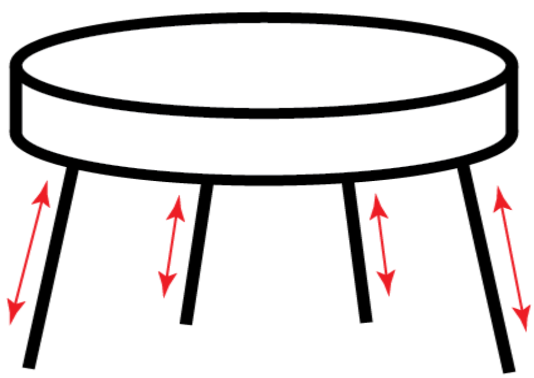


Figure A.8: Four leg platform similar to Figure 11 (pg. 10). It uses four linear actuators. It has little more freedom in achievable angles, but much more difficult to control the tilting motion.

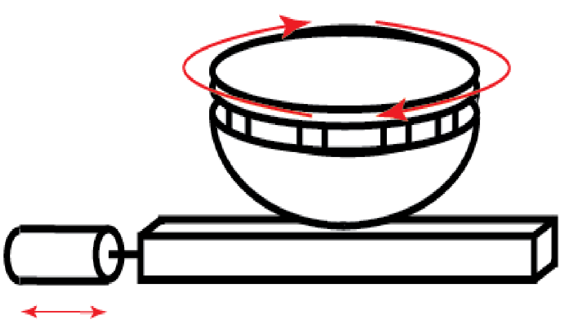


Figure A.9: Platform using round bottom. As the linear motor attached below the top platform moves the base plate, the round bottom slightly rotates to achieve the tilting motion. At the same time, it requires a PCB motor to rotate the top surface.

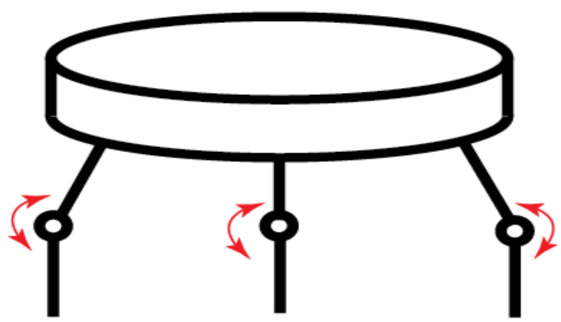


Figure A.10: Three leg platform using a pin joint and micromotors. This is also similar to Figure 11 (pg. 10), yet it requires micromotors.

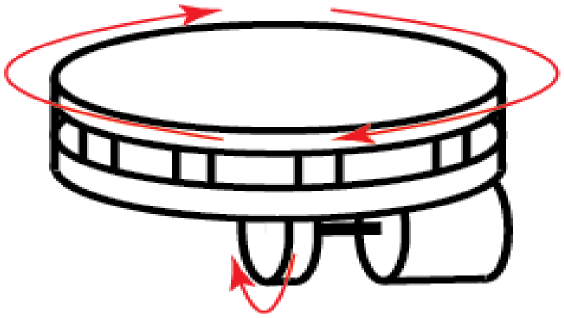


Figure A.11: One micromotor plus PCB motor platform. This design is similar to Figure A.1, but its tilting motor is located at the bottom plate and in plane rotation is actuated by a PCB motor.

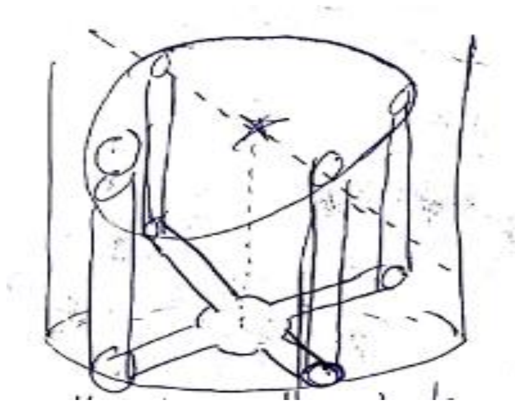


Figure A.12: Four leg mechanism similar to Figure A.8. It uses linear motors to control the lengths of the legs, but unlike Figure A.8, the bottom plate of the legs stay stationary.

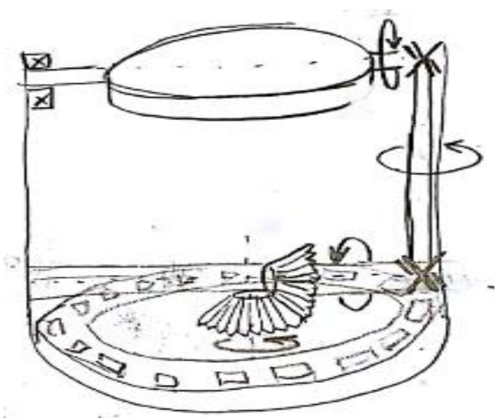


Figure A.13: One motor plus PCB motor platform. It is similar to Figure A.7, but it uses the meshing of the gears to rotate the side cylinder, which transmits torque to tilt the platform.

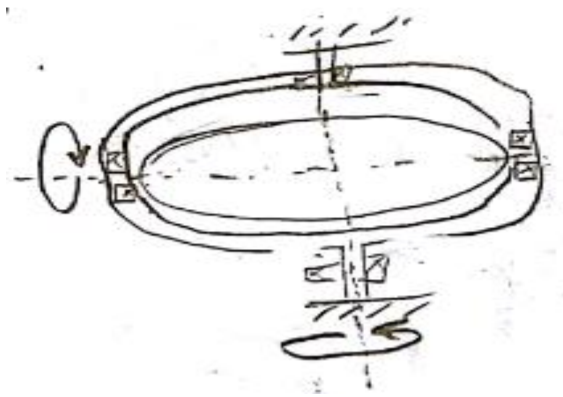


Figure A.14: Gimbal stage. This mechanism mimics the mechanism of gimbal to actuate the two degree of freedom motion. The platform is attached at the center of the gimbal mechanism.

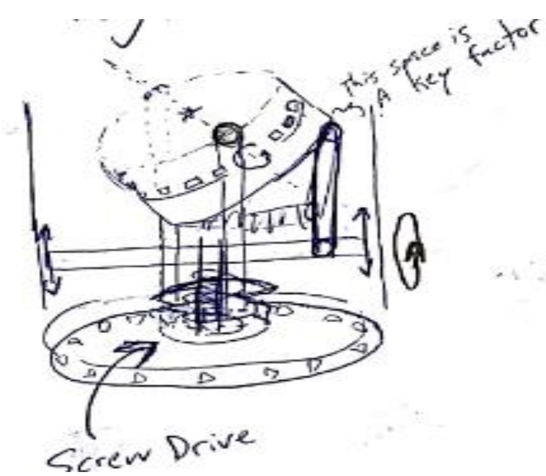


Figure A.15: Ordinary two motor mechanism using a belt and screw drive as a transmission to rotate the mechanism along two different axes.

APPENDIX B: FMEA ANALYSIS TABLE

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurrence	Current Design Controls	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Revised Rankings				
											Actions Taken	Severity	Occurrence	Detection	RPN
PCB motor: Provides rotation	Parts can't align precisely which causes huge offset of motion.	Human error in implementation; Precision error of the parts both from purchasing and manufacturing	6	Alignment problem	5	Specified dimensions by the supplier	8	240	Assembly careful, not to damage the parts						
	Motors can't drive whole mechanism.	Purchased motors are not qualified for maximum required torques	8	Motor could not overcome the varying load.	3	Read carefully about the specs of the motor and compare to the required specs	1	24	Calculate the potential contact friction and compare to the motor specs in advance before making orders						
Platform: supporting the microstructure	Top platform doesn't fit in space constraints.	Mechanism cannot rotate to certain angles.	5	Incorrect dimension to fit into the shell	4	Reduce the thickness of the top platform	2	40	Calculate the dimension precisely		Manufacture the reduced size of the platform	5	1	2	10
Circuit board: control the input the signal of PCB motors	Not function at all;	Whole system will be severely affected.	8	Part damage;	1	Be careful of both transporting and assembling those parts	1	8	Be careful of both transporting and assembling those parts						
	Not compatible with our system (code doesn't work well)	Cause uncontrollable error	6	Code design; driver of the PCB motor not working well.	3	Consult with product suppliers' technicians	4	72	Consult with product suppliers' technicians						
Rod: converts rotary motion from PCB motor to Tilt motion of the platform	Couldn't overcome the friction from the contact between rod and upper plate	If the friction between the rod and the cup holding it is too great we will not be able to tilt the platform to the angle we specify.	7	Rough surface of the material used for the ball linkage	5	Have smooth surface for the ball joint	2	70	Add some oil in the connection parts		Put some more oil	7	3	2	42
	Structure of rod is not tough enough to stand the weight of the upper platform and the microstructure standing above.	The rod may yield due to the weight of the upper platform and microstructure.	8	Low yield strength of the material than the compression force from the plate	3	Have higher material strength or make the rod thicker	2	48	None						

APPENDIX C: INITIAL DESIGN

Since our project is a small scale product whose dimension is less than 25mm x 25mm x 20mm (initial dimension constraint from sponsor), we couldn't apply ordinary manufacturing process like milling, lathe or band saw cut. To achieve the precision we need for our micro rotary platform, we decided to use 3D printing technique. Except for top surface of the platform, which is required to be electric conductive by sponsor, the other parts of this product are planning to be created by high resolution 3D printer. For the top surface, we plan to use water jet cutting technique to produce an extremely thin aluminum plate.

