Design for Manufacturing, Reliability and Economics

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

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ABSTRACT

During the design process of the subsonic articulating robotic arm the ergonomics of assembly and operations were kept in mind. By constructing the mechanism out of detachable plates, the prototype could easily have its inner components placed and aligned before the structure was closed. This kept the machining and assembly times to a minimum due to the simplicity. By selecting thicker materials for the housing the mechanism has very little chance of having a structural failure in this area. The only portion of the design that has the possibility of any deformation is the sting. Based on FEA presented, the deformation is well within 0.25" maximum set by the standard. The system will have a lifetime that will allow it to be used for years. Gears will last for 10^5, this combined with the low revolution count for operation the mechanism will not fail with routine lubrication. Finally, the prototype produced was well within the allotted budget of $2,000, having a total price of $1,316. Even when the cost is adjusted to incorporate the price of donated materials, the prototype is less than 5% of the price of similar devices.

ACKNOWLEDGMENTS

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 Bachelors 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.

Recognition

Team 12 would like to recognized sponsor Dr. Michael Sytsma and Dr. Kumar for 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 he design process. Team 12 would also like to recognize the teacher Dr. Gupta for continued guidance throughout the semester.

1. Introduction

With the removal of the model mounting mechanism at the Air force Research Lab senior design group 12 was given the task of producing a replacement. The articulating robotic arm must be able to withstand and operate in the 22 m/s flows produced by the low speed wind tunnel where it will be utilized. As the arm manipulates the held models through pitch and yaw ranges respectively, the center of mass of the models must be maintained to receive meaningful data during testing. Throughout the manipulation process the mechanism needs to be able to control its position reliably, whether in motion or holding the model still. With the mechanism being robotic in nature the researchers would be able to control it remotely through a simple and easy to use user interface. The report will describe the manufacturing process, reliability, and budgeting.

2. Design for Manufacturing

1.1.0 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.

1.1.1Bearings 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 views of the bearings can be found in appendix B.

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 view of the roller assemblies can be found in appendix B.

1.1.2 Support assembly

With the bearings pressed and the rollers pieced together the main support structure can be assembled. 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. A more detailed view on the bottom support assembly can be found in appendix B.

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. More detail on the components of the top support assembly can be found in appendix B.

