

3-Axis Automated Probe Traverse for Aerodynamic Testing

Final Design Report



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Statement of Disclaimer

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Chapter 1 | Introduction

1.1 | Sponsor Background

The Fluids Laboratory for Interdisciplinary Projects (FLIP) is a team at Cal Poly that is upgrading the features of Cal Poly's low-speed wind tunnel. The project is headed by Dr. Graham Doig, who is a faculty member of Cal Poly's Aerospace Department. The purpose of the wind tunnel rebuild is to integrate a moving ground, cooling and vacuum fans, a force balance, and a more accurate automated measurement system into the tunnel. Multiple senior project teams have worked on various wind tunnel upgrades. Our senior project focuses on replacing the tunnel's present traverse system with a more streamlined and automated device.

Cal Poly's low speed wind tunnel is a very important feature at the school. It is used regularly by the students and faculty of the Cal Poly Aerospace department. It is also used by various student clubs and organizations at Cal Poly, such as the Formula Society of Automotive Engineers, Supermileage, Human Powered Vehicle, and Prototype Vehicle Laboratory. In addition, companies in the San Luis Obispo area sometimes desire to test and validate their products in the wind tunnel.

1.2 | Sponsor Needs and Problem Definition

In an initial meeting, Dr. Graham Doig informed us about the features and requirements that he wants to see implemented for this project. Our sponsor's most important need is that the traverse minimally disturbs the flow inside the tunnel's test section. If the airflow is greatly disturbed from the measuring equipment, then the measurements themselves are not useful. Another need our sponsor stressed is that the probe movement should be automated, and controlled with a simple-to-use interface. He desires this feature because individuals with varying experience levels need to use the wind tunnel, and simple automation allows novice users to control the wind tunnel with little help. Taking these two imperative needs, and the other feedback from our sponsor, we compiled the problem statement shown below. This problem statement gives the overall goals for this project. These goals will be further discussed and quantified in later sections of this document.

Problem Statement

Our primary objective is to design, build, and test an automated traverse to hold measurement probes in Cal Poly's low speed wind tunnel. The device should cause minimal flow disturbance. It's movements must be able to cover eighty percent of the three-dimensional test section. The device should have a mounting point for interchangeable probes. The assembly is to be integrated with the current frame structure on the wind tunnel test section, and should allow very minimal deflection of the measurement probe. The user should be able to control the motion of the traverse via a computer interface which supports automatic data collection. The cost of this project must remain under two-thousand dollars.

1.3 | Specification Development

After our initial meeting with Dr. Doig, we used his information to create the problem statement outlined in Section 1.2. Another meeting was then arranged with Dr. Doig where we discussed our problem statement and the relative importance of the tasks it outlines. We used the feedback from our second meeting to determine which project goals are absolutely necessary and which ones may be overlooked if there is not time for them to be properly addressed.

To allow for better understanding of the project goals and their relationships with each other, our sponsor's feedback was placed into a Quality Function Deployment (QFD) chart (Appendix A). QFD is a chart in which a design team can see the relationship between a customer's desires and the functional requirements of the design. This chart helps designers notice what requirements are most important, and if they are related to each other in a positive or negative way. Knowing how the requirements and specifications are related allows the designer to create a balanced design which has an advantage over their competitors.

The meetings with our sponsor allowed us to complete the "customer requirements" section of the QFD chart. We then developed engineering specifications to explain how we would meet our sponsor's requirements. The engineering specifications are parameters that can be physically measured, which allows us to confirm whether we have met them once a functioning prototype is built. The engineering specifications our team formulated are summarized in Table 1 below. In the paragraphs below, we use our problem statement and QFD chart to categorize whether our customer's requirements are absolutely necessary (primary goals) or should be attempted only if the primary objectives are completed (secondary goals).

Spec #	Parameter Description	Requirement/Target	Risk	Compliance
1	Probe deflection	< 1 mm @ 125 mph wind	H	A, T
2	Flow disturbance	< 5 psi pressure drop over probe arm @ 125 mph wind	H	A, T
3	Holds variety of probe sizes	1/8" to 5/16" diameter, interchange within 5 minutes	L	T
4	3D probe coverage of test section	188x69x93cm coverage	M	T
5	Automated resolution input	Input gives expected output	M	T
6	Repeatability in probe positioning	Position probe within 2mm of desired location	H	T
7	Integrated controls	System controlled from single display	H	I
8	Internal routing cavity	40mm diameter to allow for significant tubing	M	I
9	Integrates into existing structure	standardized attachments and dimensions	L	I
* (A) Analysis, (T) Test, (S) Similarity to Existing Designs, (I) Inspection				

Table 1. Engineering Specifications

In Table 1, the engineering specifications for this project are summarized with their quantitative target values. These target values provide our team with engineering standards to use when we test our final design. The type of testing that will take place to validate our final design is also noted. Analysis (A) involves engineering calculations based off relevant theory to prove the design is sufficient. Test (T) implies physically measuring parameters of the final system to insure requirements are met. Similarity to Existing Designs (S) implies that our design is so similar to an existing design validated design that no additional validation is needed. Lastly, we may validate certain features by Inspection (I), which implies that validation can be obtained by mere examination of the design aspect. The risk of each requirement in Table 1 is categorized as high (H), medium (M), or low (L). These risks are judged based on how difficult we anticipate the requirements will be to meet. Our highest-risk parameters are probe deflection, flow disturbance, repeatability, space calibration, and integrated controls. Note that risk only stresses the difficulty of a parameter, but not the importance of successfully completing that parameter.

The process of creating a QFD chart has shown us that our primary objectives need to be obtaining accurate airflow measurements, covering eight percent of the test section, and allowing for automated motion of various probe sizes. Our sponsor holds these objectives to be very important, and the lack of them in the current traverse system is the primary reason for its replacement. Note that obtaining accurate flow measurements has many specifications associated with it. These specifications include limiting probe deflection, minimizing flow disturbance, and repeatability in probe positioning.

In addition to the goals previously listed, this project has some secondary objectives. Completion is not required for these secondary objectives, although we will make an effort to fulfill as many of them as

we can in our timeframe. One such objective is that probe control and data collection is completely automated, and accomplished from a single user interface. Another secondary objective is that the budget be kept under fifteen-hundred dollars, although with Dr. Doig's permission we may use up to twenty-five-hundred dollars. To keep costs low, it is preferred that we use the motors from the wind tunnel's previous measurement mechanism. It is also suggested that if there are alternative motors or components that are out of the budget range, a plan for future integration of the part/component can be made to improve the performance of the machine.

1.4 | Team Member Introductions

Zander Oostman:

I am a mechanical engineering student at Cal Poly. I am currently involved with the Cal Poly Supermileage club, which competes each year in a competition to design and build a fuel-efficient vehicle. My academic interests include fluid mechanics, heat transfer, and thermodynamics.

Tananant (Mel) Boonya-ananta

I am a fourth year Mechanical Engineering student from Bangkok, Thailand. I have previous work experience in areas of R&D mechanical tooling and semi-automated manufacturing machines. I am interested in pursuing a career involving mechanical controls systems/mechatronics and biomedical instruments. I have moved around throughout world while growing up and have always been amazed at the difference in technology in areas of the world. I aspire to work in Antarctica.

Ricky Wai:

I am from Los Angeles, CA and am studying Mechanical Engineering. I have been involved with Formula Society of Automotive Engineering (SAE) and enjoy design and analysis of systems. My interest in this project lies in the fact that this will be a useful tool for future teams to build faster racecars. I have had lots of time in the machine shops machining parts, so I am big on design for manufacturing. In my free time I enjoy mountain biking and eating Thai food with friends.

Teyvon Brooks:

I am a fourth year Mechanical Engineering major from Paso Robles, California. I have experience in mechatronics and robotic design which leads to my interest in control system analysis, design, research & development in alternative robotic techniques and sensors. My goal in the future is to get involved in automated space exploration and work to develop the next generation of state of the art commercial technology.

Chapter 2 | Project Management

2.1 | Method of Approach

Our first step for this project was to familiarize ourselves with Cal Poly's wind tunnel and the requirements for our project. To do this, we met with our sponsor to learn more about our project and his expectations. After this meeting, we were able to construct a table of customer requirements and specifications for our project, which can be found in Table 1 in Section 1.3 of this report. With a table of design requirements and target values, we then started the conceptualization process. Once a variety of concepts had been presented, we filtered through each of them, validating the merits and functionality of the design. Concept selection was made into a quantitative process by creating matrices and tables to numerically compare our various concepts. For a full description of the concept selection process, please see Chapter 3.

Once a concept was selected and approved by our sponsor, we began the analytical phase of the design process. This consisted of rigorous analysis of all the critical components to ensure all of our components perform up to the requirements outlined by our sponsor. With a completed detail design, we are ready to begin manufacturing and testing our design once it is approved by our sponsor.

Figure 1 is a color-coded flowchart of the design process outlined above. The blue boxes indicate different stages of the design process that primarily involve the members of our team. The square boxes that are orange indicate deliverables for our senior project course. The orange rounded blocks indicate the senior project expos that occur during the course of our project. Green boxes indicate essential sponsor interactions which may require approval or evaluation of our concepts. Lastly, the red stars on the chart indicate the end of each academic quarter.

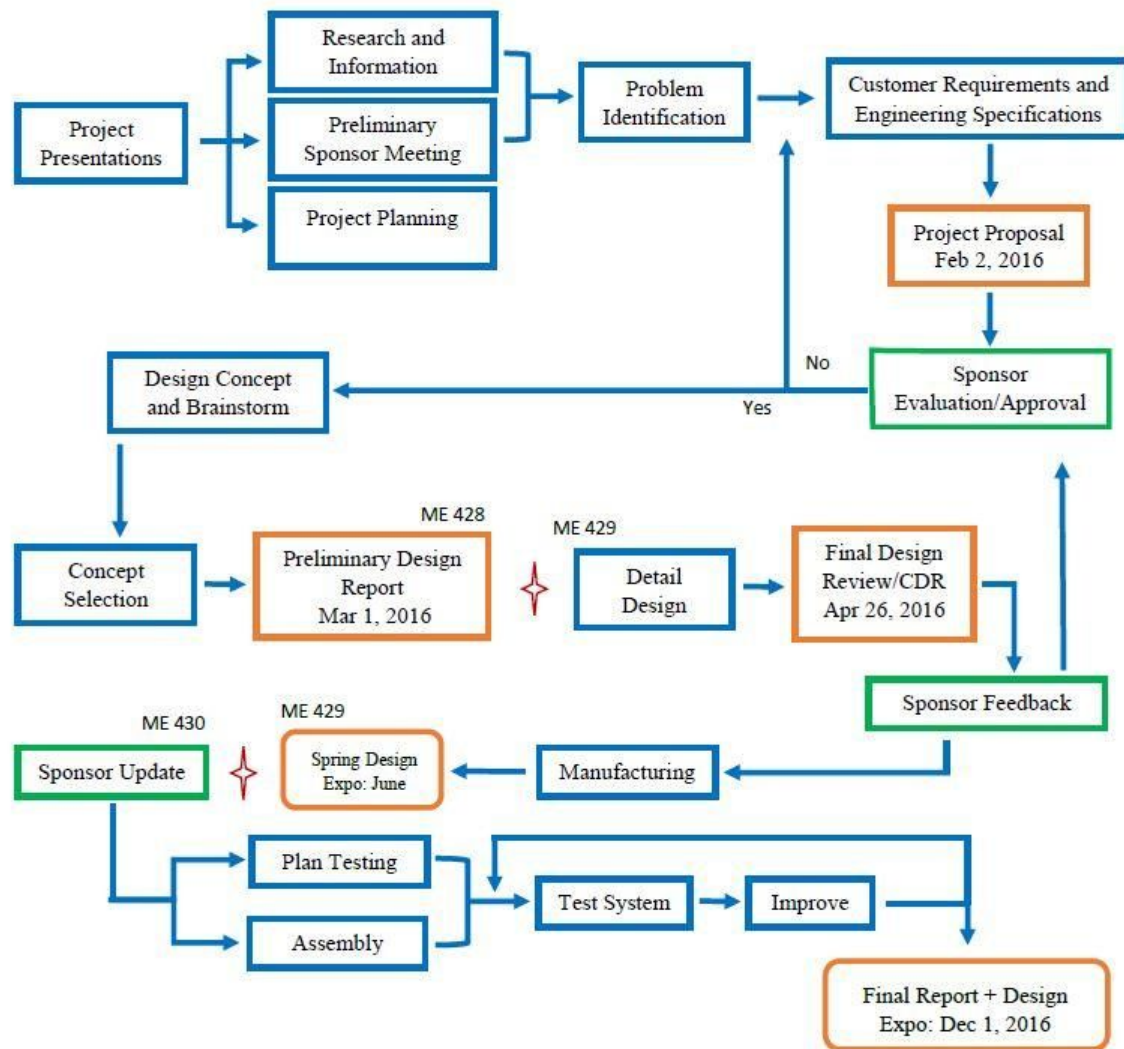


Figure 1. Detailed design process flowchart from Winter 2016 to Fall 2016.

2.2 | Milestones/Schedule

In order to outline our ideal project schedule, we have a Gantt chart each academic quarter of this project. These charts are shown in Figures 2, 3, and 4. Each chart outlines what tasks are to be completed and the corresponding due dates. This gives us a concrete timeline for each process outlined in our flowchart.