C.1. MANUFACTURING PROCEDURES

The first step is to use water jet cutter to manufacture the top platform surface. The water uses a basis CAD program as a model to send to computer. We created a SolidWorks files and saved it as DFX file which can be transferred to water jet code. As we know, the precision for water jet is approximately 0.25 to 0.5 mm. Thus, we made our CAD model for the top surface (Figure C.1), prepared aluminum plate for the water jet and we will get our work done. The advantages of water jet are that we could control dimension of our parts even though it is small and the precision of water jet is higher than traditional manufacturing process which is definitely what we need for our project. The disadvantages are also simple that it will consume lots of energy and those machine cost highly. In addition, the process is slow which lower down material processing productivity.

The second step is to apply high precision 3D printer to print motor holders and the linkage system. The method of 3D printing is almost similar to water jet cutting. To begin with, we created SolidWorks files for all the parts we need. Then, we put the files into a slice program to transform to G-code. After that, we uploaded G-code onto 3D printer and prepare the 3D printing material which we will use Acrylonitrile butadiene styrene (ABS). It took three to four days until we received our finished parts. We have searched that the smallest resolution 3D printer can achieve is approximately 0.3 mm which should be high enough in this project. The advantages of 3D printing are cheap and easy to operate. Also, it can build any shape that you need. But the disadvantages are that it is a time-consuming and material-limited process. Thus, if we find out that those materials do not work for our project, we cannot use 3D printing any more.

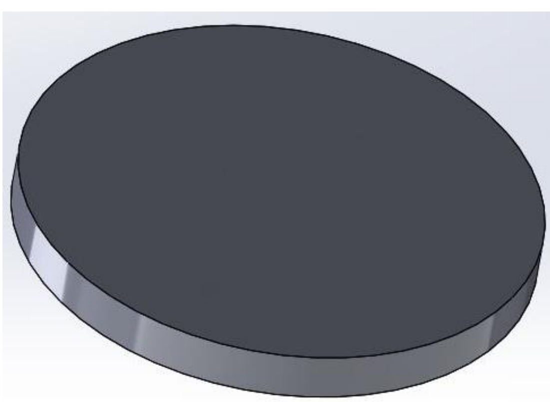


Figure C.1: CAD for top platform surface.

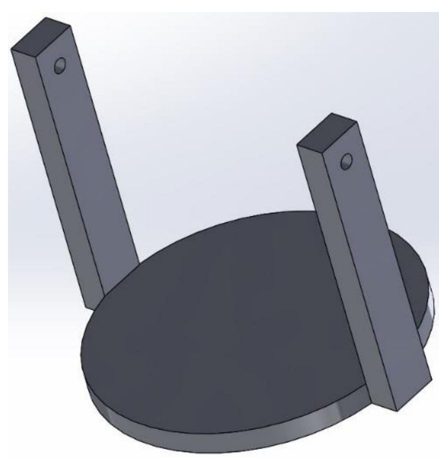


Figure C.2: CAD for bottom plate.

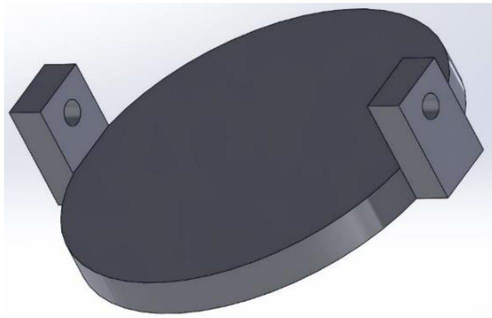


Figure C.3: CAD for top plate.

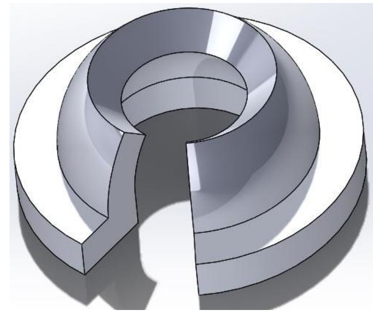


Figure C.4: CAD for call caster.

Figure C.5: CAD for linkage (ball).

Figure C.6: CAD for linkage (bar).

In Figure C2 and C3, we attached wall shape holders for the top and bottom platform to perform as pin joint. Our consideration is that since the holders may afford most of the load which comes from gravity of top platform and PCB motor plus drag force from driving bar system, we need a strong holders to overcome these forces. To make it wall shape, we could make bigger contact area and less stress. Figure C.4, C.5, and C.5 can be assembled to a ball caster assembly to connect top and bottom plate.

C.2. ASSEMBLING PROCEDURES

The following figure shows that how we will assemble our product and the blue parts are PCB motors we are going to use. Since our project is extremely small, some procedures will need very delicate operation. The first step is to fix two small balls on the two ends of the bar. The second step is to stick the balls in the hollow part of fasteners. The third step is to attach fasteners on the top surface of bottom PCB motor and the bottom surface of the top platform. The last step is to assemble the rest of parts together. Figure C.7 shows the explosive view of the assembly and Table C.1 is included to show bill of materials.

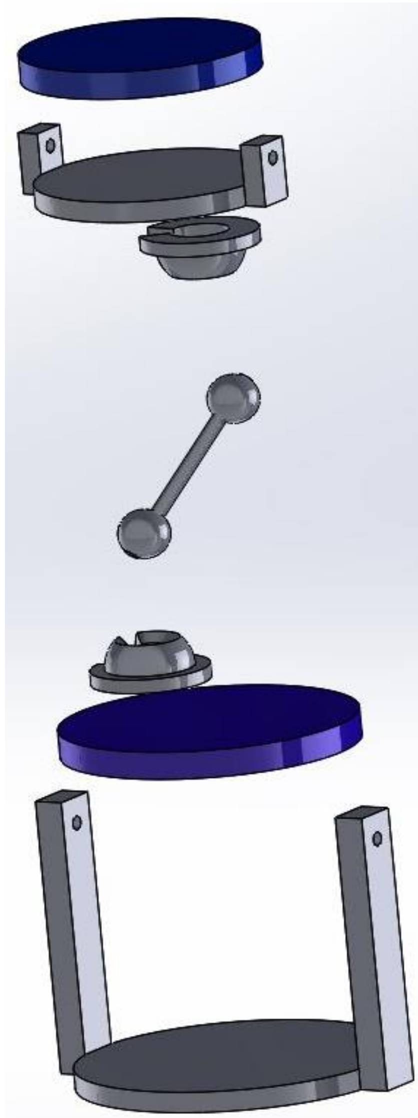


Figure C.7: Explosive view for current design.

