Final Design Report

Team No: 12
Project Title: Articulating Robotic Arm for Wind Tunnel

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Date Submitted: 4/10/2015

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ABSTRACT

The Aerodynamic Characterization Facility (ACF) of the Research and Engineering Education Facility (REEF) has requested a mounting and actuating mechanism in order to continue testing. This facility hosts an open subsonic wind tunnel with a maximum wind speed of 22 m/s. The design must be able to adjust pitch (-5° to +20°) and yaw (-10° to +10°) while the tunnel is in operation and maintain the specimen in the center of the air flow. The design features 105 degrees of a 25 inch radial arc with a 1 inch by 1 inch square shaped cross-section. The circular arc will be mounted in two locations in order to stabilize it during wind tunnel operation. Rollers with rubber coating and bearings will be used to reduce friction and help dampen vibrations. This arc will be actuated through a drive train consisting of a worm, worm gear, spur pinion, and gear rack on the back of the arc. A sting mount placed in the arc and held by set screws will be utilized to hold specimens in the center. Upon completion of the assembly, testing yielded failure of the gear to shaft set screw mounting mechanism. "D" shafts were used in order to make the set screws hold and this resolved all issues. The test mechanism is completed and ready to be sent to the sponsor.

ACKNOWLEDGMENTS

Team 12 would like to recognize the sponsor Dr. Michael Sytsma and the advisor Dr. Kumar for their exceptional guidance throughout the design phase of this project. The team is grateful for Dr. Sytsma's contributions and for allowing the team to visit the REEF center. Dr. Kumar has provided the team with a lot of help in regards to technical analysis of the system needed to finish the design process. Team 12 would also like to recognize the instructor Dr. Gupta for continued guidance throughout the semester and aid in the electrical design portion.

1. Introduction

Due the removal of the current model mounting system, the Air Force Research Lab has requested the production of an articulating robot arm to be used in a subsonic wind tunnel. The arm would allow research conducted at the facility to continue and will enable the researchers to manipulate the pitch and yaw of aircraft models in an active flow. The articulation of the robotic arm will be dictated by a stepper control unit that will be linked to a remote user interface. The yaw and pitch movements of the arm will be carried out through the use of two separate stepper motors. Any specimens held by the arm will be mounted utilizing a sting. The wind tunnel that the robot arm will be placed into is an open test section and is located at the Aerodynamic Characterization Facility (ACF) of the Research and Engineering Education Facility (REEF). The wind tunnel as the ability to generate wind speeds that can reach up to 22 m/s or approximately 50 mph. The inlet of the wind tunnel has a square cross-sectional area that is 42” by 42”.

1.1 Problem Statement

The open wind tunnel located at the REEF center used by the Air Force Research Lab requires a mechanism in order to test specimens. The mechanism must be able to hold a specimen in the center of the jet flow and manipulate both the pitch and yaw during operation. The mechanism must maintain the specimen’s position in the center of the jet at the conclusion of any manipulation.

1.2 Design Requirements

The goal of the project given to Senior Design Group #12 is the design and production of a cost effective mechanism that can hold and adjust the orientation of a specimen being tested in a subsonic wind tunnel. The sponsor of the project presented a set of objectives to be achieved by the robotic arm. The arm must be structural sound enough to withstand the maximum forces generated by the wind tunnel, 22 m/s. The arm must also be able to manipulate the orientation of the mounted specimen while the tunnel is operating at maximum velocity. During the manipulation of the specimen, the position of the specimen (center of mass) must not change. The two aspects of the specimen’s orientation that will be adjusted are the pitch (angle of attack) and the yaw (side slip). The pitch of the specimen should be able to be adjusted to any position between -5° below center and 30° above center. The yaw of the model should be able to adjust 10° left or right of center position. The final objective set forth was that when the model is in the desired position the model must not move. The set of listed objectives include:

- Arm able to withstand maximum force generated by wind tunnel
- Arm able to operate at maximum tunnel velocity
- Center of mass of specimen must not change
- Adjustable pitch range of -5° to +30°
- Adjustable yaw range of ±10°
- Model must not move when in set position

1.3 Design Constraints

While attempting to meet the objectives set forth by the sponsor multiple constraints had to be considered. The sponsor has requested that the user interface that will operate the robot arm will be run by a LabVIEW program. Using LabVIEW offers the opportunity to create an easy to use system, as well as having the ability for the system to report the angle that is actually at in comparison to the requested position. A second constraint in regards to the operation of the arm requires that the orientation of the arm should be within 0.25° of the requested orientation. When at any position the sting has the potential to deflect, the maximum deflection that is allowable is 0.25”. To ensure validity of any results taken while using the system in addition to the structural integrity, the sponsor has required a factor of safety of 5. The final major constraint of the project is the operating budget; the team has been allotted $2,000 to complete the project. To assist with limitations of the budget and overall design, some components have already been provided by the sponsor. The listed constraints for the mechanism include:

- User interface involves LabVIEW
- 0.25° orientation accuracy
- Maximum Deflection of 0.25”
- Factor of Safety of 5
- $2,000 budget

2. Background and Literature Review

2.1 Wind Tunnels

Wind tunnels offer a cost effective way to test aerodynamic designs in a controlled environment. When a properly scaled model is placed in a wind tunnel, dimensionless numbers can be utilized to generate flows that are dynamically similar to conditions that would been seen by the full-size aircraft. The data recovered from testing would allow for modification and improvement before starting full-scale production.[2] Wind tunnels operate by having a fan pull air into the entrance of the tunnel, often through screens and straighteners to help straighten the flow and reduce the turbulence. The cross sectional area of the tunnel is then reduced to increase the velocity of the incoming flow, which then proceeds to the test section. In an open circuit facility, once the flow has passed through the test section it continues to the diffuser and is discharged.[1]

The facility that the robot arm will be utilized in is an open test section subsonic wind tunnel. In an open test section wind tunnel there are no walls bounding the flow immediately after the inlet contraction. This means that as the flow moves away from the test section entrance, the boundary layer of the flow will expand outward.[2] This type of wind tunnel orientation is most often used for acoustic testing purposes. Figure 1 shows an example of an open test section open circuit wind tunnel that is housed at the same facility where the robotic arm will be used.

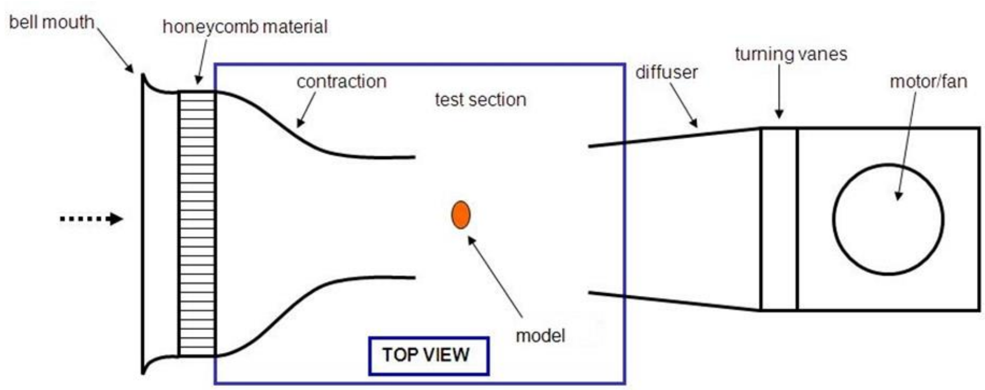


Figure 1: General representation of an open test section wind tunnel.

To achieve ideal results from testing, it is imperative that the model mounting system be minimally invasive. This is especially true for subsonic wind tunnels as the upstream adjusts to downstream objects and blockages. A common method of model attachment is the utilization of a sting mount.[2] This type of mount attaches to the rear of a model and provides minimal interference to the flow approaching the model. Figure 2 shows a model held by a sting mount as well as representation of the flow direction. Measurement devices may be placed on the end of the sting, such as an internal balance or strain gage, to provide data on the specimen during experimentation.[3]

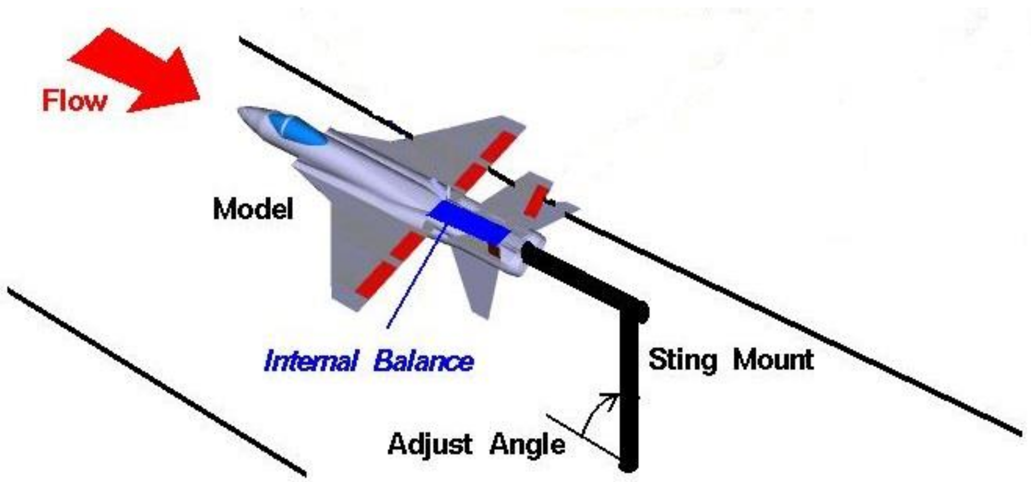


Figure 2: Example of a specimen held by a sting mount in a wind tunnel.

2.2 Testing Facility

The device is being requested by a division of the Air Force called the Air Force Research Lab. The University of Florida has a shared facility with the Air Force called the REEF center. This center is located in Shalimar, Florida. It is a research center that has various wind tunnels for different types of propulsion and aerodynamic testing. Our mechanism is going to be used in a low speed wind tunnel within this facility at maximum speeds of 22 m/s. The purpose of the testing remains unknown. Figure 3 shows the wind tunnel in the REEF facility that this mechanism is being designed for. The figure shows both the compressive intake that speeds up the air and the exist portion that has a motorized fan that draws air through the testing chamber.

Figure 3: This figure shows in the large intake (left) and motorized air drawing exit (right)

2.3 Similar Mechanisms

One already existing mechanism that accomplishes the same objectives is the mechanism that was previously used for the low speed wind tunnel. This mechanism was called "pitch-plunger" by our sponsor Dr. M. Sytsma. Figure 4 shows this mechanism. The pitch poles adjusted the pitch of the mechanism while maintaining the specimen center and the yaw adjustment device rotated the specimen at its center of mass so its movement was left unchanged. However, we could not recreate this device due to its price tag of approximately $180,000. Also, this mechanism was highly over designed for this wind tunnel and was capable of high frequency dynamic testing. The mechanism our group has been instructed to build is for static testing and does not require the same robustness and cost.

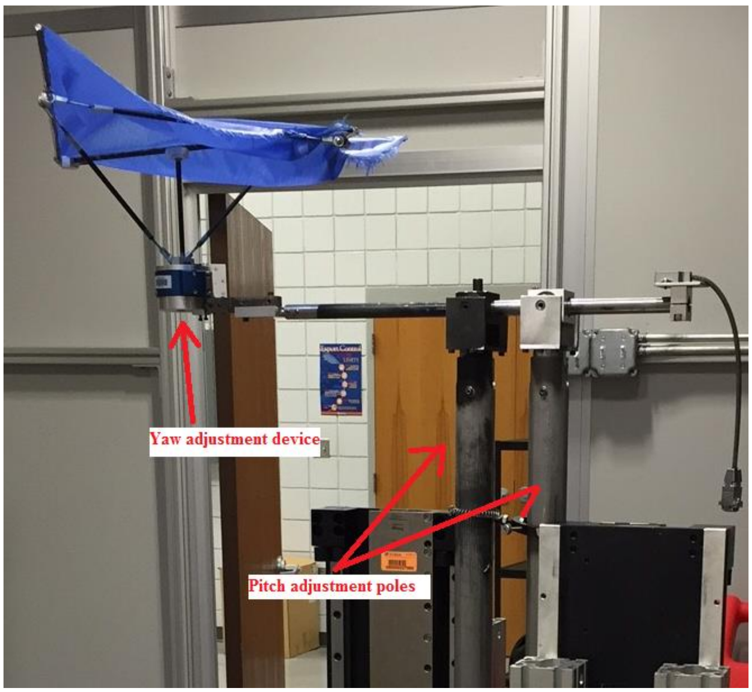


Figure 4: Current sting mount mechanism

Another mechanism design that is used to accomplish these movements, while also maintaining the center of mass in the center of the flow, is shown in figure 5. This device adjusts the pitch along the circular arc in the back. As it moves along that arc the center is maintained. The device can also roll along the sting shaft axis. Finally, this entire system is set on top of a turn table with the mechanism in the center. This way, when the table operates, the mechanism still sits in the center of the flow.

Figure 5: Sting mount mechanism

3. Concept Generation

3.1 Functional Analysis

The process by which the mechanism will operate can be broken down into four distinct sections; the structure, the user interface to the controller, and the controller to the two different stepper motors. The structural portion of the mechanism will be responsible for withstanding the wind tunnel forces and mounting the test specimen. This part will be designed to be as aerodynamic as possible in order to minimize forces and vibrations.

The mounting mechanism for the structural portion will be actively controlled by the user. Therefore a user interface will be required to enter commands for pitch and yaw that will feed into the stepper controller. There will be a user interface (UI) that consists of a command prompt in which the manipulations to the models alignment can be typed; these commands will be fed to the controller.

Once the commands have been passed from the stepper controller to the stepper motors, they will initiate their operation. The two motors will be controlled independently, one changing the angle of attack and the other adjusting the yaw by controlling rotation of a turn table provided by the sponsor. The stepper motors will be connected to a torque amplification system in order to increase the torque produced by the motors. This will allow them to easily adjust the pitch and yaw through their full range of desired motion. Table 1 summarizes the functional analysis.

Table 1: Functional Analysis

Equipment	**Function**
Controller	Used to pass command from user interface to respective stepper motors
Stepper Motor	Motor used to adjust the angle of attack (pitch) of the chosen mount design
Stepper Motor/Turn Table	A turn table (provided by sponsor) that has already been integrated with a stepper motor
Structure	Mounts the specimen and provides a structure for which the motors actuate to accomplish inputs

3.2 Previous Design Ideas

Our first design concept was a simple sting mount with a recessed portion to allow the base to rotate about the centroid of our model. This design is extremely simple to produce as some bent medal tube, or some separate straight portions screwed together would produce a satisfactory product. This design is shown in figure 6. It is a very useful design for yaw calculations, as the rotation about the models centroid would prevent any translation in the flow field, ensuring accurate data. However, this design is only advantageous for very low angles of attack. Once the model is adjusted to some angle of attack, the model will be moved in the flow field as well as no longer rotate about its centroid. This would skew the data to the point that it is no longer useful. With these considerations and the input from our sponsor this design would require extra actuation in order to re-center the model in the air flow.

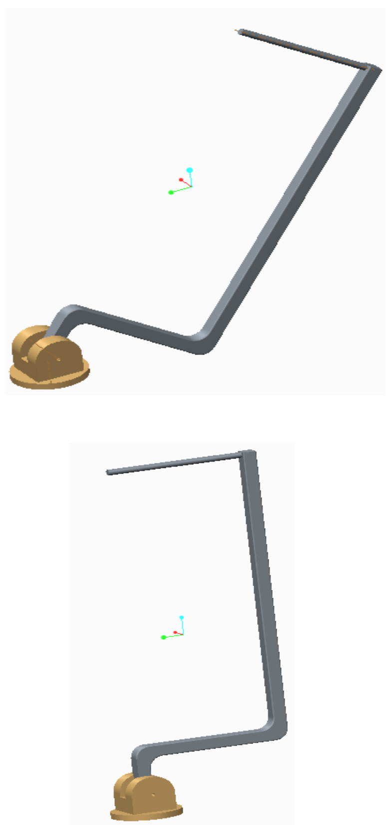


Figure 6: Design Idea 1

In order to maintain the model location within the flow field, two more designs incorporating a circular arc was developed. This design is shown in figure 7. The arc design allows for the angle of attack (pitch), to be changed within the flow field without translating the model in any direction. By placing the pitch center of rotation in line with the same axis as the yaw rotation, the model can be adjusted during operating conditions without data corruption. Figure 8 illustrates the circular arc concept. As shown, the circular arc can be adjusted through a fixed point and maintain the models center.

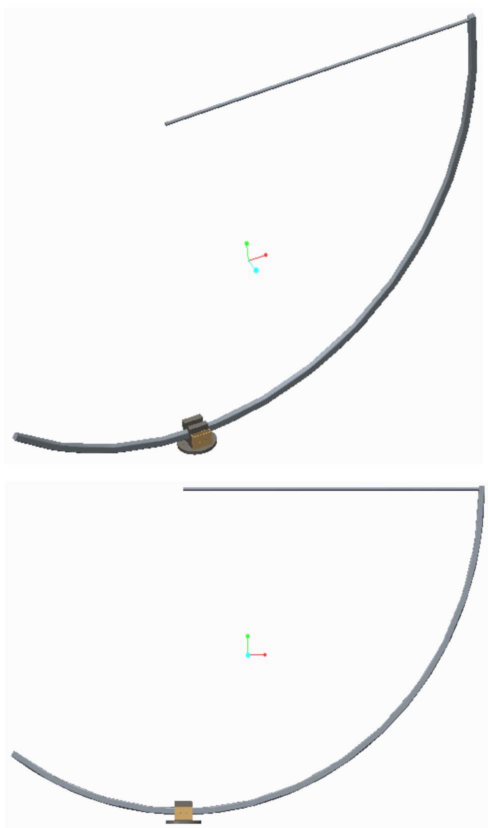


Figure 7: Design idea 2

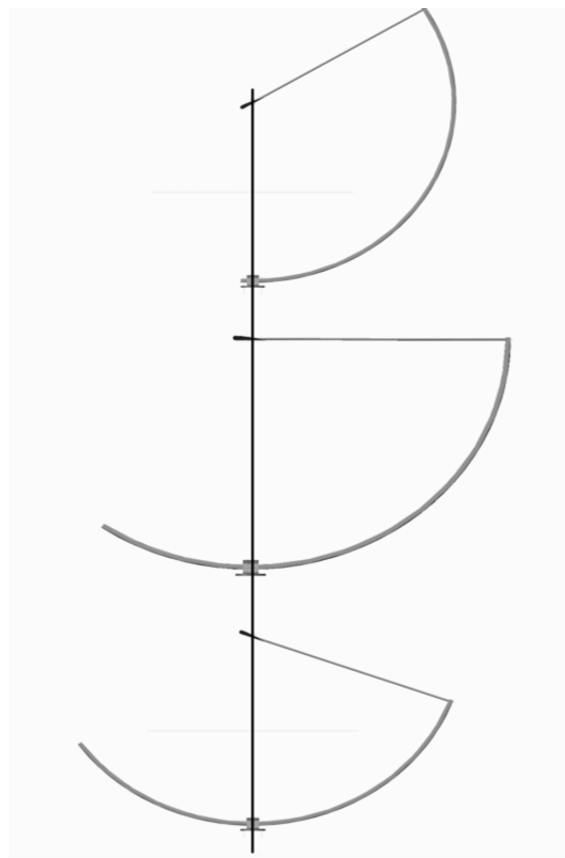


Figure 8: Proof of arc design concept

The arc design however is more complex to manufacture. The radius of the arc will have to be approximately 25 inches in order to stay out of the flow field. This would be very difficult to find off the shelf or machine, and will probably have to be custom made. The arc will be mounted on a turn table with a built in stepper motor. This would turn the arc on the horizontal plane, adjusting the yaw. The pitch would be adjusted by a stepper motor with some type of torque amplification system. A worm gear would allow a fine degree of control and wouldn't be back drivable, thus maintaining its position under a load.

Similar to design two, design three utilizes an arc to maintain the model location during dynamic testing conditions. This design, shown in figure 9 was developed to help mitigate the amount of material in front of the model, and maintain designed flow conditions upstream. However, because subsonic fluid can sense the presence of a boundary ahead and adjusts, the arc would need to be properly spaced in the fluid in order to maintain fluid conditions. By placing the arc mounting mechanism at the rear of the arc, the amount of material in the arc is reduced. This reduction in the amount of arc used could result in significant cost savings if it must be custom manufactured. The arc would still require a radius of approximately 25 inches in order to have a sting that centers the model over the turn table. However, because more material would be in the flow, stronger motors would be required in order to adjust the pitch and yaw during tunnel operation. This would require more structure material, larger motors and higher costs.

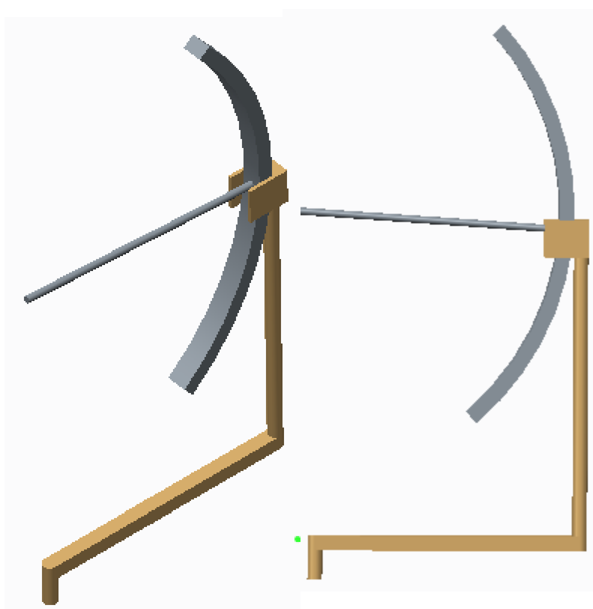


Figure 9: Design idea 3

3.3 Selection of Optimal Design

The criteria we chose to judge our different designs upon are shown in the decision matrix. The decision matrix is shown in table 2. Strength, cost, efficiency and complexity were the main evaluating factors. Each of these criteria were given a weight factor based on the scale 3, 6 and 9. Each design was then given a score of 1, 3, 7 and 9 based on its strength in each criteria category relative to one another. The scores were multiplied and summed together to get a total score. The strength of the design was evaluated based on geometric principles and amount of flow that was located in the within the wind tunnel flow. Design #1 had approximately half of its supporting structure in the flow. This would induce more drag on the design relative to design number 2 and was given a score half of that than design # 2. Design 3 had majority of its design in the flow as well and would induce more drag than design 2 as well. The relative scores reflect this difference.

Table 2: Decision Matrix

Criteria	**Strength**	**Cost**	**Efficiency**	**Complexity**	**Total**
Weight Factor	9	6	9	6	
Design #1	3 27	3 18	3 27	7 42	138
Design #2	7 63	7 42	9 81	3 18	180
Design #3	3 27	3 18	7 63	3 18	125

The cost portion of the score was mainly determined by the section of the design that will shift the pitch, as the yaw of all three designs will be adjusted in the same manner. Designs #2 and #3 would require a very precise arc to be purchased or fabricated which could potentially cost double to triple what the mounting structure for design #1 would be comprised of. Also, design 2 and 3 would require a technical form of actuation which also may be expensive. The relative scores of this are shown in the decision matrix. The complexity of the design and the cost of the design are interrelated and share the same general trend in the decision matrix; design #3 scoring the lowest and design #1 scoring the highest.

The efficiency component of the decision matrix took multiple factors into account to produce its score. One big factor in this score was the amount of movements required. Design #1 required 4 movements (2 for actuation and 2 for re-centering) while the other designs only required 2 movements. Another consideration was the amount of flow interruption in comparison to stability. The mount must refrain from interrupting the flow before it reaches the test model and must maintain a stable unmoving position. Design #2 scored the highest on this portion as it is mostly kept out of the flow and requires only 2 movements.

The cost was analyzed based on the amounts of material and additional equipment required. Designs 1 and 2 have more material due to the moment arm that extends to attach behind the object. Also, design 1 requires more motors in order to keep the objects center of mass stationary. This would require significant more costs due to the stepper motor and encoder combination. For this reason, design 2 scored the best. It would only require one additional stepper motor and would require material just for an arc.

Efficiency grading was developed based on how easily the mechanism will move. In design 2, one movement covers both translation and centering. It also has just the sting mount in the flow. Design 3 has similar efficiency but has a large arc in the flow. Since the tunnel is subsonic, this would change results due to the fluid being able to adjust to the upcoming boundary. Design 1 had the lowest efficiency because it would require 4 movements to accomplish the same task as designs 2 and 3 accomplish with 2 movements. This also ties into the complexity grading. Although design 1 is extremely simple, it has complexity in terms of keeping the mount centered in the flow. Design 2 has complexity about its arc, but generally does not interrupt the flow patterns. Finally, design 3 has a relatively large object in the flow. This would be hard to analyze and would require many assumptions. It would also require research beyond what is known. For this reason, it scored low.

Overall, design concept 2 was the final selection. This was because it was the most optimized case of strength, cost, efficiency, and complexity. The next section will further analyze this design. In the next section, each of the different components will be analyzed along with FEA analysis and the programming logic required.

4. Final Design

4.1 Design for Manufacturing

4.1.1 Components

The final design is comprised of many sub-assemblies that come together in order to complete the full assembly. The sub-assemblies comprise of the mounting system assembly, follower assembly, arc-sting assembly, and drive train assembly. Each of these are comprised of different parts that are joined and constrained by different methods. When joined together on the base plate, it is place onto the turn table to complete the final design. Figure 10 shows the complete design with each sub assembly labeled.

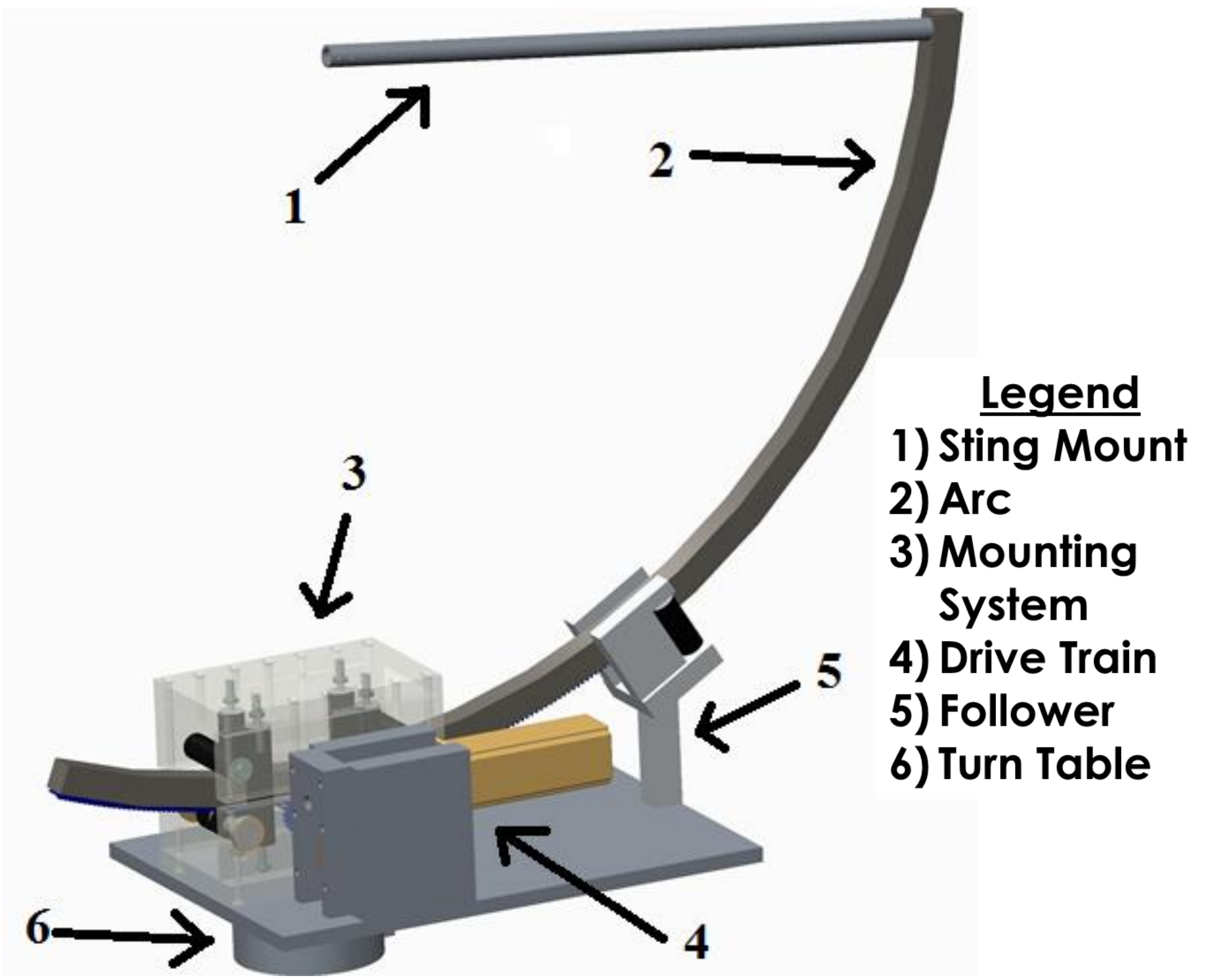


Figure 10: Full assembly

4.1.2 Assembly

The arc system was designed in methodical fashion to ensure ease of assembly upon delivery to the customer. There are sub-assemblies that can be constructed individually and then pieced together to complete the assembly process. The only tools needed are a press, to fit the bearings, a screwdriver, a set of allen wrenches, and JB weld. The bill of materials for the entire project can be found in appendix F.

4.1.3 Bearings and Rollers

The first step is to press-fit bearings into each section of the housing. Each bearing was selected so there would be no confusion as to where the bearing should be placed in the housing. Each bearing of appropriate size should be seated fully so the machined lip on the housing stops the bearing, and ensures proper shaft alignment. Detailed drawings of the bearings can be looked up using the part number found in appendix A.