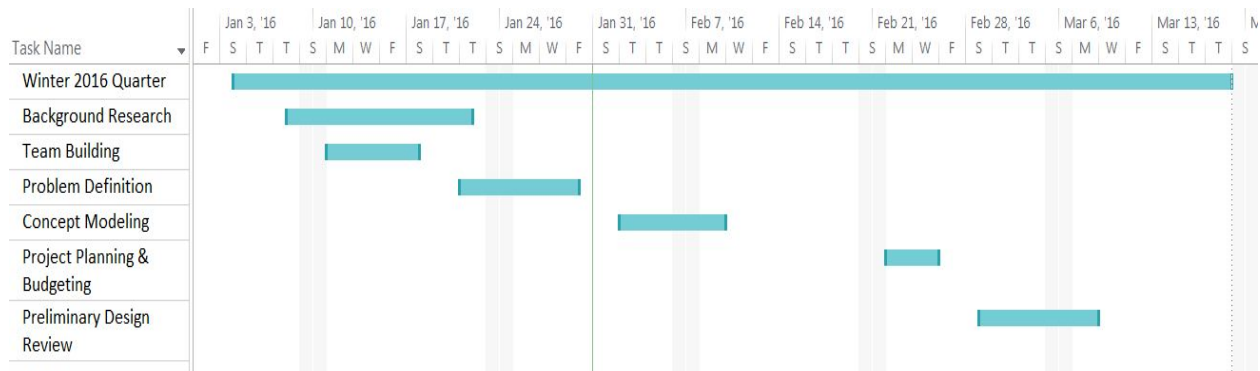


Figure 2. Gantt Chart for Winter Quarter

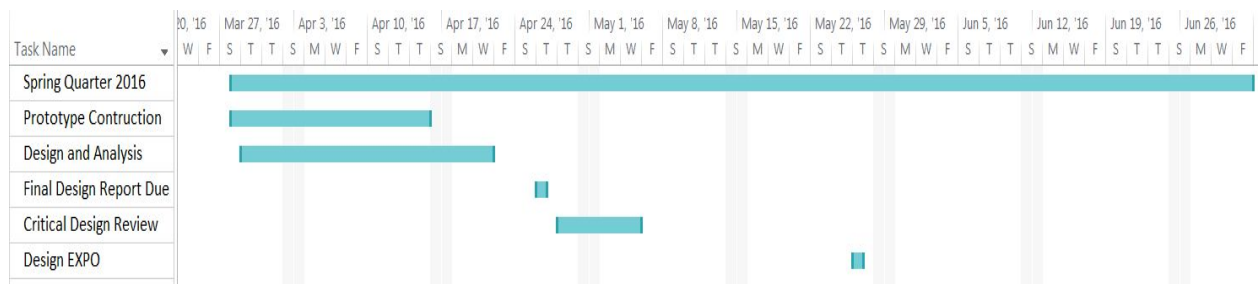


Figure 3. Gantt Chart for Spring Quarter

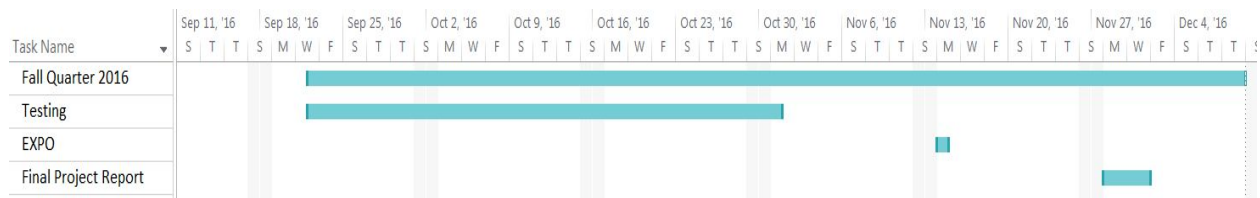


Figure 4. Gantt Chart for Fall Quarter

2.3 | Management Plan

The following management plan identifies which team member will have the primary responsibility for our various project tasks:

Communications Officer - Mel Boonya-ananta

- a. Be the main point of communication with sponsor and consultants

Team Treasurer - Zander Oostman

- a. Maintain team's travel budget
- b. Maintain team's materials budget (in 2nd quarter)
- c. Works with Manufacturing Lead

Secretary/Recorder - Ricky Wai

- a. Maintain information repository for team (team binder, Google Docs site)
- b. Records meeting minutes during meetings with sponsor and adviser
- c. Ensure weekly meeting agendas are completed before meeting with adviser

Design/CAD Managers - Mel Boonya-ananta and Zander Oostman

- a. Ensures team meets design goals and specifications
- b. Keep track of revisions and conflicting copies
- c. Responsible for design testing plans
- d. Analyze designs

Manufacturing Lead - Ricky Wai and Teyvon Brooks

- a. Makes sure the team is designing for manufacturing
- b. Makes sure manufacturing Gantt chart is up to date
- c. Communicates with parts vendors
- d. Responsible for prototype fabrication

Software Integration Lead - Teyvon Brooks

- a. Controls and integration with hardware
- b. Programming and controller design

2.4 | Pert Chart

A Pert chart is a tool used to outline the management path of a project. Our Pert chart, seen in Figure 5, is a flow diagram depicting the general path of our project and dependencies between each project process.

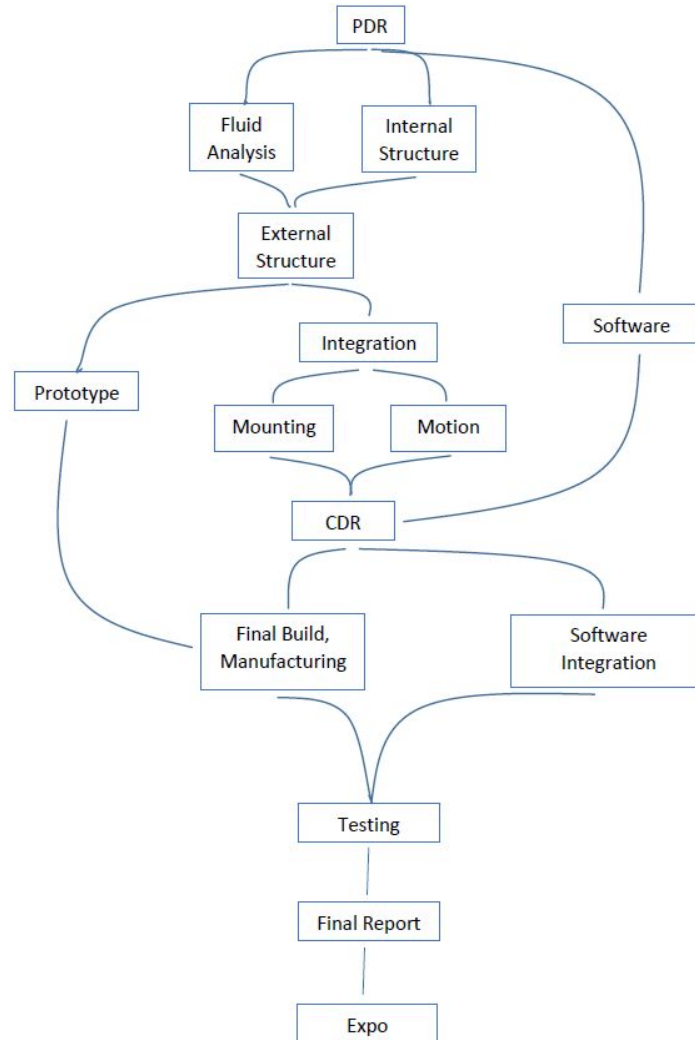


Figure 5. Pert Flow Diagram

At the top of our Pert chart is a Preliminary Design Review (PDR). For this milestone, a final concept needs to be selected using a quantitative approach. A written report and a presentation of the team's progression is needed for the PDR stage. Once the PDR process is complete, the team then starts the analysis phase, which is split into 3 designated sections. One section is the fluid flow analysis, which entails evaluating the interactions between the design and the flow inside the wind tunnel. The second section is internal structures, which involves the movement mechanisms and their supports. Device software is the third section, and it involves configuration of the motors and the computer software used to control them and any other parts of the wind tunnel.

Once the fluid analysis and internal structure designs are complete, the focus shifts to external structures, which deals with components that are exposed to the airflow. From this point, the process branches off into prototyping and integration. Integration involves designs to mount the device to the outside of the test section and to control the motion of the device. The next step in the Pert chart brings the mechanical analysis and software design together for the Critical Design Review (CDR), which is presented to our sponsor. CDR involves presenting our final design with detailed part designs, materials, and dimensions. Once the CDR is complete, the building and manufacturing steps commence, as well software integration and implementation. Once assembled, the final design will undergo testing for improvements and performance. After testing, the final report will be compiled and presented at the fall senior project expo.

Chapter 3 | Background

This chapter addresses the research and background that is most relevant to our final design. For additional research on possible solutions and patents relating to our project, please see Appendix H.

3.1 | General Background

Wind Tunnels

Wind tunnels are used to experimentally measure the characteristics and behaviors of airflow across an object of interest. Unless an object has very simple geometry, it is almost impossible to analytically determine the airflow characteristics around the object. With computers, engineers can numerically solve for flow fields around complex geometries. However, this numerical method is an approximation and designers who use computer flow analysis often certify their results in a wind tunnel test. Knowledge of an object's flow disturbance patterns is important because it allows an engineer to optimize their designs. For example, an automobile travelling at a high speed experiences a great drag force from the air around it. An engineer can use scale models of the automobile in a wind tunnel to simulate the air drag force, and experiment with designs that can reduce drag.

A computer rendering of the low-speed wind tunnel operated by Cal Poly is shown in Figure 6. This wind tunnel is powered by a fan which is capable of pulling air through the test section at speeds up to one-hundred-and-twenty-five miles per hour. Due to the fact that the tunnel's maximum air speed is less than the speed of sound, this wind tunnel is considered to be "low-speed". The test section has a cross-sectional area of four feet by three feet, and is six feet long. A rolling road has recently been added to the test section of this wind tunnel. The rolling road is a large belt which acts as the floor of the wind tunnel. When a model vehicle is placed into the tunnel, the belt is rotated, thus allowing the vehicle's wheels to rotate. This simulates the air resistance on a vehicle driving, and allows for a more accurate representation of the airflow characteristics between the vehicle and the ground.

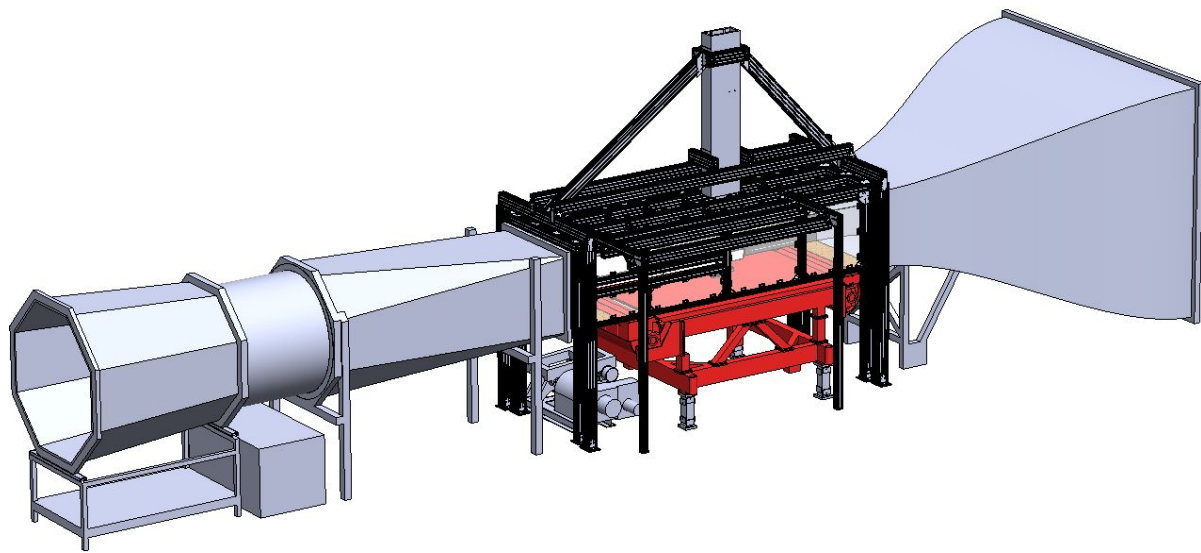


Figure 6. Rendering of the Cal Poly wind tunnel. The structure in black is the frame for the test section, and it encloses the rolling road mechanism shown in red to simulate a rolling vehicle.

Flow Measurement Techniques

There are many different techniques to determine the flow field around an object in a wind tunnel. Some of these techniques include using laser imaging, smoke generators, and pressure probes. This design project focuses on providing a traverse system that moves pressure probes to various locations of interest behind a test object. Taking air pressure readings at many different locations behind the test object allows one to map out the velocity and pressure fields of the air. To obtain accurate pressure field data, the probe's location relative to the test object must be known with a large degree of accuracy. Locational accuracy is important because often times scale models are used in wind tunnels. Any uncertainty in the location of a measurement on a model will be amplified by the scale of that model. For example, consider a measurement taken on a one-third scale vehicle in a wind tunnel. If the wind tunnel probe location has an uncertainty of one inch, this will translate into an uncertainty of three inches for the pressure measurement on the life-size vehicle. This shows that location accuracy is very important for wind tunnel testing, and should be carefully addressed in this project.

3.2 | Present Solution

Motion

Currently, probes in Cal Poly's wind tunnel are supported in the test section by a large steel beam. The steel beam assembly, shown in Figure 7, is referred to as the "Sword of Excalibur". The "Sword of Excalibur" can be moved about a horizontal plane in the test section using three linear motors that are mounted on the outside of the tunnel. A photo of one of the traverse's linear motors can be seen in Figure 8. Two of these motors are connected in series perpendicular to the tunnel wall, which allows for up to four feet of movement across the width of the wind tunnel (perpendicular to the flow). The third motor is

mounted parallel to the wind tunnel wall, which allows the apparatus two feet of movement forward and back through the flow. Because the motors are outside the wind tunnel, the “Sword of Excalibur” must enter the tunnel test section through a slot (shown in Figure 9). This slot presents a design challenge, as it allows a considerable amount of air to leak out of the test section if it is not properly sealed. The current solution for sealing the slot is to place aluminum tape over it and around the stationary “Sword of Excalibur”. This solution is very inefficient timewise, as it requires manual labor to remove the tape every time the probe needs to be moved.