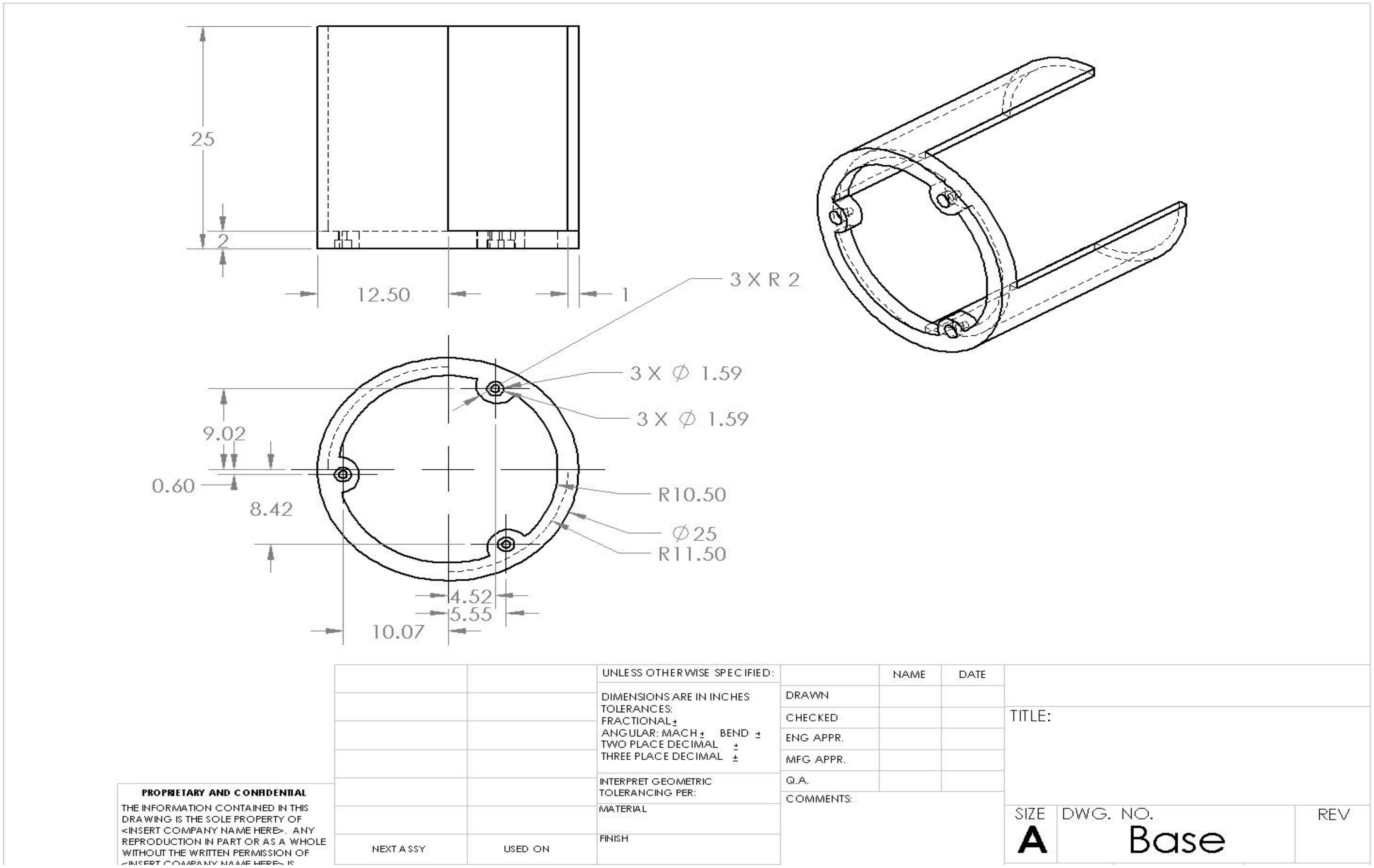
Table C.1: Bill of Materials.

Component	Quantity	Part Number	Supplier	Price
Aluminum Plate, 1/4" x 12" x 18"	1	9246K45	McMaster-Carr	N/A
ABS, 3D printing material	1	N/A	HATCHBOX	$29.9
PCBmotor eval kit	1	N/A	PCBmotor	$640
Steel Rod, 0.04" x 2"	1	3023A376	McMaster-Carr	$1.71
			TOTAL PRICE	$671.61

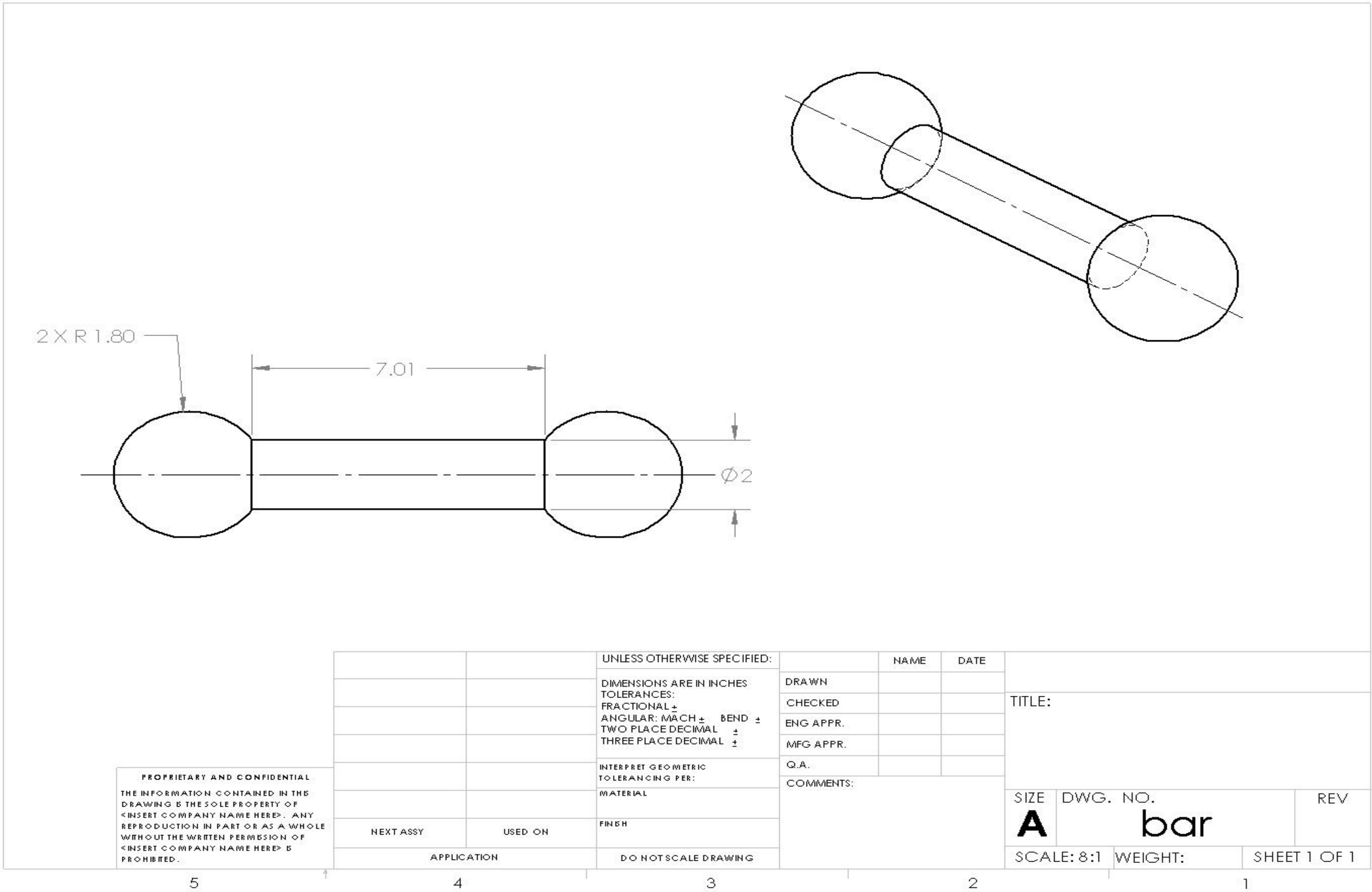
C.3. ENGINEERING DRAWINGS

Note that all dimensions are in the unit of millimeters.