To assemble the rollers, the appropriate steel shaft and rubber roller should be matched up. The roller inner diameter will match the shaft diameter, and the length of the roller will be approximately 2 inches shorter than the shaft length. Again the sizes were selected such that the shafts can only go to the intended rollers. The roller should be slipped over the steel shafts and placed between the machined slits for the c-clips. Once the roller is in place, c-clips should be applied so the roller is set to a fixed position on the shaft. One important consideration, for the lower half inch inner diameter rollers, is that the rollers must be positioned with a half inch gap between each roller. This gap is to allow for the tracked section to navigate through the roller section. A detailed drawing of the rollers can be looked up by getting the part number in appendix A.

4.1.4 Main Mounting Housing

The most important part of the design is the main mounting mechanism. This mechanism is comprised of polyurethane rollers, steel shafts, bearings, and an aluminum 6061 housing that holds it all together. Figure 11 shows the mounting system with each component labeled. The ½

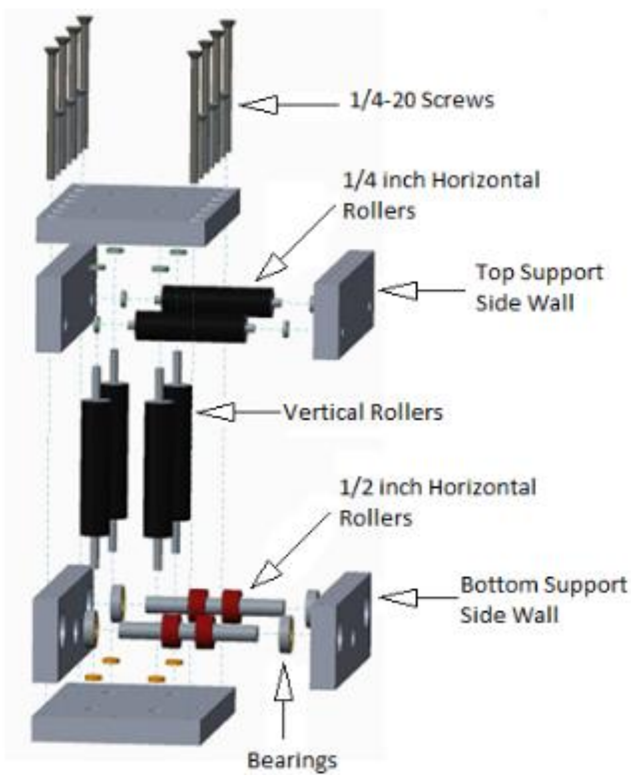


Figure 12: Housing exploded view

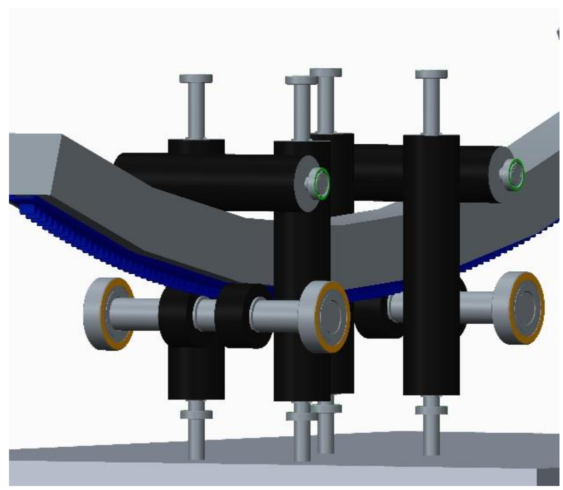


Figure 11: Housing assembled view

inch rollers and vertical rollers constraint movement in both the x and y direction. These are mounted on to shafts through form fit and c-clips. The shafts are then placed into the housing wall supports with bearings to minimize friction. A fully constrained housing is shown in figure 12 that shows an assembled view of the assembled housing.

4.1.5 Follower Assembly

The follower is constructed in a manner similar to the main housing system. However, it differs in the fact that it does not constrain vertical movement. The follower's main use is for constraining torque and preventing low modes of frequency when the arc is being used at high yaw angles. Figure 13 and 14 show both an exploded view and assembled view of the follower. The follower support assembly can be secured to the turn table base plate. Use the single 1/4-20 bolt on the bottom to bolt the structure to the plate. The follower will be placed behind the housing assembly, directly in line. There is only one hole in the plate where the follower assembly can be mounted. Note the follower assembly need to be aligned to the base assembly. This is done by aligning the edge of the plate and the edge of the square support rod. More information on the turntable can be seen in the data sheets in appendix B.

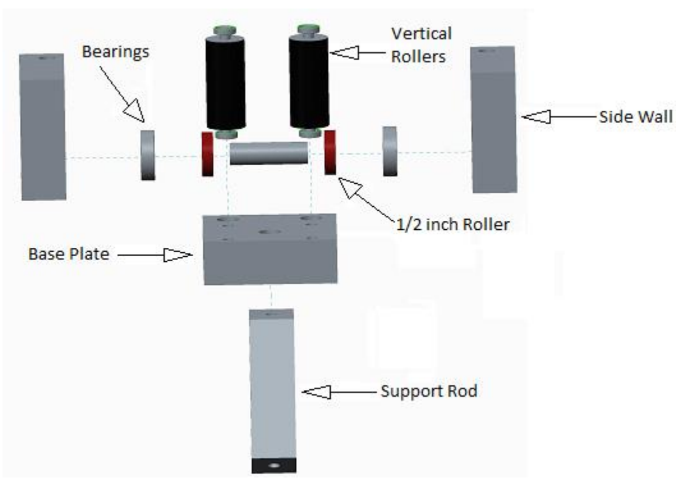


Figure 14: Exploded follower assembly

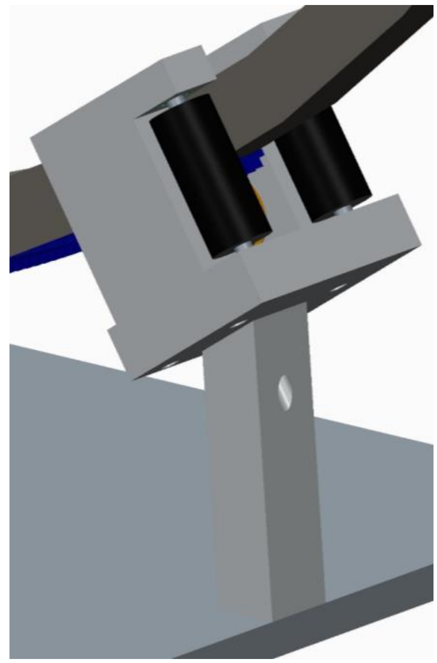


Figure 13: Assembled follower assembly

4.1.6 Arc-Sting Assembly

The arc-sting assembly is fairly simple and straight forward. There are 3 main components: the sting, the gear track, and the arc. The sting is form fitted into a mounting hole in the arc. Set screws in the side of the arc are used to secure the sting so that it has adjustable forward and backward movement. The set screws are standard 10-32 set screws. Figure 15 shows the exploded view of the arc sting assembly. Detailed drawings can be found in the appendix C.

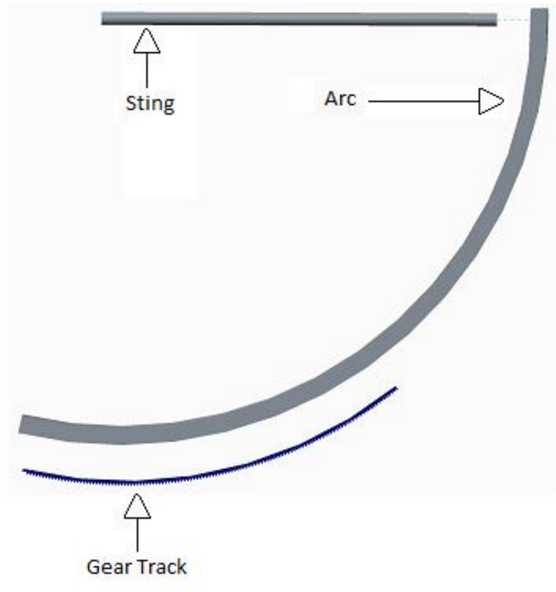


Figure 15: Arc-Sting assembly

4.1.7 Drive train assembly

The motor housing assembly consists of three plates and three bearings. The plates are arranged in a manner that the bearings will all face toward one another. The plates can be bolted directly together as there are no components that are confined within the structure. The exploded view and assembled view of this assembly are shown in figure 16 and 17.

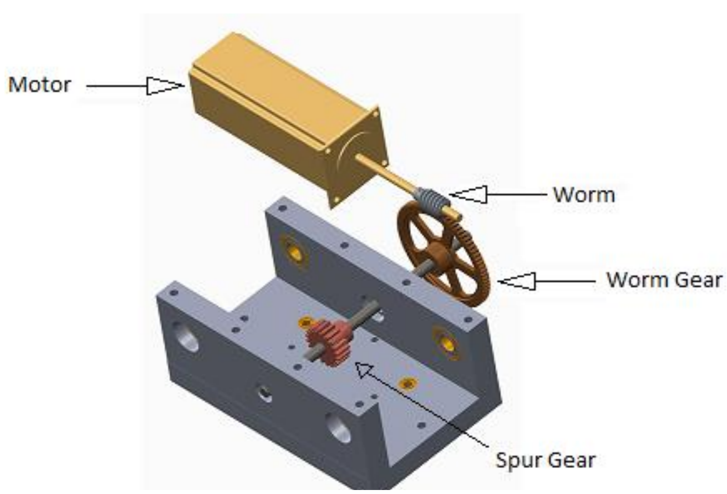


Figure 16: Drive train exploded view

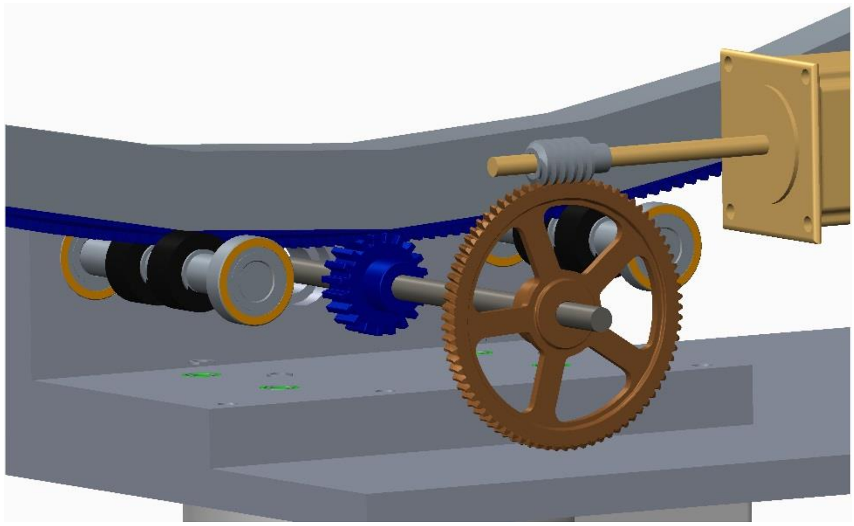


Figure 17: Drive train assembled view

With the motor housing and the bottom support assembly mounted to the turntable plate, the power train can be connected. The powertrain consists of the motor, motor shaft extension, shaft coupler, worm, worm gear, power transmission shaft, spur gear, and two shaft collars for the power transmission shaft. The first step is to mount the spur gear and work gears. Begin by sliding the power transmission shaft through the outside of the motor housing, place the worm gear in the motor housing assembly and slide onto the power transmission shaft. Continue sliding the power transmission shaft through the other side of the motor housing, and through one side of the bottom support assembly. Slide one shaft collar, the spur gear, then the other shaft collar onto the power shaft, then continue to push the shaft through until it is flush with the outside of the bottom support assembly. Secure the shaft in place with the two shaft collars by sliding each shaft collar to the side of the support housing, and they make contact with the bearings. Tighten the shaft collars in place once they are in place. Once the shaft is in place align the spur gear and worm gear so that the geared section is directly centered in each of their respective housings. When they are positioned, tighten the set screw on the gear hub.

With the gears in place, the motor can be mounted to the motor housing assembly. There are four screws to mount the motor on the housing. The motor should be positioned so the connectors do not face the arc. Place the motor over the holes and bolt in place. With the motor mounted, slide the shaft coupler over the motor shaft, do not tighten the coupler yet. Slide the shaft extension into the housing through the bearing opposite the motor. Slide the worm over the shaft extension and continue to slide the extension until it seats against the motor shaft. Slide the coupler over both the motor shaft and tighten the coupler to both shafts. Spin the worm gear such that the worm will mesh with the worm gear directly tangent to the shaft. When in position tighten the worm in place by the set screw. More detail on the power train assembly can be found in appendix C.

After the power transmission assembly is in place, the vertical rollers can be put into position. Simply slide the each of the four rollers into one of the four bearings pressed at the base of the bottom support structure.

4.1.8 Complete assembly

An overall assembly can be seen in figure 18. The follower assembly consists of three plates, one square support rod, two vertical rollers, one horizontal roller, and six bearings. Again the rollers should be placed in their respective positions before bolting the structure together. With

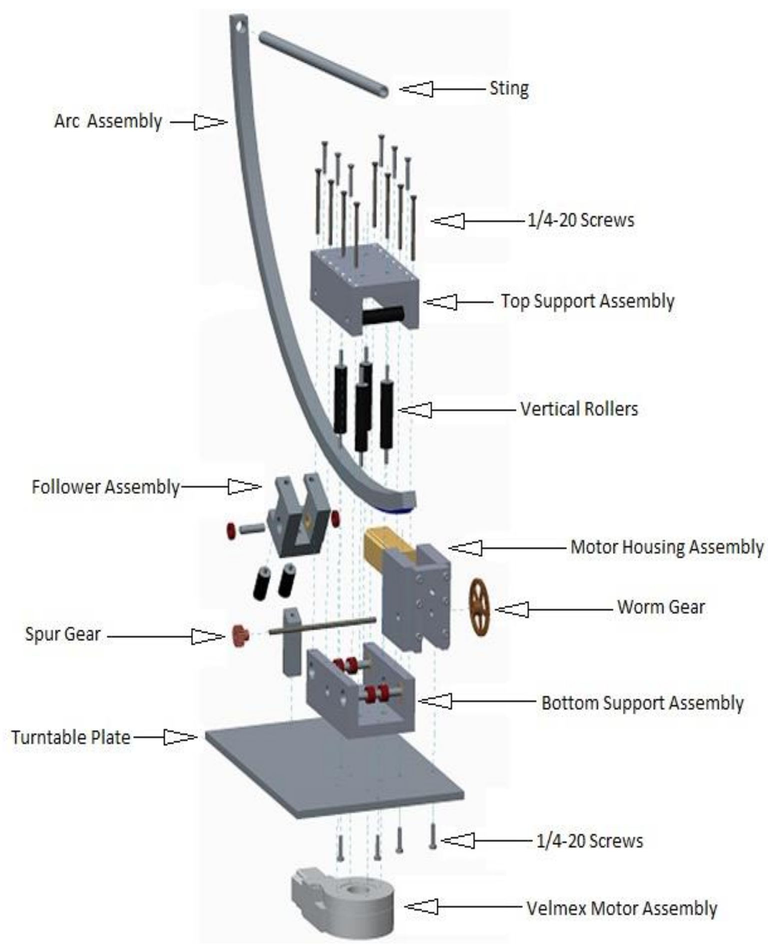


Figure 18: Complete assembly exploded view

the rollers in place, bolt together the side and bottom plates with the 1/4 -20 screws. Once secured, the support rod can be bolted to the bottom plate. It is imperative that the support rod and the bottom plate be aligned such that the sides are parallel. This is easily achieved by placing the support and the rod in their side just before the bolt is tight. Doing so will allow the table to align the support. More information on the follower assembly can be found in appendix C.

4.1.9 Time for assembly

In order to assemble the arc system we allotted two weeks to test fit each component and build the sub-assemblies. This was done to ensure when the entire system was constructed, there would be no issues. The physical labor required to construct the entire assembly was approximately seven hours, thirty-one hours if the epoxy cure time for the arc is included. Bolting the sub-assemblies, constructing the rollers, and fitting the bearings took three hours. Gluing the gear rack to the arc took an hour of labor, plus a full twenty-four hour cure time. Lastly wiring the motors and zeroing the unit took three hours. The assembly of the entire system took less time than expected. The test fitting that was performed throughout the machining process ensured an easy assembly.

4.1.10 Design Optimization

The design implemented is the optimum design for the REEF facility wind tunnel. The requirements of achieving adjustable pitch and yaw, while maintaining a fixed position in the tunnel jet stream or impeding the incoming flow, was achieved. A few of the parts that were utilized could have been milled from one solid piece of aluminum instead of the bolted design that was chosen. However, this would have raised cost, and in the event of a catastrophic failure of that component, resulted in more expensive repair. The bolted option gave more benefit for little additional complexity. The only additional components that would increase the functionality of the arc would be an inclinometer at the tip of the sting to ensure accuracy. Any other additional components would unnecessarily complicate the system.

4.2 Analysis

4.2.1 Calculations

Geometric analysis

Before any other analysis could be completed, geometric analysis had to be completed in order to size the mechanism correctly. It was a constraint to have most of the mechanism outside of the flow. Since an arc was the mounting mechanism chosen, this means that throughout its entire actuation motion (-5 to 20 degrees), it must not imping on the flow field. The arc was analyzed in its most extreme condition plus 10 degrees for safety. This would be 30 degrees since this would place part of the arc into the flow as shown in figure 19. Using equation 1, and a jet half-width of 20 inches, the radius of the arc was calculated to be 24.4inches. This was rounded up to 25 inches for simplicity and clearance.

$$radius = \frac{l}{\cos(35)} = 24.4\ inches \sim 25\ inches \tag{1}$$

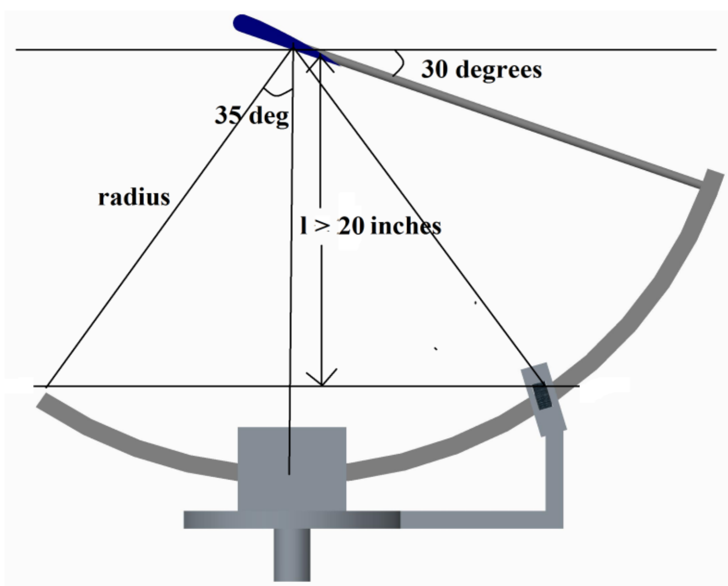


Figure 19: Geometric Analysis

Assumptions

Before any of the structural analysis could be completed, the flow around the body had to be analyzed. Utilizing some conservative assumptions, the flow around the body could be analyzed in order to obtain lift and drag forces. The assumptions used to obtain the lift and drag forces are shown in table 3. Appendix D shows all of the Mathcad calculations completed to arrive at maximum lift and drag forces. Results of the flow analysis are shown in table 4.

Table 3: Assumptions for calculations

#	Assumptions
1	-Maximum flow blockage of 10%
2	-Coefficient of lift (CL) = 2
3	-Coefficient of drag (CD) = 1
4	-Multiplication factor of 1.5 for unsteady loads

Table 4: Results of significant calculations

Variable	Value (units)
Max Lift	12 (N)
Max Drag	60 (N)
Max Moment	38 (N*m)

Gear Analysis/Motor Selection

Because there was limited budget, motor sizing and gear train construction had to be simple yet effective. Once the assumptions were complete and a conservative force was estimated on the arc design, a gear train could be constructed. With use of a gear train to amplify torque, a smaller motor could then be selected.

Since there was a considerable 15lb force on the sting at 25 inches away, the system was going to experience a lot of torque in order to actuate through an attached plastic gear track. A worm gear was selected for this purpose and because it is not back drivable. A worm was attached to a worm in a single start 50:1 ratio. The worm actuated the worm gear attached to the shaft with a plastic spur. This spur mated with the track on the back of the arc. Calculation for the torque amplification can be found in the appendix D. Stress analysis calculations are also completed in the appendix in order to make sure the plastic gear would not fail.

Once the gear train was sized, the motor could be selected. A few components to consider when selecting the motor was the power, RPM, and torque available in the motor. The specification sheet for the selected motor can be found in appendix B. This motor has torque curves that allow for calculation of RPM throughout the system. Using these RPM values, life-cycle could be determined for the plastic gears once the surface strength has been determined. RPM calculations can be found in appendix D. Surface strength calculations and life cycle analysis will be discussed later on.

4.2.2 Stress Analysis

The main concern for failures due to over stressing components came into consideration for sting mount deflection and the spur gear teeth. The sponsor required that the sting deflect no more than 0.25 inches. Larger deflections would add error into the desired angle of attack and could cause modal vibrations to occur at a lower frequency. The spur gear teeth could fail because they are plastic and would fail before the hardened steel and brass gears do. FEM was performed on the arc-sting design in order to show deflection and stresses seen by on the assembly.

Arc-Sting design

One requirement in the project was to design a sting mount that deflected no more than 0.25in and had at least 3 factors of safety for dynamic forces. Finite element analysis was run in Creo Simulate on the arc and sting together in order to determine the maximum forces and deflection seen by the assembly. A 15 lbf was placed axially and perpendicular to the tip of the sting to be conservative in the FEA. The arc sting assembly was constrained by the housing and follower in the FEA shown in figure 20. The deflection chart is shown in figure 21. The maximum

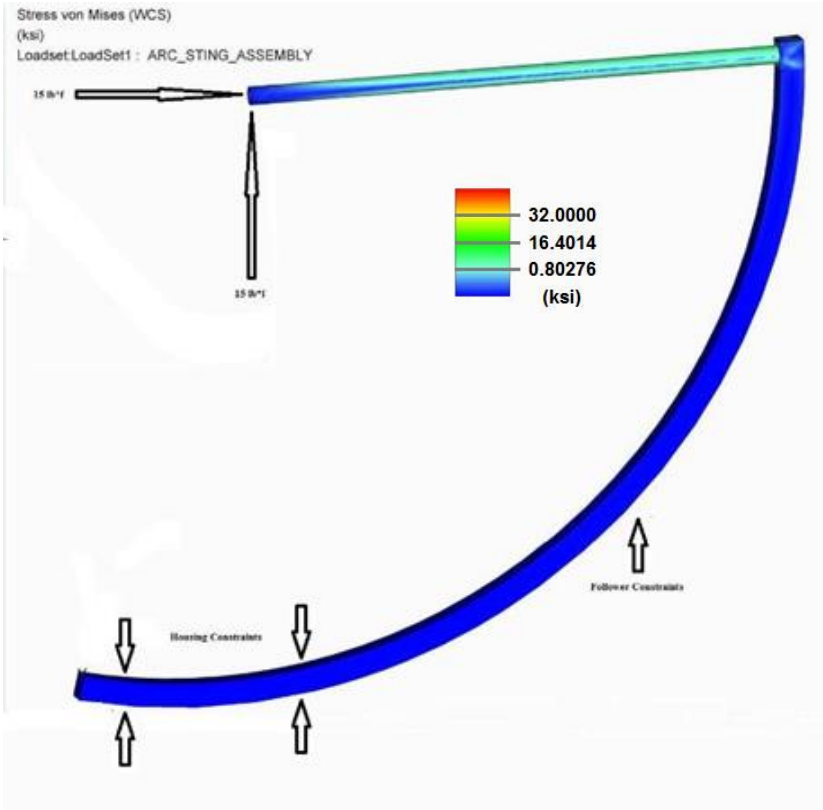


Figure 20: FEM Stress Analysis- Von Mises stresses

forces seen on the sting is approximately 10 ksi with a max allowable of 32 ksi. This gives over 3 factors of safety. The maximum deflection is about 0.1 inches while the max allowable was 0.25 inches. This design gives over 2 factors of safety and meets the sponsor requirement.

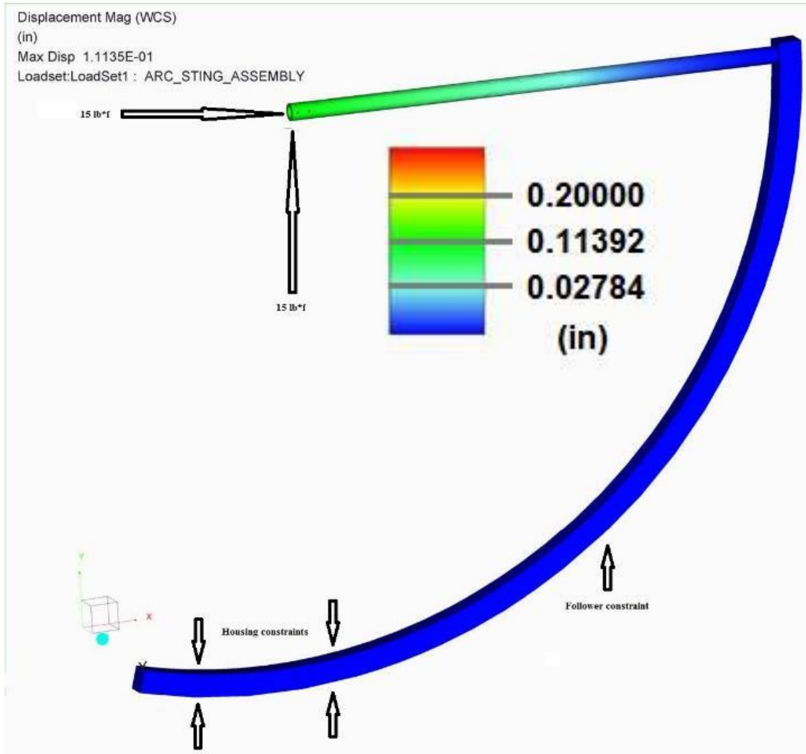


Figure 21: Displacement Analysis

Spur Gear Stress Analysis

The plastic spur gear that mates with the arc will experience the most force amongst all of the gears. It is also made of plastic unlike the other gears. There is a possibility of 15lbf loaded on a tooth at a time. Bending and surface strength had to be analyzed on the teeth in order to ensure integrity of the system. The bending strength calculations found that the tooth had a factor of safety of 1.5 when tip loaded with 15lbf. This factor of safety also has a 1.5 factor of safety built in for unexpected dynamic loads. When the surface strength was analyzed, it was found that the surface would remain intact for approximately 10^5 cycles when performing gear analysis on it. The calculations for the bending and surface strength of the design can be found in appendix D.

4.2.3 Design for reliability

This arc-actuation mechanism is expected to be used to complete testing at the REEF center. In order for proper testing and operation to occur, the life cycle of this mechanism must be analyzed in order to ensure long-lasting life. The spur gear and polyurethane rollers were analyzed for their life cycle due to the fact that they could eventually creep and cause deformation. A suitable prediction for the amount of cycles expected from the mechanism were drawn from the analysis. Calculations for the plastic spur gear and rollers can be found in appendix D.

Lifecycle Analysis- Spur Gears

The plastic spur gears are most suspect for wear over time since they will see the largest applied forces on a small areas of the teeth. The maximum allowable bending stress and surface strength were analyzed and compared to standards in order to determine a suitable life cycle for the spur gear teeth. These calculations are shown in appendix D. The max allowable bending stress is used for bending failure while surface durability calculations are used for life cycle analysis. Knowing the life cycle can aid in inspection checks and give an approximation for when parts should be replaced. The calculations yielded a maximum allowable force of 20lbf and approximately 4 kgf/mm^2 for surface strength. This gives about a 1.3 factor of safety on the bending stress and approximately 10^5 cycles when comparing to figure 22.

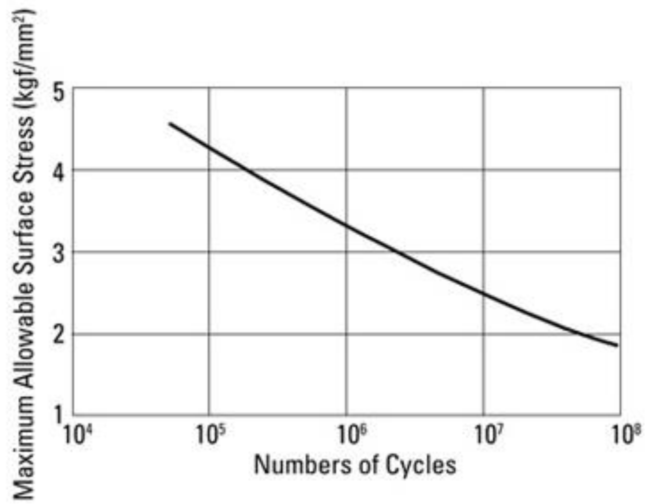


Figure 22: Number of allowed cycles

Lifecycle Analysis- Polyurethane Rollers

The polyurethane L167 rollers have an elastic modulus of 1.8 ksi and a tensile strength of 5 ksi. When considering the horizontal rollers, there are 3 load sharing rollers which breaks up a maximum possible load of 20lbf. This gives each horizontal roller approximately 7 lbf of vertical force. Assuming a contact area of 0.5 inches by 0.05 inches and using a vertical force of 7lbf, each roller experiences 0.3 ksi. This results in over 10 factors of safety for the max strength and 5 factors of safety for escaping the elastic region. Also, because the material is flexible, large forces would increase the surface area and lessen the stress seen. Following the same logic, there are 3 vertical rollers with a max force being only 15lbf and a 1in by 0.05in cross section. The horizontal rollers would fail first. Due to the drastic factors of safety on the rollers, it is assumed that the gears would fail first. A good plan for managing the rollers would be to inspect each time the spur gear is inspected. Search for wear and deformation over time and determine a suitable changing period. Therefor 10^5 cycles is the limiting factor on the mechanism due to the gearing system. Calculations are shown in appendix D.