Figure 7. The “Sword of Excalibur.” One end is attached to the pressure probe rake and the other the ISEL linear drive motor. This setup is bulky and extremely heavy.



Figure 8. One of three ISEL LES5 Linear Drive motor units. Each have a linear travel of 24” and have T-slots in the housing for mounting onto the wind tunnel structure.



Figure 9. This photo shows the slot in the test section frame that allows for a traverse arm to enter and maneuver around to make measurements. The structure around and directly above the slot can be used for mounting motors and mechanisms for the traverse.

Flow Measurement

The primary method of flow measurement in Cal Poly's wind tunnel involves using Pitot-static probes. A Pitot-static probe is a hollow tube bent into an "L" shape. The tube measures the static and stagnation air pressures of the flow, which allows one to calculate the flow velocity at a point. Because Cal Poly's wind tunnel does not have automated vertical probe motion, a Pitot-tube "rake" configuration is used when measuring an object's flow field. An example of such a device is shown in Figure 10. This device is attached to the end of the "Sword of Excalibur" so that the air pressure at many different locations in an object's wake can be measured. This setup is difficult to stabilize (it is prone to vibrations) and has a very low resolution, as the Pitot tubes cannot be placed too close to each other. A setup where a single Pitot-tube can be moved to many different vertical locations can collect more useful data than a Pitot-tube "rake".



Figure 10. Rake of pressure probes to simulate a third axis of measurement; mounted to the “Sword of Excalibur”. The problem with this setup is that it requires long setup times and controlling deflections and vibrations is difficult at higher wind tunnel speeds.

3.3 | Relevant Products

Probe Mounting Approaches

One important consideration of our design is how to mount the probes to the traverse. Generic off-the-shelf probe mounts are not widely available. This is because diameter, length, and bend angle of Pitot-static probes vary. Dantec Dynamics currently sells a probe support for their probes, which retails at over \$500. An image of this design is shown in Figure 11. Their design is a chuck, in which you insert the probe and then tighten the chuck, as you would a drill bit in a drill press. This setup is too expensive for our scope and we will look into other designs which improve productivity and reduce cost. For this project we will be looking into a probe mounting system that allows for efficient installation of probes and is easily adaptable for the three-axis traverse.

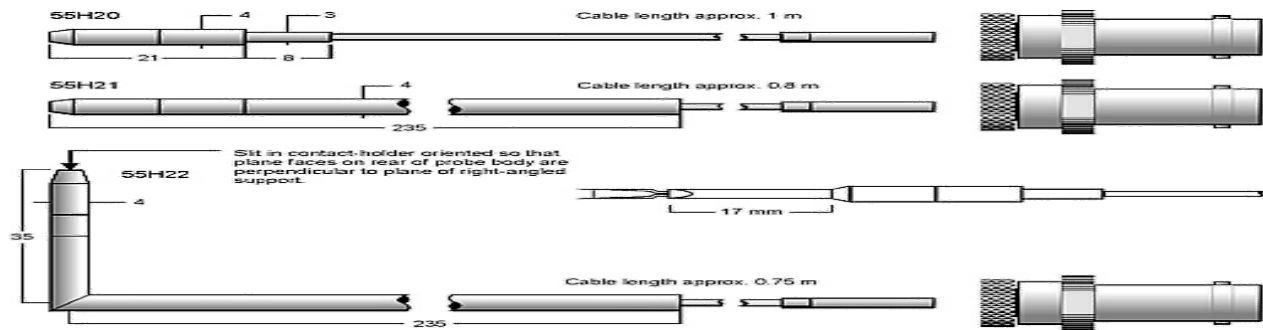


Figure 11. Dantec Dynamics Probes and Probe Supports. Their design appears to allow only a 4mm. diameter probe [3].

Alternatives to the drill-chuck style holder would be a hole and set-screw arrangement, or a collet that allows for probes of various diameters to be attached. We will also look into other approaches such as 3D printing adapters specific to the probes required for the wind tunnel tests, because there is a 3D printer readily available inside the wind tunnel lab.

Rail Traverse Systems

A rail system can be used as a reliable method of probe arm movement. Rails allow for precise and low-friction movement back and forth along a single axis. One benefit of these rails is that they can be attached onto an existing rail to provide increasing degrees of motion. This multi-axes concept is shown in Figure 12. Note that the setups in Figure 12 use linear motors to drive the motion, similar to the existing “Sword of Excalibur” setup. Although the systems in Figure 8 allow for two-dimensional motion, the concept may be extended to create a three-dimensional system of motion.

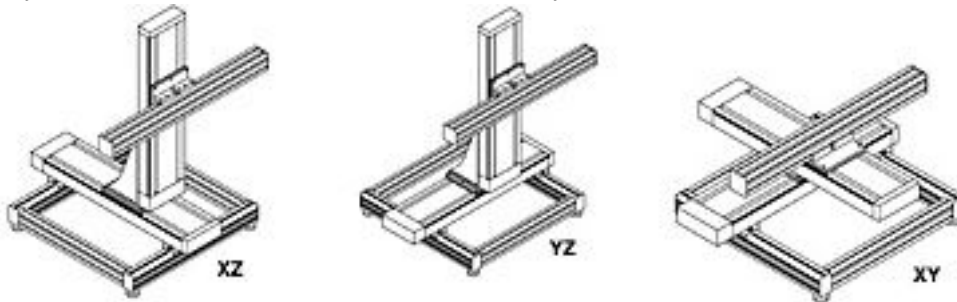


Figure 12. Directional Mounting Axes [4]

Airfoils

A well-designed airfoil will minimize the turbulent wake which forms behind an object. In low-speed wind tunnels, the turbulent wake disturbances propagate both upstream and downstream in the airflow. Upstream disturbances interfere with a probe’s measurements of a model’s pressure field, and should be avoided. The proper airfoil shape for a specific application can be found using computational fluid dynamics (CFD) software, or from building a model airfoil and testing it in a wind tunnel. Figure 13 shows an airfoil analyzed with CFD. There are many faculty members on Cal Poly’s campus who understand CFD and can help analyze airfoil shapes to find one which works for our design. In addition, the University of Illinois at Urbana-Champaign (UIUC) has a database of airfoil coordinates for different

applications. This database likely has airfoil shapes that can minimize flow disturbances for our application. An airfoil shape from the UIUC database can be tested in a wind tunnel on campus to insure it meets our requirements for minimal flow disturbance.

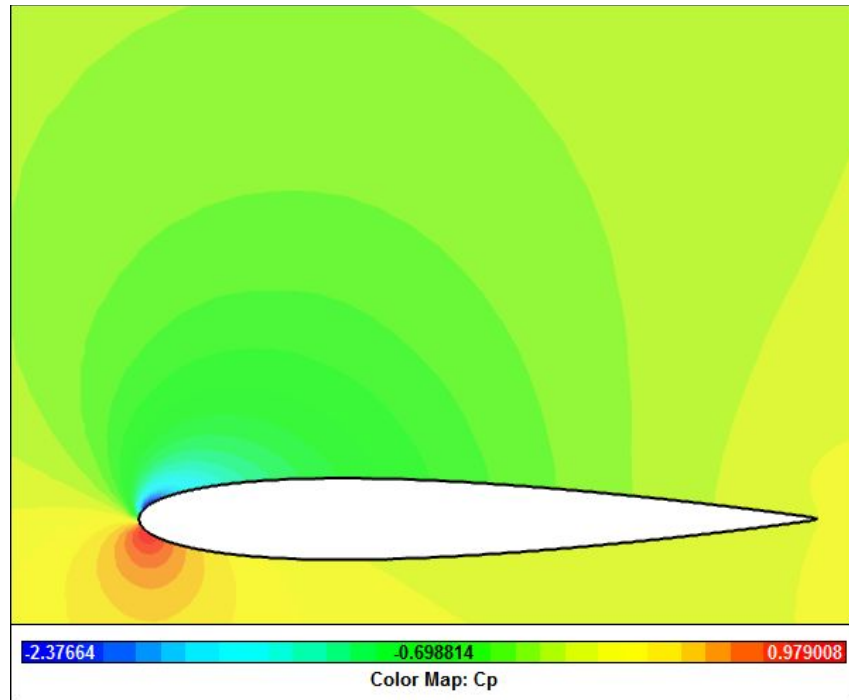


Figure 13. Computational Fluid Dynamics (CFD) used to analyze fluid flow on an airfoil shape [5].

Patents on Relevant Designs

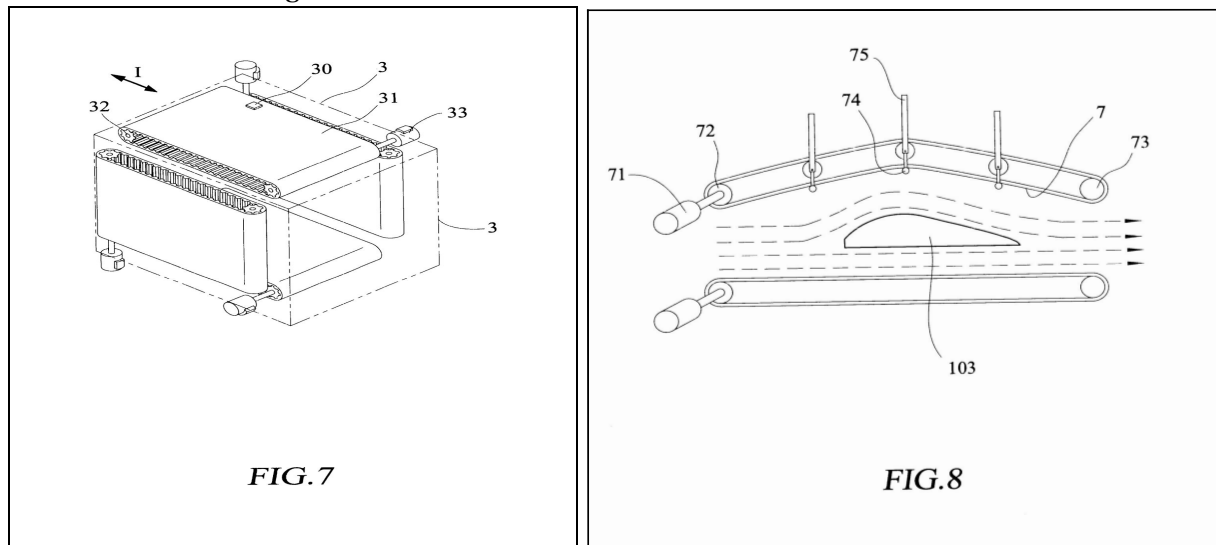


Figure 14. Wind tunnel boundary layer control concept by Industrial Technology Research Institute (Reference 6).

The design in Figure 14 involves placing a moving wall (31) in a wind tunnel. The moving wall is a large belt which is driven by a set of gears (32) attached to motors (33). It is well known that air flowing along a surface will be stagnant relative to that surface, and will then approach the free-stream fluid velocity through a velocity gradient. This velocity gradient creates a boundary layer, where the fluid properties are different from the free-stream fluid properties. The design in Figure 14 moves the walls of a wind tunnel at the same speed of the free-stream fluid velocity in the tunnel. This stops a boundary layer from developing in the wind tunnel, as there is no velocity gradient between the free-stream fluid flow and wind tunnel walls if they are moving at the same speed. This concept could possibly be used to eliminate any flow disturbances which our design concepts cause in the wind tunnel.

3.4 | Applicable Standards

After discussion with our sponsor, we have determined that there are not any applicable standards that need to be considered for this project. This is because we are mainly retrofitting an existing structure, so the majority of the components for this project are similar or identical to the design currently in place. For example, we are reusing the current design's linear motors with the same wiring scheme. Also, because our design is a one-off system for a university, and not a product meant for mass distribution, legal action resulting from misuse or failure of our design is not likely.

Chapter 4 | Design Development

4.1 | Concept Designs and Selection

Our initial design process started with using our QFD chart to create a table of important device functions. These functions dictate the categories for idea generation, and can be found in Table 2. Using the functions listed in Table 2, three different idea generation methods were used to develop concepts. These three conceptualization methods are brainstorming, brainwriting, and SCAMPER.

Device Functions								
Universal Probe Mount	High Accuracy	Mount to Frame	Minimize Deflection	80% of Test Section	Minimal Flow Disturbance	Space Calibration	Internal Routing	Feedback Collision

Table 2. Device Functions

The first conceptualization method, brainstorming, is the simplest of the three methods. This method involves the team writing as many ideas as possible that relate to the function of interest. These ideas are then documented. The second conceptualization method, brainwriting, is a more involved method of idea generation. During brainwriting each team member sketches their solutions or ideas for a specific function. After a set time has passed, each member's sketches are passed around and the next team member expands on the drawings. The last ideation method, SCAMPER, is an acronym for substitute, combine, adapt, modify/magnify, put to another use, eliminate, and reverse. This method involves looking at concepts from multiple angles or combining them to satisfy a function.

The first quantitative approach we used for design selection was a morphological chart (see Appendix B). This chart allowed us to rapidly generate many ideas for each desired function of our design. From the ideas we had on the morphological matrix chart, and additional concepts generated, we created a Go/NoGo table, as seen in Appendix C. This table allowed us to start narrowing down our concepts to ones that are possible given our resources and timeframe. After the Go/NoGo table, we combined our individual concepts for each design function into five different traverse designs. These five designs were then compared in a Pugh Matrix (see Appendix D) using the existing "Sword of Excalibur" design as a datum. This table favored our modified "Sword of Excalibur" design, with a telescoping ball-and-socket mechanism coming in second. In addition, we also compared our concepts using weighted decision matrices for minimal flow disturbance (Appendix E) and motion drives (Appendix F).