1.1.3 Complete Assembly

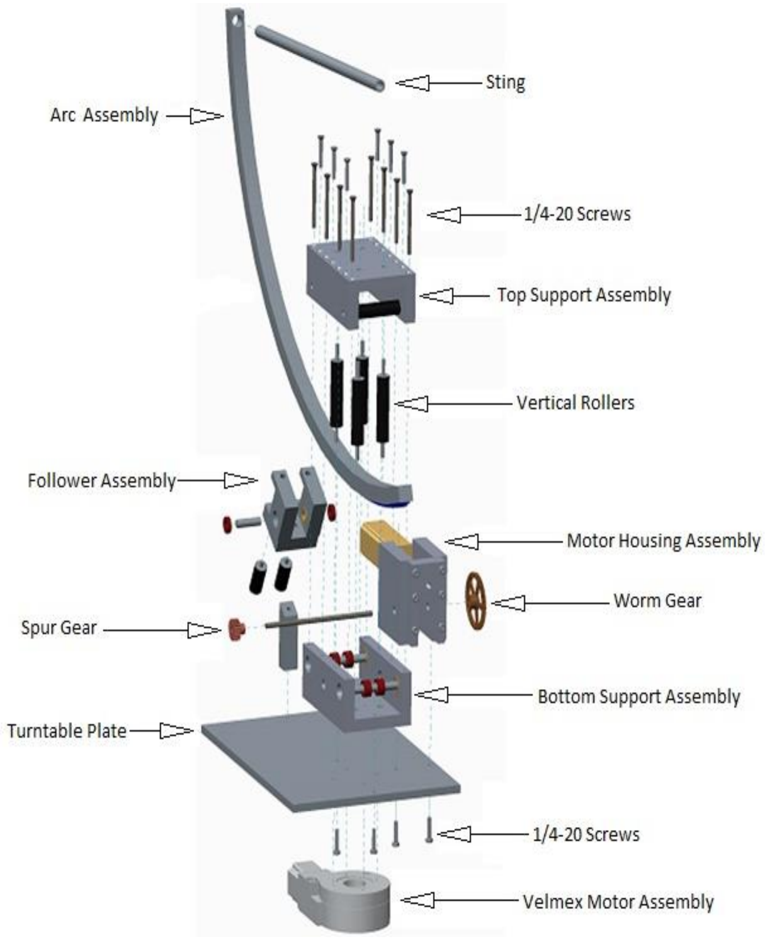

Figure 1: Exploded View of assembly

An overall assembly can be seen in figure 1. 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 support. More information on the follower assembly can be found in appendix B.

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. More detail on the Motor housing assembly can be found in appendix B.

The arc assembly consists of three main components, the arc semicircle, the gear rack, and the sting shaft. The gear rack must be glued to the convex side of the arc with a strong epoxy and allowed twenty-four hours to cure for strength. The gear rack must be positioned so that the geared section will run from the opposite end of the milled hole, to half way up the arc. It must also be positioned directly in line with the center of the arc. There should be a quarter inch of arc remaining on either side of the gear rack once it is positioned. Once the epoxy has cured, the sting can fitted inside of the milled end, and secured with set screws. Set screws on each side help to ensure the sting is securely fastened. A detailed view of this assembly can be found in appendix B.

The turntable is the plate that will constrain all of the sub-assemblies. The first components that will attach to the turn table is the already complete Velmex stepper motor assembly, and the bottom support assembly. The Velmex assembly bolts into place with four 10-25 screws that run through the bottom support, through the turntable plate, and into the stepper motor assembly. Placement is simple as there are only four holes in the plate where the screws will align. Ensure that the plate is facing forward and the rotor is set to zero, as this will align the plate and the stepper motor assembly. Two additional 1/4-20 screws will attach the plate to the bottom support structure. With the stepper motor assembly, and the bottom housing bolted to the table, the motor housing assembly can be mounted to the plate. Using the included metal spacers, place the assembly on top of the spacer with the front plate toward the front of the turntable plate. Use the 1/4-20 screws to secure the motor housing assembly in place.

Lastly the follower support assembly can be secured to the 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 assembly can be seen in appendix B.

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 B.

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.

With the vertical rollers in place, slide the top support assembly over the roller shafts. The rollers will have to be aligned to the top support bearings by hand. Once the assembly is on top of the bottom support structure, thread the four inch 1/4-20 bolts into place. Do not tighten the bolts, only turn them in enough to hold the assembly on the bottom assembly. The support should be able to go up and down.

With the top assembly loosely in place, take the arc section and begin to feed the bottom leading end through the support structure rollers. When the gear rack hits the spur gear the arc may stop, if this happens lift the arc until the teeth disengage, and continue feeding the arc through until the arc is seated on both lower rollers, and the follower.

With the arc in place, begin to tighten the four inch screws. Alternate sides and only tighten to finger tight, as the rubber rollers can crush if too much torque is applied. Tightening the screws completes the mechanical assembly of the arc system. The complete set of drawings for this assembly can be found in appendix E.

1.1.4 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.

1.1.5Design 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.

3. Design for Reliability

3.1.0 Main Reliability Concerns

This assembly, although built on several factors of safety, has a few areas of high concentrated stresses. These areas include the sting that mounts the test specimen, the arc-track connection and spur gear teeth. Also, because plastic spur gears were used, life-cycle analysis had to be completed on them. Because the maximum overall forces seen over will be approximately 15 lb*f, the steel worm set, the steel rods, and bearings will not be concerning since they are rated for much greater loads.