Failure Modes

Because this design has areas of concern for failure, all of the potential failure modes and preventative measures must be considered. Using a FMEA (Failure Mode Effect Analysis), failure modes could be analyzed for their potential causes, effects, and solutions. Also analyzed by the FMEA is the severity, occurrence, and ability of early detection. The product of these three variables gives an RPN that represents the overall concern level. The concerns are listed in order from greatest to least important. The FMEA can be found in appendix E. The most critical failure modes with the highest RPN include:

- Destruction of flexi-rack
- Destruction of spur gear
- Loose gear connections
- Loose flexi-rack attachment

4.3 Programming Logic Design

The function of this project is to secure a test specimen in the center of the wind tunnel flow. The system must be able to move the specimen in the pitch and yaw directions during tunnel operation. This system utilizes multiple software and hardware. Figure 23 displays the system's operational flow.

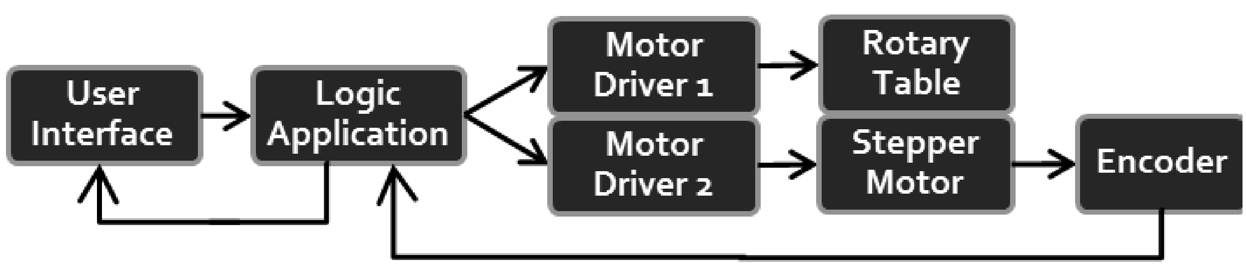


Figure 23: Operational Flow

The user interface is developed through LabVIEW. LabVIEW is also responsible for much of the logic application. It processes and compares the entered and current position values with data returned from the controller. It then sends commands to the controller for movement and program execution. The motor drivers for the system are internal to the Galil controller. Each one communicates with a motor to actuate the system. The stepper motor for pitch movement is equipped with an encoder which will feedback the motor's position to the controller. The controller will then send this information to LabVIEW to be processed. If the system movement is valid, a message will be returned to the user that movement is complete and the user will be able to enter new values.

The functional diagram in appendix E displays the program flow. It is important to note that a programming emergency stop will be connected into the entire system so that the program can be aborted at any time.

4.4 Assembly Instructions

The arc system consists of four main assemblies, the arc structure, roller support housing, power train, and the follower. To construct the arc, first use a high strength epoxy to bond the flexible gear track to the arc. Ensure the track has a quarter inch of clearance on both sides of the arc to allow proper translation while in the support structure. Once the epoxy has cured, fit the sting by placing the shaft through the milled hole in the end of the arc. Use the provided set screws to secure the sting in place. Figure 24 is an exploded view of the arc.

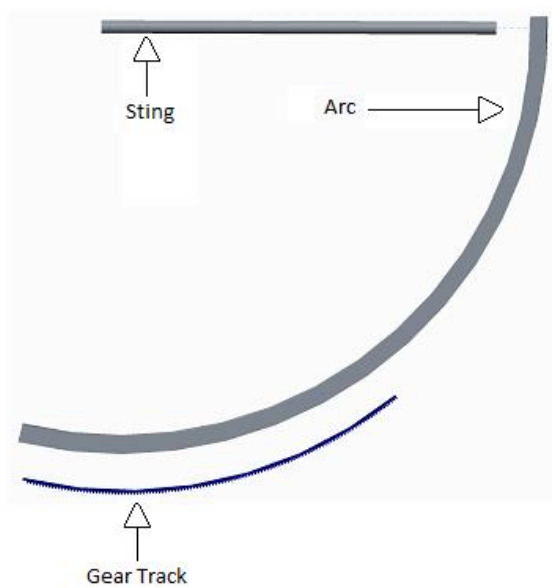


Figure 24: Arc-Sting Assembly

The roller support housing is the most critical force bearing assembly within the assembly. It is a combination of two housings, a top roller support housing and a bottom roller support housing. The bottom support assembly consists of three main plates, ten bearings, and two rollers on half inch shafts. The two side plates are placed on the bottom plate such that the bearings are facing inward, towards the other plate. Without screwing the plates in place, place the half inch roller assemblies in their respective bearings. With the rollers in place, use the 1/4-20 bolts provided and screw down the side plates to the bottom plate. It would be a good idea to use a semi-permanent thread lock adhesive, to ensure the bolts do not back out while in use. Once the side plates are secured with the rollers in place, the bottom support assembly is complete. The top support assembly is constructed almost the same way as the bottom support assembly. The assembly consists of three plates, eight bearings, and two horizontal rollers on quarter inch rollers. The vertical rollers are not placed into the support structure until both the top and bottom support structures are assembled and ready to be fastened together.

Note: the power transmission gears must be placed within the bottom support, before the

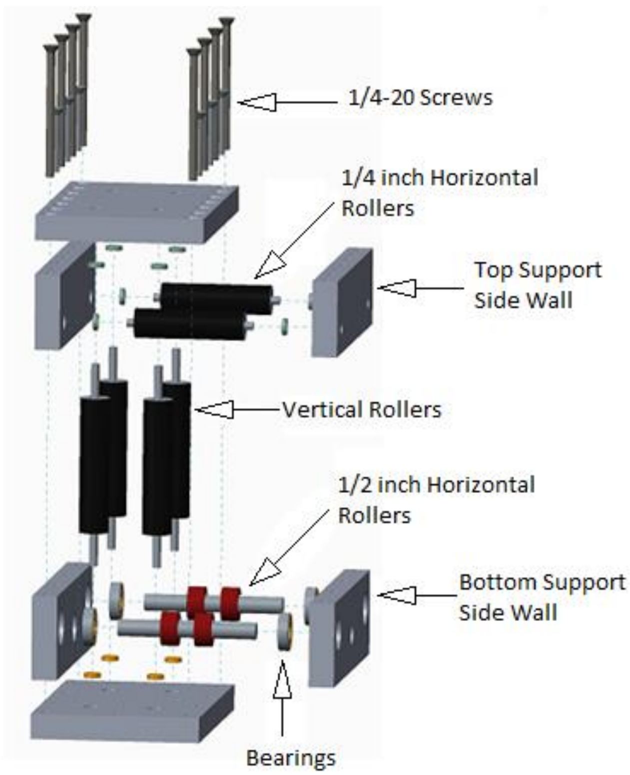


Figure 25: Housing assembly

vertical rollers, or the top support can be connected. The vertical rollers can be placed by hand into their bearings on the bottom support structure. Lastly the top support can be lowered onto the vertical shafts, and the bolts can start to be threaded. Keep the bolt loose to allow movement to integrate the arc. Figure 25 is an exploded view of the support structure.

The power train consists of the mechanical gears and motor used for arc manipulation, as well as their respective housings. The motor housing assembly consists of three plates and three bearings. The plates are arranged in a manner that the bearings will all face toward one another. The plates can be bolted directly together as there are no components that are confined within the structure. The powertrain consists of the motor, motor shaft extension, shaft coupler, worm, worm gear, power transmission shaft, spur gear, and two shaft collars for the power transmission shaft. The first step is to mount the spur gear and work gears. Begin by sliding the power transmission shaft through the outside of the motor housing, place the worm gear in the motor housing assembly and slide onto the power transmission shaft. Continue sliding the power transmission shaft through the other side of the motor housing, and through one side of the bottom support assembly. Slide one shaft collar, the spur gear, then the other shaft collar onto the power shaft, then continue to push the shaft through until it is flush with the outside of the bottom support assembly. Secure the shaft in place with the two shaft collars by sliding each shaft collar to the side of the support housing, and they make contact with the bearings. Tighten the shaft collars in place once they are in place. Once the shaft is in place align the spur gear and worm gear so that the geared section is directly centered in each of their respective housings. When they are positioned, tighten the set screw on the gear hub.

With the gears in place, the motor can be mounted to the motor housing assembly. There are four screws to mount the motor on the housing. The motor should be positioned so the connectors do not face the arc. Place the motor over the holes and bolt in place.

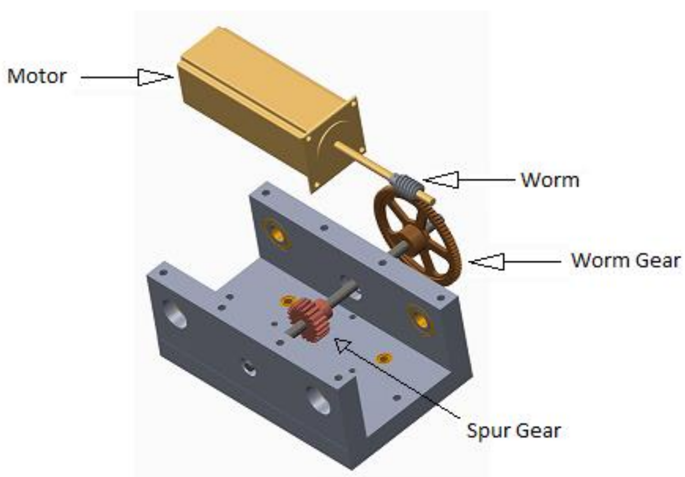


Figure 26: Drive train assembly

With the motor mounted, slide the shaft coupler over the motor shaft, do not tighten the coupler yet. Slide the shaft extension into the housing through the bearing opposite the motor. Slide the worm over the shaft extension and continue to slide the extension until it seats against the motor shaft. Slide the coupler over both the motor shaft and tighten the coupler to both shafts. Spin the worm gear such that the worm will be positioned so that it meshes with the worm gear directly tangent to the shaft. When in position, tighten the worm in place by the set screw. Figure 26 illustrates a completed power train.

Lastly the follower assembly is critical for the arc to avoid bending while the model is in a side slip condition. The follower assembly consists of three plates, one square support rod, two vertical rollers, one horizontal roller, and six bearings. Again the rollers should be placed in their respective positions before bolting the structure together. With the rollers in place, bolt together the side and bottom plates with the 1/4 -20 screws. Once secured, the support rod can be bolted to the bottom plate. It is imperative that the support rod and the bottom plate be aligned such that the sides are parallel. This is easily achieved by placing the support and the rod in their side just before the bolt is tight. Doing so will allow the table to align the rollers and the rod itself. Figure 27 is an exploded view of the follower assembly. Figure 28 shows the complete assembly.

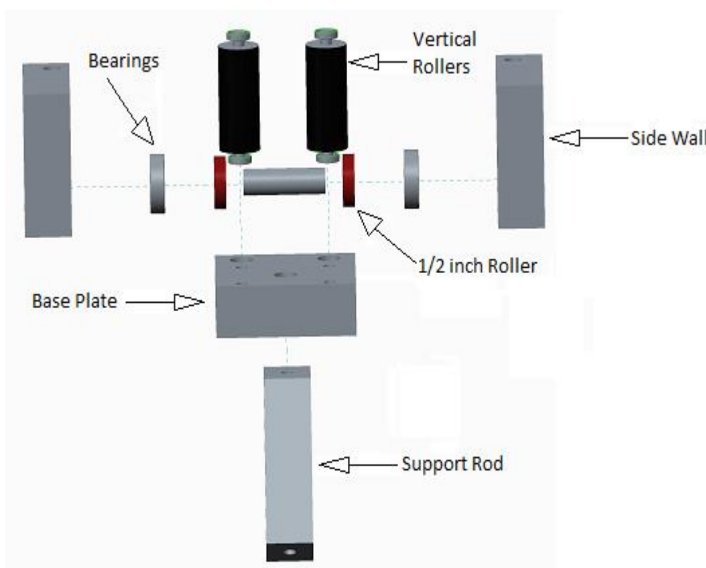


Figure 27: Follower assembly

Figure 28: Full Assembly

4.5 Operating instructions

4.5.1 Operation

Due to the design of this project, the user only need interact with the LabVIEW interface that has been created specifically for this system. In the event the Galil controller is reset or replaced (the program burned into the memory would be lost) we have provided a secondary LabVIEW VI which will re-download and burn the program to the Galil once more. The main interface, pictured in Figure 29, is what the user will be using to operate the system. The following list describes the operation window:

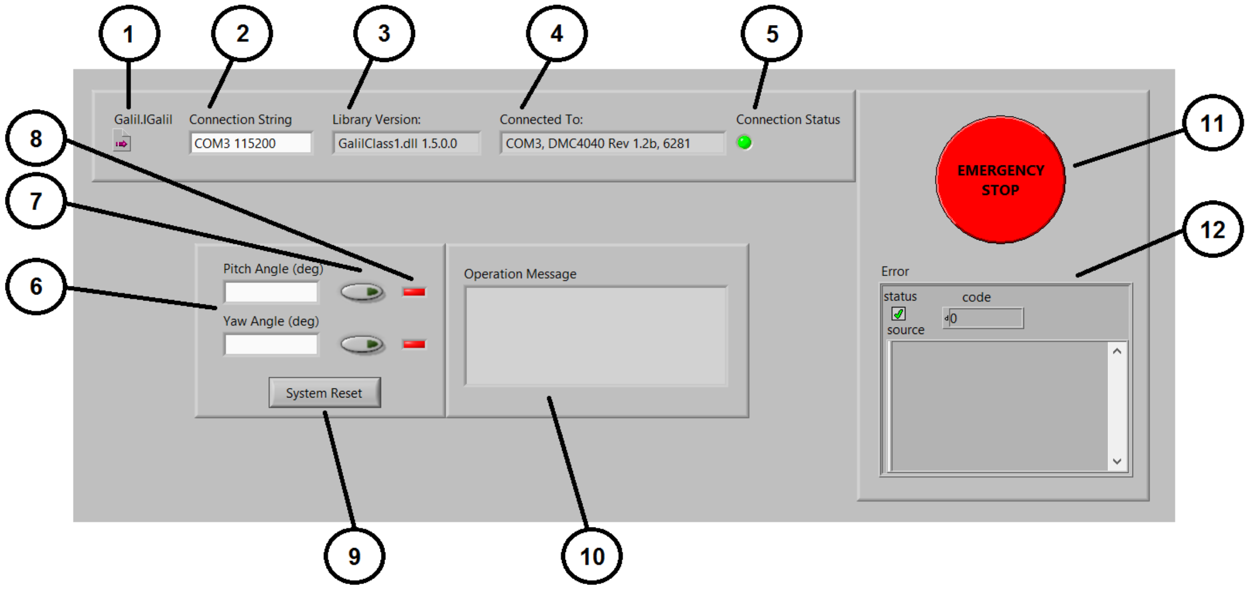


Figure 29: LabVIEW UI

- (1) starts the program so the interface will be usable.

- (2) is a user entered connection string (this string will change per the computer being used, it is suggested to always use the 115200 setting because that is the faster processing), the displayed example is for serial connection, if network connection is to be used an IP address must be given to the controller and entered into the connection string box

- (3) will display the library version being run by the controller once a connection has been made, this is so that the user will always be sure of what library they have if any changes need to be made

- (4) will display the connected port (or IP address) and controller name if the connection is successful

***it is important to note that 3 and 4 will be empty if there is no connection

- (5) is an indicator linked to the connection status of the controller, in the example the controller connection has been successful and so the indicator is green, if there is no connection or a connection effort has been unsuccessful the indicator will be red

***it is important to note that the functions of 6, 7, and 8 apply to both rows of objects displayed, one row applies to the pitch movement and the other applies to the yaw movement

- (6) is a data entry field for the desired position of the specimen in degrees, there are separate data fields for each pitch and yaw

- (7) is a button to send the angle entered to the program for processing, it is important to note that the value is not sent just by entering it into the field, this prevents the program from having to be restarted for each movement and also helps to prevent accidental mistypes, when the button is clicked it will light up (bright green) and will remain pressed until the program has processed the value entered

- (8) is an indicator to display the status of the angle sent for processing, this indicator will always display red until an angle is entered, processed, and returned as valid, once an angle is returned valid and until the motion in the respective direction is complete the indictor will display bright green

***it is important to note that new angles can't be entered until the motion in both directions is complete and/or the angles entered are returned invalid

- (9) is the system reset, this will return the specimen to 0deg pitch and 0deg yaw

- (10) will display an operational message to the user, these messages have been set in the program and will display depending on the status of the system, some examples are listed:

    -motion has been completed, angle entered is invalid, system has been reset

- (11) is the emergency stop button, it is important to note that this only stops the system program, it is important to incorporate an electrical kill switch into the entire system, this emergency stop is wired into each stage, therefore it can stop the program at any point

- (12) displays error codes returned by the system, this is separate from operational messages which are returned based on the system programming, error codes are returned by the controller and/or software. Once the system movement has been completed, new position values can be entered.

4.5.2 Troubleshooting

In this section, we will discuss possible failure modes and troubleshooting methods in order to resolve these issues. We will break down these issues into a few different modes in order to direct you to the appropriate solution diagram. The troubleshooting diagrams shown in appendix E should aid the user in solving issues. They break down issues into mechanical and electrical issues and then provide practical solutions. If issues are not resolved through these diagrams, the user is instructed to call the manufacturer.

4.5.3 Regular Maintenance

In order to ensure proper lifecycle of the assembly, there should be regular maintenance checks and actions. The maintenance and actions required are broken down by hours of use in the following table 5. Many of the parts such as gears and rollers are given a life cycle based on a particular amount of use. As shown in the reliability section, they can endure up to 10^5 cycles. If a shaft rotates at an RPM of 30, this equates to an approximate life cycle of 138 continued hours of use. Recommendations for replacements begin at 50 hours in order to be safe and plan for future possible failures. Maintenance and checks include visual inspections, part replacement, lubrication, and alignment checks.

Table 5: Maintenance by hours of use

Hours of Use:	Action Required:	Purpose:
Every Use	Visual inspection	Use of damaged equipment
	Gear and bearing lubrication	Facilitates arc movement
	Check wire connectivity	Ensures proper communication
	Check gear connections	Ensures rigid connection for actuation
0-10	Lubricate	Smooth actuation
	Alignment Check	Looks for shaft and roller alignment
10-50	Lubricate	Smooth Actuation
	Check for gear wear	Protects against failure
50-100	Consider purchasing spare plastic gear parts	In case of failure
	Continued Inspections	Visual Wear inspection
100+	Consider purchasing spare rollers and flexi-rack	Connection might begin to detach

4.5.4 Spare Parts

Of the parts that were purchased for the completion of the prototype, there are few extra of excess parts. There will be leftover machine screws of varying sizes and thread count. In addition to this, there are extra lengths of steel rod stock in varying diameters and leftover flexible gear track. If there is any failure of the consumer off the shelf parts they can easily be replaced from McMaster, Grainger or QTC. The complete purchase orders are in D. If anything needs to be purchased for additional parts, the bill of materials can be found in appendix F.

4.6 Design for Economics

To complete the subsonic articulating robotic arm a wide variety of parts in varying quantities had to be purchased. The items purchased were predominantly for the construction of the physical system and could be broken into four general categories; raw metal, gearing, consumer off the shelf parts and motors/drivers/encoders. Of the four categories the raw metals took up the largest percentage of the team's budget with 34%, this was comprised of three aluminum 6061 plates of varying size and thickness. The next largest section was the consumer ready parts that were purchased from either Grainger or McMaster-Carr. The items that fit into this category were assorted rollers, shafts, screws and bearings, which took up the largest portion. The motor category of the budget was able to be kept lower due to the sponsor's prior ownership of resources. The budget breakdown is seen in figure 30. The sponsor provided the team with a Galil DMC-40x0 motion controller, costing $2,295, and a Velmex B4800TS motorized rotary table. The remainder of the budget used was taken up by the gears used for articulation and the total tax/shipping on all items. The grand total of all the items listed above came out to be $1,316.23, being well within the original budget allotted to the team of $2,000. Figure 31 shows the breakdown of the entire budget.

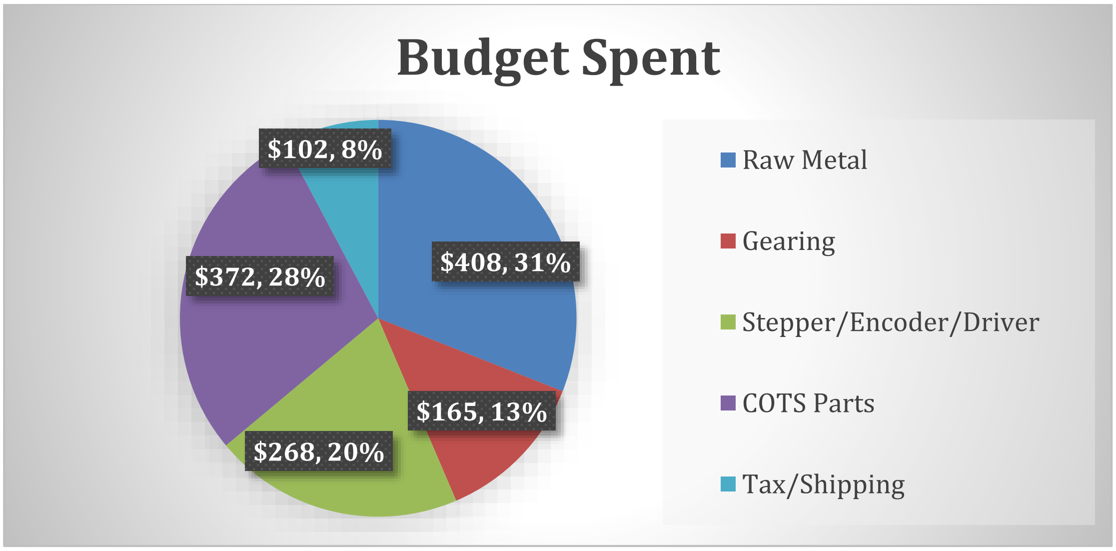


Figure 30: Budget Analysis based on budget spent

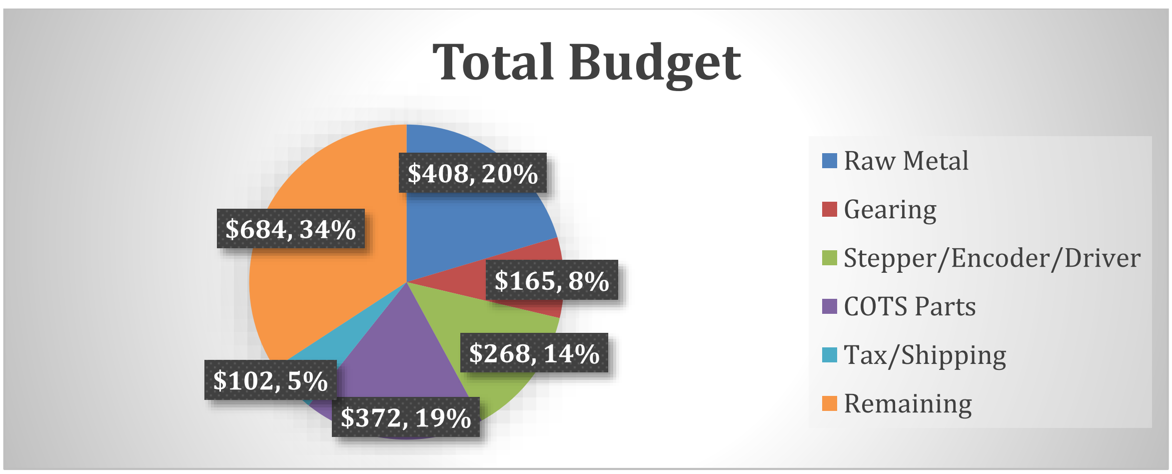


Figure 31: Budget Analysis based on total budget

Comparing the mounting system produced for the design project to market products is complicated. Figure 32 shows an overall breakdown of the pricing. Mounting systems to be used in wind tunnels are usually custom designed to the specifications of the wind tunnel and the type of testing that will occur. Based upon general information given by the faculty advisor for the team, quotes for these systems can reach $100,000 or higher. The existing model used at the facility is approximately $80,000. The price tag for the system can be broken into three parts; $40,000 for the actuators, $30,000 for the drivers and $10,000 for the metal necessary to construct it. The price of the prototype produced by the senior design team, as mentioned earlier, is $1,316.23. Even if this number is adjusted to include price of components donated by the sponsor, approximately $3,611, the total comes out to be much less than the mechanism currently in use. Appendix A shows all purchase orders made for this project.

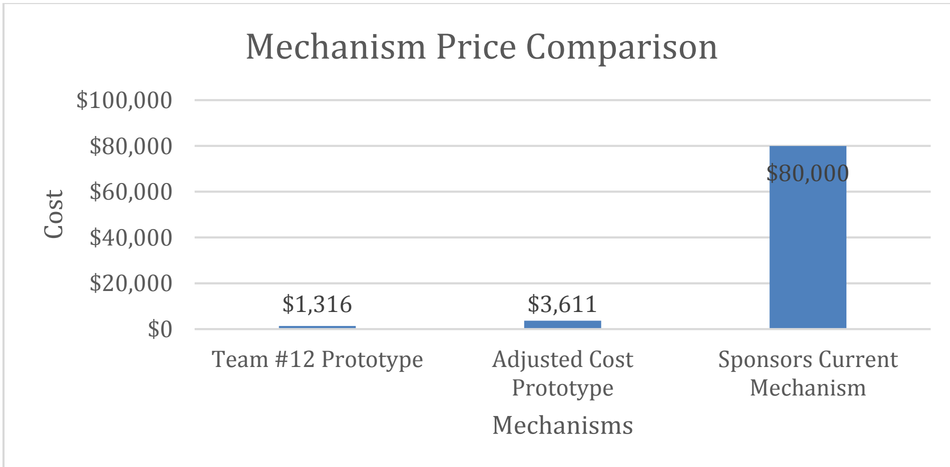


Figure 32: Price Comparison for prototype

5. Prototype Testing

5.1 Unloaded testing

Unloaded testing was performed on the arc mechanism on Friday 4/3/2015. The arc moved with no issues. There was smooth motion with no interruptions. The gears meshed quietly and smoothly as well. The motor was moved at a variety of speeds and tested the different pitch and yaw boundaries. The boundary conditions seemed to be successful as the motor did not actuate past those boundaries during testing. A picture of the mechanism during testing can be seen in figure 33.

Figure 33: Testing of pitch and yaw of mechanism unloaded

5.2 Load testing

The arc was tested at a few different progressive loading conditions. Because there was no way to simulate the wind tunnel conditions for testing, point loads were used at the end of the sting in order to simulate high lift and drag forces on the tested specimen. Due to the issue that only static testing can be performed, the modal vibration analysis could not be tested. It was calculated that due to the mechanisms heavy weight and minimal air flow disruption design that it would suffice under low speed wind conditions under 22m/s. Four different loaded conditions were attempted by hanging a 3lb, 5lb, 8lb, and 10lb weight at the end of the sting. The quality of the arcs movement was then analyzed. Table 6 below summarizes the results.

Table 6: Testing summary

Test Run	Load Applied	Results	Action Taken	Problem Solved?
1	3lb	Actuation smooth and successful	N/A	N/A
2	5lb	Actuation smooth and successful	N/A	N/A
3	8lb	Occasional worm gear slipping on shaft	Tightening	Yes
4	10lb	Worm gear full slip	Use of D-shaft	Yes

The initial tests of 3lb and 5lb were successful. The mechanism ran quietly and smoothly the entire time of actuation. The arc was moved the full positive 20 degrees and -5 degrees with no complication. Once the testing for the 8lb weight occurred, the worm gear began slipping on the shaft. The meshing still occurred but no torque was transferred to the drive shaft because of the occasional slipping. The group then tightening down the set screw with a large allen wrench in order to get more torque on the set screw. This solved the slip issues at 8lbs. Once the 10lb testing began, the worm gear slipped 100% of the time during actuation. A different solution other than tightening had to be used in order to solve the issue. The shafts were then sanded in the location of the set screw to form a “D” spot on the shaft. This would prevent the set screw from slipping and provide a flat surface for mating with the shaft. Re-testing with this modification yielded positive results.

All other aspects of the testing resulted as expected. The aligned was ensured and smooth actuation occurred. Another way to solve the slipping gear issue would be to key the shafts and the gears. This would put the torsional force on a hardened key and would prevent slipping. Lubrication should constantly be applied to the mechanism’s gears every few uses in order ensure frictionless gear mating and actuation.

6. Environmental, Safety, and Ethics Considerations

Because this model has several moving parts and is in a very dynamic environment, there are always associated risks. Ensure the gears and rollers are clear of any obstructions, and hands are not on the mechanism during operation. Also because grease and lubrication are going to be used on the gears, proper disposing of materials is important so that pollution doesn't occur from the lubricants. The rollers and gears could produce a pinching/ crushing hazard that could result in injury. While the tunnel is in operation if any point on the mechanism were to fail, the sting, support arm, base plate, it could result in a loss of control of the model and mechanism. In the event of a catastrophic failure where a total separation of the model from the arc were to occur, the model and resulting broken pieces would create a projectile hazard. The group has also been given several thousand dollars' worth of equipment. These items must be incorporated in the design, or be returned to the sponsor. Also, all work must be given to the sponsor in order to follow creation of the design since it is not a privately owned design by the team.

7. Project Management

7.1 Schedule

In this section we discuss how the work was divided and on what time scale throughout the semester. A Gantt chart for the final section of the year is also provided in order to provide a realistic time scale for particular actions and efforts taken by the group. Also, improvements in time management will be discussed along with a more realistic fabrication time from ideation to prototype.