4.2 | Comparison of Best Two Designs

Our two best designs were selected through team discussions and quantitative reasoning. These two traverse design are referred to as the top mounted structure, and the modified Excalibur. An overview of each design and a comparison of the two designs is given below.

Top Mounted Design Overview

The top mounted design is sketched in Figure 15. This design has all of its components mounted on the top of the test section inside the wind tunnel. The main concept consists of a vertical airfoil in the test section that has an internal pulley system to move a test probe vertically in the test section. The top of the airfoil is attached to linear rails which allow movement perpendicular to the airflow. This movement is controlled by a rack-and-pinion system attached next to the linear rails. The entire assembly is then mounted on linear rails positioned parallel to the airflow, and located on the ceiling of the wind tunnel. Movement on these parallel rails is also controlled with a rack-and-pinion system.

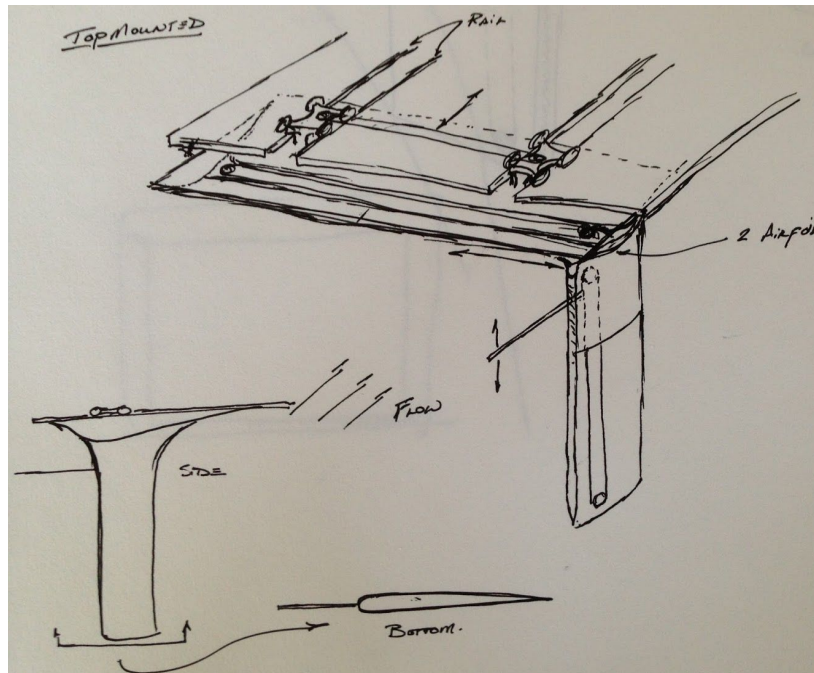


Figure 15. Top mounted traverse structure design sketch

Modified Excalibur Design Overview

The modified Excalibur design was developed using feedback from Dr. Doig (discussed in detail in Consumer Opinions below). This design is sketched in Figure 16. The modified Excalibur design is similar to the existing wind tunnel traverse in that it has a cantilever beam which is mounted to a motor system outside the wind tunnel. The beam enters the test section through a slot in its side and can be moved around the test section both perpendicular and parallel to the airflow with linear motors mounted

outside the tunnel. This modified design changes the shape of the cantilever beam to an airfoil, which limits flow disturbance. A vertical airfoil is also attached to the end of the beam. This airfoil has an internal pulley system which moves the measurement probe vertically, allowing the system to have a three-dimensional range of motion in the test section.

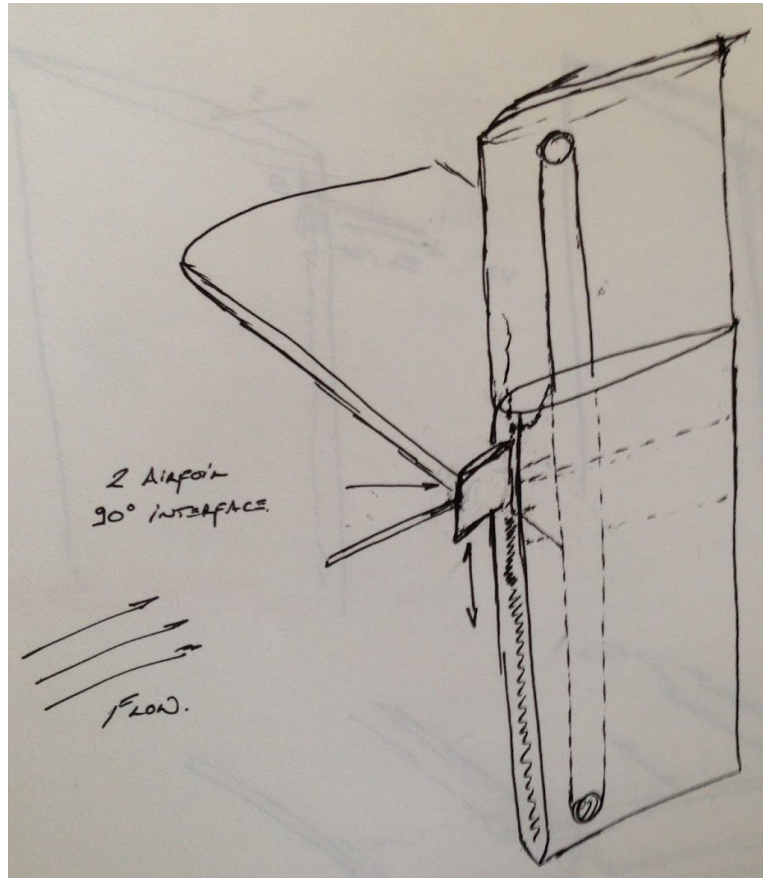


Figure 16. Modified Excalibur design

Comparison of Two Designs

A decision matrix comparing the top mounted structure, the modified Excalibur, and the current “Sword of Excalibur” is shown in Table 3. The design criteria were created from our customer’s feedback and our QFD chart. The highest weighted design criteria in Table 3 is flow disturbance. Flow disturbance is a significant issue because it directly inhibits the system’s ability to measure air properties in the test section. Two additional high-weighted criteria are accuracy and precision. These two factors involve the repeatability of the measurement, ability for the probe to repeatedly return to the same location with the same input within a given tolerance, and for the probe to read the correct measurement.

The low-weighted criteria in Table 3 include space calibration, durability, disassembly and material cost. These criterias are important, but when compared to the previously mentioned design criteria they stand on a lower scale.

Design Criteria	Material Cost	Minimize Flow Dist.	Durability	Accuracy	Precision	Space Calibration	Disassembly	User Friendly [CAL]	Overall Satisfaction
Concepts	0.05	0.25	0.075	0.15	0.2	0.125	0.05	0.1	1
Original SOE	10	3	4	2	6	2	8.5	3	4.025
Mod SOE	0.5	0.75	0.3	0.3	1.2	0.25	0.425	0.3	
Top Mount	6	5.5	6.5	7	7	7.5	5	7.5	6.55
	0.3	1.375	0.4875	1.05	1.4	0.9375	0.25	0.75	
	3	1.5	7.5	8.5	9	8	3	5	5.8125
	0.15	0.375	0.5625	1.275	1.8	1	0.15	0.5	

Table 3. Design Selection Weighted Decision Matrix

After extensive evaluation, it has been found that the modified “Sword of Excalibur” concept best meets the engineering requirements for our project. Figure 17 shows a computer rendering of the preliminary design inserted into an assembly containing the frame of Cal Poly Aerospace’s wind tunnel. This virtual assembly has help us change the modified “Sword of Excalibur” concept into the fully detailed design shown in the

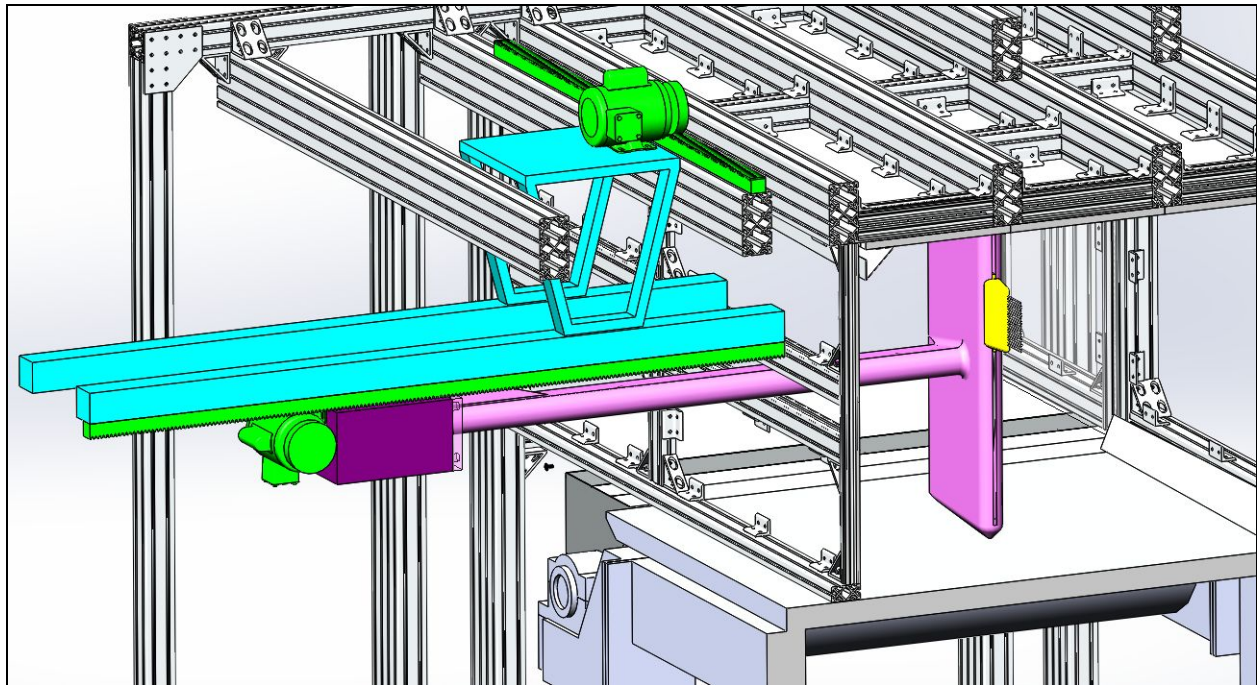


Figure 17. Modified Excalibur CAD

4.3 | Feedback

Customer Opinions

During comparison of our best two designs, our sponsor gave us his opinions on our concepts. Dr. Doig expressed concern over the amount of cross-sectional area the top-mounted body takes up in the test

section. Reducing the cross-sectional area of the test section speeds the flow up in the section. This can affect the accuracy of measurements in the test section of a model's flow field. Dr. Doig also explained that turbulent vortices generally form behind large bodies in wind tunnels. These vortices also have the potential to affect upstream flow conditions in the test section. In addition to flow disturbances, Dr. Doig is concerned that the top-mounted traverse will interfere with the particle image velocimetry technology (PIV) used in the wind tunnel.

In addition to Dr. Doig, we talked about our designs to Andrew Furmidge. Andrew is the design lead on renovating the entire wind tunnel. We were able to meet Andrew at the wind tunnel facility to see how our designs fit with the other renovations happening on the wind tunnel. After iterating Dr. Doig's concerns about our design interfering with the PIV system, Andrew showed us in the wind tunnel where the PIV system is mounted and the region that needs to be kept clear for the laser beams. Like Dr. Doig, Andrew was concerned that our top-mounted traverse would interfere with the PIV and suggested that we look at alternative mounting locations.

Consultations

In addition to soliciting feedback from our customers, we asked an outside expert for his opinion on our traverse designs. This expert was Dr. Russell Westphal, a professor of fluid mechanics at Cal Poly with years of experience in fluid flow analysis, flow control, and drag reduction. The main purpose of this meeting was to find out how our designs will affect the airflow in the wind tunnel test section. Dr. Westphal explained to us that the wake behind an object in a wind tunnel will always be turbulent, and this wake will affect flow conditions upstream of the object. He explained an accepted rule that the flow disturbances of an object become negligible (less than one percent of the dynamic pressure) at an upstream distance of five to ten widths of that object. Dr. Westphal also explained to us that there is a lag time associated with pressure measurements from a Pitot-tube. This lag time is prevalent in long tubes with small diameters, and is due to the lag associated with pressure propagation in the tube. In order to minimize this lag, Dr. Westphal explained that the length of our tubes should be kept to a minimum and if long tubing is necessary, the diameter of the tubing should be increased.