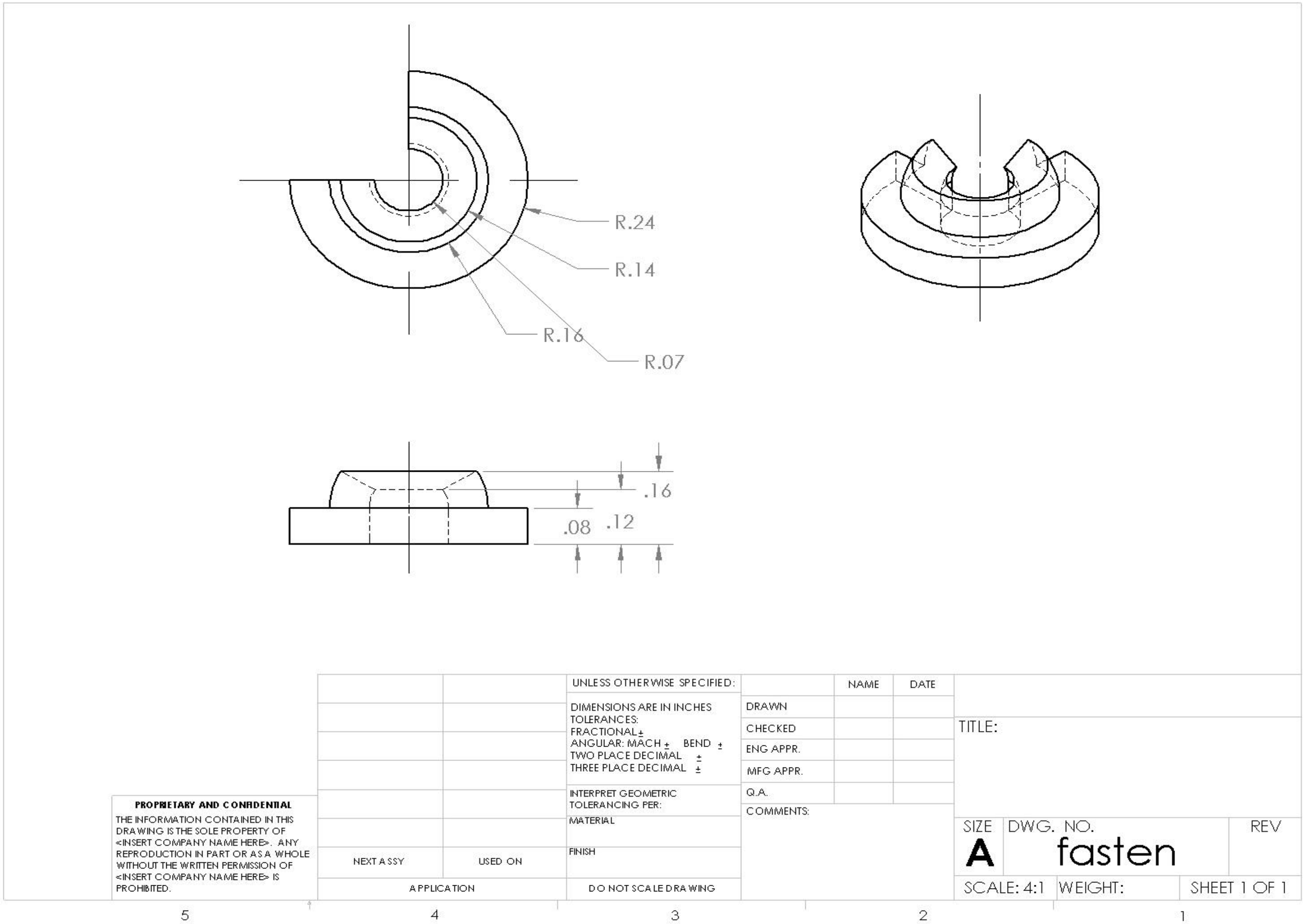
Engineering Drawing for Base Plate



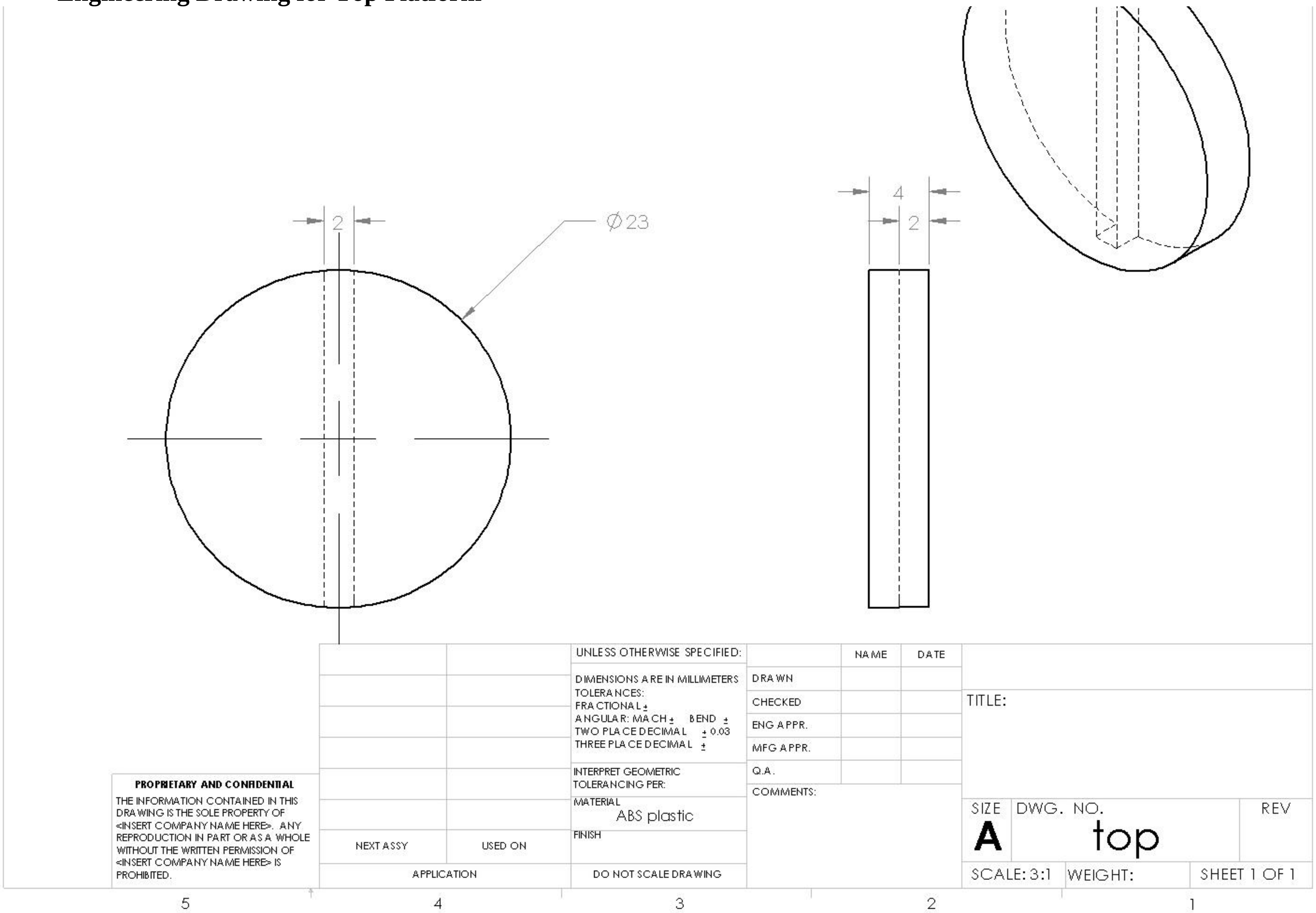
Engineering Drawing for Bar



Engineering drawing for Ball Caster



Engineering Drawing for Top Platform



APPENDIX D: CHANGES IN DESIGN AFTER DR4

There are multiple changes in the design since Design Review 4 (DR4). Our design was modified due to the change in the engineering specification of the constrained dimension. Compared to our original dimension limits (24 mm in diameter and 20 mm in height), our new dimension is 25.5 mm in diameter and 31 mm in height. This gave more room for our mechanism, and for the ease of manufacturing and assembling procedures, we enlarged our design and changed key components' designs as shown in Figure D.2. Figure D.1, showing the previous design, is added to compare with the design change since DR4. This modified design is the same as our final design that we would like to ultimately achieve.

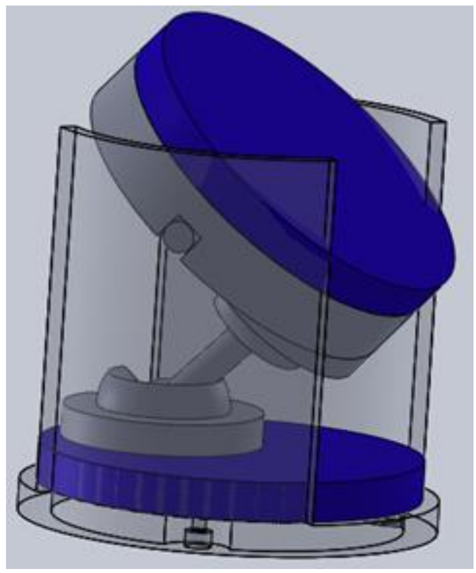


Figure D.1: Old design of the mechanism at DR4. This figure can be compared with Figure 21 to show the changes made in our design since DR4.

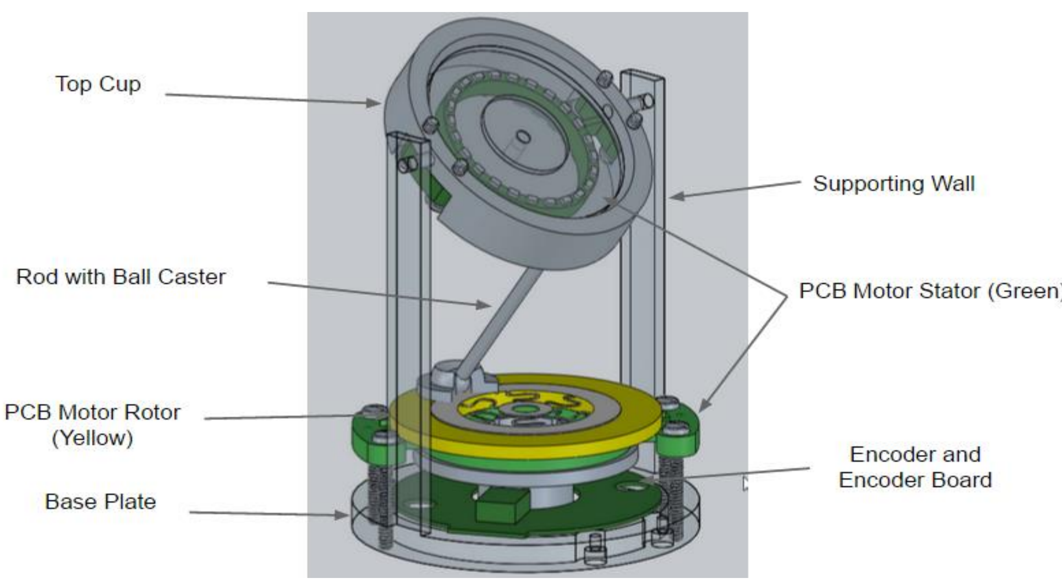


Figure D.2: Changes made to final design after DR4. This design is our final design as mentioned in Figure 20.