Work Breakdown Structure

Throughout the semester, the work break down structure was divided up into many smaller sections. The Gantt chart provided in each paper expanded upon the breakdown structure. Table 7 shows the overall breakdown structure and approximate time taken to complete each portion. Only the main headings are discussed here and individual Gantt charts must be looked at in order to gain more detailed breakdowns.

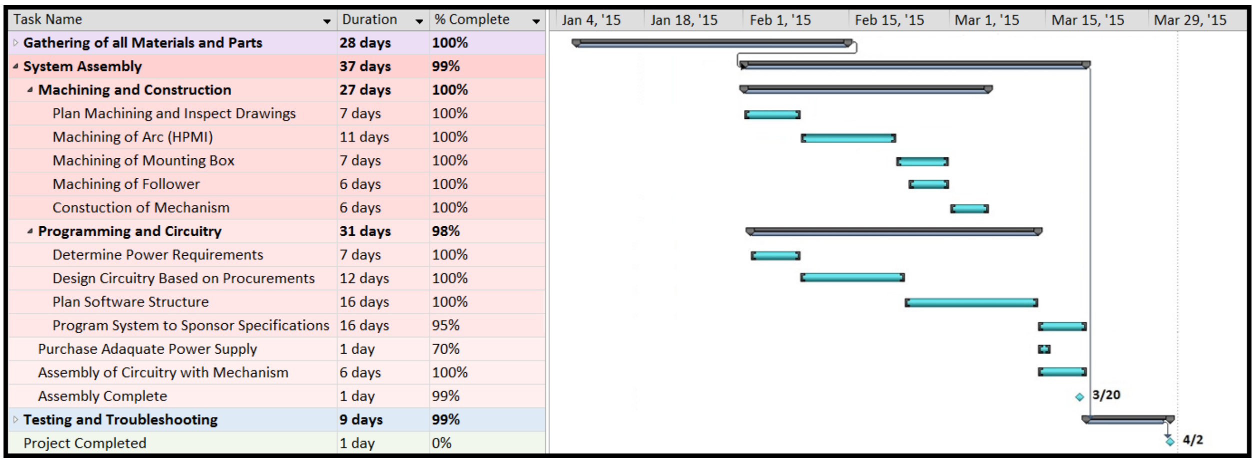
Table 7: Overall Work Breakdown Structure

Tasks	**Time for completion**
Initial Design Formation	3 weeks
Design Specifications	2 week
Preliminary Design	2 weeks
Calculations	2 weeks
Design Adjustments	4 weeks
Finalize Design	4 weeks
Machining and Purchasing	10 weeks
Assembly and Prototype Testing	2 week
Total Time	**30 weeks**

The overall design time took about 30 weeks. This is the combination of the two semesters excluding breaks. The breakdown assumes no overlaps in time sections. As seen in the table, the machining and purchasing portion took over two months to complete. This was a far too extended period of time and was because of being inappropriately prepared. Realistically, this should not take more than 3 weeks. If all drawings are prepared along with purchase orders, the process should be much quicker than taken. Also, design adjustments and finalizing the design took longer than it should have. In order to reduce this time, the group should have consulted the advisor and sponsors more often. Realistically, these portions could been a week or 2 shorter. Overall, if working efficiently, the project should take no longer than 20 weeks.

Gantt chart

The Gantt chart provided shows the breakdown and work percentages complete up until this point. It will show that the project is mostly complete with few tasks remaining. The remaining tasks include final testing adjustments, presentations, and delivering to the sponsor. This Gantt chart is shown in figure 34.



Task Name	Duration	% Complete
Gathering of all Materials and Parts	**28 days**	**100%**
System Assembly	**37 days**	**99%**
Machining and Construction	**27 days**	**100%**
Plan Machining and Inspect Drawings	7 days	100%
Machining of Arc (HPMI)	11 days	100%
Machining of Mounting Box	7 days	100%
Machining of Follower	6 days	100%
Constuction of Mechanism	6 days	100%
Programming and Circuitry	**31 days**	**98%**
Determine Power Requirements	7 days	100%
Design Circuitry Based on Procurements	12 days	100%
Plan Software Structure	16 days	100%
Program System to Sponsor Specifications	16 days	95%
Purchase Adaquate Power Supply	1 day	70%
Assembly of Circuitry with Mechanism	6 days	100%
Assembly Complete	1 day	99%
Testing and Troubleshooting	**9 days**	**99%**
Project Completed	1 day	0%

Figure 34: Gantt chart for final term

7.2 Resources and Allocation

This team utilized many resources in order to complete a variety of tasks. Resources differentiated depending on which portion of the project we were on. For example, the resources utilized for machining were not the same resources used for purchasing and design. The listed out resources and their respective purposes are show in table 8. Resources utilized were the sponsor, advisor, vendors, college of engineering machine shop, and school faculty. Each individual member of the group was a resource for a particular aspect of the project as well. This way, each member had a specific responsibility and was an expert for a particular design aspect in the project. The way each resource was allocated is shown in the table.

Table 8: Resource Allocation

Resource	Purpose
COE Machine shop	All machining and assembly aid
HPMI Machine shop	Water-jet of arc
Keith Larson's Machine Shop	Some machining and assembly aid
Vendors	Technical purchased equipment information
Sponsor/ Advisor	Aid in design and manufacturing
Jacob Kraft	Mechanical Design Lead
Caitlan Scheanwald	Electrical Design Lead
Justin Broomall	CAD Designer
Andrew Baldwin	Purchasing and Procurement Lead

7.3 Procurement

With the design fully assembled and in testing phase, all purchases have been complete. The purchase orders can be seen in appendix A and are organized by vendor. Multiple vendors were used throughout the procurement process. Different vendors offered different material options, prices, delivery times, and scheduling. The different vendors are shown in the table 9 below and are organized by type of product purchased. As shown above in figure 31, the project was approximately $700 under budget. Table xx below shows each of the vendors, the type of product purchased from them, and approximate delivery time. In order to contact any of the vendors, please refer to the appendix purchase orders.

Table 9: Vendors Used and Approximate Delivery Time

Vendor	Product Type	Delivery Time
Anaheim Automation	Motor Components	1-2 weeks
Mc-Master Carr	Mechanical Components	Next day at FSU
Grainger	Shaft couplers	1 week
Stock Drive Products	Gear Components	2 weeks
QTC Gears	Flexible Gear Track	1 week
Tallahassee Metal Fabrication	Raw Materials	1 week

7.4 Communications

Communications were split up into two different categories, bi-weekly meetings and team meetings. Bi-weekly meetings were done with the sponsor, advisor, and instructors. Team meetings occurred between the group members. The main form of communication among staff members and the advisor was email while the team mostly used group texting and a Facebook group.

Biweekly Meetings

These meetings were usually set up through email at the beginning of the semester for the sponsor and instructors. A weekly reminded was sent out by the group leader to ensure that these meetings were still going to occur. The sponsor meetings usually entailed design specifications and changes. They occurred in a procedural manner, starting with updates and then with plans for future action. Instructor staff meetings were procedural in the same manner. The purpose of the instructor staff meetings was to help the team avoid bad time management and to ensure that progress is being made. The combination of both of these types of meetings aided in the progress and development of our final assembly.

Team Meetings

Team meetings occurred multiple times during the semester. The team had multiple forms of communication. For quick questions and concerns, group text messages were sent out because responses were quick. For scheduled plans to meet, the team used email in order to find a time everyone was available. This system worked well since email was checked a few times a day by all group members. The Facebook group was used to keep track of all the deliverables and documents completed throughout the semester. The team had an efficient system and benefitted from it.

8. Conclusion

8.1 Summary

The goal of this project is to create a mounting mechanism for AFRL's REEF center in Shalimar, FL. This mounting mechanism must be able to adjust a specimen's pitch and yaw in a low speed, open test-section, wind tunnel with maximum speeds of 22 meters per second. The pitch and yaw must be able to achieve a range of -5 to 20 degrees and -10 to 10 degrees respectfully. The specimen must remain in the same 3 dimensional location at the end of actuation. The mechanism must be a cost effective solution since the maximum budget allotted is 2,000.

Several other designs were considered and analyzed for feasibility. The decision matrix helped the team decide that the best option for actuation was a circular arc with an attached sting mount for holding the mechanism. This design was chosen because it was able to actuate pitch while maintaining the central location of the model. Adjusting the yaw through use of a turn table beneath the body's center of mass allowed the location to remain the same as well. The issues with this design were fabrication and actuation methods.

Analyzing the optimum chosen design allowed the team to design an effective mounting system, choose an actuation system, and select a material. The arc was designed to be 105 degrees of a circle with a radius of 25 inches. This allows the arc to be actuated outside of the flow while maintaining its capability to operate the full range of motions. Aluminum 6061 was chosen upon stress and deflection analysis. The stress and deflection analysis in Creo illustrated a factor of safety of approximately 10 and a deflection less than the quarter inch constraint. Max deflection was shown to be approximately 0.14in. Drawings and dimensioning of the design are shown in appendix C.

A designed control system for the arc-mechanism was designed using LabVIEW. LabVIEW had a built in command library that communicated with the Galil controller used in the project. The inputs included a prompting of desired pitch and yaw angles. The arc moved one dimension at a time and actuated until completion. An emergency stop button was implemented in order to stop the arc in its exact location. The display window in LabVIEW will display a prompt when finished with actuation.

The team performed well under budget. It was determined that these types of constructs cost upwards of $100,000 dollars. It was designed in approximately $1500 dollars out of the allotted $2,000 dollars. Overall, the team made a cost effective mechanism that will provide useful to the sponsor. It completes all design constraints and is ready to be handed over to the sponsor.

A few recommendations I would make for incoming juniors include: practice time management, practice leadership, exercise connections, and give forth your best effort. Time management is often an issue for a lot of engineers as procrastination is prevalent in the major. Time management and starting things early make senior design a breeze compared to what it feels like for those who wait until the last minute. Leadership skills are required or will be learned by select members of our group. It is absolutely necessary to have a single focal point. All of the friends and connections you’ve made until senior year are helpful. Utilize the connections as it will make some tasks easier.

8.2 Future Modifications

There are a few modifications and adjustments the sponsor can make in order to make the design more efficient. One modification would be to insert a shaft into the turn table so that an encoder can be used. The encoder would provide feedback to the controller and allow for movement checks. These would ensure that the motor is in the right location when actuation is complete. A vibration damping base is going to be built into the mechanism by the sponsor as well.

Another modification that could be made would be to place a gyroscope at the end of the sting to provide a final feedback at the end of actuation. This would feed back to the controller so that the motors can adjust if needed. The purpose of this item would be in case there was deflection at the sting or slipping of a gear on their attached shafts. The system would then be able to detect imperfect movement and send an error message or adjust.

Finally, the arc could be made more aerodynamic. Doing this would reduce the asymmetrical vortices the device is going to shed as it is placed into higher wind speeds. By placing a wedge or point on the square cross section, it would more easily cut into the wind stream and possibly reduce vibration the mechanism might see. A counter weight could also be placed on the end of the arc in case the motor does not have enough power to actuate the arc effectively. However, tests have shown that this is not an issue. The main modifications that can be added to the device would ensure more accuracy in actuation

Appendix A- Purchase Order

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)

[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION

INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 3/24/15

*REQUESTOR NAME Andrew Baldwin

*PI Signature

*REQUESTOR EMAIL akb11c@my.fsu.edu

*ACCOUNT/PROJECT

*# VENDOR NAME Tallahassee Metal Fabricati

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[✓] YES

[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE

Senior Design Group #12 Purchase Order for raw Aluminum 6061 plate
Vendor Name: Tallahassee Metal Fabrication. Team is able to pick up order from vendor when ready
Online: http://www.metalfabtallahassee.com/ Phone: (850) 205-2300
Quote from Vendor attached

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. Aluminum 6061 Plate, 18"x12"x1/2"	1	52.05	$ 52.05
2.			
3.			
4.			
5.			
6.			

GRAND TOTAL $ 52.05

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)
[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION
INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 2/20/15

*REQUESTOR NAME Andrew Baldwin
*REQUESTOR EMAIL akb11c@my.fsu.edu
*# VENDOR NAME Grainger

*PI Signature
*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[✓] YES
[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE
Senior Design Group #12 Purchase Order for assorted parts

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. Coupling, Rigid Steel, Itm#:29NL38	1	14.39	$ 14.39
2. Epoxy Adhesive, Cold Weld, Itm#:2UV83	1	6.89	$ 6.89
3. Machine Screw, 10-24 x 1/2, Pk 100	1	2.59	$ 2.59
4.			
5.			
6.			

GRAND TOTAL $ 23.87

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)

[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION

INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 2/20/15

*REQUESTOR NAME Andrew Baldwin

*PI Signature

*REQUESTOR EMAIL akb11c@my.fsu.edu

*ACCOUNT/PROJECT

*# VENDOR NAME McMaster Carr

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[✓] YES

[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE

Order for Senior Design Group #12
Page 2 of 2 (10 items)
Grand Total: $157.57

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. 8920K265, Steel Rod, 5/16" Diameter, 3' length	1	3.36	$ 3.36
2. 6383K15, Ball Bearing, 5/16" ID, 7/8" OD, 1/4" Wi	2	4.75	$ 9.50
3. 89895K762, Stainless Steel Tubing, 0.51" ID, 3/4'	1	45.95	$ 45.95
4. 9697K117, Tubing, 95-A Hard, 1/4" ID, 7/8" OD, 4	2	9.31	$ 18.62
5.			
6.			

GRAND TOTAL $ 77.43

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)
[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION
INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 1/28/15

*REQUESTOR NAME Andrew Baldwin
*REQUESTOR EMAIL akb11c@my.fsu.edu
*# VENDOR NAME QTC Metric Gears

*PI Signature
*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[ ] YES
[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE

Senior Design #12 Purchase Order for Flexible Gear Rack
Vendor: QTC Metric Gears Online: http://qtcgears.com/
Image of shopping cart included

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. KDR1.5-2000	1	64.55	$ 64.55
2.			
3.			
4.			
5.			
6.			

GRAND TOTAL $ 64.55

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)
[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION
INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 1/23/14

*REQUESTOR NAME Andrew Baldwin
*REQUESTOR EMAIL akb11c@my.fsu.edu
*# VENDOR NAME McMaster Carr

*PI Signature
*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?
[✓] YES
[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE
McMaster order for supplies for Senior Design Group #12
Page 1 of 2
McMaster cart order attached with Purchase Order
Total Order Grand Total: $201.16

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. #60185K911, Durometer 90-A	4	3.91	$ 15.64
2. #9697K117, Durometer 95-A	6	9.31	$ 55.86
3. #57155K356	12	4.98	$ 59.76
4. 60355K704	4	8.74	$ 34.96
5. #98808A330	1	8.53	$ 8.53
6. #98808A360	1	6.65	$ 6.65
		GRAND TOTAL	$ 181.40

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)
[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION
INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 1/23/15

*REQUESTOR NAME Andrew Baldwin
*REQUESTOR EMAIL akb11c@my.fsu.edu
*# VENDOR NAME Anaheim Automation

*PI Signature
*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[ ] YES
[✓] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE

Senior Design Group #12 Purchase Order for stepper motor
Vendor: Anaheim Automation Online: https://www.anaheimautomation.com/index.php
Image of Shopping Cart Attached

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. #23MD306D-10-00-00	1	268.00	$ 268.00
2.			
3.			
4.			
5.			
6.			

GRAND TOTAL $ 268.00

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)
[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION
INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 1/23/15

*REQUESTOR NAME Andrew Baldwin
*REQUESTOR EMAIL akb11c@my.fsu.edu
*# VENDOR NAME Tallahassee Metal Fabrica

*PI Signature
*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[ ] YES
[✓] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE

Senior Design Group #12 Purchase Order or raw Aluminum 6061 plates
Vendor Name: Tallahassee Metal Fabrication. Team is able to pick up order from vendor when ready
Online: http://www.metalfabtallahassee.com/ Phone: (850) 205-2300
Quote from Vendor attached

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. 12" x 48" x 1" Aluminum 6061 Flat Bar	1	278.40	$ 278.40
2. 12" x 24" x 3/4" Aluminum 6061 Flat Bar	1	77.52	$ 77.52
3.			
4.			
5.			
6.			

GRAND TOTAL $ 355.92

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)
[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION
INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 1/23/15

*REQUESTOR NAME Andrew Baldwin
*REQUESTOR EMAIL akb11c@my.fsu.edu
*# VENDOR NAME McMaster

*PI Signature
*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[✓] YES
[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE

McMaster order for supplies for Senior Design Group #12
Page 2 of 2
McMaster cart order attached with Purchase Order
Total Order Grand Total: $201.16

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. #8927K96	1	4.10	$ 4.10
2. #8927K18	1	6.16	$ 6.16
3. #6383K15	2	4.75	$ 9.50
4.			
5.			
6.			

GRAND TOTAL $ 19.76

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)

[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION

INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 1/28/15

*REQUESTOR NAME Andrew Baldwin

*REQUESTOR EMAIL akb11c@my.fsu.edu

*# VENDOR NAME SDP/SI

*PI Signature

*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?

[ ] YES

[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE

Senior Design Group #12 Purchase Order for gears
Vendor: Stock Drive Products/Stirling Instruments Online:https://sdp-si.com/eStore/Catalog
Image of Shopping Cart Attached

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. A 1B 6-Y24080	1	63.63	$ 63.63
2. A 1M 2MYZ15020	1	5.84	$ 5.84
3. A 1Q 5-Y24	1	31.45	$ 31.45
4.			
5.			
6.			

GRAND TOTAL $ 100.92

A

PURCHASE ORDER REQUISITION FORM

[X] Aero-Propulsion, Mechatronics and Energy Center (AME)

[ ] Florida Center for Advanced Aero-Propulsion (FCAAP)

Please Fill in All Information

Incomplete Requests Will Not Be Processed

Date 2/20/15

*Requestor Name Andrew Baldwin

*Requestor Email akb11c@my.fsu.edu

*# Vendor Name McMaster-Carr

*PI Signature

*Account/Project

Is this vendor on the approved vendor list?

[✓] Yes

[ ] No. *If no, please contact department purchaser before submitting P.O. Request.

Purpose

Order for Senior Design Group #12 for assorted parts
Page 1 of 2 (10 items)
Grand Total: $157.57

*** Please attach quotes or copies of catalog pages whenever possible. ***

Item Description (include series/model/part #)	Quantity	Unit Price	Total Cost
1. 91735A546, Machine Screws, 1/4-20 x 1-1/2"	2	5.89	$ 11.78
2. 60185K911, Roller, 90-A Hard, ID-1/2",OD-1"	2	3.91	$ 7.82
3. 9697K115, Tubing, 95-A Hard, 7/8" OD, 1/4" ID, 2	2	5.08	$ 10.16
4. 91771A544, Machine Screws, Flathead, 1/4-20 x	1	8.00	$ 8.00
5. 57155K356, Ball Bearings, 1/4" ID, 1/2" OD, 1/8"	5	4.98	$ 24.90
6. 60355K704, Ball Bearings, 1/2" ID, 1-1/8" OD	2	8.74	$ 17.48

Grand Total $ 80.14

A

PURCHASE ORDER REQUISITION FORM

[X] AERO-PROPULSION, MECHATRONICS AND ENERGY CENTER (AME)
[ ] FLORIDA CENTER FOR ADVANCED AERO-PROPULSION (FCAAP)

PLEASE FILL IN ALL INFORMATION
INCOMPLETE REQUESTS WILL NOT BE PROCESSED

DATE 4/2/15

*REQUESTOR NAME Andrew Baldwin
*REQUESTOR EMAIL akb11c@my.fsu.edu
*# VENDOR NAME McMaster Carr

*PI Signature
*ACCOUNT/PROJECT

IS THIS VENDOR ON THE APPROVED VENDOR LIST?
[✓] YES
[ ] NO. *IF NO, PLEASE CONTACT DEPARTMENT PURCHASER BEFORE SUBMITTING P.O. REQUEST.

PURPOSE
Order from McMaster Carr for 3 different types of shaft collars

*** PLEASE ATTACH QUOTES OR COPIES OF CATALOG PAGES WHENEVER POSSIBLE. ***

ITEM DESCRIPTION (INCLUDE SERIES/MODEL/PART #)	QUANTITY	UNIT PRICE	TOTAL COST
1. #6436K16, Two Piece Clamp on Shaft Collar for 3/4", black oxide	2	5.48	$ 10.96
2. #6436K51, Two Piece Clamp on Shaft Collar for 5	2	3.78	$ 7.56
3. #6436K14, Two Piece Clamp on Shaft Collar for 1	4	3.56	$ 14.24
4.			
5.			
6.			

GRAND TOTAL $ 32.76

A

Appendix B- Data Sheets

GALIL
WE MOVE THE WORLD

DMC-40x0

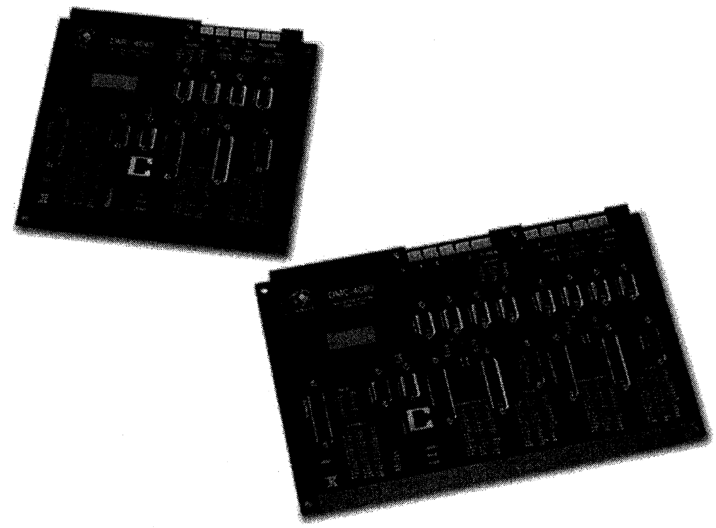
More Info

- General Info
- Features
- Price List
- Cables & Accessories
- Product Comparison
- Internal Amplifiers & Drives
- Part # and Quote Generator

Downloads

- User Manual
- Data Sheet
- Command Reference
- Software
- Firmware
- API
- CAD Drawings

B - Galil



Ethernet/RS232 Multi-Axis Motion Controllers, 1-8 axes

The DMC-40x0 motion controller is Galil's highest performance, stand-alone motion controller. It belongs to Galil's latest generation motion controller family, which accepts encoder inputs up to 22 MHz, provides servo update rates as high as 32 kHz, and processes commands as fast as 40 microseconds-10 times the speed of prior generation controllers. The DMC-40x0 is a full-featured motion controller packaged with optional multi-axis drives in a compact, metal enclosure. The unit operates stand-alone or interfaces to a PC with Ethernet 10/100Base-T or RS232. The controller includes optically isolated I/O, high-power outputs capable of driving brakes or relays, and analog inputs for interfacing to analog sensors. The DMC-40x0 controller and drive unit accepts power from a single 20-80 VDC source. The DMC-40x0 is available in one through eight-axis formats, and each axis is user-configurable for stepper or servo motor operation. With a powerful RISC processor, the DMC-40x0 controllers provide such advanced features as PID compensation with velocity and acceleration feedforward, program memory with multitasking for simultaneously running eight applications programs, and uncommitted I/O for synchronizing motion with external events. Modes of motion include point-to-point positioning, position tracking, jogging, linear and circular interpolation, contouring, electronic gearing and ecam. Like all Galil controllers, programming the DMC-40x0 is simplified with two-letter, intuitive commands and a full set of software tools such as GalilSuite for servo tuning and analysis.

GALIL
WE MOVE THE WORLD

Since our introduction of the first microprocessor-based motion

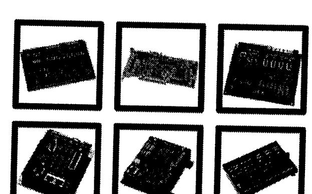
Contact Details

Address: 270 Technology Way, Rocklin, California 95765

Toll-Free: (800) 377-6329 (US Only)

Phone: (916) 626-0101

Product Gallery



Latest Tweets

The Micron Level 3-D Confocal Profiling and Thickness Measurement System uses the DMC-4020 to scan leaves for drought tolerance! 198 days ago

Galil controllers direct lasers in Sychrotron SOLEIL beamlines,

B - Galil

controller in 1983, Galil has remained a leading innovator. By offering our customers powerful, cost-effective and simple-to-use motion controllers and PLCs backed by superior application support, our commitment is to be the primary source for any motion control and I/O application.

Fax: (916) 626-0102

Email: support@galilmc.com

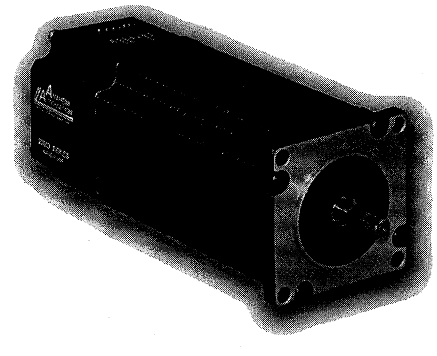
see: http://t.co/XMZwns999C for the story! 198 days ago

B-Galil

23MD Series - Integrated Stepper Motor/Drivers

FEATURES

- ***Stepper Motor/Microstep Driver Combination***
- ***Eliminates Motor Wires***
- ***Microstep Divisors of 8, 4, 2, or Full Step***
- ***Compact Package***
- ***12-24V Power Requirement***
- ***TTL Logic or 24V Level Inputs Available***
- ***Ideal for Precise Positioning***
- ***0.225° Resolution at Eighth Step***
- ***Efficient and Durable***
- ***RoHS Compliant***



DESCRIPTION

The 23MD Series is a compact construction that implements a microstepping driver and a stepper motor in one streamline package. With the two parts combined into one casing, the need to include motor wires has been eliminated. The high-torque step motor can generate up to 230 oz-in of torque. The microstepping driver will operate off 12VDC minimum to 24VDC maximum with a maximum power intake of 40W. The inputs are capable of running from either open collector or TTL level logic outputs, or sourcing 24VDC outputs from PLCs. The microstepping driver features resolutions from 200 - 1600 steps/revolution, providing smooth rotary operation. The 23MD series comes in either a single shaft version or a double shaft version with optional encoder and motor stack lengths of 1/2, 1, 2, or 3 allowing for varying amounts of start-up torque and inertia. The 23MD series features include built in over temperature and short circuit shut down, automatic 70% reduction in current after clock pulses stop being received, and status LED's to indicate power on (green LED) and clocks being received (yellow LED).

CUSTOM ORDER LAYOUT

Example: 23MD106S-10-24-00

Table 1

Model #	Frame Size	Bipolar Torque (oz-in)	Rotor Inertia (oz-in-sec^2)	Weight (lbs)	"L" Length (in)
23MD006	23	76	0.0017	1.20	2.98
23MD106	23	175	0.0042	1.75	4.03
23MD206	23	262	0.0068	2.41	4.94
23MD306	23	425	0.0103	3.51	5.94

Table 2

Shaft Option	Description
S	Single
D	Double

Table 3

Encoder Option	Description
-00	No Encoder
-04	400 Line Encoder
-10	1000 Line Encoder

Table 4

Sourcing/Sinking Options	Description
-00	Sinking Inputs
-24	Sourcing Inputs

Table 5

Special Options	Description
-00	Standard Products
-##	Other Options

Note: Other Speed Options, Custom leadwires, cables, connectors, and windings are available upon request

SPECIFICATIONS

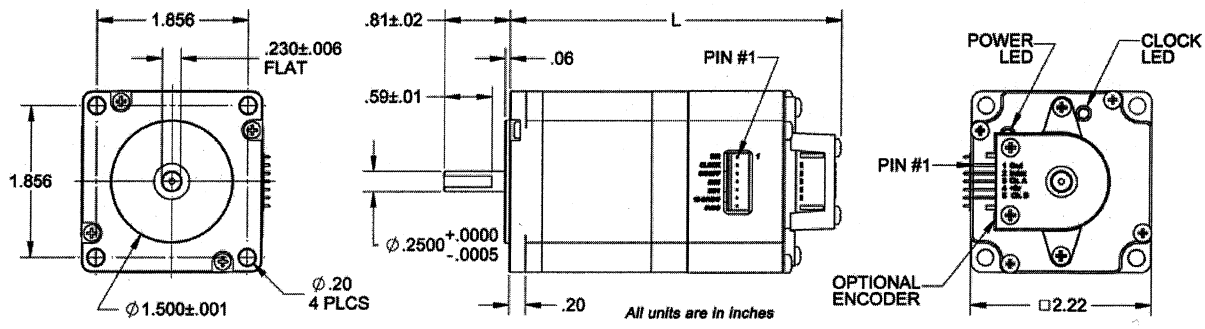
Step Angle:	1.8°	Insulation Resistance:	100M ohm Min., 500VDC
Step Angle Accuracy:	±5%	Dielectric Strength:	500VAC for one minute
Resistance Accuracy:	±10%	Shaft Radial Play:	0.02 Max. (1lb load)
Inductance Accuracy:	±20%	Shaft Axial Play:	0.08 Max. (1lb load)
Temperature Rise:	80°C Max. (rated current, 2 phase on)	Max. Radial Force:	16.9lbs (0.79 in from the flange
Ambient Temperature:	-20°C to +50°C	Max. Axial Force:	3.37lbs

L010413

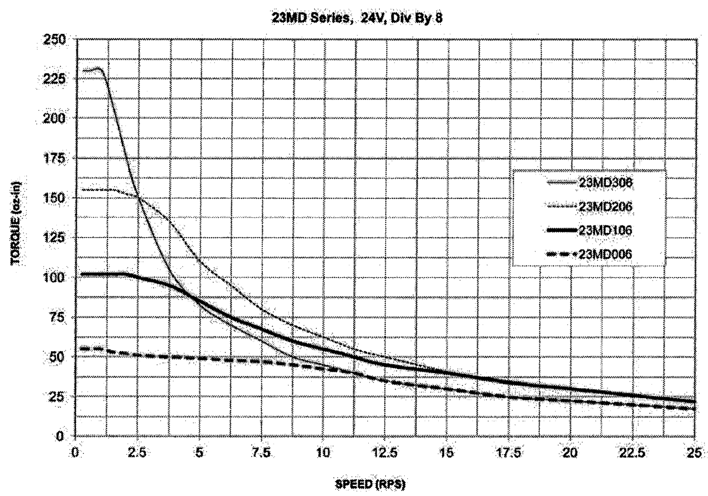
910 East Orangefair Ln. Anaheim, CA 92801 **Tel. (714) 992-6990** Fax. (714) 992-0471 **www.anaheimautomation.com**

B - Pitch Stepper

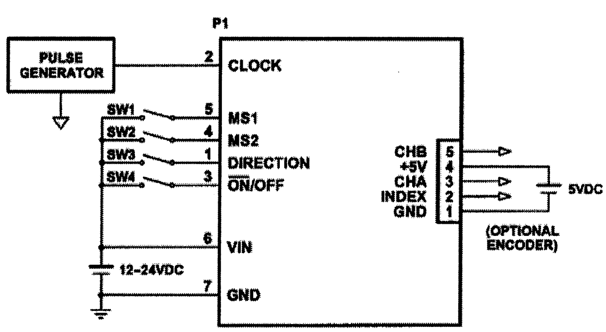
DIMENSIONS



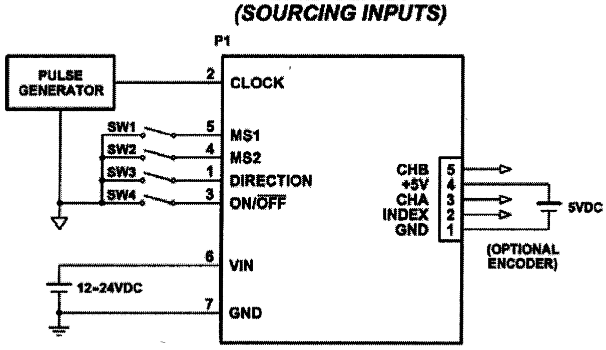
TORQUE CURVES



WIRING INFORMATION



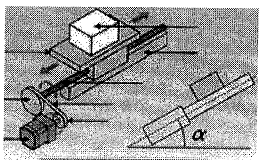
23MD SERIES
(SOURCING INPUTS)



23MD SERIES
(SINKING INPUTS)

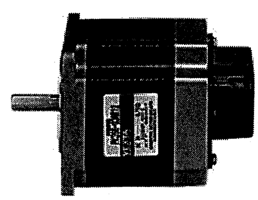
Terminal Block Pin	Description	CBL-AA4031 Wire Color
1	Direction	Brown
2	Clock	Red
3	On/Off	Orange
4	MS2	Yellow
5	MS1	Green
6	12VDC-24VDC	Blue
7	0VDC (Gnd)	Violet

B - Pitch Stepper



All Categories > Item # PK264-03AR12

REQUEST INFORMATION | ADD TO CART



larger image

Item # PK264-03AR12, 2-Phase Stepper Motor
Web Price $194.00

The standard PK series 2-phase stepper motor offers balanced performance enhanced by high torque, low vibration and low noise.