3.1.1 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 lb*f 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 2. The deflection chart is shown in figure 3. The maximum

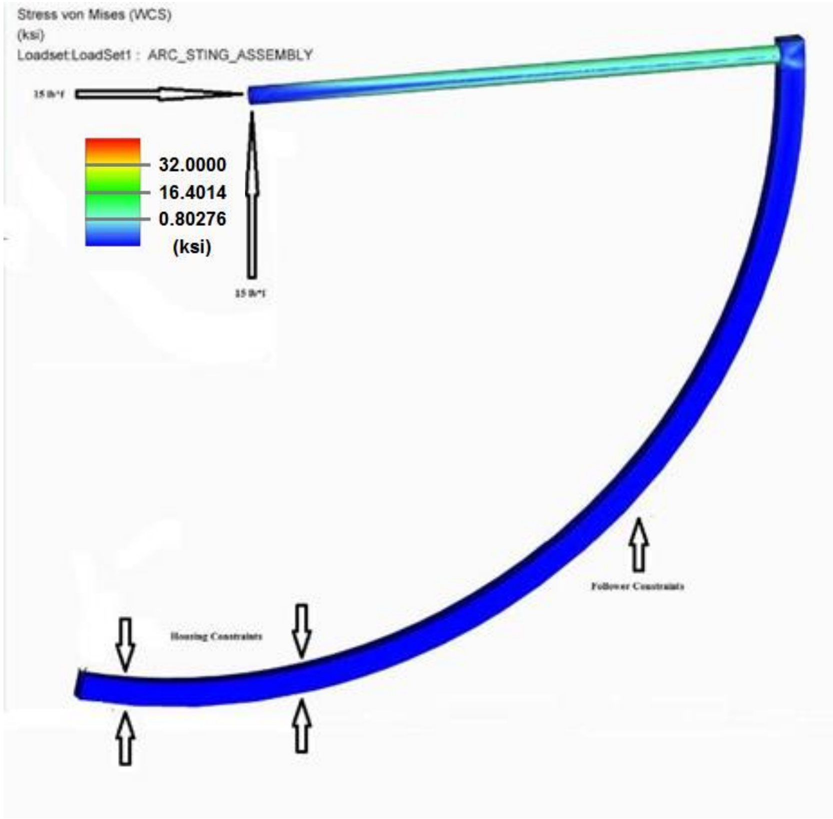

Figure 2: FEA on arc-sting assembly

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.

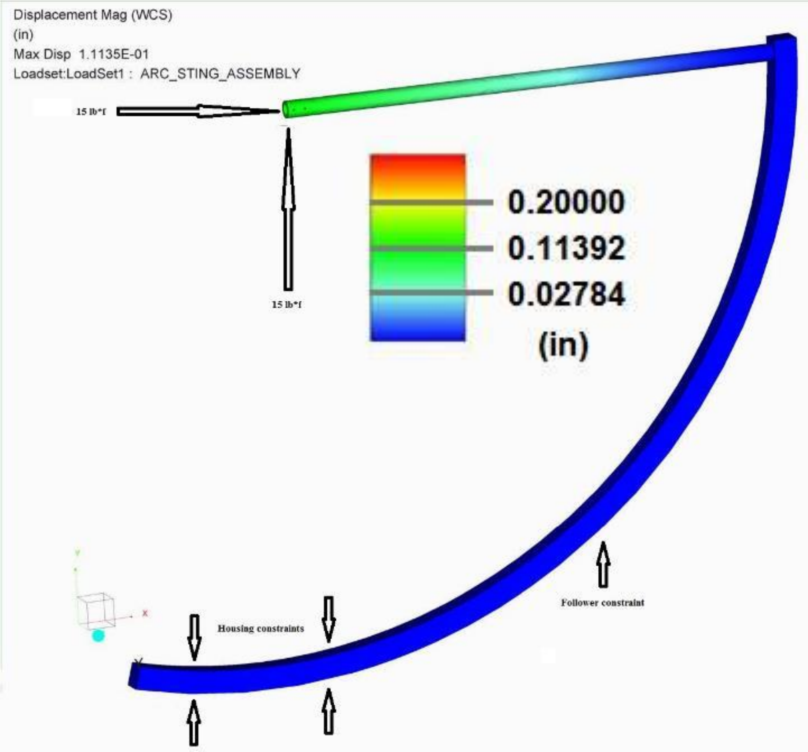

Figure 3: Displacement analysis on arc-sting design

3.2.0 Life- Cycle Analysis

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 xx.