Chapter 5 | Description of the Final Design

5.1 | Overall Description

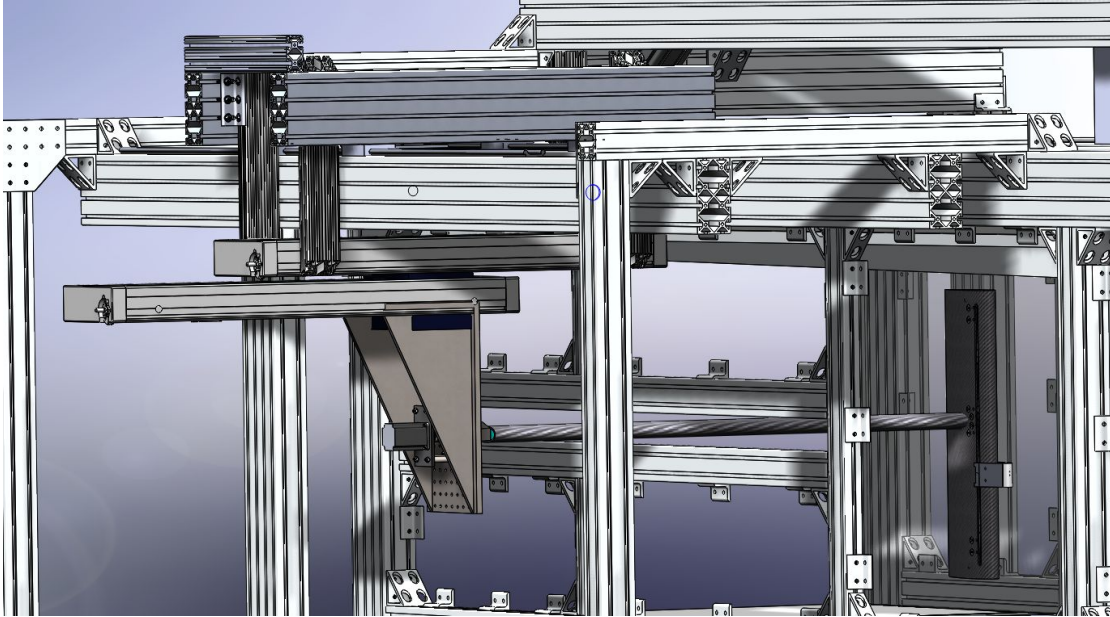


Figure 18. Traverse design attached to wind tunnel.

The finalized “Sword of Excalibur” design, shown in Figure 18, has a few major subassemblies. The first subassembly is composed of automating the wind tunnel downstream traverse, which stays attached to the wind tunnel aluminum structure. Attached to that is the existing motor assembly, which moves the probe arm in and out of the wind tunnel test section. The third subassembly stays inside the wind tunnel, and is responsible for the motion of the probe inside the wind tunnel. The second major subassembly is the pink airfoils and yellow probe holder. This inner subassembly is inside the wind tunnel test section, and it is moved and supported by the outer subassembly. The inner subassembly is designed to be aerodynamic so that it does not disturb the flow inside the wind tunnel. It is also designed to be lightweight, as it is fully supported by the outer subassembly. Because the outer subassembly is located outside of the wind tunnel, it can be bulky and does not have to have aerodynamic characteristics. Instead, we designed the outer subassembly to be very strong and rigid, as any deflections or vibrations in this structure will affect our ability to accurately position the measurement probe.

The clear definition of axes for this wind tunnel is important when referring to each component and each drive direction. The axes definition for this wind tunnel follows the standard Cartesian coordinates system based on the “right hand rule”. The X axis is defined as the axis along the length of the wind tunnel, in the same direction of the flow. The X direction will be positive moving down the wind tunnel from the intake to the fan. This axis refers to the traverse moving along the length of the wind tunnel. The Y-axis, or the horizontal axis, is the axis perpendicular to the X axis in the horizontal plane. The positive Y direction is out of the slot of the wind tunnel. This axis refers to the traverse moving in and

out of the tunnel. The Z-axis is in the vertical direction, perpendicular to the plane that contains X and Y. The positive Z direction is up. This refers to the probe motion moving up and down vertically.

Throughout this document, analyses, CAD models and drawings both metric and english unit system are used. Although it is very common to work in consistent units and can potentially result in errors, many of the parts that exist are in english units however, specifications were given in both unit systems. The team that works with Dr. Doig prefers to work with the english unit systems since many stock T-Slot parts are made in english units whereas, Dr. Doig prefers the metric system. Therefore the team decided to work with both and to be very careful when sizing and picking parts.

5.2 | Analysis Results

From basic analysis on the behavior of the airflow in the test section, we found that the worst-case drag force on our airfoil is thirty-seven pounds, and the worst-case lift force is two pounds. These forces were analyzed using an angle of attack of three degrees. Ideally, the angle of attack for our airfoil is zero degrees, but our frame may bend slightly under load, causing the airfoil to become angled relative to the flow. These forces from the airflow were considered when analyzing the loads on our structure.

Motor Selection/ gearing required

From the calculations in Appendix H *For Probe Traverse*:

Probe traverse maximum feed rate: 1 in/second

Torque required: 1.5 N-m at the drive shaft

Select Omega OMHT23-600 Stepper motor

Direct mount via shaft coupler

Timing belt: XL series, $\frac{3}{8}$ " wide,

X-axis Drive Analysis

The main concern initially of this driving axis was that the power screw and its associated motor would need to be able to move the entire weight of the supporting system with a safety factor. However, through weight isolation and the addition of rails this power screw drive is only required to move acting against horizontal linear motion. This decreases the size of the power screw and nut required since it is a lower operating load. This comes from the friction within the linear support rails. Using properties of the power screw, the nut, and the rail friction the torque required was calculated to be 20.24in-lbf which is 2.3 N-m. This torque is quite low and allows for a smaller motor.

The power screw is also checked for self locking. A $\frac{3}{4}$ -7 ACME power screw is selected with plastic flange nut. Under the assumed friction factor the power screw is self locking. This is only a concern if there is enough force from the wind tunnel to move the mounting assembly when the device is in the desired position. These two calculations can be seen in Appendix J.

Airfoil Design

- Max Deflection: .050"
- 1x1.5" rectangular tubing (.120" wall, 4130 steel) spar tube with carbon fiber-wrapped foam composite
- Layup: $[0]_2 [-45/+45]_4$
- Attachment points: vertical airfoil shell bolts onto aluminum brace member. Horizontal airfoil bolted to "tombstone" block.
- Horizontal airfoil: layup carbon on a female mold

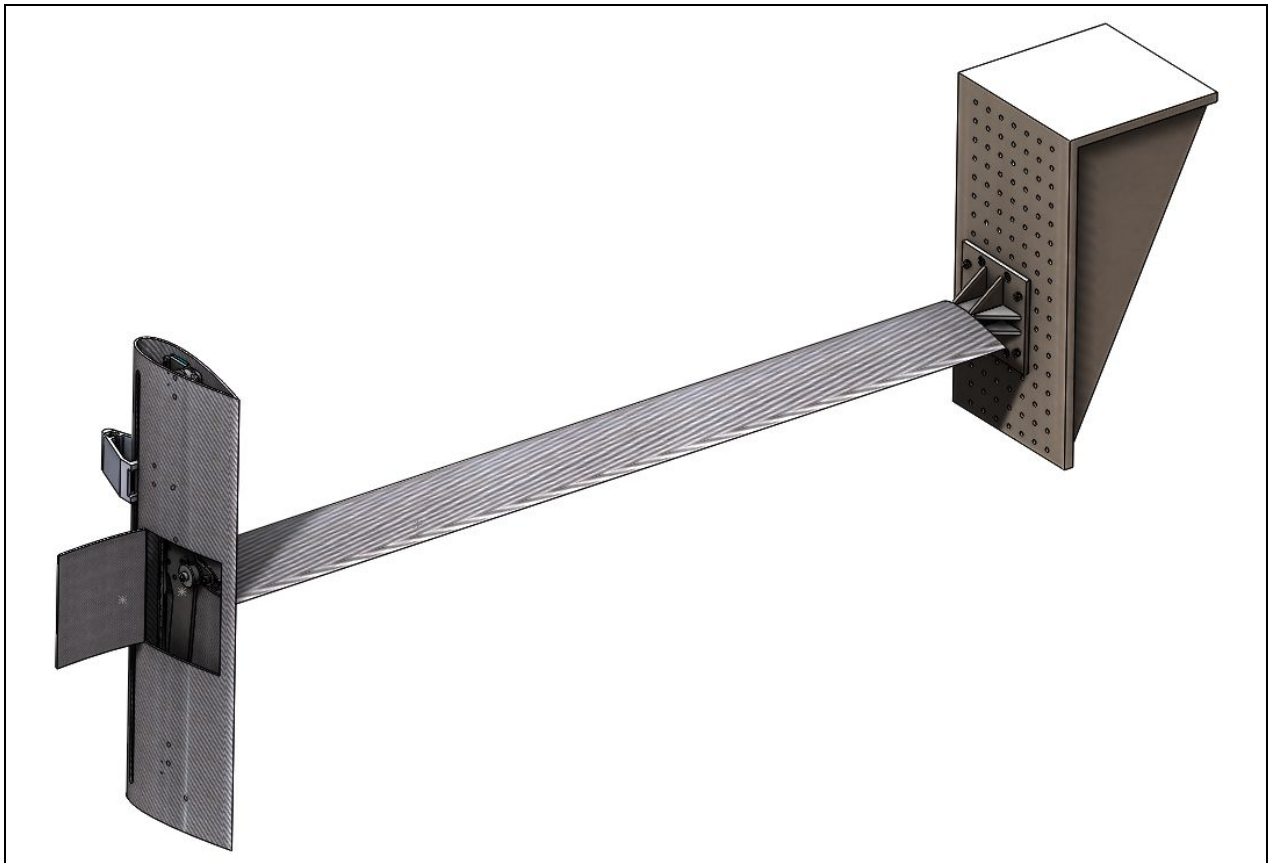


Figure 19. Traverse arm assembly that is installed inside the wind tunnel test section.

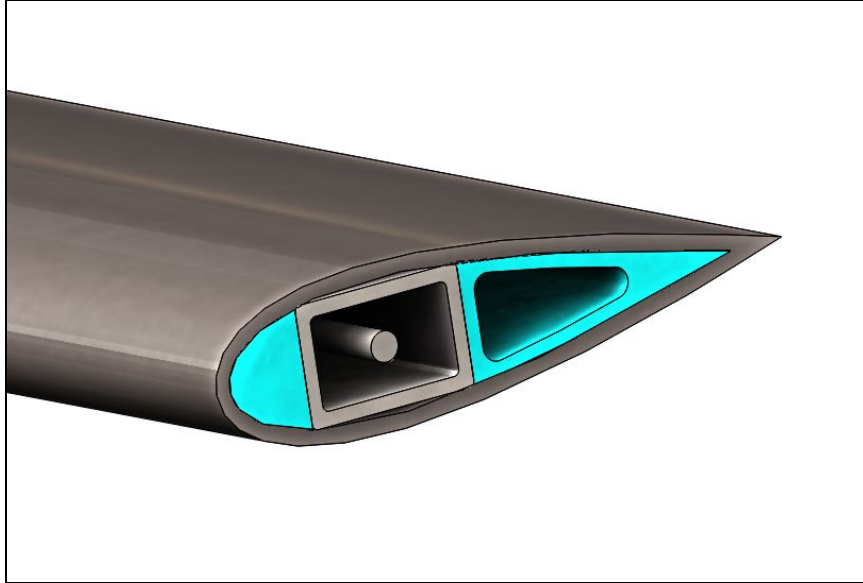


Figure 20. Cross section of horizontal airfoil. A steel spar tube is bonded to foam inserts and carbon fiber is laid up around to form the airfoil shape. The probe traverse drive shaft passes through the spar.

5.3 | Component Selection

Y-axis Motion Design

The two ISEL LES5 motors already in the wind tunnel will be utilized for one of the axis of traverse movement. They have been configured to be stacked on top of each other such that it acts as a telescoping mechanism. Attached to the motors is a tombstone block which has an array of 1" spaced holes for mounting hardware.

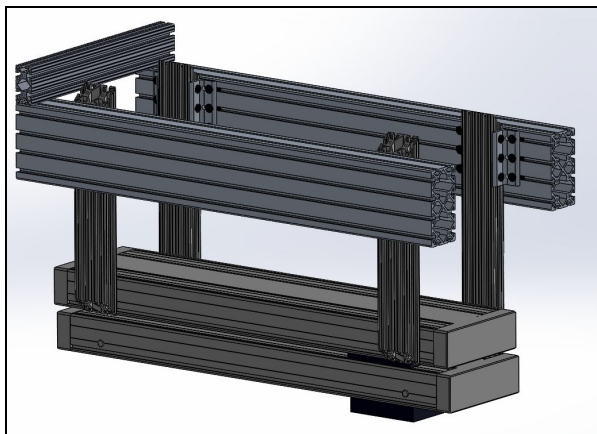
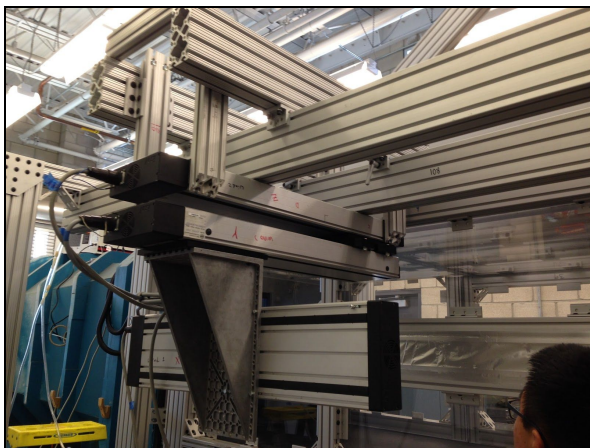


Figure 21. Two LES5 motors stacked for telescoping operation.

Figure 21 shows the two linear motors stacked together with a large steel tombstone block for mounting hardware; the previous wind tunnel traverse was set up with third LES5 motor as the downstream movement. The third motor will be removed with our design, but the two stacked motors will be kept and mounting system modified for automation.

This support structure is connected to the main overhanging beams of the wind tunnel via linear guide rails and carriage. These linear rails are shown in Figure 22 .