Compared to the simplified figure shown from DR4, Figure D.2 specifies the detailed assembly of the motor and top and bottom plates. The changes in our design are shown in the format of ECN (Engineering Change Notices), and discussed in the following paragraphs.
First major change is that the length of the rod is increased. As the height constraint is relieved, we could elongate the length of the rod to 17.4 mm. While longer rod can create larger tilting angle, this length did not completely increased the tilting angles because of thicker bottom and top assembly. As a result, maximum tilt angle rather decreased down to 38 degrees, which is still greater than the engineering specification.

Second, we changed the designs of top and bottom plates. For the top part, we changed it to a shape of cup, so that it can surround and constrain the motor assembly to stay at the right position even if the platform is tilted. Inside this cup, PCB motor and a conductive platform surface will be placed so that engineering specifications on 360 degrees in plane rotation and having conductive surface can be met. Also, the two holes on the side of the cup is to connect the top cup with the wall of the base plate. As the bottom PCB motor rotates, two precision pin joints can guide the tilting of the platform. For the bottom part, the arc length of the base plate's wall is decreased so that it does not interfere with the stator board of the PCB motor or with the encoder board. Moreover, four holes for #4-40 screws are created to hold the stator tight.

Lastly, the shape of the stator board for top and bottom PCB motors is changed. Because we need to make the board fit inside the cylinder shape, and the stator needs to be fixed tightly to properly transmit the resonance into rotation, we cut the board in the shape as shown in Figure D.3.

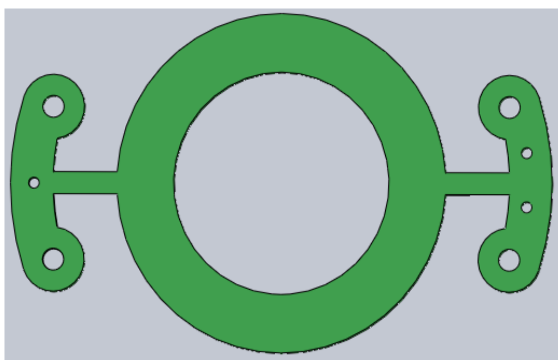


Figure D.3: Changed shape of stator board. Stator will be placed on the large circle at the center. Four larger holes on the side are for #4-40 screws, and three smaller holes are for wires from the stator.

General procedure for manufacturing the top and bottom parts, and the rod and fastener has not changed from the previous design. Our team is still considering a method to manufacture a precision pin joint connecting top cup and supporting wall (shown in Figure D.2), which can guide the tilting motion when the bottom PCB motor is rotating. Furthermore, general procedure for assembling has not changed as well since general functions of each component do not drastically differ in comparison with the previous design. As shown from Figure D.2 and D.3, there are four #4-40 screws added to each stator of top and bottom parts during the assembly process.

Table D.1 shows the updated bill of materials. As already discussed with our sponsor, our team is planning on purchasing 13 mm PCB motor in order to provide more room for adjusting the stator of the motor. When our team attempted to adjust 20 mm PCB motor in the PCBmotor Eval Kit, because of the tight diameter constraint, the motor was damped and barely converted the resonance into rotation of the rotor. Therefore, 13 mm PCB motor will enhance the functioning of our mechanism and reduce the problems from tight dimension constraint.

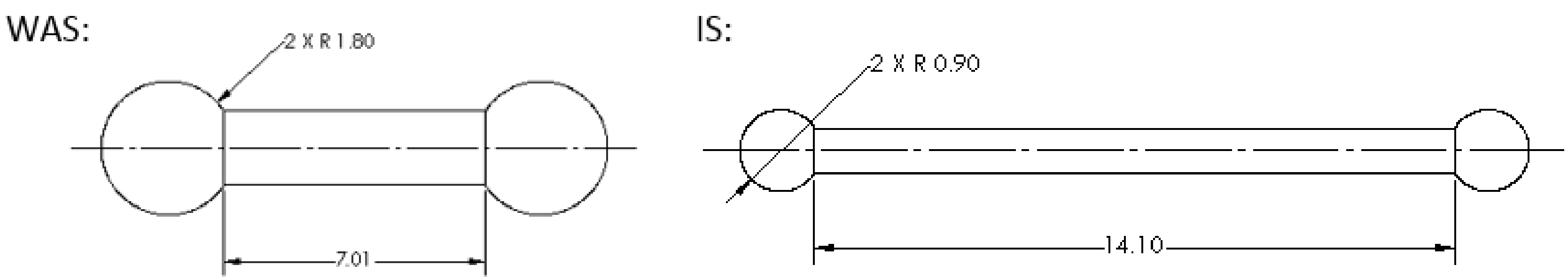
Table D.1: Bill of Materials.

Component	Quantity	Part Number	Supplier	Price
Aluminum Plate, 1/4" x 12" x 18"	1	9246K45	McMaster-Carr	N/A
ABS, 3D printing material	1	N/A	HATCHBOX	$29.9
PCBmotor Eval Kit	1	N/A	PCBmotor	$640
13 mm PCBmotor	1	N/A	PCBmotor	$200
Steel Rod, 0.04" x 2"	1	3023A376	McMaster-Carr	$1.71
#4-40 Phillips Head 0.375’’ Screw	12	PE1005-2	Assembly Room	N/A
#4-40 Nut	12	PE1008	Assembly Room	N/A
			TOTAL PRICE	$871.61

D.1. ENGINEERING CHANGE NOTICES

Note that all dimensions are in the unit of millimeters.

Engineering Change Notice for Rod



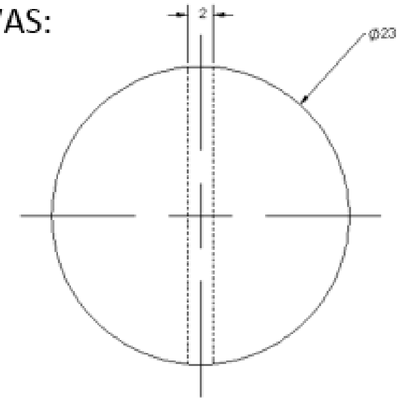
Notes:

Needed to increase the length of the rod to increase the tilting angle with relieved dimension constraints. Also needed to decrease the size of the ball to make the ball caster assembly fit on the rotor of PCB motor.

Mechanical Engineering 450, University of Michigan	
Project: 3D Imaging of Microstructure	
Ref. Drawing: Bar	
Engineers: Team 21	3/27/2015
Proj. Mgr: Prof. Wei Lu	3/31/2015
Sponsor: Prof. Wei Lu	3/31/2015

Engineering Change Notice for Top Cup

WAS:



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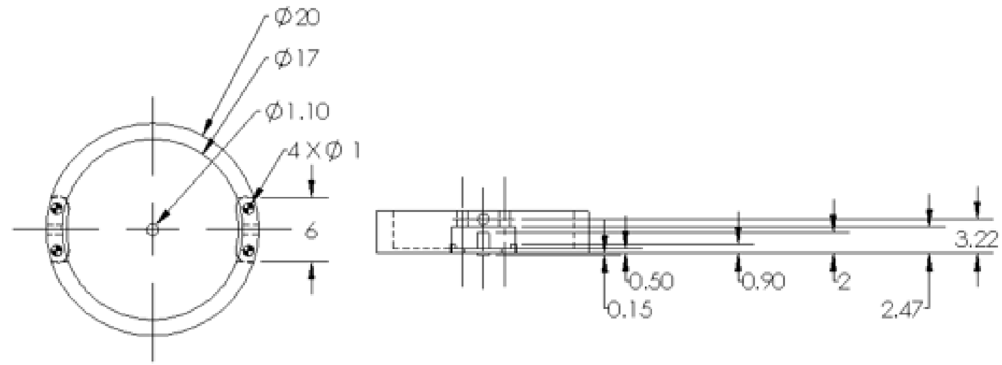


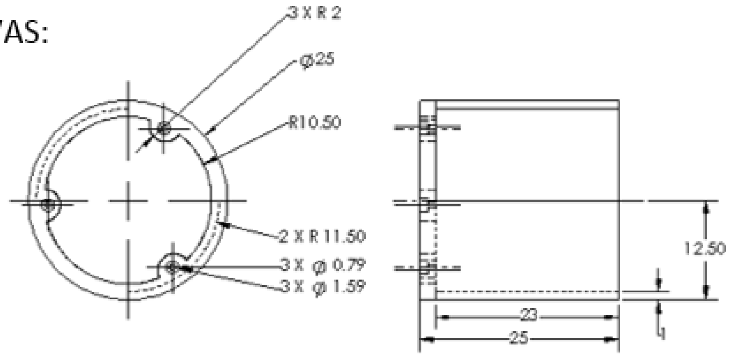
Notes:

Needed to change the design to the shape of cup to mount the motor assembly inside it so that the motor does not move when tilting. Needed to add a hole at the center for M1 screw to fix the motor assembly as well. Also needed to add four holes for #4-40 screws to fix the stator board and add two holes on the side to connect it to the wall of the base plate and to guide the rotation into tilting.