- Encoder Model

RoHS

Download PDF
Printable Page
Email This Page
Save To Favorites

MORE IMAGES
- Motor Dimensions
- Connection Diagram
- Speed - Torque Characteristics

DOWNLOADS
CAD Drawing (3D) (CAD)
PK Series Product Catalog (PDF)
2-Phase Encoder Motor Operating Manual (PDF)

Unit of Measure: ◉ Imperial | ○ Metric

Lead Time · Specifications

Lead Time

Available to Ship[1]	1 ~ 10 pcs 04/10/2015

[1] Quoted Ship Date for orders placed before 12:00pm PST in quantities listed.
A newer version of this product is available, contact your local sales office for more information.

Specifications

Product Line	VEXTA ®
Motor Type	2-Phase
Motor Frame Size	2.22 in. sq.
Shaft/Gear Type	Round Shaft (No Gearhead)
Holding Torque	Bipolar (Series) 68 oz-in Unipolar 55 oz-in
Type	Standard
Connection Type	Bipolar (Series) Unipolar
Lead Wires	6
Current per Phase (A/phase)	2.1 [Bipolar (Series)] 3 [Unipolar]
Encoder	Equipped
Shaft	Single
Voltage (VDC)	2.6 [Bipolar (Series)] 1.9 [Unipolar]
Resistance (Ω/phase)	1.26 [Bipolar (Series)] 0.63 [Unipolar]
Inductance (mH/phase)	2.4 [Bipolar (Series)] 0.6 [Unipolar]
Step Angle	1.80 °
Rotor Inertia (oz-in^2)	0.66 oz-in^2
RoHS Compliant	Yes
Insulation Resistance	100 M Ω or more when 500 VDC megger is applied between the windings and the case under normal ambient temperature and humidity.
Dielectric Strength	Sufficient to withstand 1.0 kVAC at 50 Hz or 60 Hz applied between the windings and the case for 1 minute under normal ambient temperature and humidity.

B - Yaw Stepper

Temperature Rise	Temperature rise of the windings is 176°F (80°C) or less measured by the change resistance method. (at rated current, at standstill, 2 phases energized)
Insulation Class	Class B [266°F (130°C)]
Ambient Temperature Range	14 ~ 122°F (-10 ~ 50°C) (non-freezing)
Ambient Humidity	85% or less (non-condensing)
Shaft Runout	0.05 mm (0.002 in.) T.I.R.
Concentricity	0.075 mm (0.003 in.) T.I.R.
Perpendicularity	0.075 mm (0.003 in.) T.I.R.
Radial Play	0.025 mm (0.001 in.) maximum of 5 N (1.12 lb.)
Axial Play	0.075 mm (0.003 in.) maximum of 10 N (2.2 lb.)
Step Accuracy	±3 arc minutes (±0.05°)
Encoder Type	Incremental
Encoder Resolution (P/R)	400
Output	2-Channel A, B
Input Current (mA)	17 (Typ.)
Input Voltage (V)	5 ±10%
Output Type	TTL
Output Voltage (Low)	0.4 volts @ 3.2 mA (Max.)
Output Voltage (High)	2.4 volts @ -40 μA (Min.)
Response Frequency (kHz)	100 (Max.)

REQUEST INFORMATION   ADD TO CART

B - Yaw Stepper

Motor Driven Rotary Tables

What else do you make?
HELP!
I need linear slide too
I need a motor control

Catalog pages with specs and drawings | Specifications | Like this, only manual drive | Application photos and videos

Velmex offers two motorized rotary tables designs. Click on either image for details.

- 5" diameter Series B4800TS. Choice of three gear ratios:72, 36 and 18:1

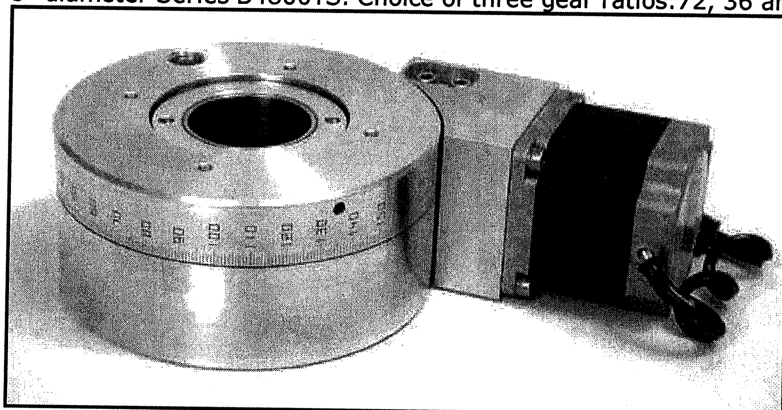


Photo 1: Model B4836TS Rotary Table

More Information. Load Capacity = 200 lbs.
DRAWING DOWNLOAD: 2D.pdf 2D DXF file; 3D .SAT , 3D.STP

- 1.7" diameter Model B5990TS with a gear ratio of 90:1

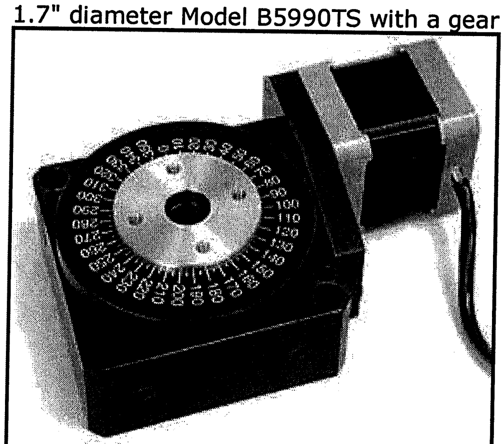


Photo 2: Model B5990TS Rotary Table

More Information Load Capacity = 50 lbs
DRAWING DOWNLOAD: 2D.pdf, 2D DXF file;3D .SAT , 3D.STP

B4800TS Rotary Tables

B4800 is a Series of three Rotary Tables that use a worm and gear drive design with a heavy duty central rotating ball bearing. The tables accept NEMA size

All tables have a hollow spindle or clear aperture for optical applications, an 360° scale and an adjustment to minimize gear backlash. Attaches to Series 4000 or 6000 UniSlide

B- Rotary Table

23 stepper motors. Specifications

Assemblies with the A6000TX adapter plate. Plate is 6" x 6" x ¼". Attaches to BiSlide with MSPP-3 plate. Download CAD drawings.

Options and Adapters

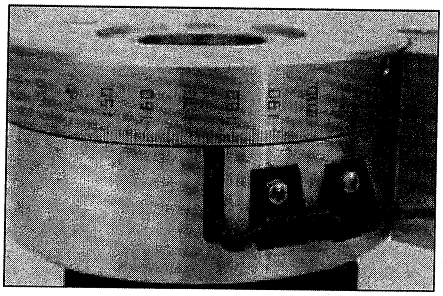


Photo 3A **Magnetic reed home switch option** This switch, analogous to a limit switch on a linear stage, provides a mechanism for homing the table. You can approach it from either direction. It provides a repeatable way to return to a specific physical location. Programming for use.

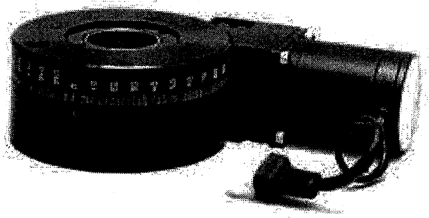
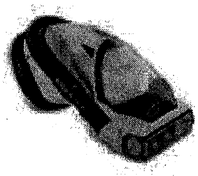
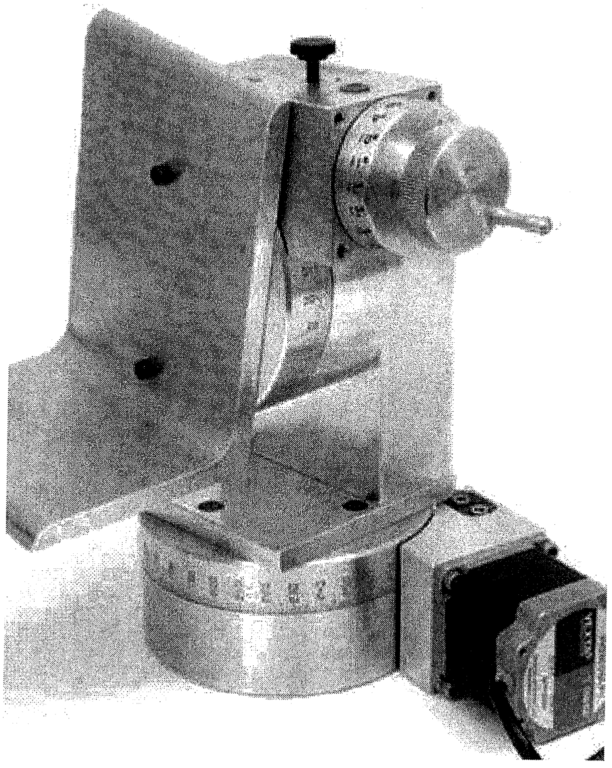


Photo 3B Black anodized finish

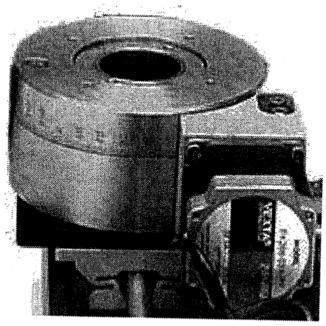


Vacuum Preparation: includes degreasing internal bearings and re greasing with vacuum compatible grease. More details.



2 each 4800 series rotary tables (1 manually operated, 1 motorized) with adapter bracket and platform shelf

B - Rotary Table



MSPP-3 Adapter plate **for BiSlide® Assemblies**

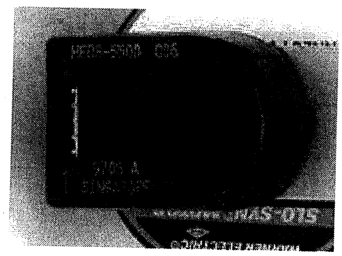


Photo 5 Rotary Encoder

Encoder attached to dual shaft motor provides 0.01° resolution

Rotary Table Gear Ratios and Performance with Velmex control and 1.9° step motor †

At maximum input of 600 RPM

Model Number	Gear Ratio	RPM	Time Per Revolution	Degrees Second	Degrees per Step	Typical Backlash
B4818TS	18:1	33.3	1.8 sec	200°/sec	0.050°*	600 arc - second
B4836TS	36:1	16.7	3.6 sec	100°/sec	0.025°*	400 arc - second
B4872TS	72:1	8.3	7.2 sec	50°/sec	0.0125°*	200 arc - second

† Using the optional M Series High Res motor (0.9°/step) would halve the above speed and double the resolution.

Load Capacity when table is...	Series B4800TS
Horizontal	200 lbs. compression load 100 lbs. tensile load
Vertical	25 lbs.
Cantilever Load (Horiz.)	500 in-lb.
Table top axial run out	0.00025" TIR
Table top radial run out	0.0005" TIR
Accuracy	100 arc - second
Repeatability	1 arc - second
Table weight	5.5 lbs. / 2.5 kg.
Max. input shaft speed	600 rpm

B - Rotary Table

Max. input shaft torque	150 oz-in

Dimensions for all B4800 Rotary Tables

Item	Inches	mm
Overall length	5.72	145
Threaded holes for payload	3.25 BC	83
Clear Aperture	1.57	40
Diameter	4.92	125
Width	5.27	134
Height	2.37	60
Pilot ring diameter (does not rotate)	2.559	65

B4800TS Mounting

An adaptor plate is required to mount the B4800 to a Velmex stage.

To mount to a UniSlide, use adaptor plate A6000TX

To mount to a BiSlide, use MSPP-3 Universal adapter plate

B4800 dimensional Drawing showing mounting holes details.

Anchoring table base: There are two approaches to securing the base of the table. First, there are two clearance holes for 10-32 UNF cap screws for attachment from above through the top access hole.

Alternatively, to attach with screws from below, there are four threaded holes. They are ¼"- 20 UNC - x ½" on a 4" diameter bolt circle.

B5990TS Motorized Rotary Table

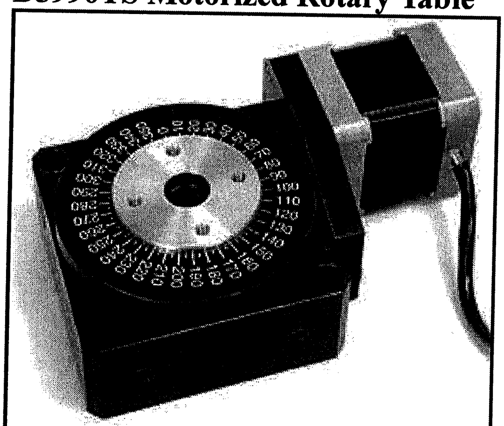


Photo 6

Gear ratios and performance for the B5990TS Motorized Rotary Table
with Velmex control and 1.9° step motor †

At maximum input of 600 RPM

Model Number	Gear Ratio	RPM	Time Per	Speed	Degrees per	Typical Backlash

B - Rotary Table

			Rotation		**Step**	
B5990TS	90:1	6	9 seconds	40.2°/sec	0.010*	160 arc - second

† Using the optional M Series High Res motor (0.9°/step) would move max speed of 20.1°/sec and have resolution of 0.005°/half step.

Specifications	**Model B5990TS**
Horizontal capacity	50 lbs. (compression) 12.5 lbs (tensile)
Vertical capacity	5 lbs.
Cantilever Load (Horiz. position)	20 in-lb.
Table top axial run out	0.00011" TIR
Table top radial run out	0.00008" TIR
Accuracy	100 arc - second
Repeatability	1 arc - second
Table weight	2.7 lbs. with motor
Max. input shaft torque	50 oz.-in.

Download CAD drawings

B5990TS Mounting

UniSlide: Mounts directly to Series A40/B40 or 4" Series A25 sliders

XSlide: Uses adapter plate

BiSlide: use MSPP-4 adapter plate. Example

B5990TS Rotary Table's Options and Adapters

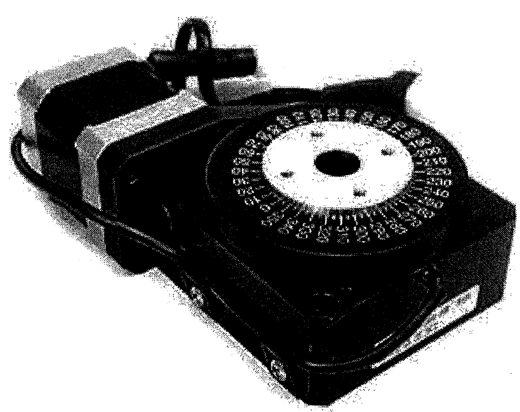


Photo 7A **Magnetic reed home switch option** This switch, analogous to a limit switch on a linear stage, provides a mechanism for homing the table. You can approach it from either direction. It provides a repeatable way to return to a specific physical location. Programming for use

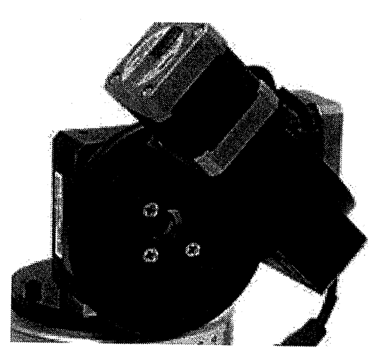
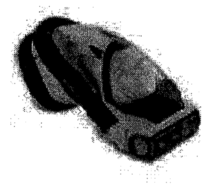


Photo 7B **B5990TXZ-BK** adapter: Use this round plate to join two rotary tables or as an intermediate plate to hold your payload. Price and photo

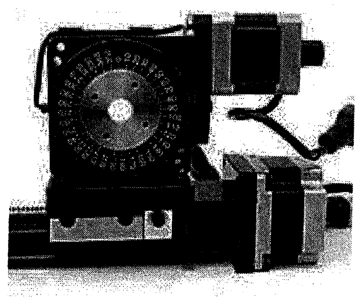
R - Rotary Table



Vacuum Preparation:
includes degreasing internal bearings and re greasing with vacuum compatible grease.
More details

Photo 7C **Rotary Encoder**

400 count encoder attached to dual shaft motor provides 0.01° resolution.



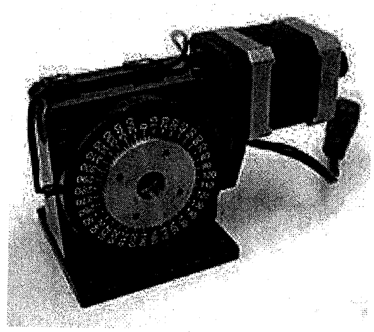


Photo 7D **Mounting to XSlides**

There are two methods:
-- the simplest method uses 2 adapter plates.
-- alternatively, you can use a gusset. This allows you to position the Rotary table further from the XSlide if your payload extends beyond the body of the Rotary table. See XSlide Adaptors

Applications for Motor Driven Rotary Tables

B - Rotary Table

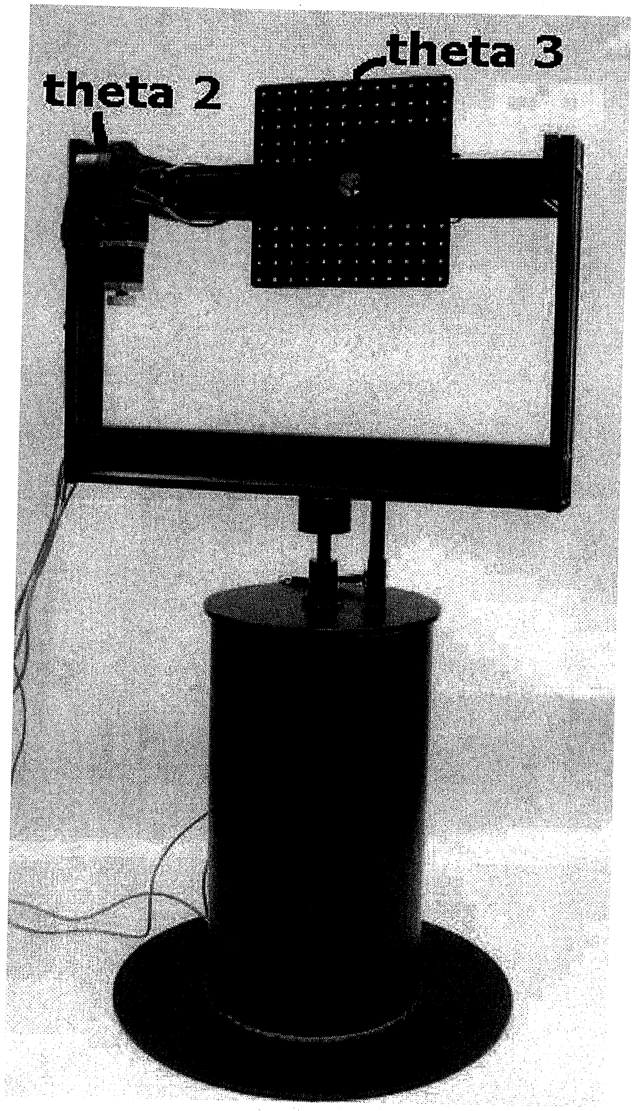


Photo 8: A three axis (tilt, pan, rotate) system consisting of a motor in the base (theta 1, hidden), a tilt (theta 2), and a pan axis behind the platen (theta 3). The payload mounts on the platen. All three motors are controlled with our VXM - 3 programmable controller.

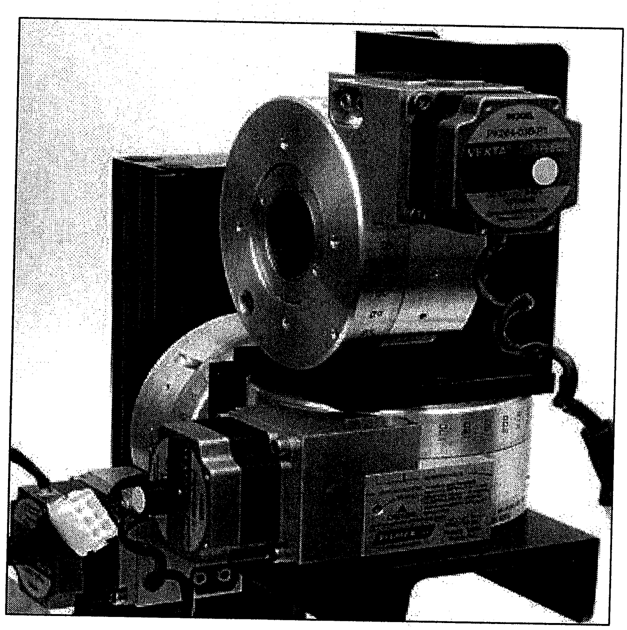


Photo 10: Three axes of rotary motion perpendicular to each other

Three Series B4800 rotary tables combined using A4001 XZ adapter bracket. These tables are used to provide for altitude and azimuth, tilt and pan or pitch and yaw motion.

Watch a video of similar system below.

<Video

B - Rotary Table

Photo 11: For lighter payloads, a three axes system consisting of 1 B4800 model and 2 B5990TS units.

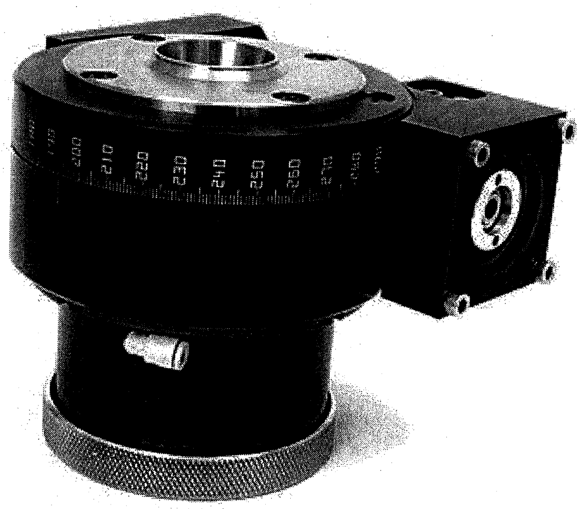


Photo 12: A combination of electro and pneumatic rotary tables. The pneumatic 5-c collet closer on the bottom is mounted to Velmex Model B4872TS Rotary table on the top (The step motor has been removed.)

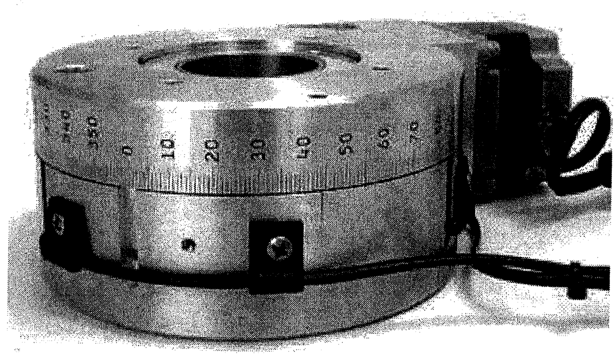
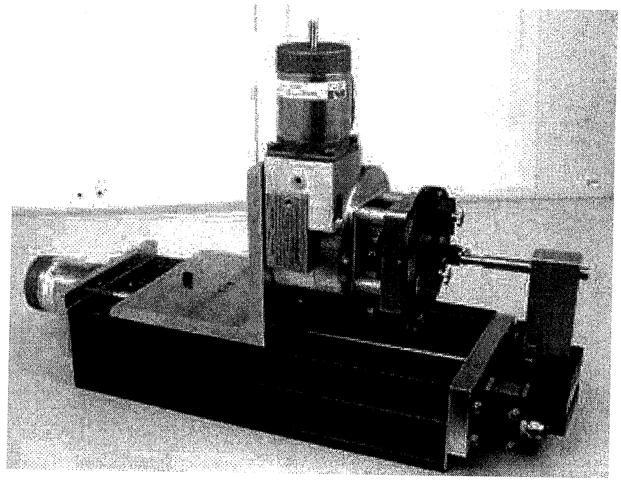


Photo 13: By adding a second zero ref switch, this table is limited to 90° rotation

B - Rotary Table



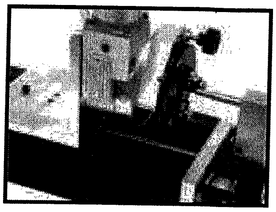


Photo 14: An A48 Rotary Table is used to support a three-jaw chuck which holds jewelry (rings) for a custom engraving application.

Larger view

Uses MB6000 UniSlide, right angle platform and pneumatically driven engraver.

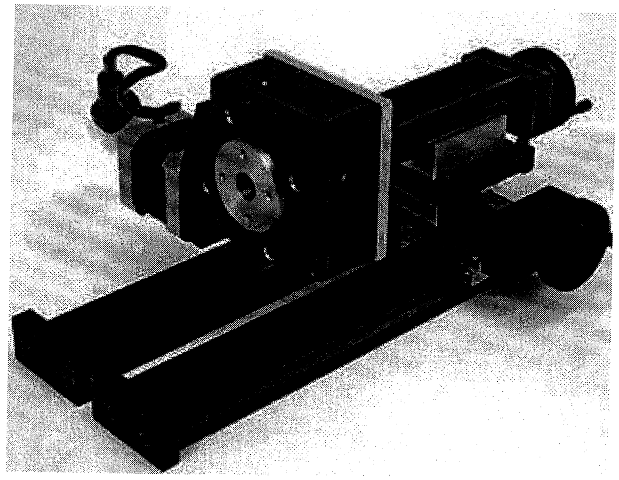


Photo 15: XYZ and Theta: An B5990 Rotary Table is mounted to two manual XSlide assemblies for use in vacuum chamber

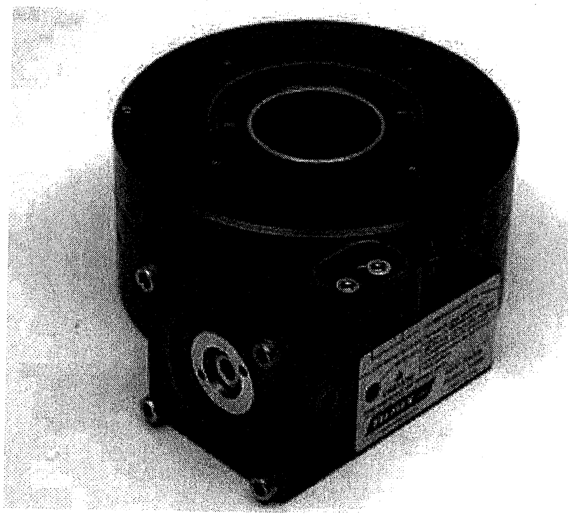


Photo 16: Rotary table with custom blue anodized finish

Content on this page requires a newer version of Adobe Flash Player.