3.1.2 Spur Gears

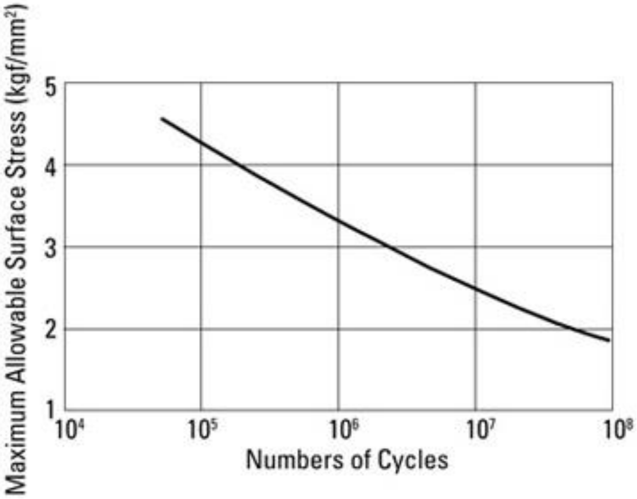

Figure 4: Life cycle based on surface stress

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 xx. 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 4.

3.1.3 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 xx.

3.1.4 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 A. 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. 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 5. 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 6 shows the breakdown of the entire budget.

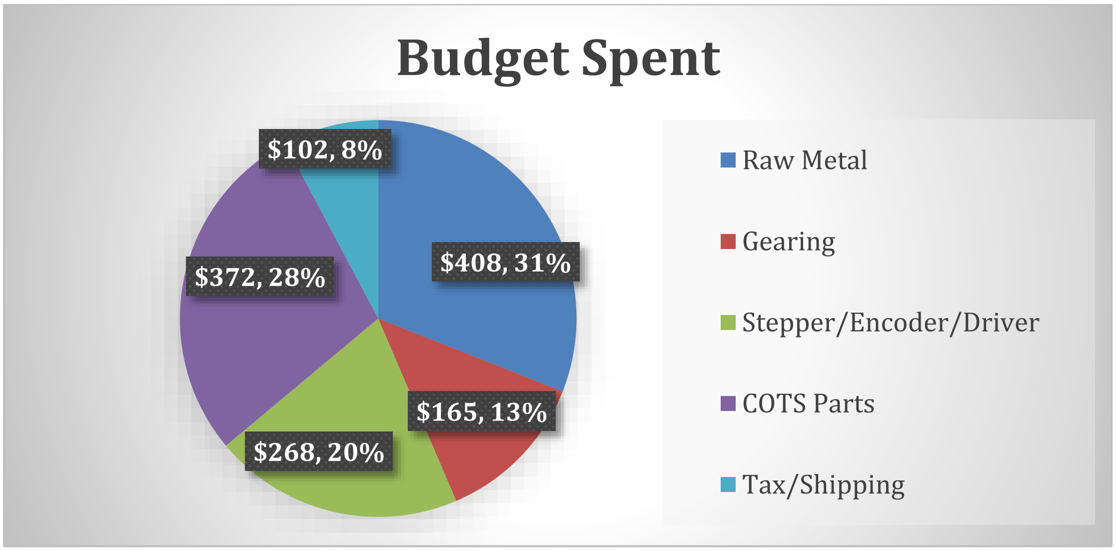

Figure 5: Budget Analysis based on budget spent

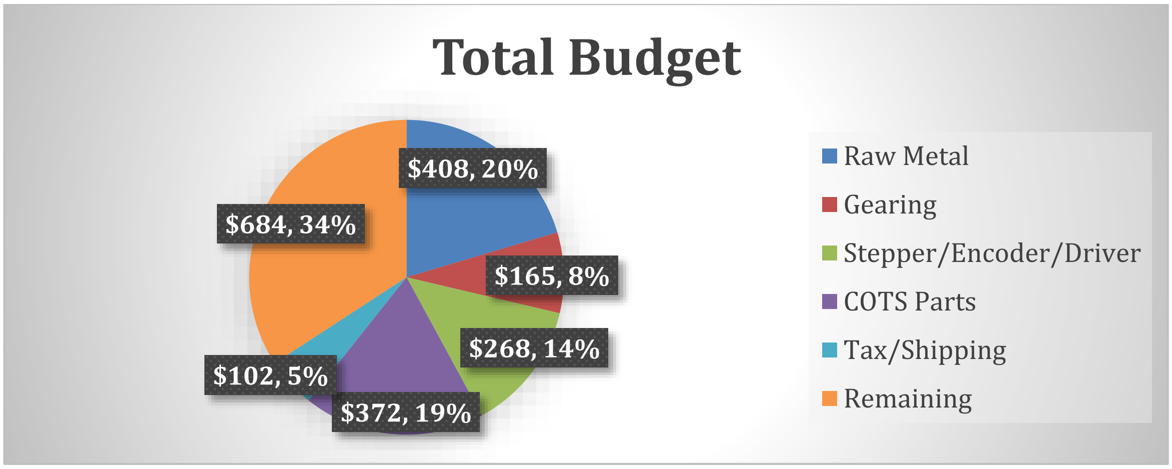

Figure 6: Budget Analysis based on total budget

Comparing the mounting system produced for the design project to market products is complicated. Figure 7 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 D shows all purchase orders made for this project.