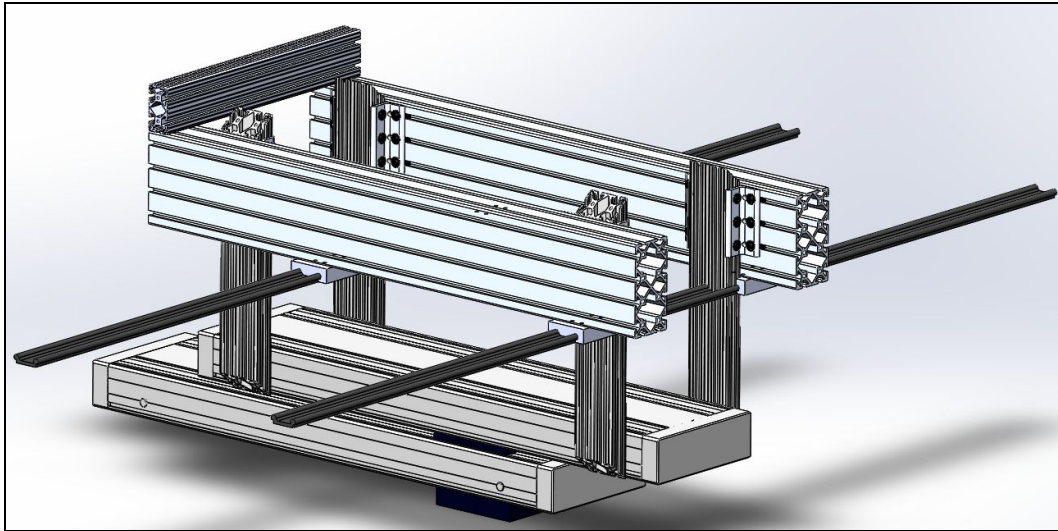


Figure 22. Support Structure Mount with Linear Guide Rails

Z-axis Motor Design

Our modified traverse arm will have a Omega OMHT23-600 NEMA23 stepper motor attached to the tombstone for z-axis control. These motors are relatively inexpensive at around \$100 each, and offer the starting torque of 1.5 N-m at 22 rpm required.

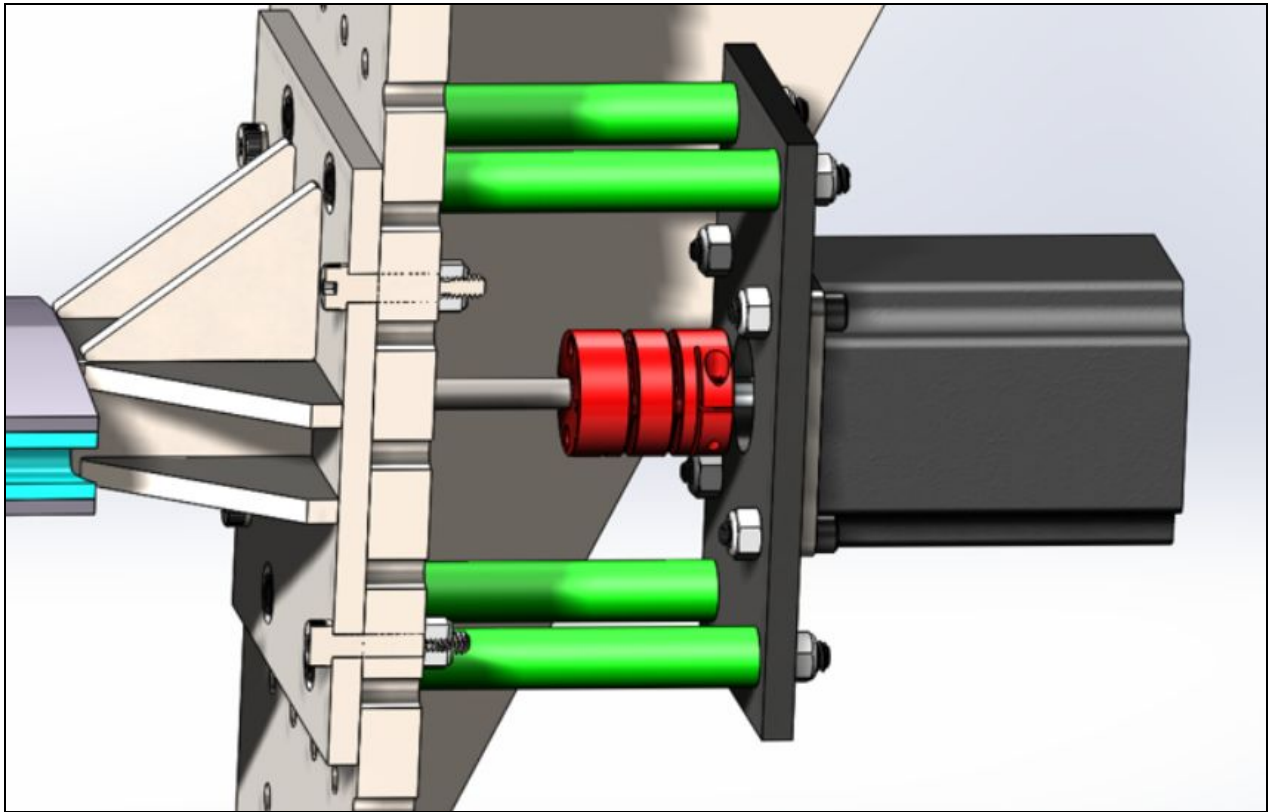


Figure 23. Omega OMHT23-600 stepper motor attached onto the tombstone via bolts and standoff spacers (green). The motor shaft is connected to the z-axis shaft with a zero-backlash shaft coupler (red).

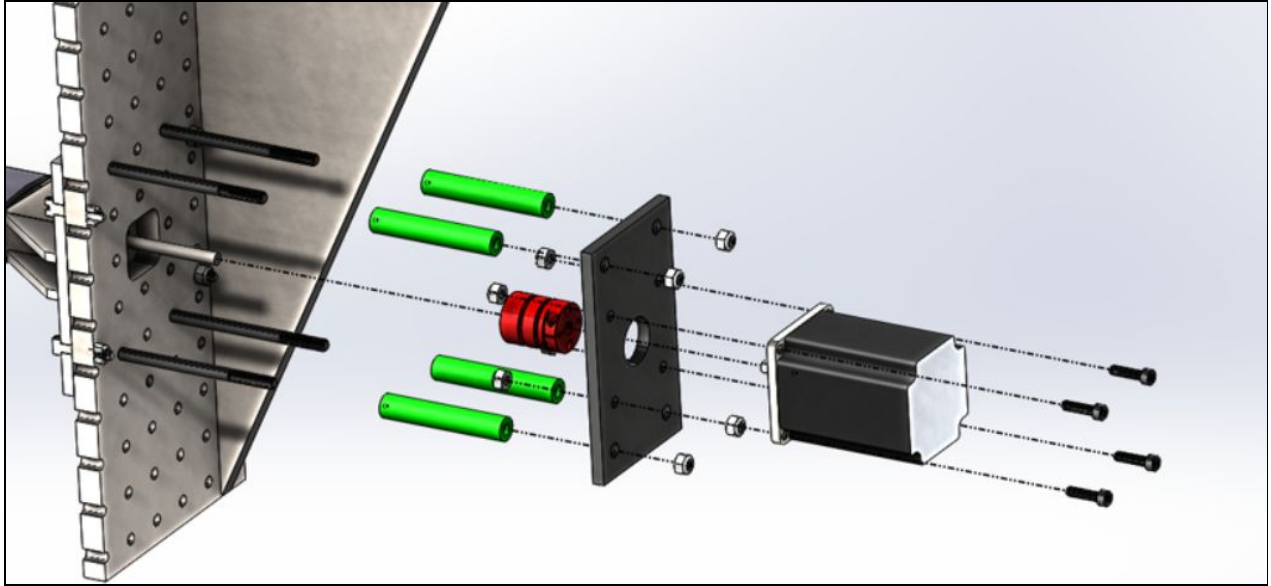


Figure 24. Exploded view of the stepper motor assembly. All are stock parts except the black mounting plate which is easily machined on a manual mill.

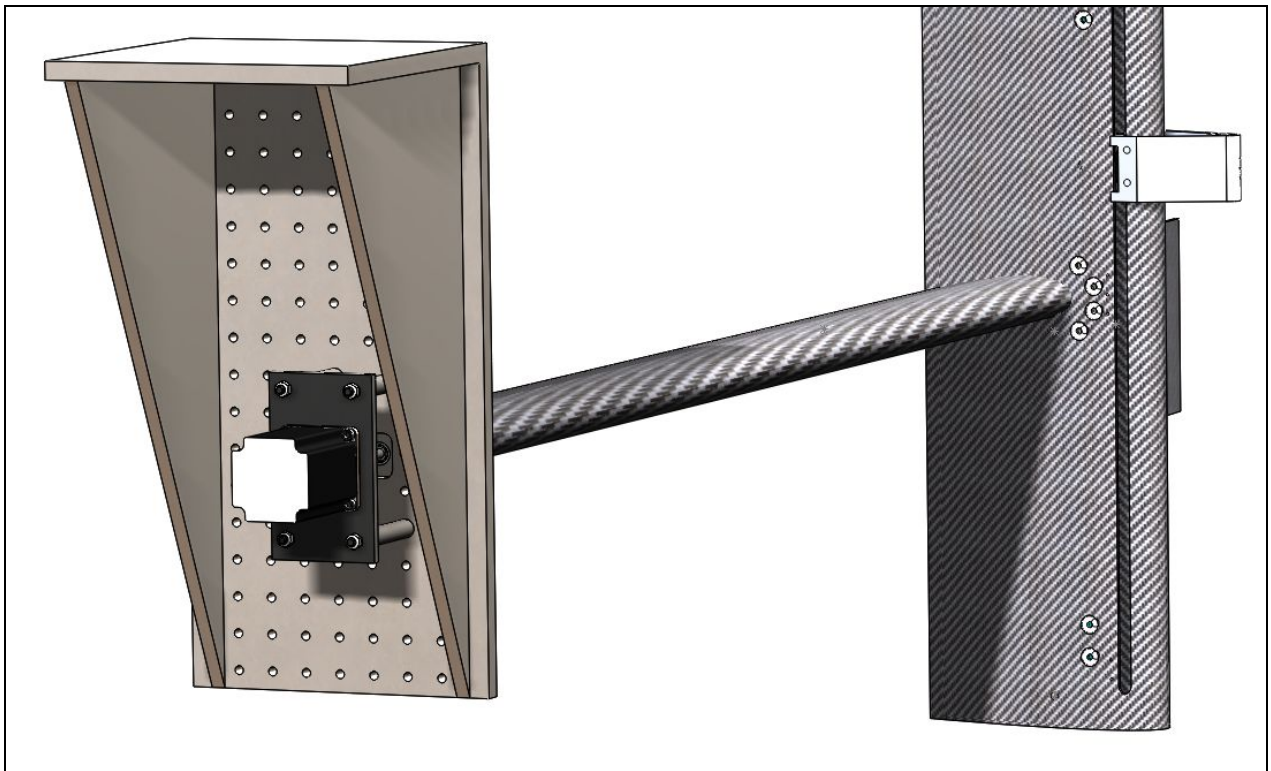


Figure 25. Stepper motor location in relation to the arm assembly.

Z-axis Traverse Arm Assembly

A waterjet-cut 6061 aluminum plate will be used to mount the linear slide and carriage, pulleys, and the vertical airfoil shell. Minimal post-machining is required for the waterjet part: reaming and tapping holes.

The carriage will be machined on the manual mill, and is used for an attachment point to the probe mount assembly.

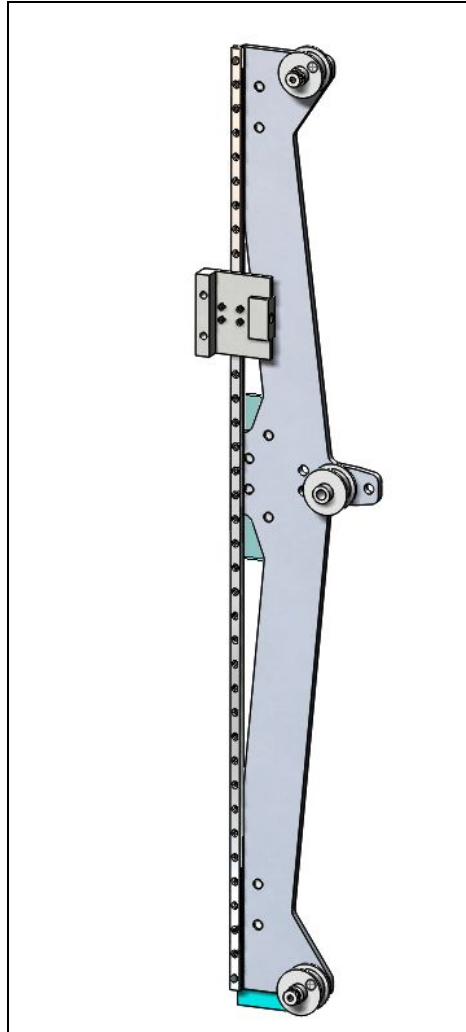


Figure 26. Brace assembly with linear slide that allows the probe mount to move up and down inside the test section. The carriage is attached to a timing belt pulley which is controlled with the z-axis motor attached to the tombstone.