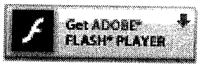
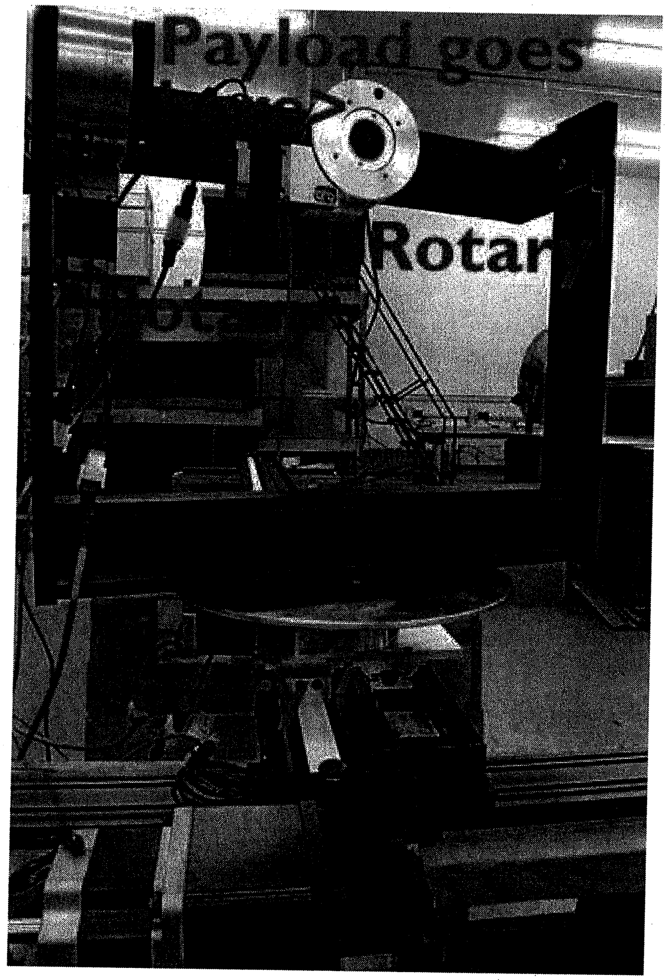


Photo 17: 3 rotary tables and single axis belt-driven BiSlide assembly. Max linear speed is 15 inches/sec. The video is silent.

B - Rotary Table



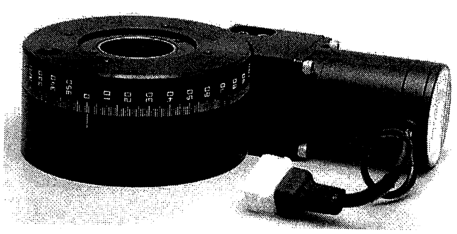
<>

B - Rotary Table

Table of Contents

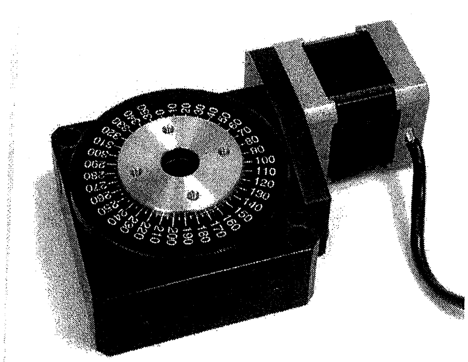
Motor Driven

Motorized Rotary Tables



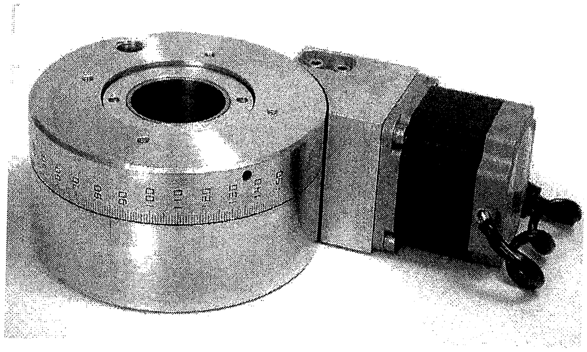
B4800TS 2.50

B5990TS 2.52



Note: *Throughout this catalog you'll see* ***Keywords in RED.*** *To get more information, including access to drawings, specs, photos of examples and the latest innovations, go to our web site,* ***www.velmex.com****, and enter the corresponding* ***Keyword in the Quick Search Box.***

B-Rotary Table



Rotary Tables

Velmex offers two sizes of every table: Series B4800TS (4.9" diameter) and Model B5990TS (1.65" diameter).

B4800TS

B4800 is a Series of three Rotary Tables that use a worm and gear drive design with a central rotating ball bearing. Gear ratios are: 18, 36, and 72:1. Models with 18 or 36 gear ratios require holding torque to maintain position. The tables can be driven by frame size 23 stepper motors, Bodine Type K or Pittman PM DC motors.

All tables have a hollow spindle or clear aperture for optical applications, an 360° scale and an adjustment to minimize gear backlash. They can be attached to the slider of the 4000 and the 6000 UniSlide Assemblies via the B6000TX adapter plate. Also mounts to BiSlide with MSPP-3 adapter plate. Plate is 6" x 6" x 1/4".

Options:

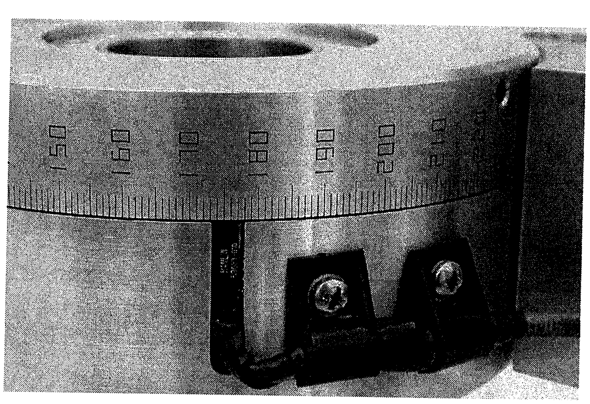
- Black anodized finish (see previous page)
- Magnetic reed home switch option
- Encoders on motor shaft extension

Mounting B4800TS

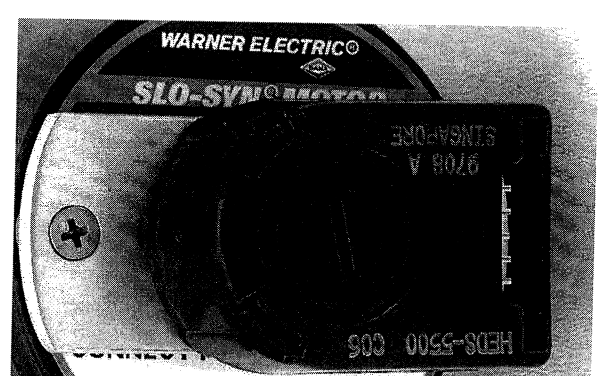
Anchoring table base: There are two approaches to securing the base of the table. First, there are two clearance holes for 10-32 UNF cap screws for attachment from above through the top access hole. Alternatively, to attach with screws from below, there are four threaded holes. They are 1/4-20 x 7/16" UNC on a 4" diameter bolt circle.

	Series B4800TS
Horizontal load capacity	200 lbs.
Vertical load capacity	25 lbs.
Cantilever load (Horizontal)	500 in.-lbs.
Table top axial runout	0.00025" TIR
Table top radial runout	0.0005" TIR
Accuracy	100 arc-seconds
Repeatability	1 arc-seconds
Table weight	5.5 lbs./2.5 kg.
Maximum input shaft torque	150 oz.-in.
Maximum input shaft speed	600 RPM.

Keyword: worm



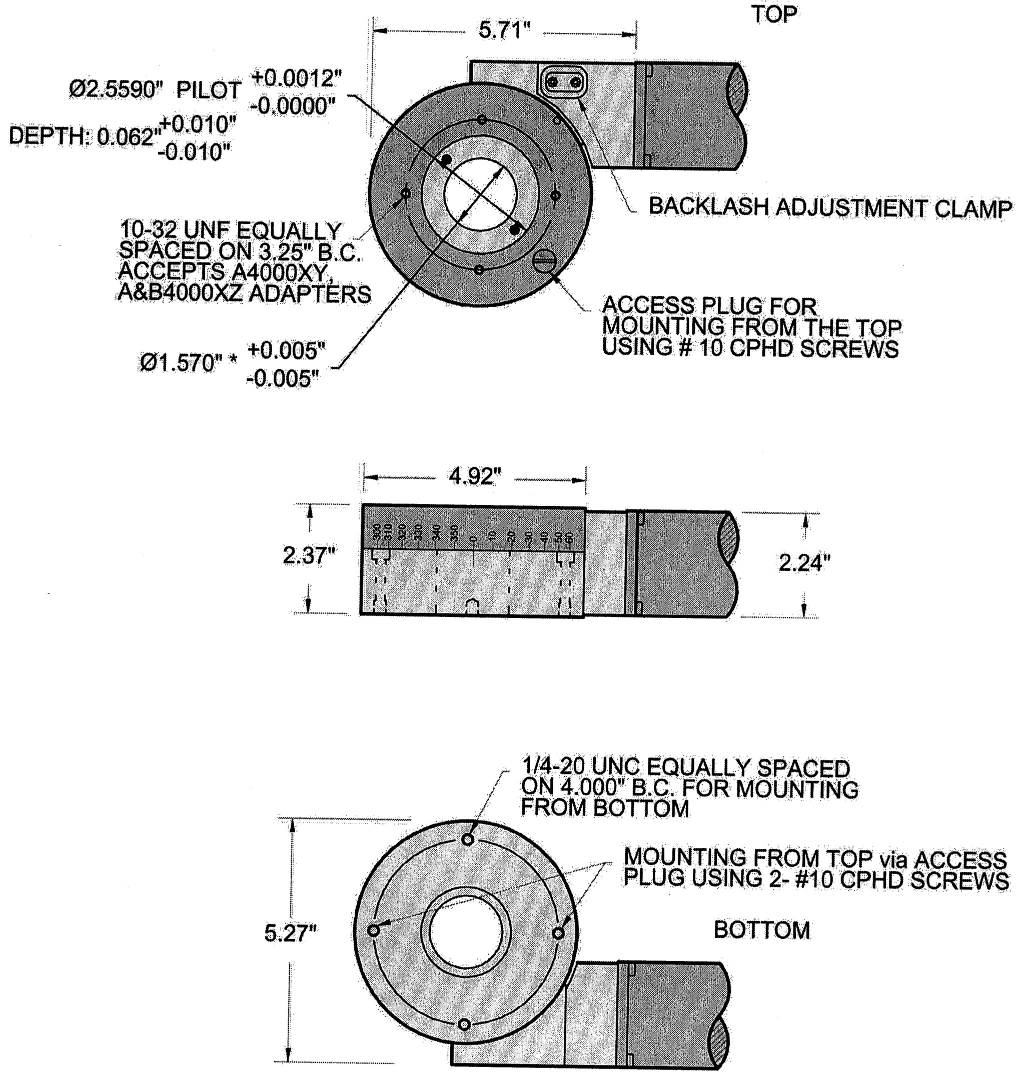
Magnetic reed homes switch option



Rotary encoder mounted to motor shaft extension

B - Rotary Table

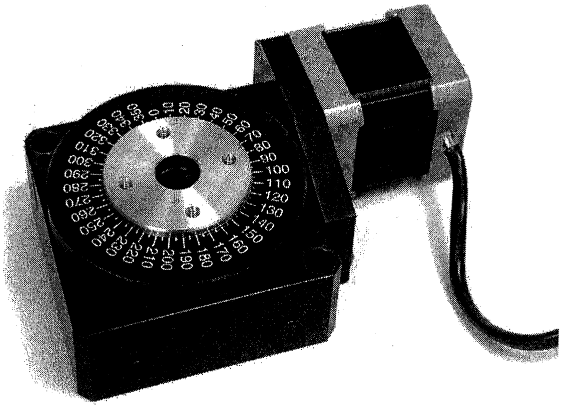
Model B4800TS



Model Number	Gear Ratio	RPM	At maximum input 600 RPM Time per Revolution	Speed	Degree per Step	Typical Backlash
B4818TS	18:1	33.3	1.8 seconds	200°/second	0.050°*	600 arc-second
B4836TS	36:1	16.7	3.6 seconds	100°/second	0.025°*	400 arc-second
B4872TS	72:1	8.3	7.2 seconds	50°/second	0.0125°*	200 arc-second

Degree per step values are based on 400 steps/revolution using a 1.8 degree step motor and a Velmex VXM motor controller operating in half step mode.

B – Rotary Table



Model B5990TS A 1.7" diameter table with a gear ratio of 90:1

	Series B5990TS
Horizontal load capacity	50 lbs.
Vertical load capacity	5 lbs.
Cantilever load (Horizontal)	20 in.-lbs.
Table top axial runout	0.00011" TIR
Table top radial runout	0.00008" TIR
Accuracy	100 arc-seconds
Repeatability	1 arc-seconds
Table weight	2.7 lbs. with motor
Maximum input shaft torque	50 oz.-in.

Model B5990TS Rotary Table

B5990TS Rotary Table is our smallest table, has a 90:1 gear ratio, and is lower in cost. The table price includes a NEMA 17 stepper.

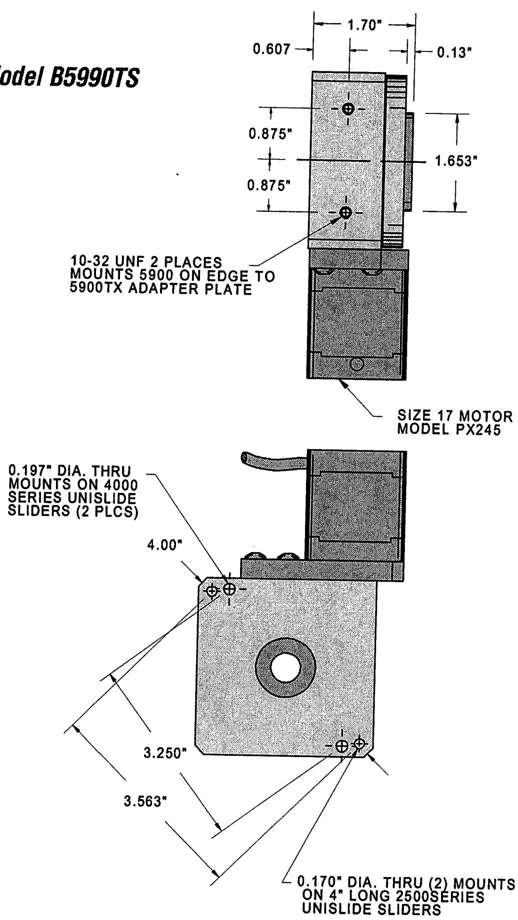
Options:

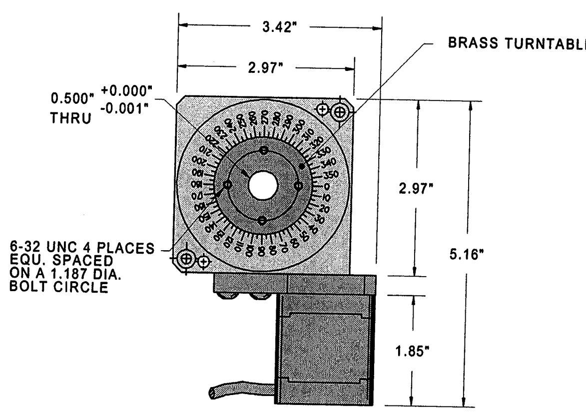
Home switch/Zero reference switch *(See photo on web site)*

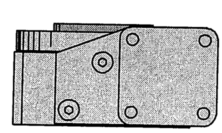
Model Number	Gear Ratio	RPM	At maximum input 600 RPM Time per Revolution	At maximum input 600 RPM Speed	Degree per Step	Typical Backlash
B5990TS	90:1	6	9 seconds	40.2°/second	0.010°*	160 arc-second

*Rotary table speed is a function of motor and driver choice. *With 400 step/rev motor.*

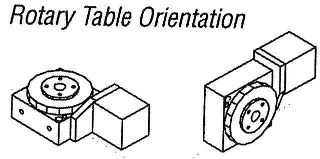
Model B5990TS







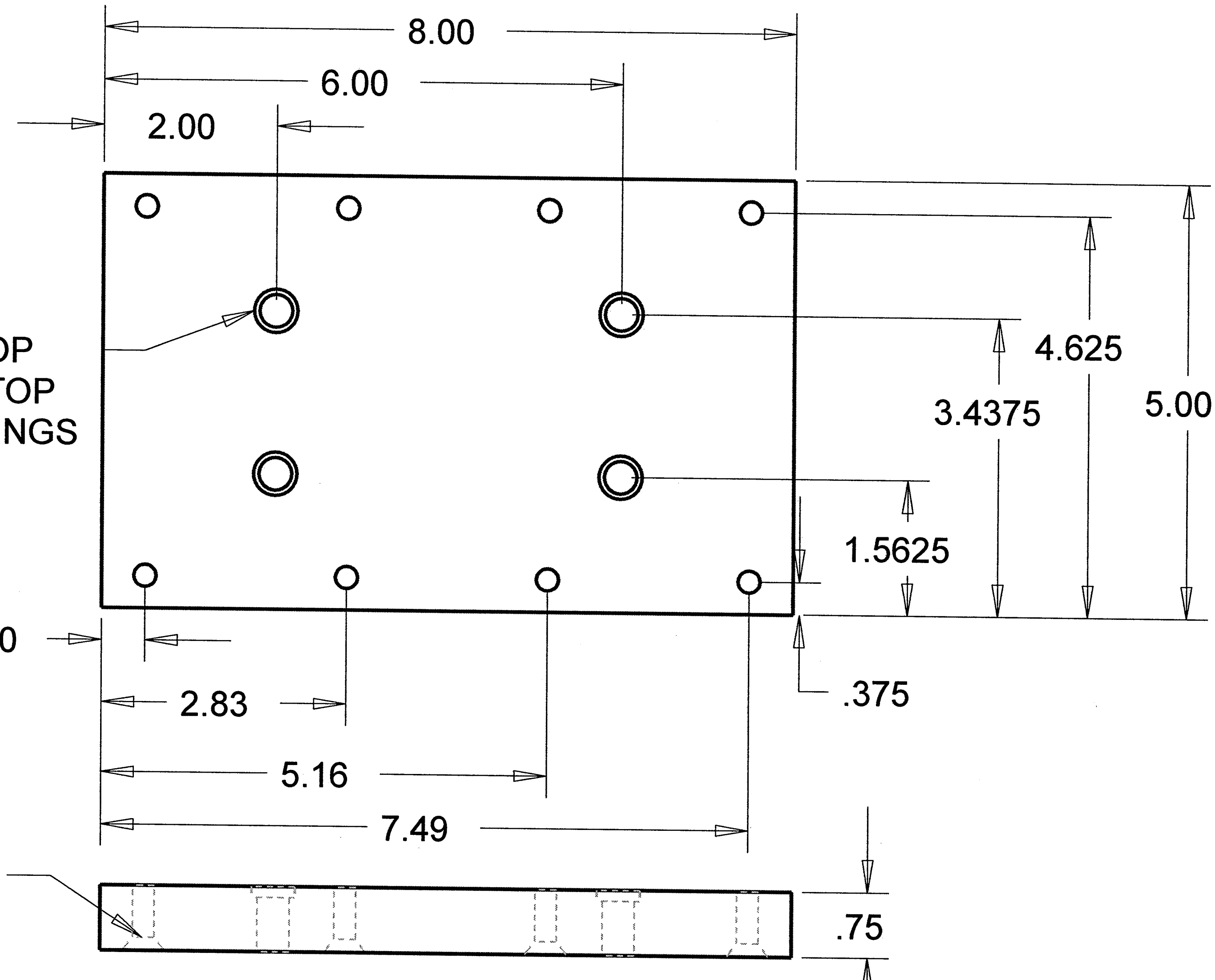
Rotary Table Orientation



Horizontal *Vertical*

R – Rotary Table

Appendix C- Drawings



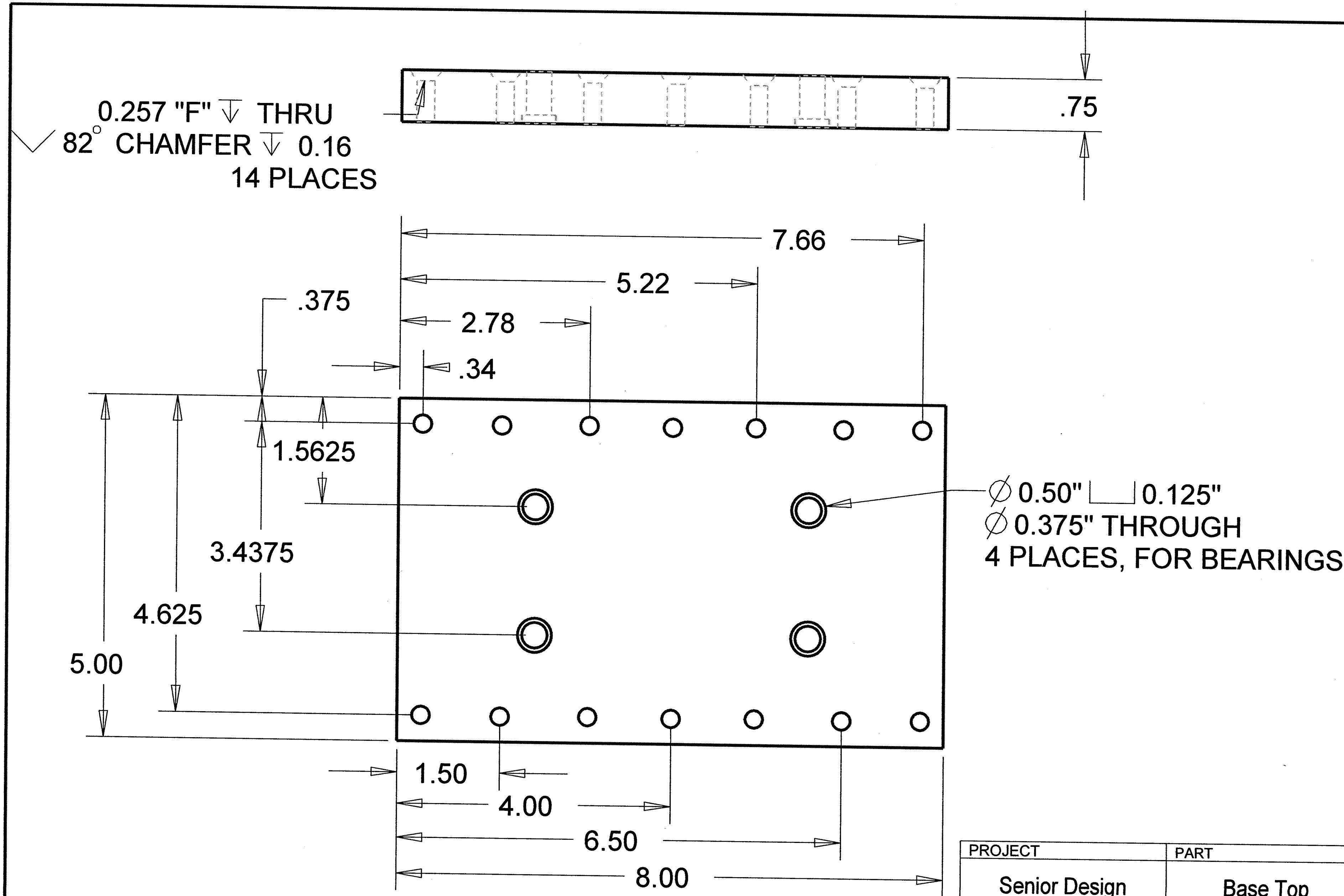
⌀0.50" ⌴ 0.125" FROM TOP
⌀0.375" ↧ THRU FROM TOP
4 PLACES, FOR BEARINGS

0.257 "F" ↧ THRU
⌵ 82° Chamfer ↧ 0.16
8 Places

MATERIAL: ALUMINUM 6061 (0.75" PLATE)
QUANTITY: 1

PROJECT: Senior Design	PART: Base Bottom	
DRAWN BY: JUSTIN BROOMALL	PART #: 02	REVISION: 01
SHEET #: 1 of 1	SCALE: 0.5	DATE: 6 FEB, 2015

C-Main housing

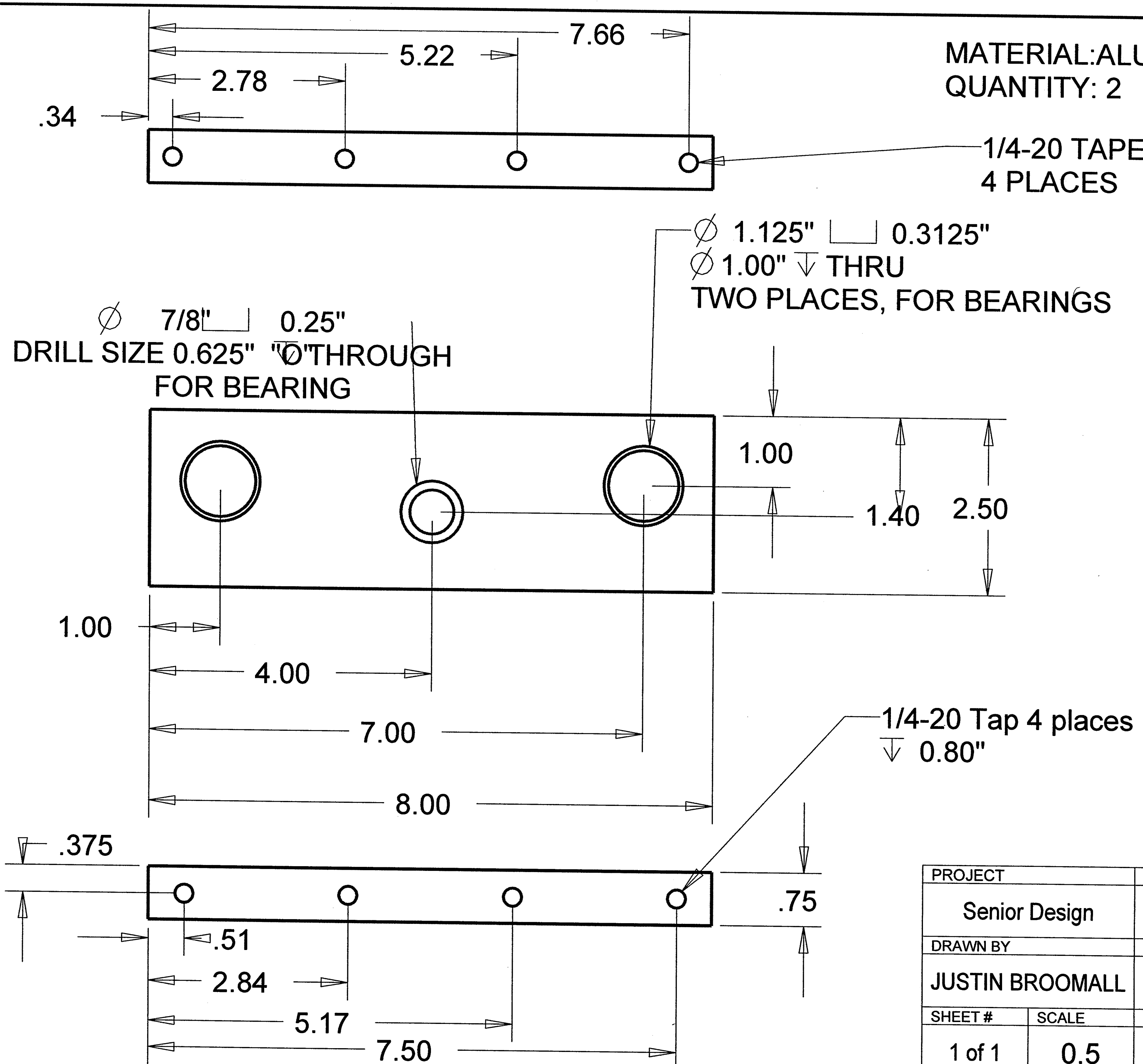


MATERIAL: ALUMINUM 6061
QUANTITY: 1

PROJECT		PART	
Senior Design		Base Top	
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		03	00
SHEET #	SCALE	DATE	
1 of 1	0.5	19 Jan, 2015	