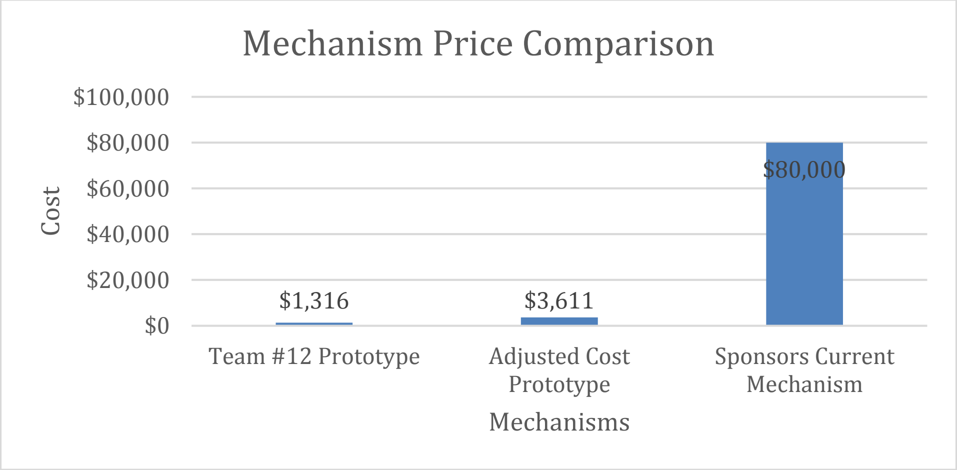

Figure 7: Price Comparison for prototype

References

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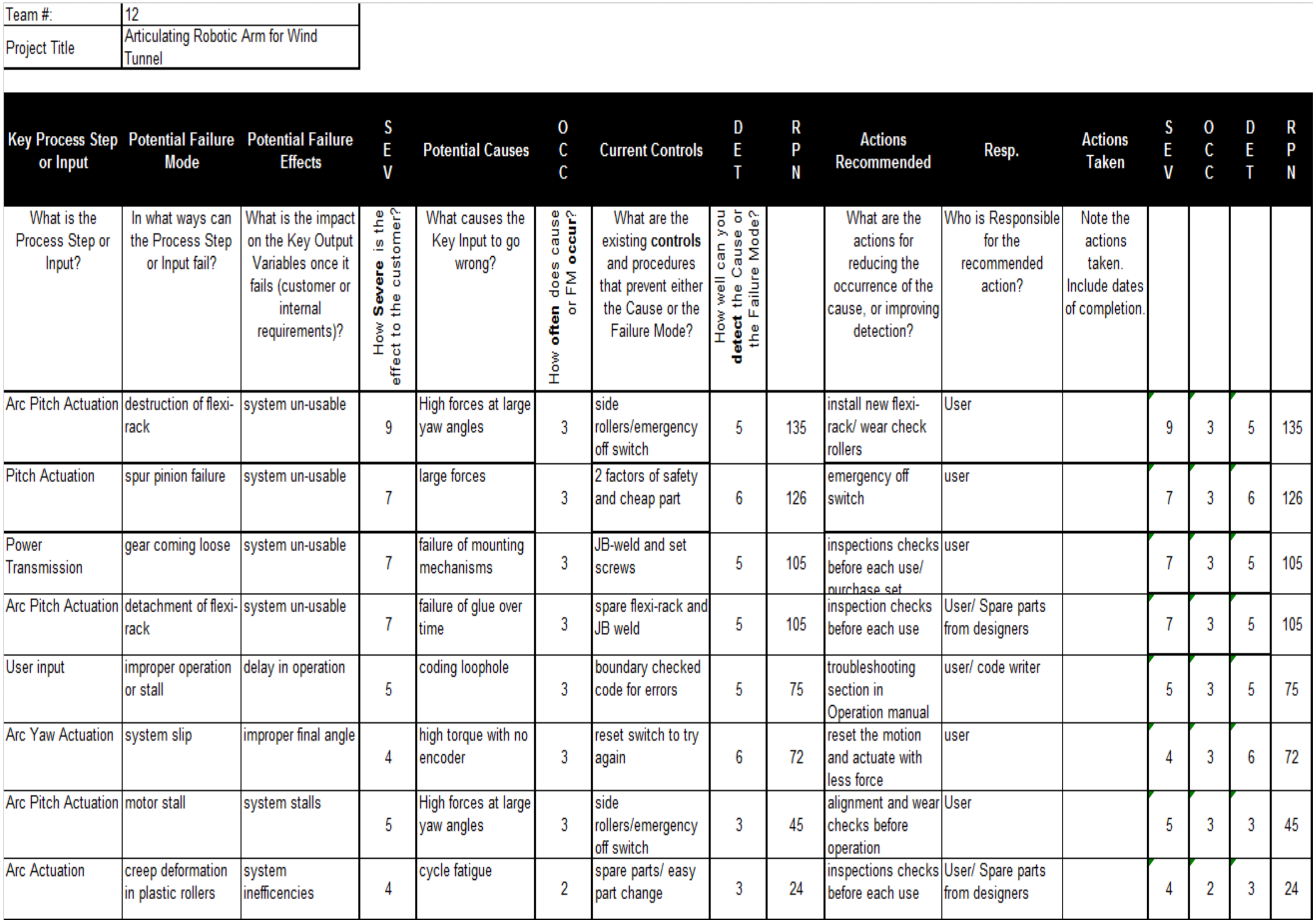
[2] R. Kumar. Modeling of skid-steered wheeled robotic vehicles on sloped terrains. In Proceedings of the ASME Dynamic Systems and Control Conference, pages 91–99, 2012.