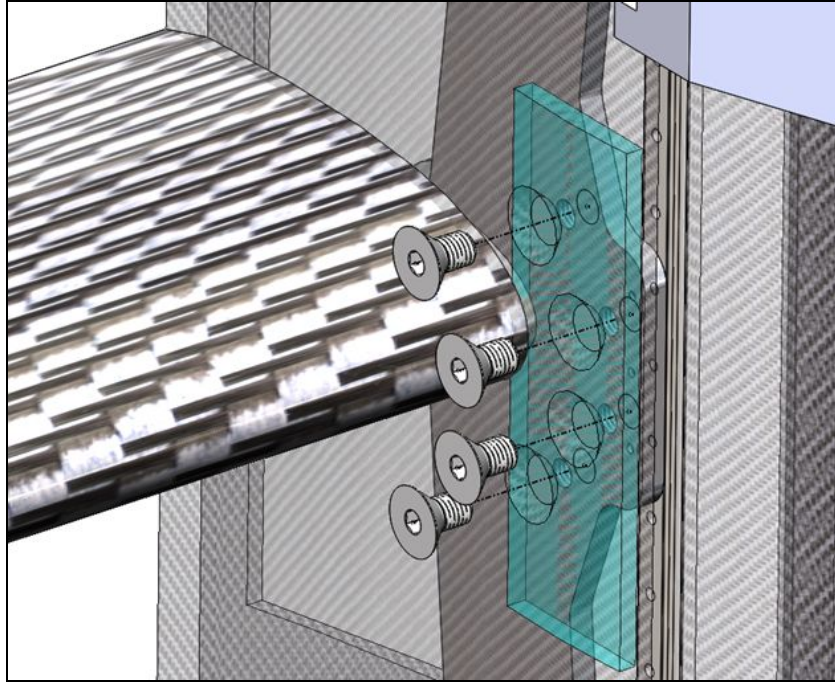


Figure 27. The vertical airfoil shell will be attached using flat head socket cap screws. Countersinks will be machined in the airfoil, and 3D printed contoured spacers will be used to distribute the load.

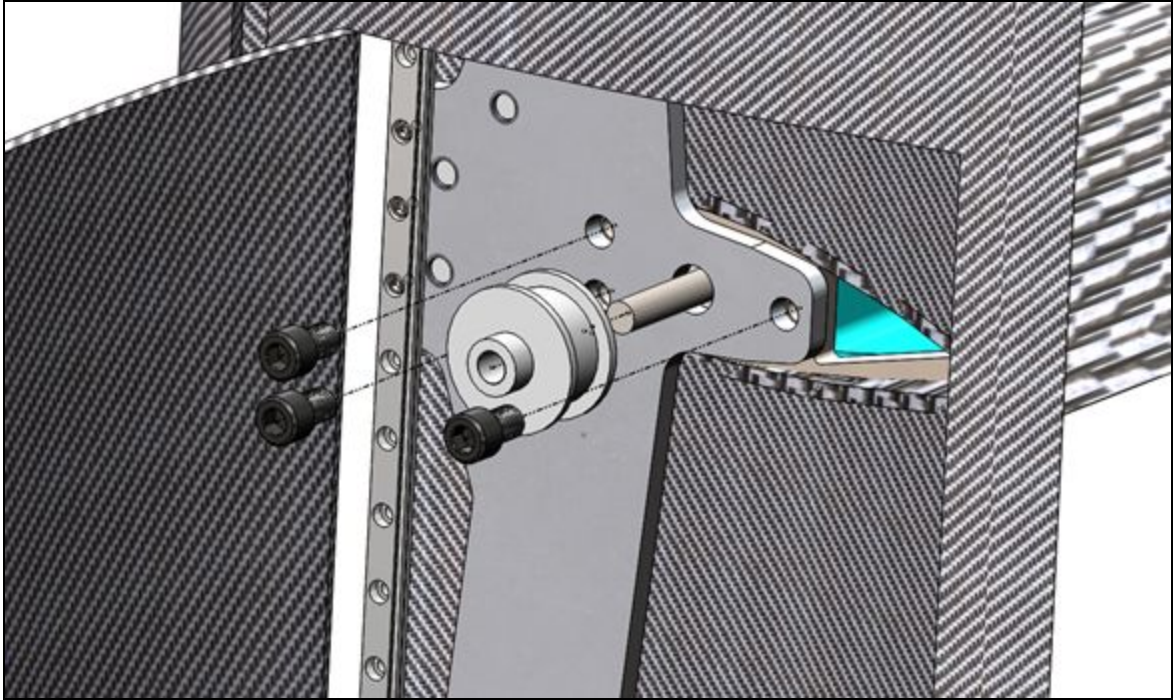


Figure 28. The vertical airfoil is attached via three socket head cap screws, directly to the horizontal airfoil. There is an access panel on the side of the vertical airfoil for ease of installation.

Z-axis Probe Mount Design

For the Z-axis the stepper motor attached to the tombstone spins a shaft that is positioned through the length of the horizontal arm section, the shaft is then attached to a pulley system and will drive the timing belt which the probe is attached to. This can be seen in figure 24.

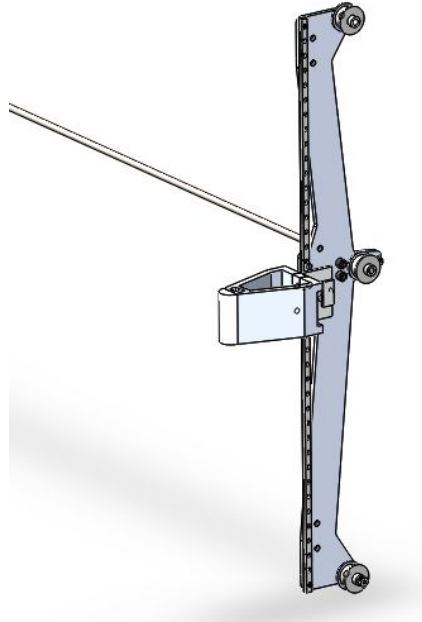


Figure 29. Z-axis Motion Drive Mechanism

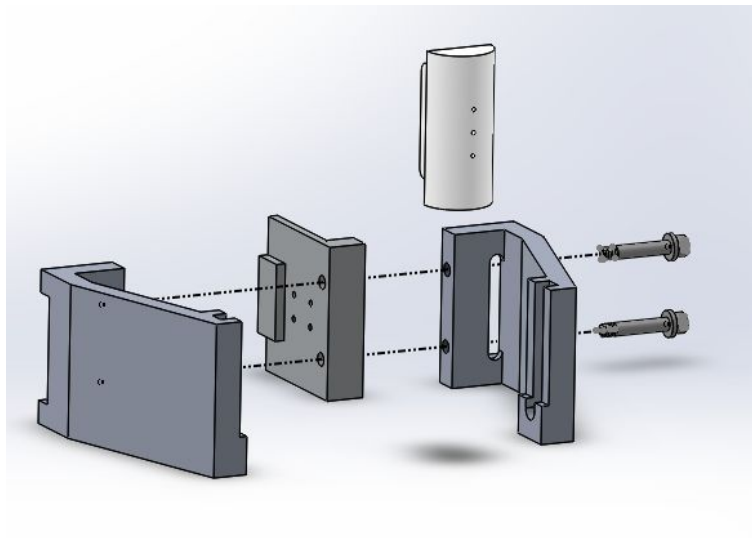


Figure 30. Exploded view of the full probe mount and probe block

The Probe structure is designed to be identically shaped brackets will be milled out of 6061 Aluminum and post processed by adding a slot and to the right most side and tapping the holes on the left hand side bracket only.

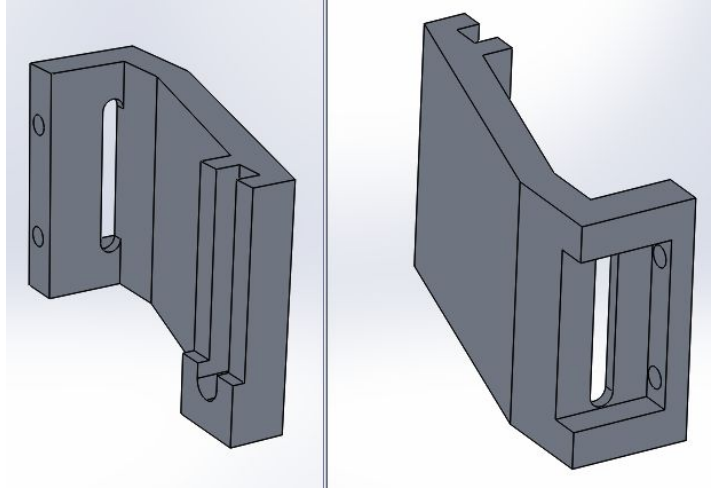


Figure 31. Probe Mounting Block (Right side)

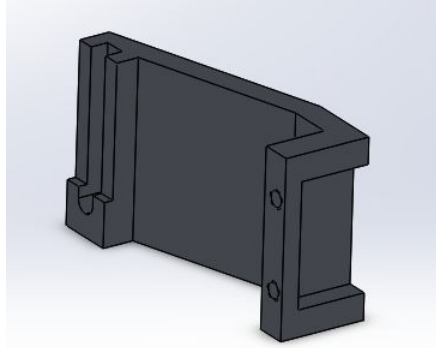


Figure 32. Probe Mounting Block (Left Side)

Once the internal vertical rail system is positioned within the vertical airfoil, both these brackets seen in figures 26 and 27 are mounted onto the machined aluminum traverse plate which correctly position the two brackets centered on the arm. The slot visible in figure 26 on the right hand side allows space for wires or tubing that are necessary for the pitot tubes and hot wire probes that will be used.

The brackets will be held all together with 5/16"-18 cap screw with a countersink washer to clamp it all. The brackets are clamped onto the transverse plate seen in figure 28, which then slides along the vertical rail.

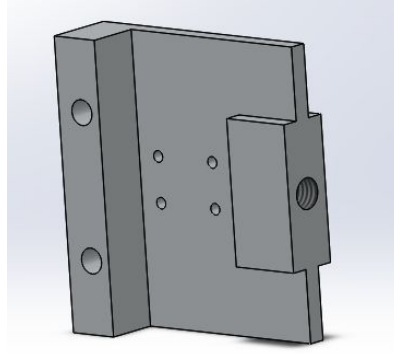


Figure 33. The Traverse plate for the probe mount to attach to and slide along the vertical rail system.

Once the brackets are securely fastened to the traverse plate, the vertical and the belt system, the 3D printed plastic probe holder (Figure 29) can be easily slid into position and sealed with a silicon cap to stop it from vibrating or moving.

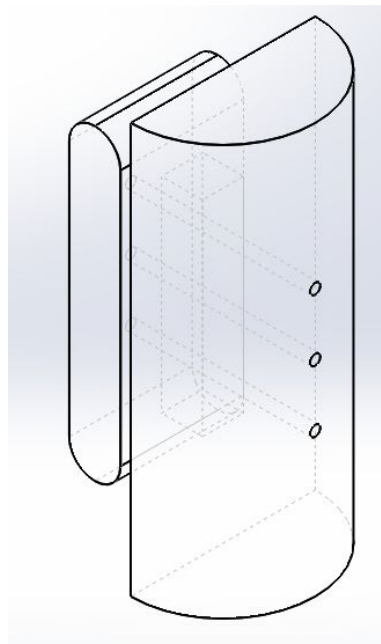


Figure 34. The universal probe holder, to be 3D printed by the our sponsor.

X-axis Traverse Motion Design

The x-axis motion is achieved through usage of a power screw mounted to a motor and two bearings at opposite ends driving a flange nut. An overview of this design is presented in Figure 31.

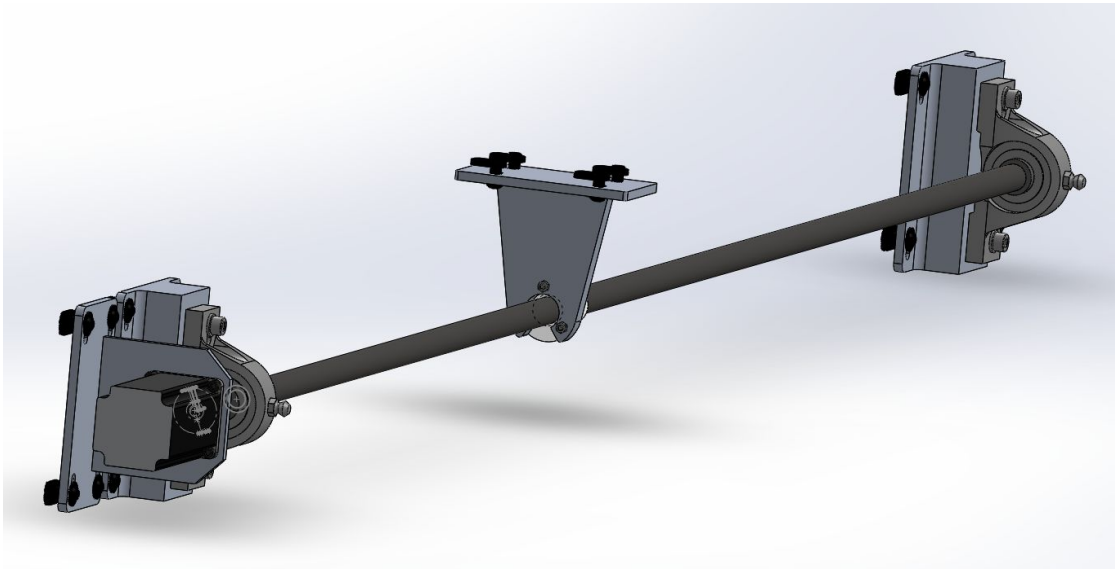


Figure 35. X-axis Motion Drive Mechanism

Figure 31 shows the 4 main components of this assembly. The flange nut in the center with a custom bracket will be connected to the larger frame which holds the two motors for the y-axis motion and the tombstone with the airfoil arm itself.

The power screw is a $\frac{3}{4}$ -7 ACME threads at 74 inches with the ends machined to 0.5in. The associated detail drawing can be found in Appendix L. This power screw is

X-axis Motor Assembly

The x-axis motor allows for the entire traverse assembly to move down the length of the wind tunnel. This motion will be driven by an Omega OHT23-603 stepper motor. This motor provides the required torque and speed, 2.3 N-m and 22 RPM at a safety factor of 2. A close up of this assembly is shown in Figure 32.