Mechanical Engineering 450, University of Michigan	
Project: 3D Imaging of Microstructure	
Ref. Drawing: Top Cup	
Engineers: Team 21	3/27/2015
Proj. Mgr: Prof. Wei Lu	3/31/2015
Sponsor: Prof. Wei Lu	3/31/2015

Engineering Change Notice for Base Plate

WAS:



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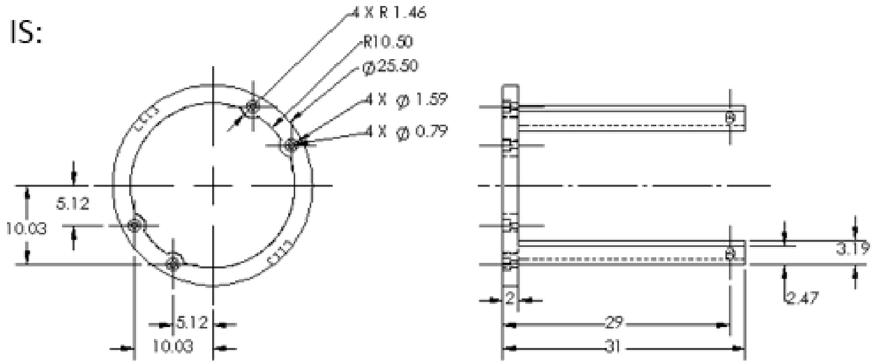


Notes:

Needed to decrease the arc length of the wall from 12.5 mm to 3.19 mm to provide more space for stator board and encoder board. Needed to increase the length of the wall from 25 mm to 31 mm as well owing to the relieved dimension constraint. Also needed to add one more hole for #4-40 screws to fix the stator.

Mechanical Engineering 450, University of Michigan	
Project: 3D Imaging of Microstructure	
Ref. Drawing: Base Plate	
Engineers: Team 21	3/27/2015
Proj. Mgr: Prof. Wei Lu	3/31/2015
Sponsor: Prof. Wei Lu	3/31/2015

APPENDIX E: FINAL PROTOTYPE

Our design from DR4 was based on the assumption that we would have time to have a custom PCB laid out to fit the footprint of our application (shown in Figure C.3 below). After corresponding with our associates in Denmark we found out that the lead time for a custom layout would be too great and we would not receive the parts until after the final expo.

We instead ordered stock 13mm stators (built, once again, for evaluation purposes). The layout of this stator is shown in Figure D.1 below. To accommodate this stock layout we refactored the CAD so that we could affix the board directly. All changes in CAD for the structure are outlined in the Engineering Change Notices below. One benefit of the stock stator is the central guide hole (made out of the same FR4 material the rest of the component is mounted on) allows us to eliminate the need for the top cup module and just sandwich the stator using that guide hole to constrain the axis.

Figure E.1: 13 mm PCB motor stator. It has support inside the stator that can constrain the axis of rotation. Similar design for the stator can be introduced to our design of the stator and eliminate additional shape of cup for the top plate.

The final bill of materials used in our project is shown in Figure D.2 below.

Table E.1: Final Bill of Materials.

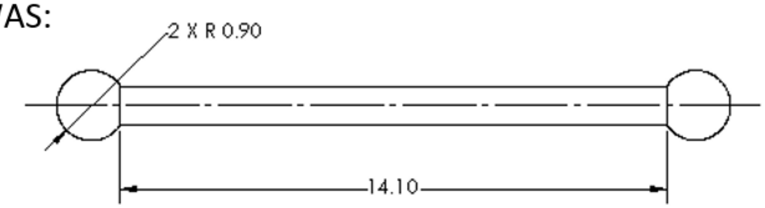
Component	Quantity	Part Number	Supplier	Price
Aluminum Plate, 1/4" x 12" x 18"	1	9246K45	McMaster-Carr	N/A
ABS, 3D printing material	1	N/A	HATCHBOX	$29.9
PCBmotor Eval Kit	1	N/A	PCBmotor	$640
13 mm PCBmotor	1	N/A	PCBmotor	$200
Steel Rod, 0.04" x 2"	1	3023A376	McMaster-Carr	$1.71
#4-40 Phillips Head 0.375’’ Screw	12	PE1005-2	Assembly Room	N/A
#4-40 Nut	12	PE1008	Assembly Room	N/A
1/8’’ Stainless SteelBall Bearing	6	57155K339	McMaster-Carr	$80
			TOTAL PRICE	$951.61

E.1. Engineering Change Notices

Note that all dimensions are in the unit of millimeters.

Engineering Change Notice for Rod

WAS:



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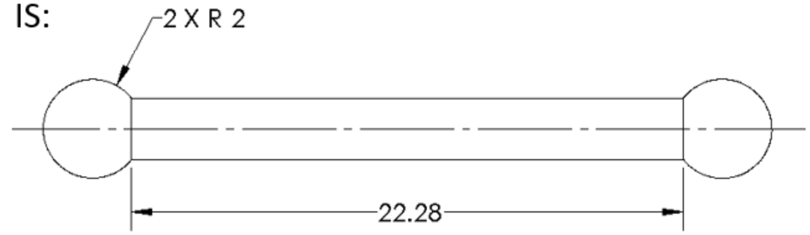


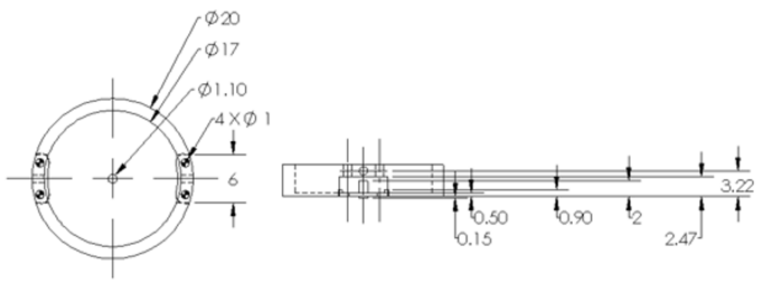
Notes:

Needed to increase the length of the rod to increase the tilt angle with relieved dimension constraints. Also needed to increase the size of the ball to make the ball caster assembly more resistant to yielding when it transfers the rotation into tilting motion.

Mechanical Engineering 450, University of Michigan	
Project: 3D Imaging of Microstructure	
Ref. Drawing: Base Plate	
Engineers: Team 21	4/12/2015
Proj. Mgr: Prof. Wei Lu	4/14/2015
Sponsor: Prof. Wei Lu	4/14/2015

Engineering Change Notice for Top Cup

WAS:



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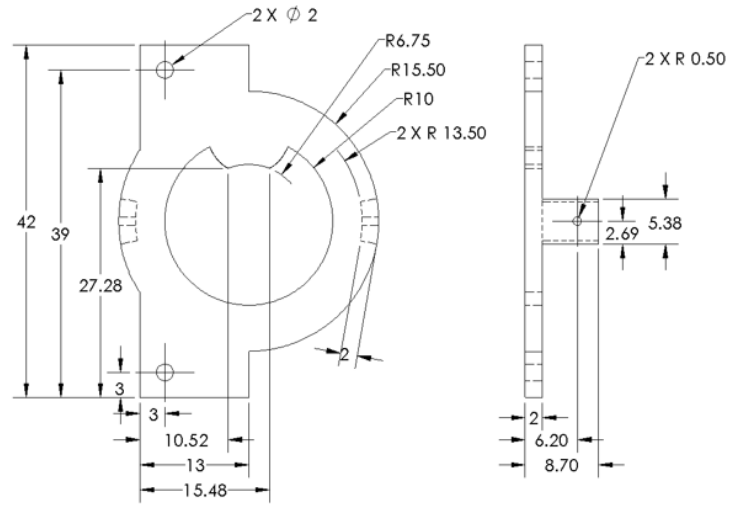


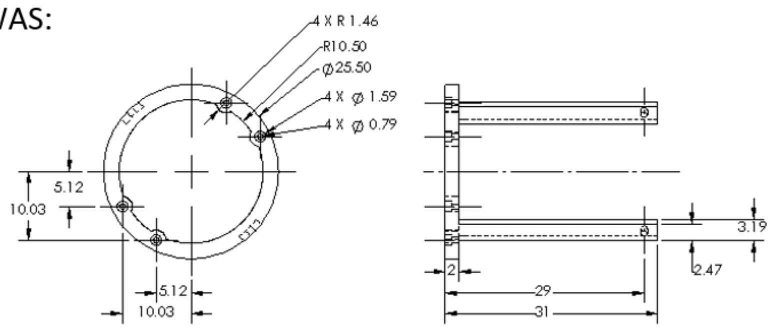
Notes:

Needed to increase the diameter of the whole plate by about 1.6 times from the old design to place the whole stator board on the plate. The height of the wall increased in the same ratio to ensure that the axis of rotation is right on the microstructure. The shape of hole at the center is changed to provide room for the ball caster. On the rectangular part, it has two holes so that the encoder board can be fixed using M2 screws.