C - Main housing

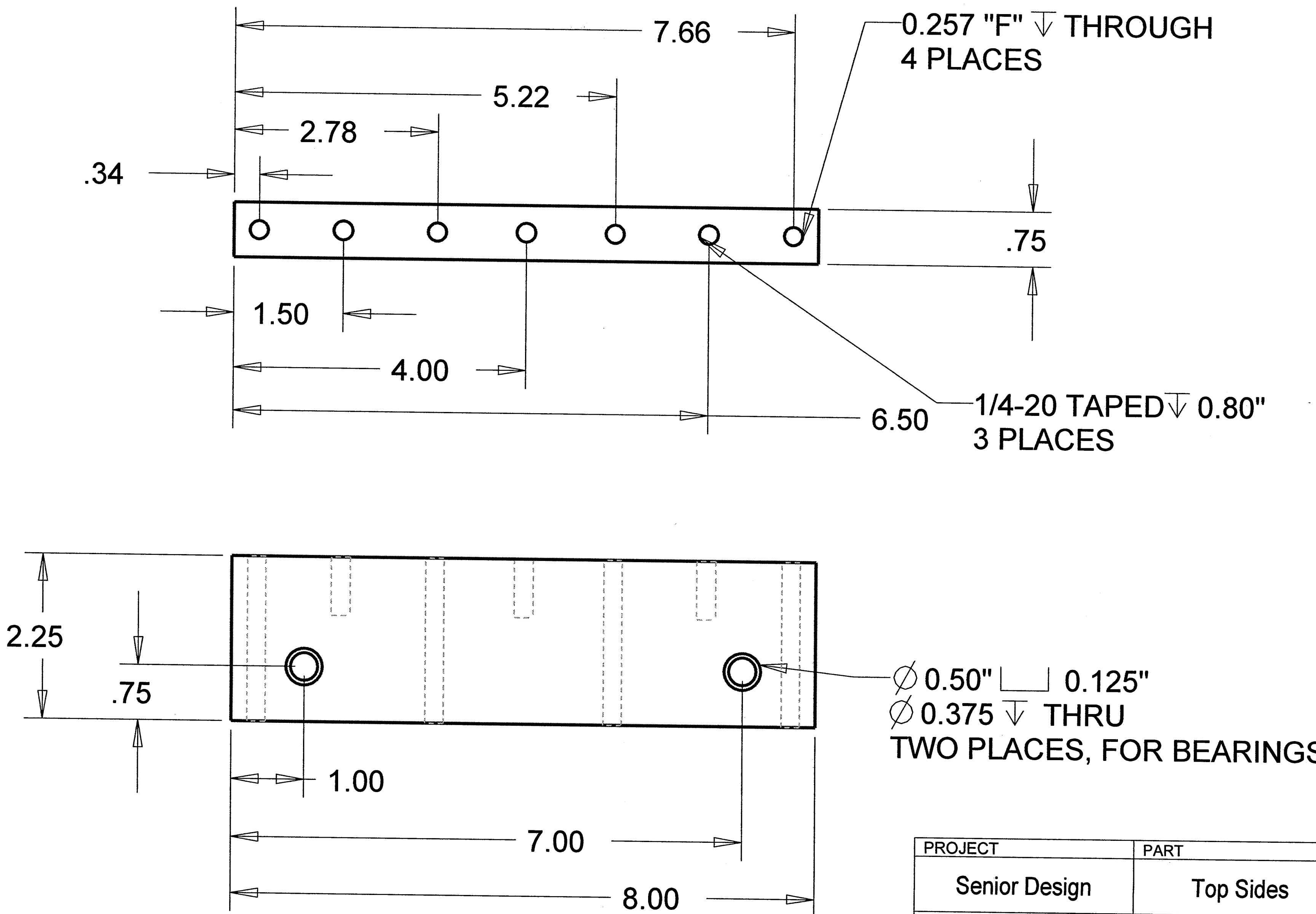
MATERIAL:ALUMINUM 6061
QUANTITY: 2



PROJECT		PART	
Senior Design		Bottom Side	
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	01
SHEET #	SCALE	DATE	
1 of 1	0.5	6 FEB, 2015	

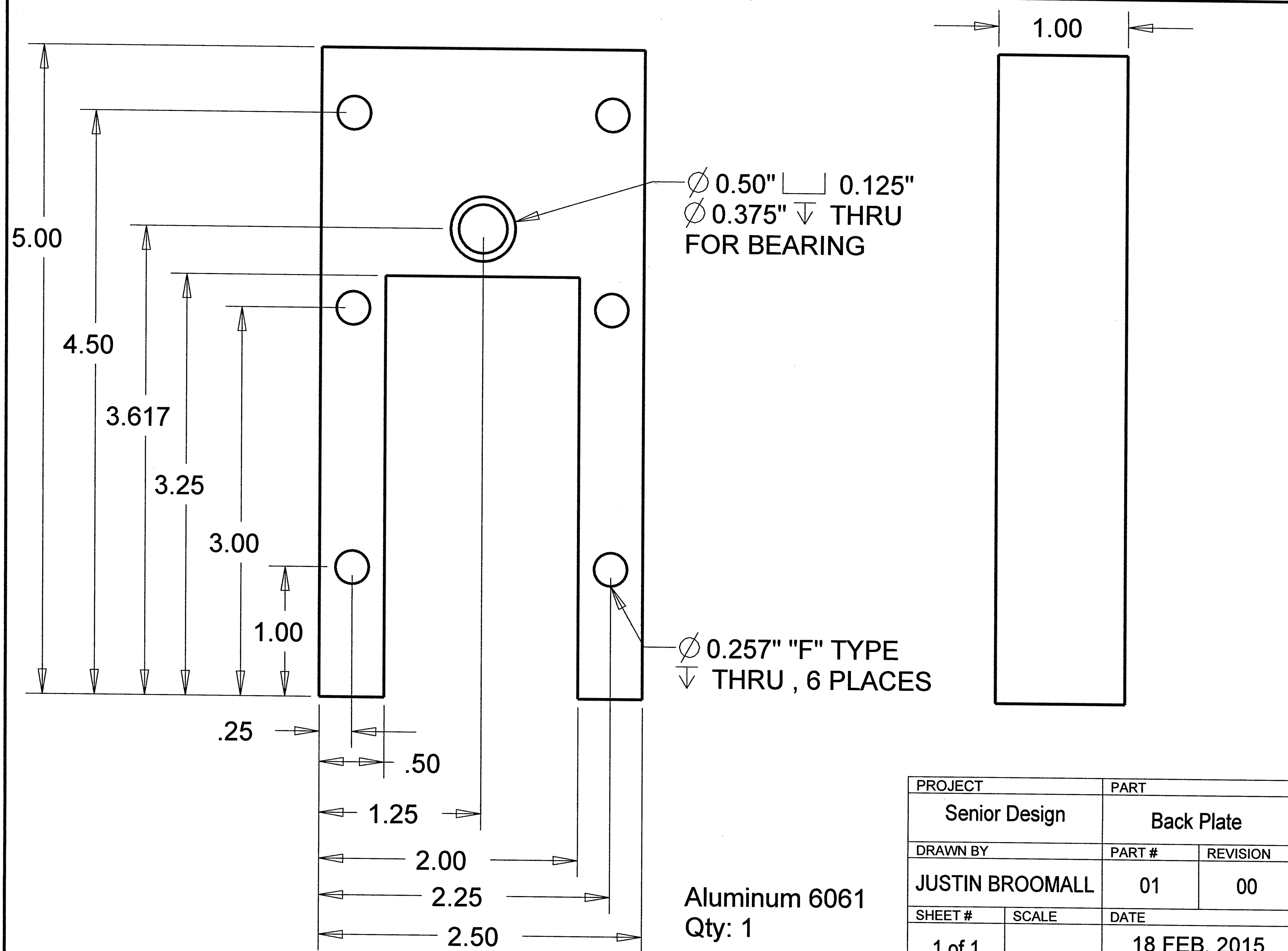
C-main housing

C - Main housing



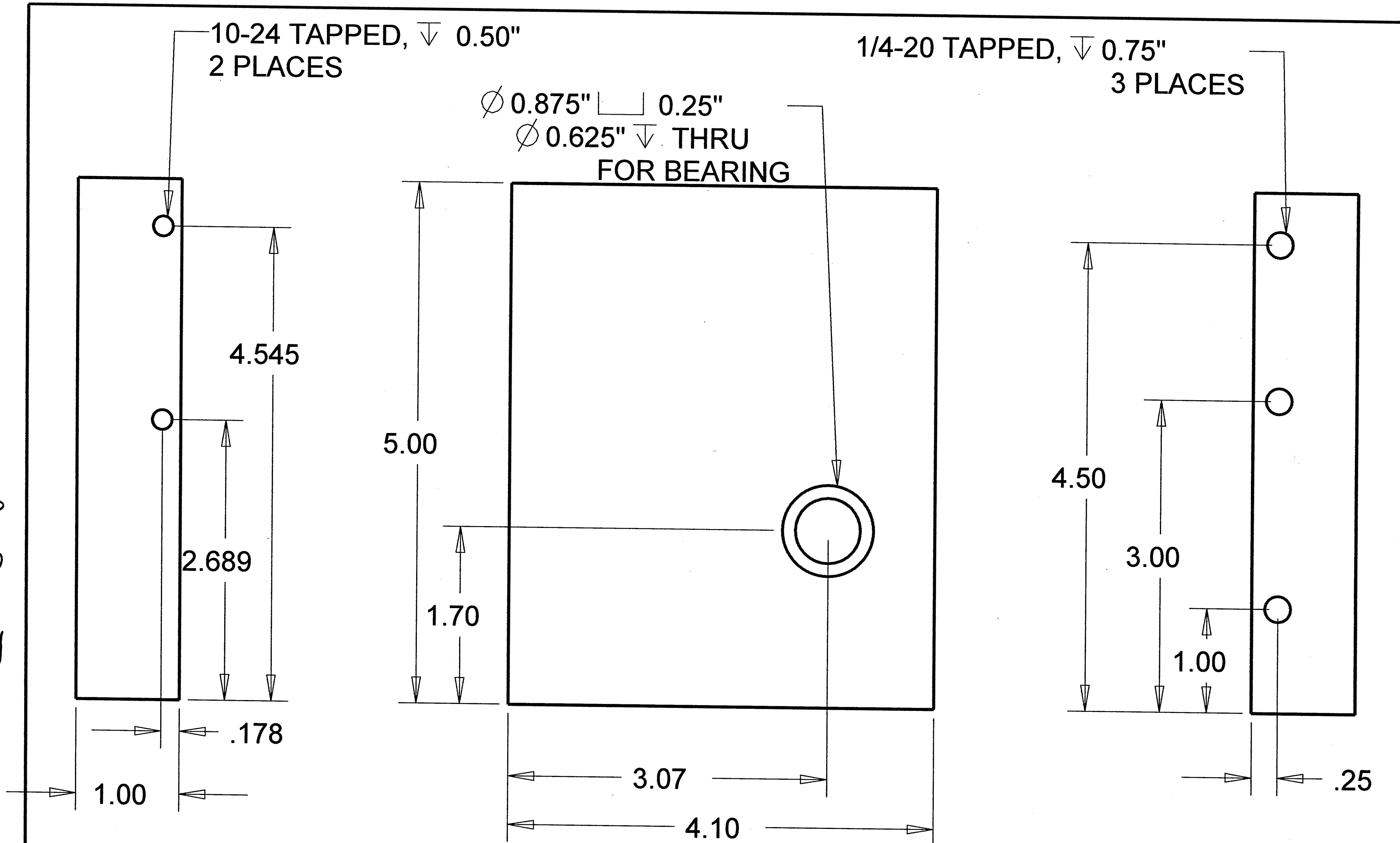
MATERIAL:ALUMINUM 6061
QUANTITY: 2

PROJECT		PART	
Senior Design		Top Sides	
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		04	01
SHEET #	SCALE	DATE	
1 of 1	0.5	6 FEB, 2015	



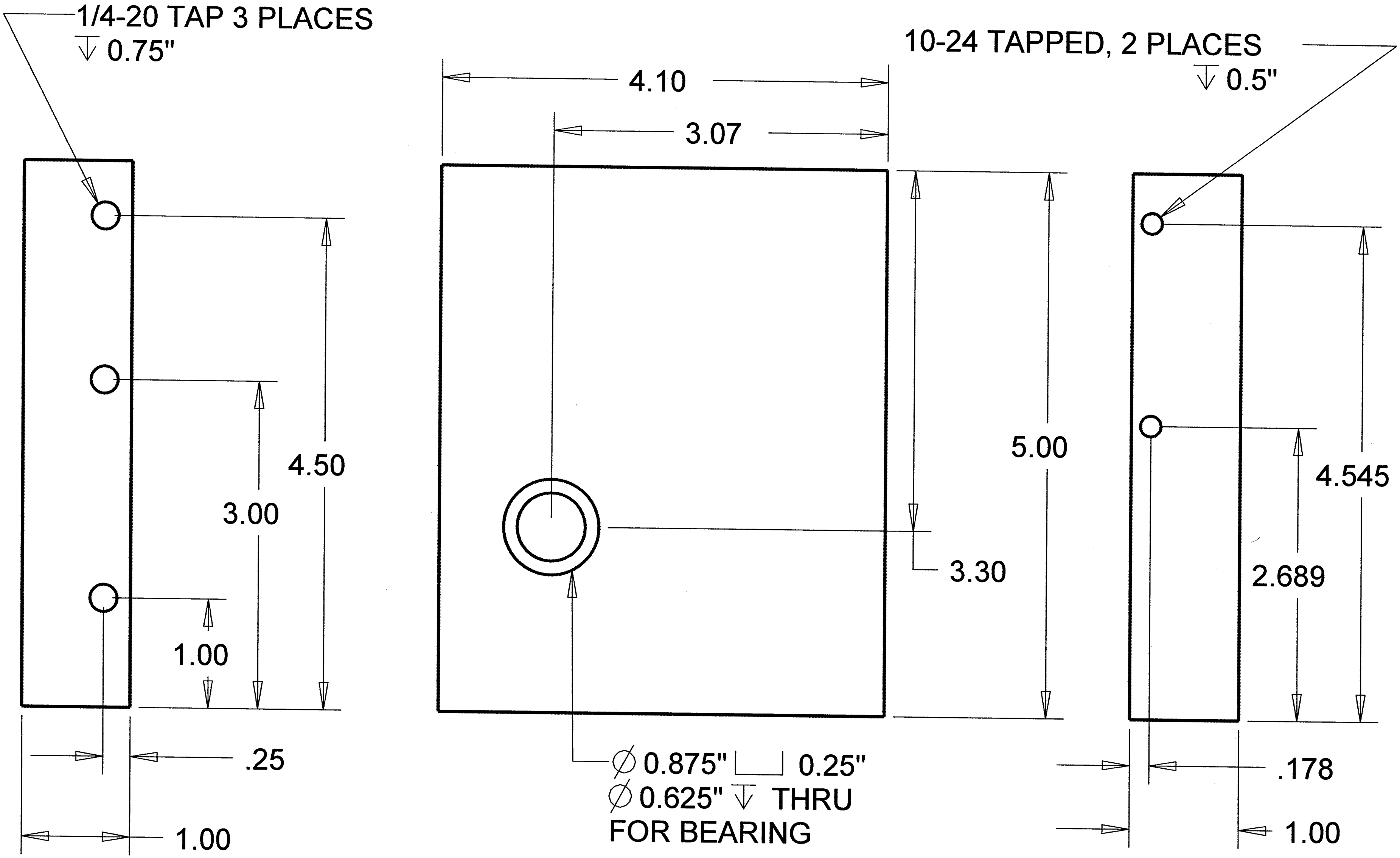
PROJECT		PART	
Senior Design		Back Plate	
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	00
SHEET #	SCALE	DATE	
1 of 1		18 FEB, 2015	

C-Power Train



PROJECT		PART	
Senior Design			
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	00
SHEET #	SCALE	DATE	
1 of 1		13 FEB, 2015	

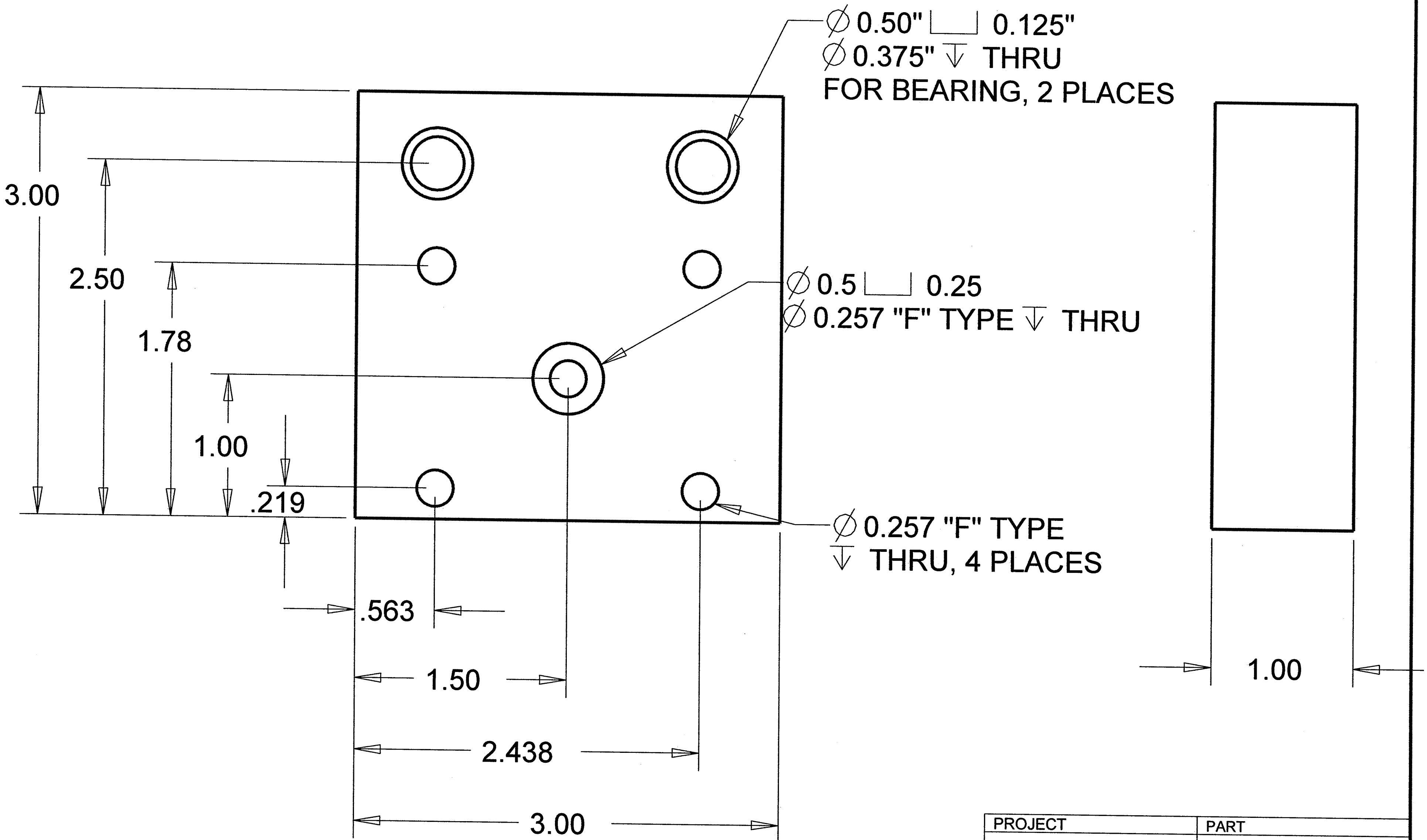
C-Power Train



AI 6061
QTY: 1

PROJECT		PART	
Senior Design		Left_Plate_Power	
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	00
SHEET #	SCALE	DATE	
1 of 1		13 FEB, 2015	

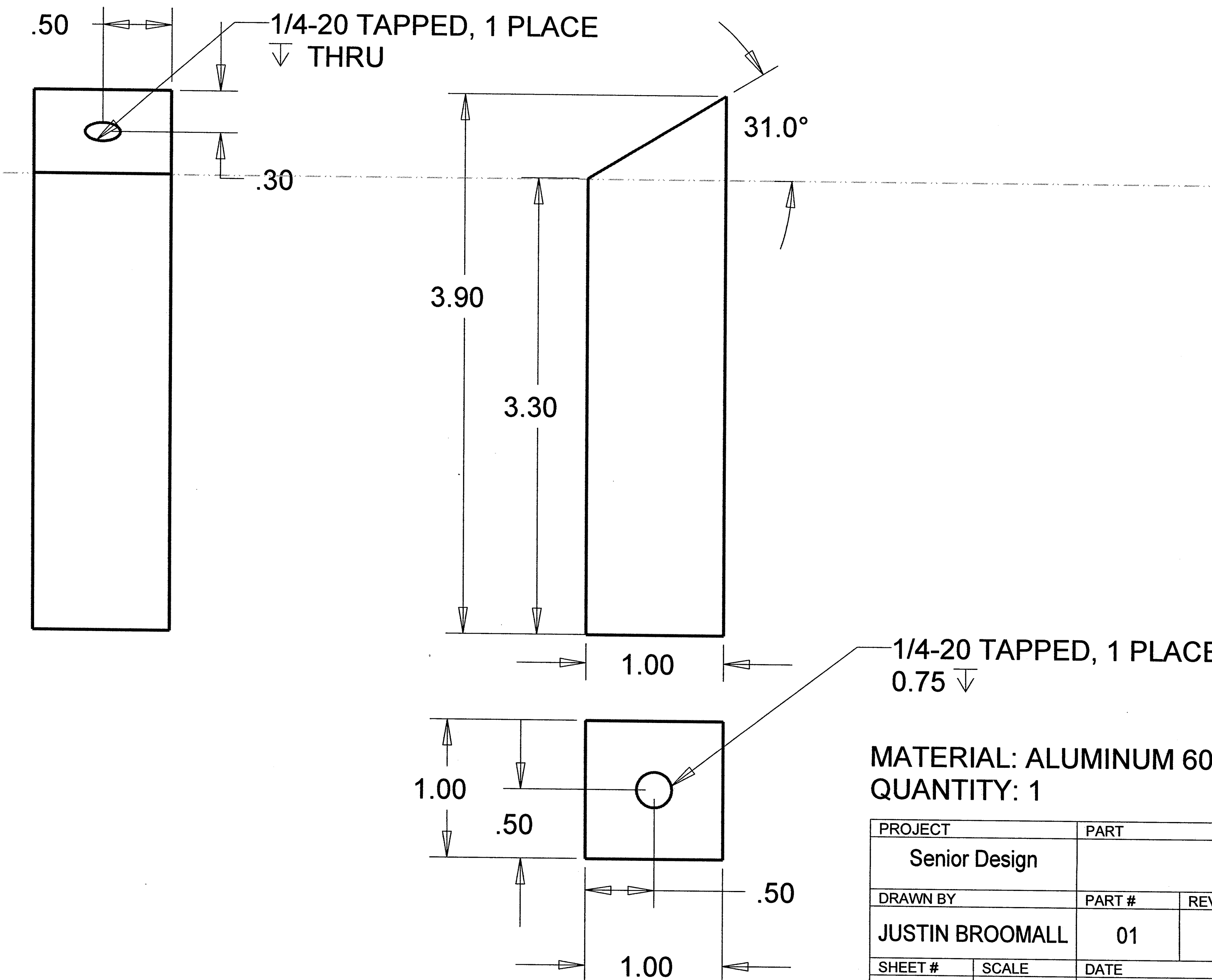
C ~Power Train



MATERIAL: ALUMINUM 6061
QUANTITY: 1

PROJECT		PART	
Senior Design			
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	00
SHEET #	SCALE	DATE	
1 of 1		13 FEB, 2015	

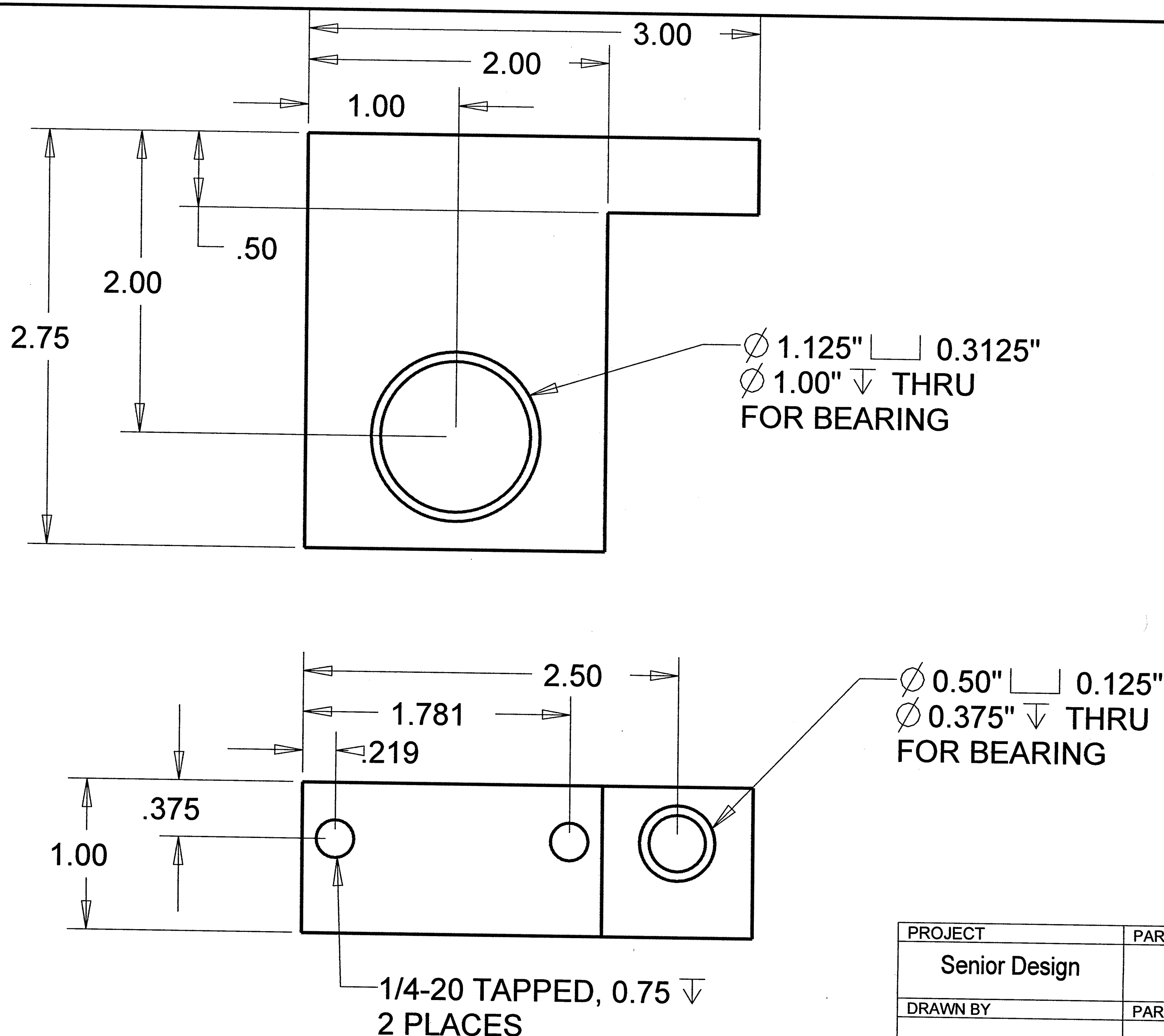
C - Follower



MATERIAL: ALUMINUM 6061
QUANTITY: 1

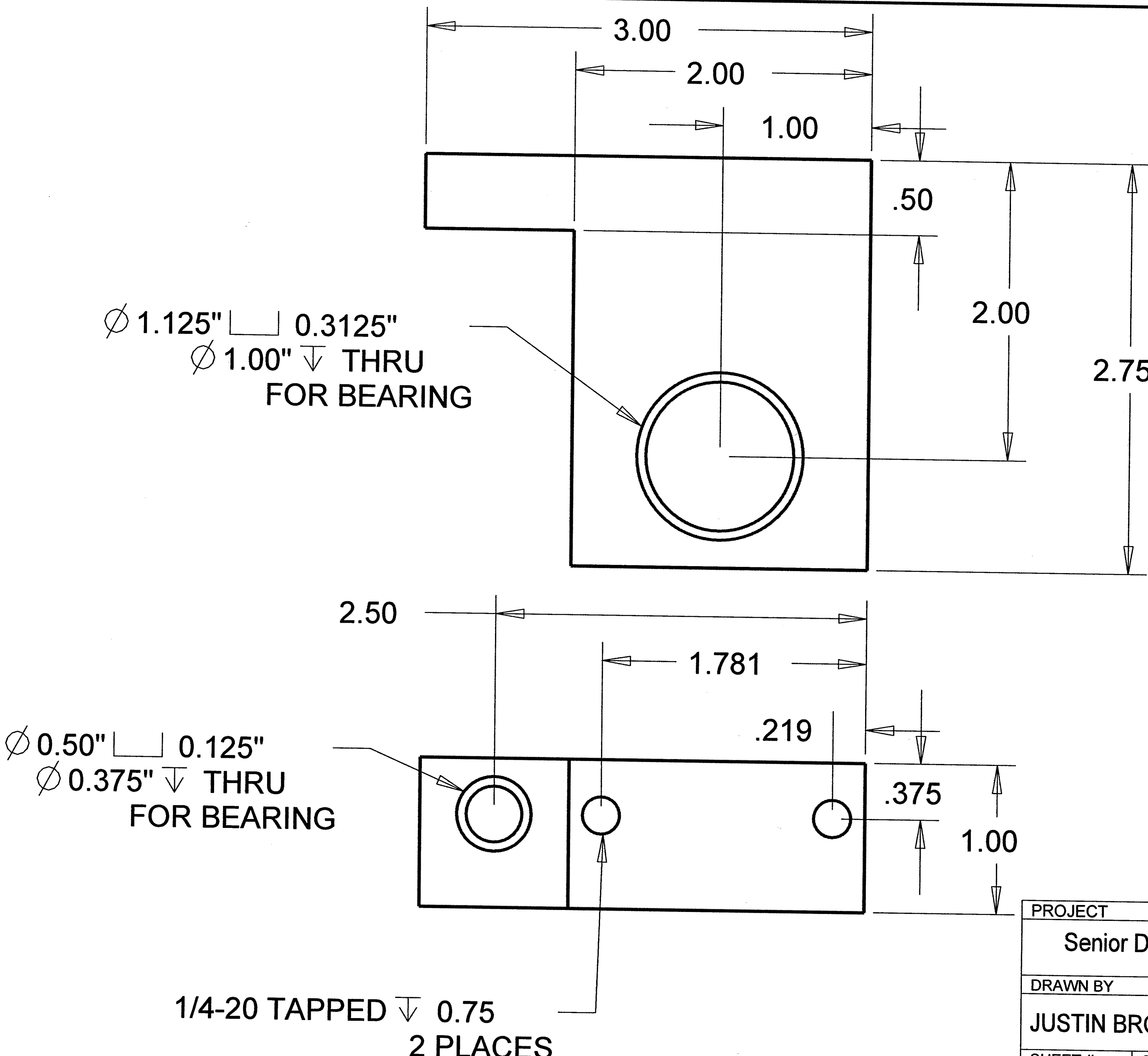
PROJECT		PART	
Senior Design			
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	00
SHEET #	SCALE	DATE	
1 of 1		13 FEB, 2015	