Appendix A- FMEA

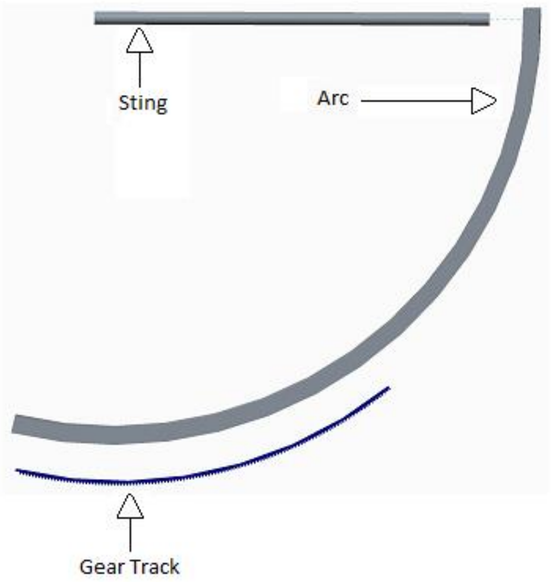


Team #:	12
Project Title	Articulating Robotic Arm for Wind Tunnel

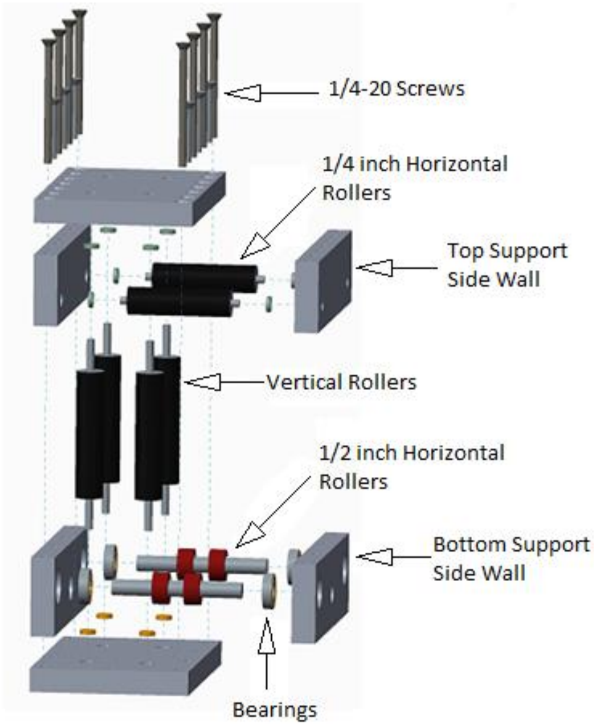
Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.	Actions Taken	SEV	OCC	DET	RPN
What is the Process Step or Input?	In what ways can the Process Step or Input fail?	