Mechanical Engineering 450, University of Michigan	
Project: 3D Imaging of Microstructure	
Ref. Drawing: Base Plate	
Engineers: Team 21	3/27/2015
Proj. Mgr: Prof. Wei Lu	3/31/2015
Sponsor: Prof. Wei Lu	3/31/2015

Engineering Change Notices for Base Plate

WAS:



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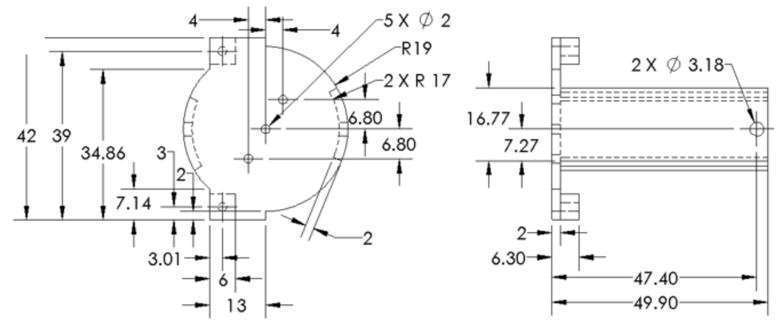


Notes:

Needed to increase the diameter of the whole plate by about 1.6 times from the old design to place the whole stator board on the plate. The height of the wall increased in the same ratio to ensure the same tilting angle. Two additional holes are made at the bottom to place the encoder board and the plate has a rectangular shape to fit the stator board on it. On the rectangular part, it has two holes so that the encoder board can be fixed using M2 screws.

Mechanical Engineering 450, University of Michigan	
Project: 3D Imaging of Microstructure	
Ref. Drawing: Base Plate	
Engineers: Team 21	3/27/2015
Proj. Mgr: Prof. Wei Lu	3/31/2015
Sponsor: Prof. Wei Lu	3/31/2015

APPENDIX F: VALIDATION PROTOCOL

F.1. VALIDATION PROTOCOL EXPECTATIONS

For our prototype, most of the requirements can be measured or determined directly such as the dimension, the input voltage, and the conductivity of top surface. But there are two empirical specifications that require us to design specific experiments to test: the resolution angle and the relationship between bottom stator rotation and tilt angle.

For measuring the resolution angle, the equipment we need is a wire and high precision ruler. The resolution angle is, as defined by our sponsor, the angle difference between the offset position and the same position after one full rotation, which is the smallest angle that our PCB motor can consistently achieve. According to the sponsor's requirement, we designed the following procedures to measure resolution angle: first, capture image of stator attached with wire at offset position and record the point on ruler that wire is pointing; second, repeat this several more times while rotating the stator one full rotation each time; third, use trigonometry to solve for angles that the stator is pointing and compare among these angles. The average angle difference is the resolution angle.

For the second specification, the equipment we need is digital camera and support stand. To find the relationship between bottom rotation and tilt angles, we designed the following experiment: first, fix the camera with the support stand at the side of prototype and make sure the center of camera is at the same high of the center of tilt platform; second, capture several images at different rotation angles and record the angles; third, use computer aided angle measurement to measure the tilt angle and it is corresponding to the rotation angle. We need to collect enough rotation angle to draw a diagram to show this relationship and also we need to repeat the experiment to get its average value to gain a more precise result. Some key factors might degrade the performance such as slop in the tilt arm or poorly maintaining a static axis of rotation. Thus we have to overcome these disadvantages before performing the experiment.

F.2. VALIDATION RESULTS

F.2.1. Resolution Angle

In order to test the achievable resolution of the PCB motor we attached a wire to the rotor extending 11.5mm. The setup is pictured to below. The pictures below the setup illustrate the resulting position of the wire after 20 steps resulting in a linear translation of just 1mm. The resulting resolution angle is 0.025 degrees/step. The equation to calculate it is shown below:

$$\frac{1}{20}\left[tan^{-1}\left(\frac{1}{115}\right) \times \frac{180}{\pi}\right] \text{ Degrees/Step} \quad \text{(Eq. F1.)}$$

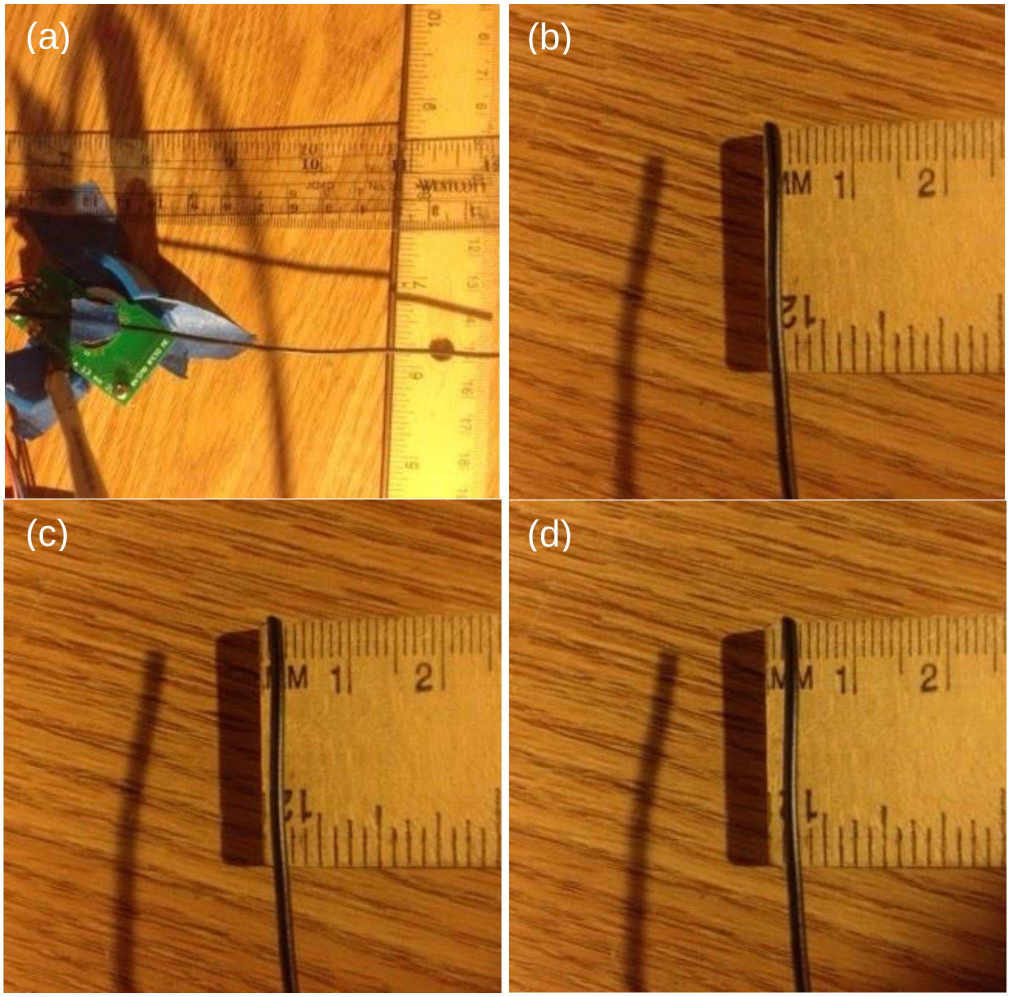


Figure F.1: (a) Validation setup and (b-d) examples of reading the values on the ruler.

Therefore, the resolution angle specified by our sponsor (≤ 0.1 degrees) was met by using PCB motor.