C-Follower



PROJECT		PART	
Senior Design			
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	00
SHEET #	SCALE	DATE	
1 of 1		13 FEB, 2015	

C-Follower



PROJECT		PART	
Senior Design			
DRAWN BY		PART #	REVISION
JUSTIN BROOMALL		01	00
SHEET #	SCALE	DATE	
1 of 1		13 FEB, 2015	

C-Follower

Appendix D- Calculations

Givens

$\alpha\_max := 30deg$ $\quad$ $V\_max := 22\frac{m}{s} = 72.178\cdot\frac{ft}{s}$

$\beta\_max := 30deg$

$\rho\_air := 1.23\frac{kg}{m^3}$ $\quad$ $l\_tunnel := 42in$

$r\_arc := 25in = 0.635\cdot m$ $\quad$ $A\_tunnel := l\_tunnel^2 = 1.764\times 10^3\cdot in^2$ $\quad$ $E\_alum := 69GPa$

Cross Section Shape

$a := 1in$ $\quad$ $r\_sting := .5in$

$\theta := 15deg$ $\quad$ $I\_sting := \frac{\pi}{4}\cdot r\_sting^4 = 0.049\cdot in^4$

$Area := a^2 = 1\cdot in^2$ $\quad$ $A\_sting := \pi\cdot r\_sting^2 = 0.785\cdot in^2$

$Iyy := \frac{a^4}{12} = 3.469\times 10^{-8}\cdot m^4$

Forces and Moments

$L\_effective := \frac{l\_tunnel}{2}$ -length of arc in air flow

$Cd\_airfoil := 1$ -Assume a airfoil coefficient of drag to be 0.1

$Cd\_max := 1$ -Assume a max coefficient of drag to be 0.8

$CL := 2$ -Assume a max coefficient of lift to be 2

$A\_airfoil := 0.1\cdot A\_tunnel = 176.4\cdot in^2$ -maximum blockage of 10% of windtunnel for test airfoil

$A\_max := 2a\cdot\cos(\theta)\cdot L\_effective = 40.569\cdot in^2$ -area of arc in airflow

$F\_lift := \left(\frac{1}{2}\cdot\rho\_air\cdot V\_max^2\cdot A\_airfoil\right)\cdot CL = 67.751\cdot N$ $\quad$ $F\_lift = 15.231\cdot lbf$

$F\_drag\_airfoil := \left(\frac{1}{2}\cdot\rho\_air\cdot V\_max^2\cdot A\_airfoil\right)\cdot Cd\_airfoil = 33.876N$

$F\_drag\_arc := \left(\frac{1}{2}\cdot\rho\_air\cdot V\_max^2\cdot A\_max\right)\cdot Cd\_max = 7.791N$

$M\_max := F\_drag\_airfoil\cdot r\_arc + F\_drag\_arc\cdot\frac{r\_arc}{2} = 23.985\cdot N\cdot m$

$Fx := F\_drag\_airfoil + F\_drag\_arc = 41.666\cdot N$ $\quad$ $Fx\_total := Fx\cdot 1.5 = 14.05\cdot lbf$

D

Stresses

$y\_max := a \cdot \cos(\theta) = 0.966 \cdot in$

$\sigma b\_arc := \frac{(M\_max \cdot y\_max)}{Iyy} = 16.965 \cdot MPa$ $\sigma b\_arc\_unsteady := \sigma b\_arc \cdot 1.5 = 25.448 \cdot MPa$

$V\_arc := F\_lift$

$\tau xy\_arc := \frac{(3 \cdot V\_arc)}{2A\_sting} = 0.201 \cdot MPa$ $\tau xy\_arc\_unsteady := \tau xy\_arc \cdot 1.5 = 0.301 \cdot MPa$

$$\sigma 1\_arc := \frac{\sigma b\_arc\_unsteady}{2} + \sqrt{\left(\frac{\sigma b\_arc\_unsteady}{2}\right)^2 + \tau xy\_arc^2} = 25.449 \cdot MPa$$

$$\sigma 2\_arc := \frac{\sigma b\_arc\_unsteady}{2} - \sqrt{\left(\frac{\sigma b\_arc\_unsteady}{2}\right)^2 + \tau xy\_arc^2} = -1.581 \times 10^{-3} \cdot MPa$$

$\sigma b\_sting := \frac{[(F\_lift \cdot r\_arc) \cdot .5in]}{I\_sting} = 26.742 \cdot MPa$ $\sigma b\_sting\_unsteady := \sigma b\_sting \cdot 1.5 = 40.113 \cdot MPa$

$V\_sting := F\_lift$

$\tau xy\_sting := \frac{(V\_sting)}{A\_sting} = 0.134 \cdot MPa$ $\tau xy\_sting\_unsteady := \tau xy\_sting \cdot 1.5 = 0.201 \cdot MPa$

$$\sigma 1\_sting := \frac{\sigma b\_sting\_unsteady}{2} + \sqrt{\left(\frac{\sigma b\_sting\_unsteady}{2}\right)^2 + \tau xy\_sting^2} = 40.113 \cdot MPa$$

$$\sigma 2\_sting := \frac{\sigma b\_sting\_unsteady}{2} - \sqrt{\left(\frac{\sigma b\_sting\_unsteady}{2}\right)^2 + \tau xy\_sting^2} = -4.457 \times 10^{-4} \cdot MPa$$

Maximum Allowable forces

$Sy\_alum := 276MPa$

$N\_arc := \frac{Sy\_alum}{\sigma 1\_arc} = 10.845$

$N\_sting := \frac{Sy\_alum}{\sigma 1\_sting} = 6.881$

Deflection in Verticle Direction

$$dV := \pi \cdot \frac{(F\_lift - 5lb \cdot g) \cdot r\_arc^3}{2 \cdot E\_alum \cdot Iyy} = 0.301 \cdot in$$

$$dH := \frac{2 \cdot Fx \cdot r\_arc^3}{E\_alum \cdot Iyy} = 0.351 \cdot in$$

Motor Selection

$$Max\_Moment := Fx \cdot r\_arc = 26.458 \cdot N \cdot m$$

$$\frac{Max\_Moment}{g} = 3.747 \times 10^3 \cdot oz \cdot in$$

$Max\_resistance := 10lbf$ -designing for 10lbf as conservative approach with 3 factors of safety

$r\_pinion := 15mm$ $\quad d\_pinion := r\_pinion \cdot 2 = 1.181 \cdot in$

$$Torque\_pinion := Max\_resistance \cdot r\_pinion = 0.667 \cdot N \cdot m$$

$$Torque\_wormgear := \frac{Torque\_pinion}{g} = 94.488 \cdot oz \cdot in$$

$d\_wormgear := 3.333in$ $\quad d\_wormgear = 3.333 \cdot in$

$$r\_wormgear := \frac{d\_wormgear}{2} = 1.667 \cdot in$$

$$Force\_Required := \frac{Torque\_wormgear \cdot g}{r\_wormgear} = 15.763 \cdot N$$

$Force\_Required = 3.544 \cdot lbf$

Gear Forces

$$F\_total := \sqrt{Fx^2 + F\_lift^2} = 79.538 \cdot N$$

D

$M1 := 225oz \cdot in \cdot g = 1.589 \cdot N \cdot m$

$Rg := 9.47$

$p\_angle := 20deg$

$lead\_angle := 9.47deg$

$$Fwt := \frac{M1}{16mm} = 99.303\,N$$

$$Vs := .5in \cdot 300rpm \cdot \sec(lead\_angle) = 0.404\,\frac{m}{s}$$

$mew := 0.07$

$$Fgt := \frac{Fwt \cdot (\cos(p\_angle) \cdot \sin(lead\_angle) + mew \cdot \cos(lead\_angle))}{(\cos(p\_angle) \cdot \cos(lead\_angle) - mew \cdot \sin(lead\_angle))} = 24.263\,N$$

$Fgt = 5.455 \cdot lbf$

D

Gear Stress Calculations

$m := 1.5mm$

$y := .544$

$b := 5mm$

$Cs := 1$ ----Surface factor

$Kv := 1$ ---Speed factor

$Kt := 1$ ---temperature factor

$Kl := 1$ ---length of time factor

$Km := 1$ ---application factor

-bending and surface factors

$$sigma\_b\_prime := 2.4\frac{kg}{mm^2}$$

$$sigma\_b := \frac{sigma\_b\_prime \cdot Kv \cdot Kt \cdot Kl \cdot Km}{Cs} = 2.4 \cdot \frac{kg}{mm^2}$$ -max bending force

$F := m \cdot y \cdot b \cdot sigma\_b = 9.792\,kg$

$F := F \cdot g = 21.588 \cdot lbf$

$$\boxed{n := \frac{F}{15lbf} = 1.439}$$ -factor of safety for the plastic spur

$sigma\_b \cdot g = 3.414 \times 10^3 \cdot psi$ -max allowable bending force

$d := 36mm$

$alpha := 20deg$

$$E1 := 250\frac{kg \cdot g}{mm^2}$$

$u := 25$

$$Sc := \sqrt{\frac{F}{b \cdot d} \cdot \frac{u+1}{u}} \cdot \sqrt{\frac{1.4}{\left(\frac{1}{E1} + \frac{1}{E1}\right) \cdot \sin(2 \cdot alpha)}} = 3.849 \times 10^7\,Pa$$ -max surface force

Cycles

$$4kg \cdot \frac{g}{mm^2} = 3.923 \times 10^7\,Pa$$ $\boxed{\text{-for 10^5 cycles}}$

D

RPM Calculations

$motor\_rps := 10$ -torqued rotation speed

$motor\_rpm := motor\_rps \cdot 60rpm = 62.832\frac{1}{s}$

$gear\_ratio := 50$ -worm gear speed reduction

$speed\_reduction := \frac{motor\_rpm}{gear\_ratio} = 12 \cdot rpm$

$drive\_shaft\_speed := speed\_reduction = 12 \cdot rpm$

$drive\_shaft\_radius := \frac{5}{16} in = 0.313 \cdot in$

$linear\_speed\_drive\_shaft := drive\_shaft\_speed \cdot drive\_shaft\_radius = 0.393 \cdot \frac{in}{s}$

Life Cycle Analysis

$drive\_shaft\_speed = 1.257\frac{1}{s}$

$Cycle\_Life := 10^5$

$rotations\_per\_hour := drive\_shaft\_speed \cdot \frac{60}{rpm} = 720$

$hours\_of\_life := \frac{Cycle\_Life}{rotations\_per\_hour} = 138.889$ -hours of life

Arc Movement

$$r\_arc := 25in$$

$$movement\_span := 25deg$$

$$distance\_traversed := r\_arc \cdot movement\_span = 10.908 \cdot in$$

$$actuation\_time := \frac{distance\_traversed}{linear\_speed\_drive\_shaft} = 0.463 \cdot min$$

$$movement\_rate := \frac{movement\_span}{actuation\_time} = 0.9 \cdot \frac{deg}{s}$$

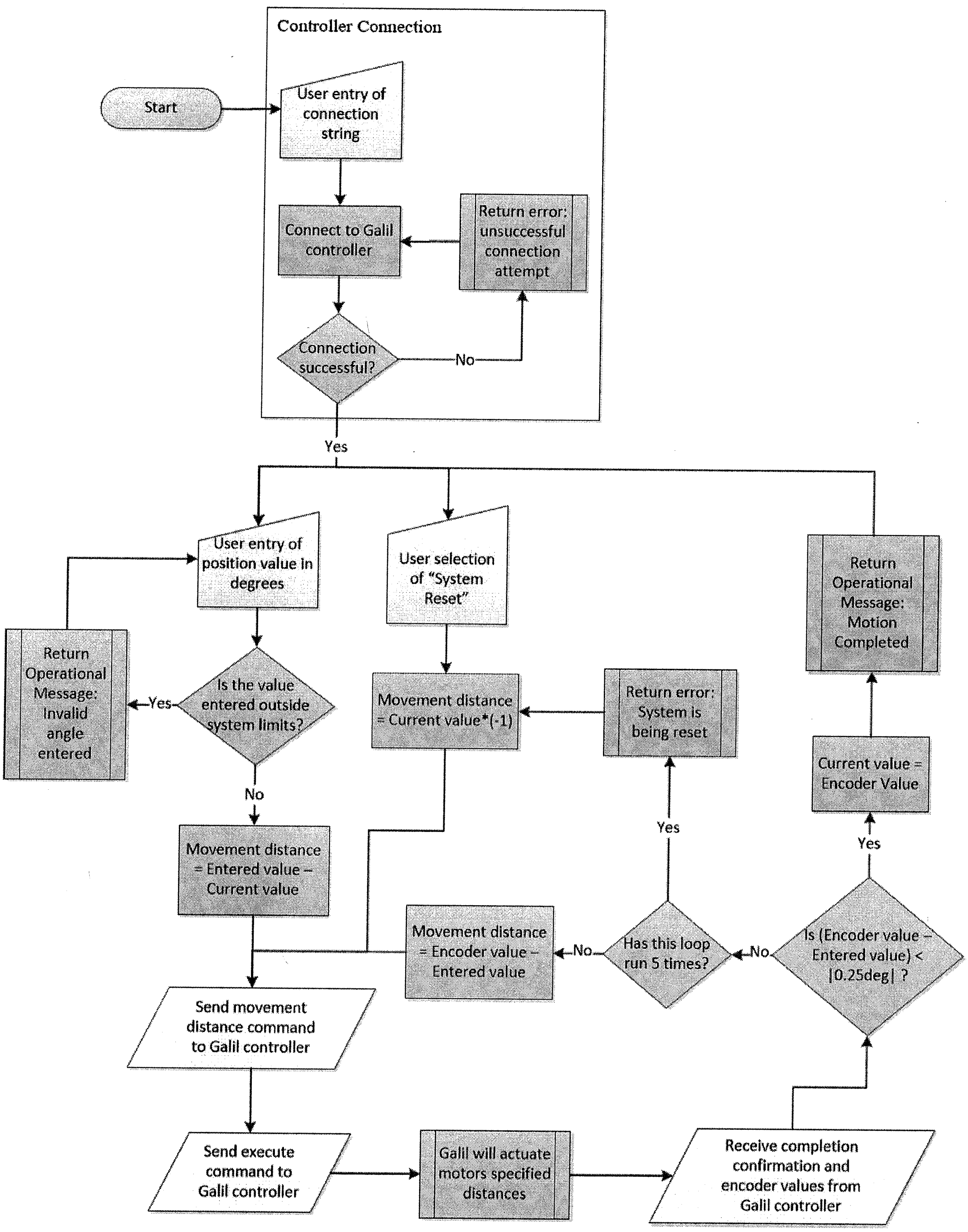
D

Appendix E- FMEA and Diagrams

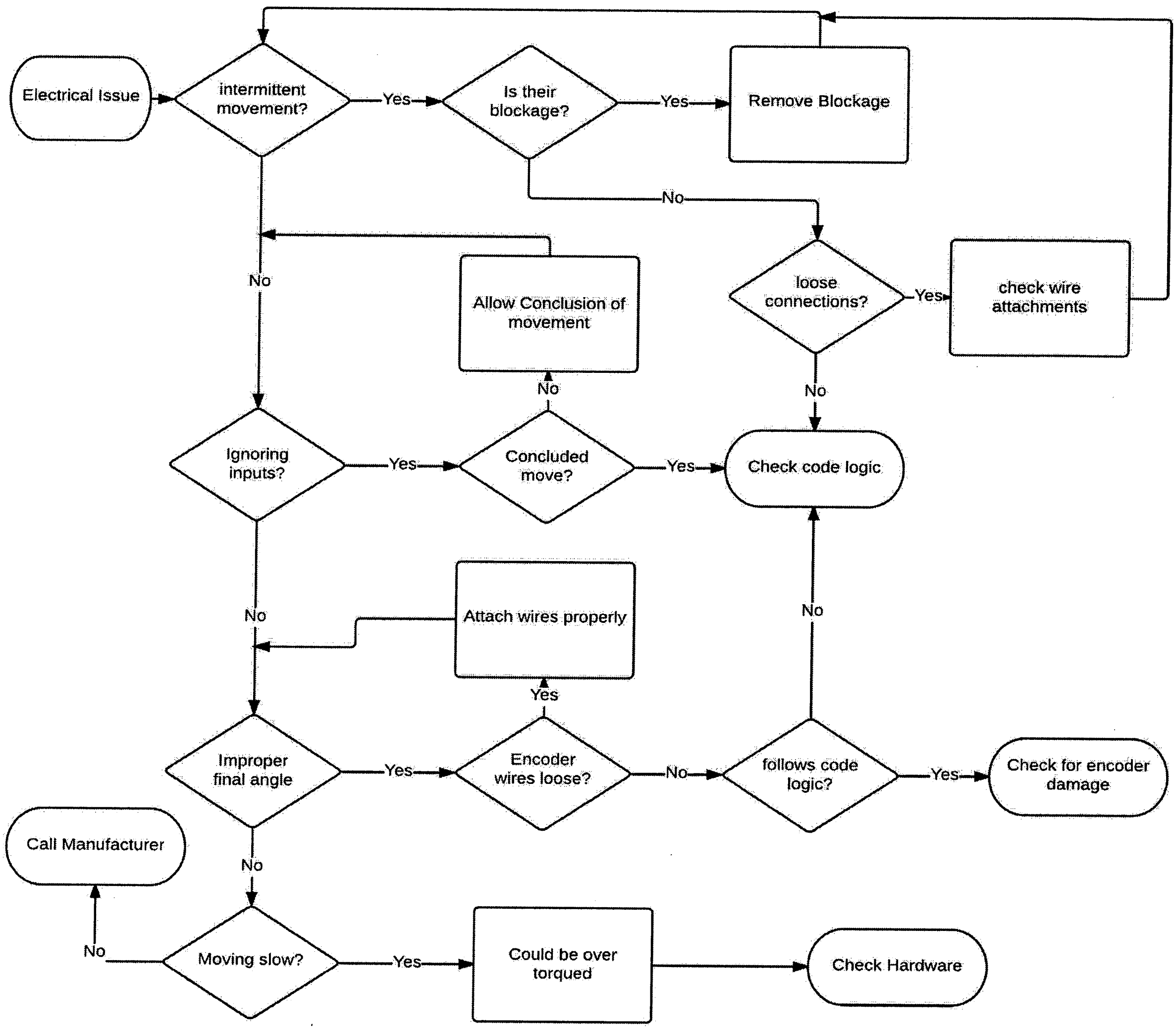
Team #:	12
Project Title	Articulating Robotic Arm for Wind Tunnel

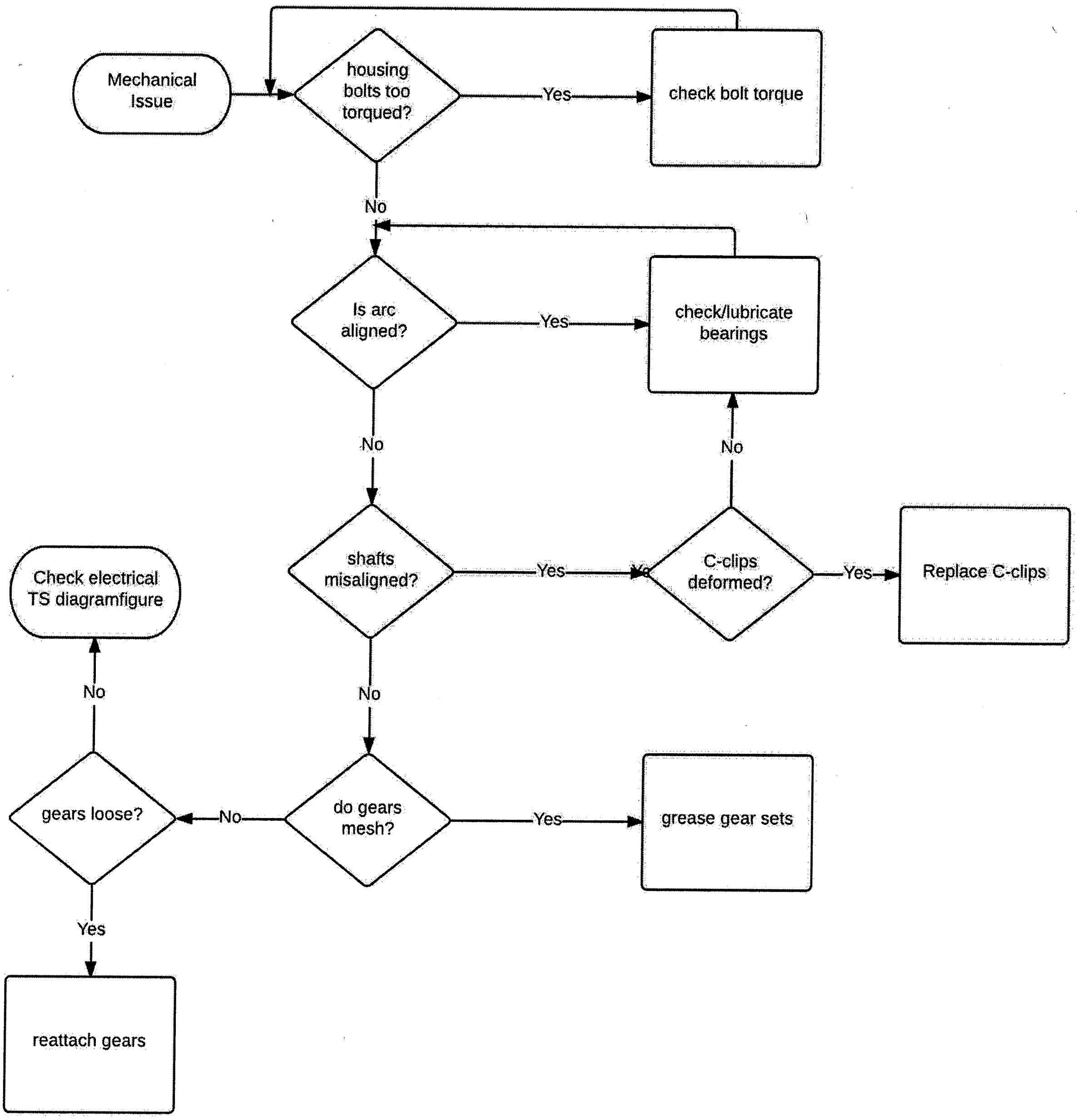
Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.	Actions Taken	SEV	OCC	DET	RPN
What is the Process Step or Input?	In what ways can the Process Step or Input fail?	What is the impact on the Key Output Variables once it fails (customer or internal requirements)?	How **Severe** is the effect to the customer?	What causes the Key Input to go wrong?	How **often** does cause or FM **occur**?	What are the existing **controls** and procedures that prevent either the Cause or the Failure Mode?	How well can you **detect** the Cause or the Failure Mode?		What are the actions for reducing the occurrence of the cause, or improving detection?	Who is Responsible for the recommended action?	Note the actions taken. Include dates of completion.				
Arc Pitch Actuation	destruction of flexi-rack	system un-usable	9	High forces at large yaw angles	3	side rollers/emergency off switch	5	135	install new flexi-rack/ wear check rollers	User		9	3	5	135
Pitch Actuation	spur pinion failure	system un-usable	7	large forces	3	2 factors of safety and cheap part	6	126	emergency off switch	user		7	3	6	126
Power Transmission	gear coming loose	system un-usable	7	failure of mounting mechanisms	3	JB-weld and set screws	5	105	inspections checks before each use/ purchase set	user		7	3	5	105
Arc Pitch Actuation	detachment of flexi-rack	system un-usable	7	failure of glue over time	3	spare flexi-rack and JB weld	5	105	inspection checks before each use	User/ Spare parts from designers		7	3	5	105
User input	improper operation or stall	delay in operation	5	coding loophole	3	boundary checked code for errors	5	75	troubleshooting section in Operation manual	user/ code writer		5	3	5	75
Arc Yaw Actuation	system slip	improper final angle	4	high torque with no encoder	3	reset switch to try again	6	72	reset the motion and actuate with less force	user		4	3	6	72
Arc Pitch Actuation	motor stall	system stalls	5	High forces at large yaw angles	3	side rollers/emergency off switch	3	45	alignment and wear checks before operation	User		5	3	3	45
Arc Actuation	creep deformation in plastic rollers	system inefficencies	4	cycle fatigue	2	spare parts/ easy part change	3	24	inspections checks before each use	User/ Spare parts from designers		4	2	3	24

Functional Diagram



TS Diagrams


Electrical Issue
intermittent movement?
Yes
Is their blockage?
Yes
Remove Blockage
No
loose connections?
Yes
check wire attachments
No
Allow Conclusion of movement
No
Ignoring inputs?
Yes
Concluded move?
No
Yes
Check code logic
No
Attach wires properly
No
Yes
Improper final angle
Yes
Encoder wires loose?
No
follows code logic?
Yes
Check for encoder damage
Call Manufacturer
No
No
Moving slow?
Yes
Could be over torqued
Check Hardware



Mechanical Issue
housing bolts too torqued?
Yes
check bolt torque
No
Is arc aligned?
Yes
check/lubricate bearings
No
No
shafts misaligned?
Yes
C-clips deformed?
Yes
Replace C-clips
Check electrical TS diagramfigure
No
No
gears loose?
No
do gears mesh?
Yes
grease gear sets
Yes
reattach gears

Appendix F- Bill of Materials

Sub Assembly	Part	Part Number	Vendor	Quantity
Raw Metal	1"x12"x48" 6061-T6 Plate*	N/A	Tallahassee Metal Fabrication	**1**
	0.5"x12"x18" 6061-T6 Plate*	N/A	Tallahassee Metal Fabrication	**1**
	0.75"x12"x24" 6061-T6 Plate*	N/A	Tallahassee Metal Fabrication	**1**
Arc assembly	Arc section*	N/A	College Machine Shop	**1**
	Sting pipe	89895k762	Mcmaster-Carr	**1**
	Flexible Gear rack	KDR1.5-2000	QTC Metric Gears	**1**
Turn Table Assembly	0.5"x12"x18" Plate*		Tallahassee Metal Fabrication	**1**
	1/4-20 bolts	91735A546	Mcmaster-Carr	**5**
	10-24 X 1/2 Screws	N/A	Grainger	**4**
Power Train Assembly	Motor	23MD306-10-00-00	Anahiem Automation	**1**
	Worm	A1Q 5-Y24	SDP-SI	**1**
	Worm gear	A1B 6-Y24080	SDP-SI	**1**
	Power transmission shaft	8920K265	Mcmaster-Carr	**1**
	Spur gear	A 1M 2MYZ15020	SDP-SI	**1**
	Shaft collars	6436k51	Mcmaster-Carr	**2**
	Shaft collars	6436k16	Shaft collars	**8**
	Rotary Table	N/A	Air force Research lab	**1**
	Shaft coupler	2UV83	Grainger	**1**
Roller Assembly	Quarter inch rollers	9697k117	Mcmaster-Carr	**8**
	Quarter inch shafts	8927k18	Mcmaster-Carr	**8**
	Quarter inch C-clips	98808a330	Mcmaster-Carr	**16**
	Half inch inner diameter rollers	60185K911	Mcmaster-Carr	**6**
	Half inch shafts	8927k96	Mcmaster-Carr	**3**
	C-clips	98808A360	Mcmaster-Carr	**8**

Bottom Support Assembly	Side plates*	N/A	College Machine Shop	**2**
	Bottom plate*	N/A	College Machine Shop	**1**
	1/4-20 bolts	91771A544	Mcmaster-Carr	**6**
Top Support Assembly	Side plates*	N/A	College Machine Shop	**2**
	Top plate*	N/A	College Machine Shop	**1**
	1/4 -20 bolts	91771A544	Mcmaster-Carr	**6**
	1/4-20 bolts	91771A573	Mcmaster-Carr	**8**
Follower Support Assembly	Square rod extension*	N/A	College Machine Shop	**1**
	Lower plate*	N/A	College Machine Shop	**1**
	Side plates*	N/A	College Machine Shop	**2**
	1/4 -20 bolts	91771A544	Mcmaster-Carr	**2**
Motor Housing Assembly	Front plate*	N/A	College Machine Shop	**1**
	Side plates*	N/A	College Machine Shop	**2**
	1/4-20 bolts	91735A546	Mcmaster-Carr	**6**
Bearings	Half inch diameter	60355k704	Mcmaster-Carr	**5**
	5/16 Diameter	6383k15	Mcmaster-Carr	**3**
	Quarter inch diameter	57155k356	Mcmaster-Carr	**16**
	***Machined in house**			

F

Biography

The Team:

Jacob Kraft - Team Lead:

Jacob is a FSU student from Stuart, FL. He has not claimed a specialty but has studied design and aerodynamics. He is a member of ASME (American Society of Mechanical Engineers) as well as a teaching assistant at the college.

Andrew Baldwin – Treasurer:

Andrew is a FSU student native to Tallahassee, FL. His area of concentration is aeronautics. He is a member of both Tau Beta Pi Engineering Honor Society and Pi Tau Sigma Mechanical Engineering Society. He also participates in Seminole Sound and is a former member of the FSU Marching Chiefs.

Justin Broomall – Secretary:

Justin is a FSU student from a small town in central Florida named St. Cloud. Growing up just sixty miles from the Kennedy space center, his childhood was filled with dreams of the final frontier. This drove him to pursue a mechanical engineering degree with a specialization in aeronautics.

Caitlan Scheanwald – Media:

Caitlan is a FSU student originally from Richmond, Va. She specializes in control systems and various programming languages. She plans to take her FE exam prior to graduation and pursue PE and PMP certifications. Currently, she works for the Department of Economic Opportunity as a project manager in software development.

Sponsor:

Dr. Michael J. Sytsma:

Dr. Michael J. Sytsma was born on March 15th 1982 in Homestead, Florida. He received his Bachelor's degree (2004) in Aerospace Engineering with a Business minor from the University of Florida. Michael continued on to receive his Masters of Science in Aerospace Engineering from UF in 2006 studying Micro Air Vehicles. He began work at the Air Force SEEK EAGLE Office in 2006 as a loads engineer, and moved to the Air Force Research Laboratory in 2009 as a research scientist.