What is the impact on the Key Output 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

Appendix B- Product Assembly

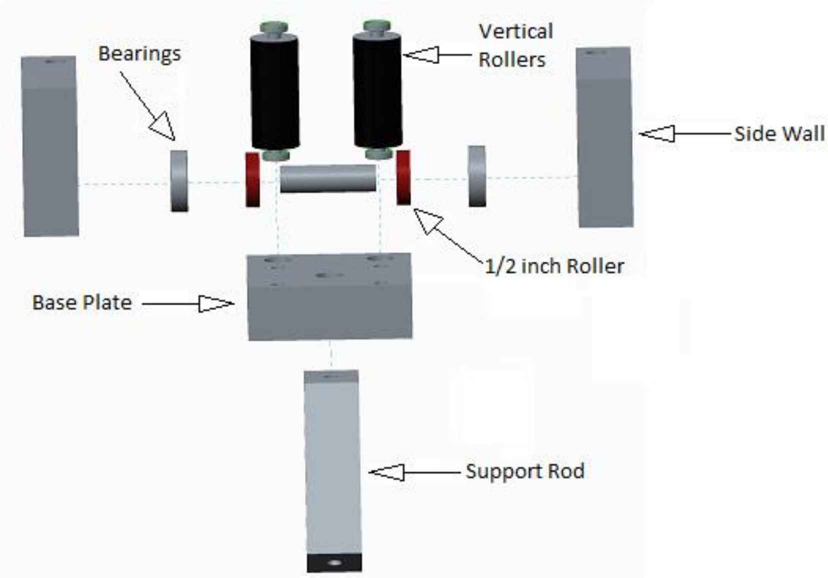
Arc-Sting Assembly



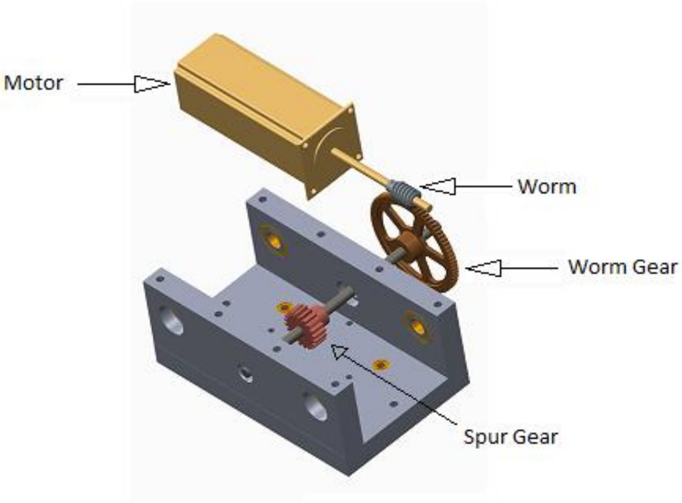
Housing Assembly



Follower Assembly



Drive Train Assembly



Appendix C- Calculations

Appendix D- Purchase Orders

Appendix E- Drawings