F.2.2. Tilt Angle and Encoder Counts

The recorded values are plotted using Microsoft Excel. Then, with polynomial fit of the curve of tilt angles versus encoder counts (Figure F.2), we come up with a relation equation for tilt angle φ and encoder count n:

$$\varphi = 8 \times 10^{-10} n^5 - 3 \times 10^{-7} n^4 + 3 \times 10^{-5} n^3 + 1.9 \times 10^{-3} n^2 + 6.6 \times 10^{-3} n \quad \text{(Eq. F2.)}$$

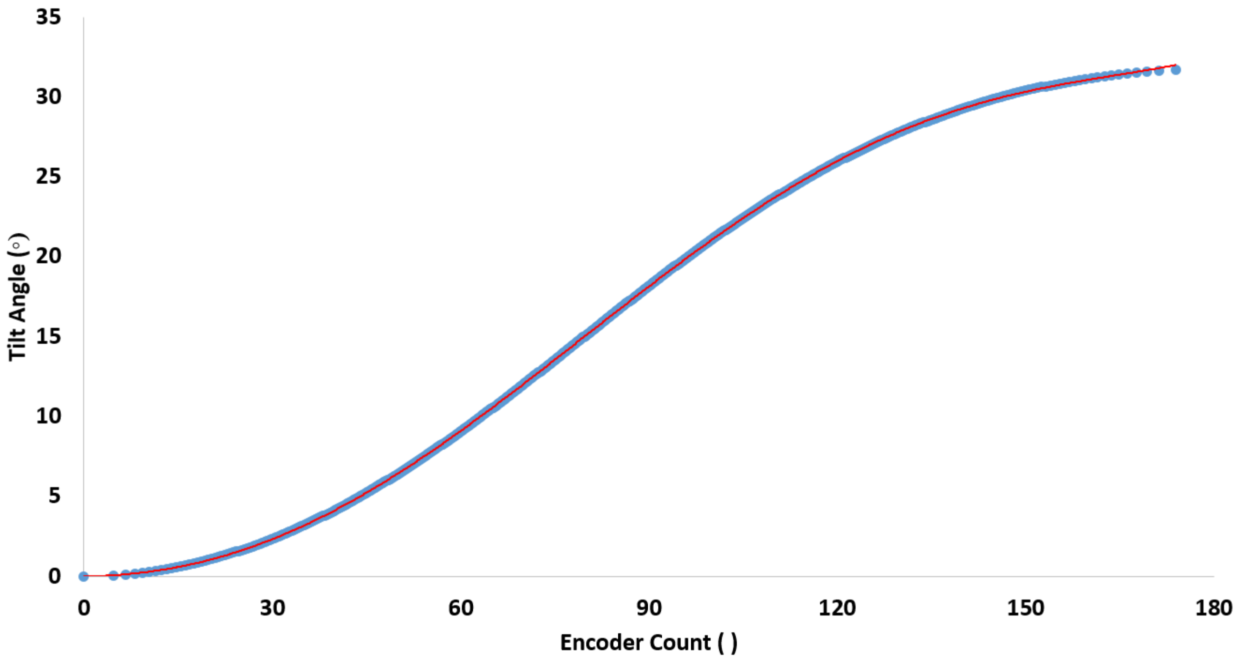


Figure F.2: Tilt angle vs. encoder count. Blue dotted line represent the data points collected from the validation test, and red solid line shows the trend line of the curve. The equation of the trend line is shown in equation F2. Maximum tilt angle of 32 degrees is achieved with the encoder count of 180.

APPENDIX G: INDIVIDUAL STATEMENTS

This section is written by each of the team member individually, and thus, it includes the names of each member who wrote the paragraph.

G.1. ETHICAL DESIGN STATEMENTS

Nathan Utiger Argetsinger:

It is somewhat difficult to assess design ethics in the regime where we are working. It is a small scale device and as far as I can tell it could only increase the users' freedom to explore and understand the world around them. There are no significant security vulnerabilities or vectors for misuse. If say we were building a bridge, then there is a significant degree of ethical consideration to be had. Do we save money on a component or procedure to reduce the cost of the bridge but also reduce the safety factor?

Qingtian Yin

Yes, from my perspective of view, our design has the Code of Ethics for Mechanical Engineers been applied to the design process. First of all, our project design is pretty small and low-voltage driven, thus it has very low possibility that it will be harmful to the user. One thing we did consider is the selection of best material we could have using 3D printing for most parts of the housing and mechanism. We chose the 3D printing method not only because it is more accurate and more desirable for our project, it is also because it is more favorable for commercial because of its material-ABS plastic. Its light and non-metal characteristic causes less damage to users, for example it can avoid producing sharp edges from aluminum metal stock.

Sungjin Kim

Code of Ethics for Mechanical Engineers has been applied to the design process. Our team managed to choose the design and manufacturing processes that can minimize bringing about any hazardous situation while using our mechanism to construct 3D images. Even though our mechanism is constrained in a small shell (25.5 mm in diameter and 31 mm in height) and limited with its supplied power input (12 Volts), our team is considering to build our final prototype using ABS plastic which has characteristics of non-conductive and light in weight. Moreover, instead of using ordinary motors and gears which may be exposed to touchable location, our team chose to use PCB motor which directly transmits the resonance of the motor to rotation, so that safety issue can be minute.

Zifeng Peng:

Our prototype is in a really small scale thus generally the users must be careful that don't let children swallow it. But since our project is for research lab, such situation can rarely happened. In addition, our project does not have any sharp edge or sting shape things, which should be very safe for users. Lastly, the require voltage input is less than 12 volts thus it is in the safe range for human beings.

G.2. ENVIRONMENTAL IMPACT STATEMENTS

Nathan Utiger Argetsinger:

Our device is small and has a low energy and material footprint. The energy required to operate the device is orders of magnitude less than other procedures, say for example, washing and drying clothes. The material used for the structure, either aluminum or PLA plastic, is very limited due to the size constraint of our design. These materials can and should be recycled but even if they weren't it would be negligible compared to many other practices in industry. Cheers.

Qingtian Yin:

Since our design is very small and most of the structure's components are made by 3D printing which means most of the material used are ABS plastic and small amount of aluminum. In addition to that, the whole system also includes two PCB motors and their compatible control board. From the perspective view of material recycling, we think our project will have very small impact on the environment because both ABS plastic and aluminum can be perfectly recycled using modern technology. The only concern is the circuit board, assume it will require more complex process to deal with, but consider the small area of those device, the environmental impacts are pretty small. Also, our project does not involve any chemical reaction that could cause environmental impact.

Sungjin Kim

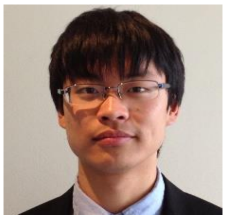
Our design uses ABS plastic and aluminum. Generally, due to the small size of our mechanism, the degree of environmental impact is superficially not notable. However, considering the energy needed to process our materials into our design, such impact is greater than our expectation. For example, to perform 3D printing of our key parts using ABS plastic, much heat is required. Also, we need to cut out much materials from aluminum rod and plate using milling machine to shape them to our design. To be honest, during the material selection, our team did not concern much about the cost and energy required to fabricate and process the materials; we mainly chose the materials that are commonly used and familiar to us. Researching more about the materials and selecting materials with more carefulness may decrease the environmental impact on our product. Fortunately, there is not much impact on environment during or after using our product because it does not require much power (less than 12 volts) and time to perform, and both ABS plastic and aluminum are recyclable when the customer is finished using the mechanism.

Zifeng Peng:

The materials we used for our project are aluminum and ABS plastic. Generally speaking, these two kinds of material are environmental friendly which means they will not cause any damage to the environment. Also, since our project is very small, we will use only a small amount of these materials. Considering the energy cost, our project is also excellent in saving energy. For the aluminum part, since the cutting volume is small, the energy to cut it won't be too large. For 3D printing part, our plan is to print the linkage bar and fasteners which is quite small and they will be finished in 10 minutes which means less energy consume.

AUTHORS

Nathan Utiger Argetsinger
I am from Ann Arbor Michigan, and currently study Computer Science and Mechanical Engineering at the U of M. I have done motion control work in the past for camera systems, but have never worked on a size scale as small as this.



Qingtian Yin
I am from China, and currently studying Mechanical Engineering and Physics at U of M. I have done certain researches in thermal areas.

Zifeng Peng
I come from Guangzhou, China who is a senior dual degree student majors in Electrical and Computer Engineering in Shanghai Jiao Tong University and Mechanical Engineering in University of Michigan.

Sungjin Kim
I came from Ulsan, Republic of Korea. I study Mechanical Engineering at the University of Michigan. This is my last semester as an undergraduate student, and want to study further in graduate school.

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