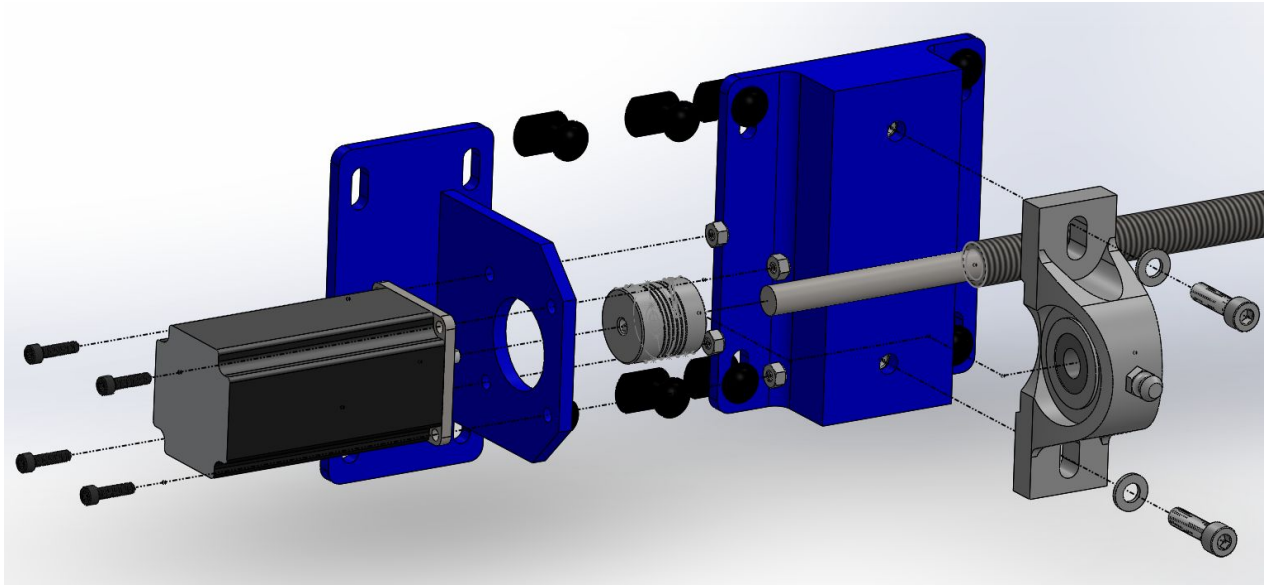


Figure 36. Motor and Bearing Mount for Power Screw Drive Exploded Assembly

Figure 32 provides an exploded view of the motor and one end of the power screw mount assembly. The parts highlighted in blue are custom parts which require manufacturing. These parts are going to be machined from 6061 aluminum. The leftmost part, the motor mount, will be two pieces welded together at 90 degrees. The detail drawings for these two parts can be found in Appendix M & N. The rightmost part marked in blue is the bearing mount bracket to interface with the T-Slot. All other parts are stock parts. The shaft coupler used for the motor and power screw interface is an aluminum helical 0.25in to 0.5in coupler. The four black screws used for motor are M5 x 0.8 socket head cap screws with four nuts. The two silver screws used for the bearing mount on the right side in Figure 30 are M8 x 1.25 socket head cap screw with washers and nuts. The bearing mount is a stock part with a 0.5in bore bearing.

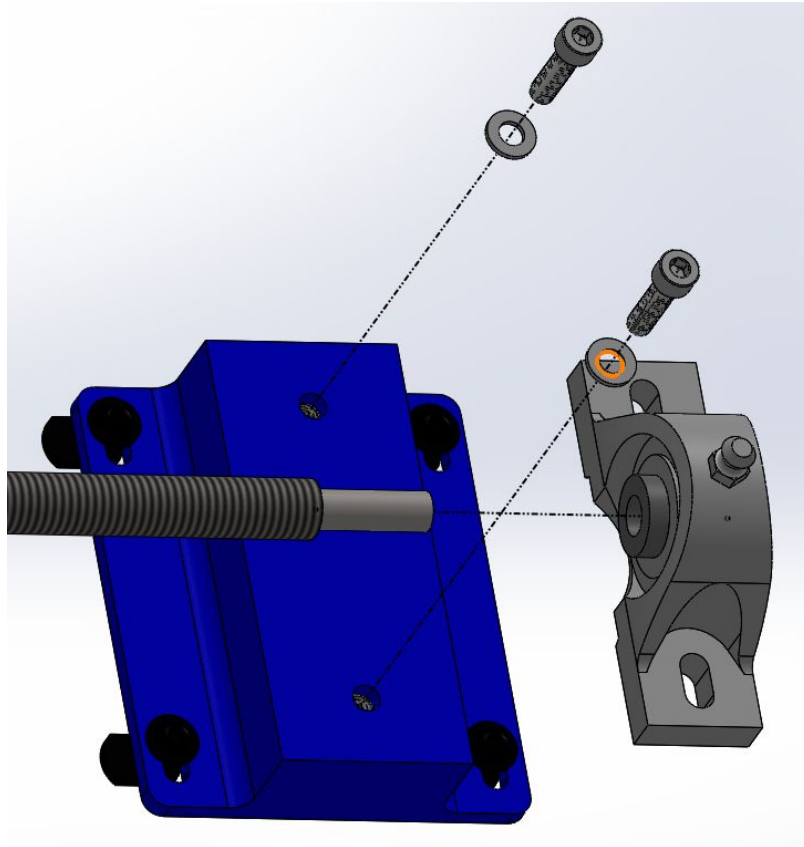


Figure 37. Bearing Mount on non-Motor End of Power Screw

Figure 33 shows the bearing mount on the opposite end of the power screw using the same bearing mount and M8 x 1.25 cap screw, washers and nuts. The part indicated in blue is the same bearing mounting bracket indicated previously at the motor end of the power screw

Flange Nut Connection to Support Assembly

The power screw mechanism drives a flange nut up and down its length. This flange nut is connected to a bracket that is mounted on the underside of a T-Slot beam of the supporting structure. This attachment can be seen in Figure 34.

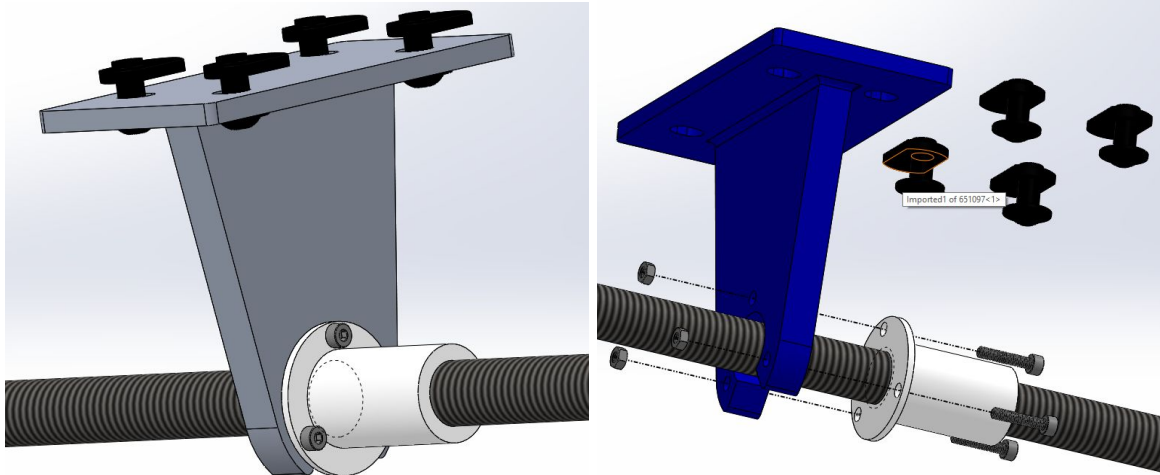


Figure 38. Power Transfer Bracket Between Power Screw and Assembly with Exploded Assembly

Figure 33 shows a side by side view of the bracket for the flange nut and the exploded assembly. The part marked in blue is a custom made part made from two pieces of 6061 aluminum welded together at 90 degrees, a detail drawing can be found in Appendix O. The flange nut is a stock part from the same supplier as the power screw with $\frac{3}{4}$ -7 ACME threads. This piece is a plastic piece with 350lb operating load rating. The support assembly is designed so that the only load that the power screw needs to overcome is the friction between the rails and the 2 carriages since the weight of the device is supported by the rails. The power screw, according to design, would take no external vertical loading due to structure weight. This allows for a relatively inexpensive flange nut with a lower load rating. The flange nut attaches by 3 holes 120 degrees apart using 3 M4 x 0.7 nuts and bolts.

5.5 | Cost Breakdown

The total cost for the modified Excalibur design is three-thousand-and-ten dollars. A breakdown of individual component costs is summarized in the BOM in Appendix K. Note that the costs included in the BOM are only for the parts we are purchasing. Our customer has many parts and raw materials that they are willing to give us. These include the three ISEL linear motors and their controller, all the T-Slot beams we need, and all the carbon fiber materials necessary to build our airfoils. The largest expenses for this project are the linear rails. We chose to use high quality rails because this greatly reduces the friction on the system, and also increases overall stability. With less friction, we can also use a smaller motor to drive the system in the direction parallel to the flow, which allows us to use a smaller and cheaper motor to drive the power screw to move the carriage back and forth along the direction of flow.

5.6 | Manufacturing Plan and Process

From initial analysis of the airfoil structure, the most difficult part of this device to manufacture is creating the thin, stiff airfoils with hollow body cavities which allow for mounting holes. Through further discussions with Dr. Doig, it was stated that his Experimental Aerodynamics class would make the airfoils and test them for aerodynamic properties which would have been quite difficult to do for the team due to the lack of experience. In the case of carbon fiber manufacturing, we have many resources in Cal Poly's aerospace department who can assist us in creating a mold and doing layups. Once the lay ups have been completed for the airfoils, recesses will be cut into the vertical foil along with the two vertical slots running its height along the side. An access panel will also be cut out of the side of the vertical airfoil, a high will be added. This panel will allow for access to internal bolts which hold the two perpendicular airfoils together. In addition to carbon fiber, many parts will need to be machined out of 6061 aluminum. The main resources available to us are the Mustang 60' and Hanger shops on Cal Poly's campus. These shops both have a variety of lathes and mills, both manual and CNC controlled. One of our team members, Ricky, is CNC certified and can manufacture some of our custom parts.

Many parts including the motor mounting plate and pulley mounting plate will be waterjet cut. This saves a lot of machining time, and holes are already located so that it will be easy to ream and tap holes as necessary.

For the x-axis motion, there are 3 components that require manufacturing processes. First, the motor mounting bracket will be machined from 0.25in thick 6061 aluminum stock in the CNC mill. The CNC will mill out the 4 slots on the base plate and the 4 small mounting holes and the larger center hole on the mounting plate. The two pieces will be machined then be TIG welded together at 90 degrees at the specified location on all 4 sides. The second piece is the bearing mounting bracket. These pieces will be machined out of 2 1.5in thick 6061 aluminum stock in the CNC mill. First the machine will mill the the general shape of the piece, then it will remove the rectangular section underneath the mount. Once those 2 processes are done, the 4 slots will be milled out and then the top holes. The last component is similar to the motor mount bracket, the mount bridge will connect the flange nut on the power screw to the support assembly. This part will be machined out of 0.5in thick stock 6061 aluminum. The two parts will be machined to size, then the features will be cut out which include the slots and mounting holes.

5.7 | Special Safety Considerations

Because of frequent exposure of wind speeds of up to 120 mph, all fasteners on all components should be checked and torqued before each use. Safety wire and/or lock nuts will be used where possible to minimize risk of parts coming undone. Hard stops will be installed on all traverse components to ensure that overtravel of any axes is not possible. Note that a Failure Mode and Effect Analysis has been completed to identify potential hazards for the system and possible solutions for the hazards.

There are also possible sharp corners that may developed from the new parts that will be installed in the device and attached to the wind tunnel. These sharp corners, points and edges will be rounded, filleted, chamfered, deburred or sanded wherever possible. It should also be noted that the existing structures on the wind tunnel already contains a significant number of hazards. These hazards include but are not limited to: T-slot corners, small wires/tubes, and both low and high extending rods. Due to the current nature of the work environment of the wind tunnel, safety and work environment hazards is not a major concern. However, the team will be ensuring that the device will not introduce other potential hazards in addition to those which are already present.

One safety concern is rotating and moving components. There are 2 rotating shafts and 1 motor extension. The power screw drive is located quite high about 8ft off the ground, this component does not pose major concern in terms safety. The power screw is located on the inside of one of the supporting horizontal T Slot beams and is not completely exposed. The extending motor drives the y-axis which will extend one of the motors out completely when the device is retracted from the test section. This presents a potential hazard since this motor stack is located approximately 6.5ft to 7ft off the ground. However, this motor stack is a current implementation that is already in operation and no problems have occurred. The team will either leave this assemble as is or create a tag of flag that may warn other users of potential danger. Lastly, the drive shaft for the z-axis is located approximately 5ft above the ground. This rotating shaft is the most easily accessible and can create pinch points. The rotating shaft and coupler is shielded by a motor mounting plate and 4 posts on the tombstone so as to prevent foreign objects from getting to close to the rotating mass which could damage the device or cause injuries.

5.8 | Maintenance and Repair Considerations

Components in this design are relatively low-maintenance. The bearings are operated at such low load that there is practically infinite life. Nothing else besides the power screw on the main traverse assembly will require periodic lubrication. The timing belt pulley for the probe traverse will wear and stretch over time. The initial stretching in the timing belt can be adjusted for with the built in adjustability of the pulleys. This belt should be replaced every 12 months to minimize the effects wear. It is good practice to ensure that all bolts are tight and torqued before operation of the wind tunnel. The vertical airfoil section should be disassembled periodically to check for wear and tear due to normal use.

As part of the design of the entire system, the modularity of the parts had to be taken into account. The system should be relatively easy to disassemble. All the components are fixed together using stock nuts, bolts, and screws. This allows for accurate reassemble and easily replaceable fastener parts. The disassembly of the airfoil arms may be required from time to time so that the laser screen measurement device can be used. However, the external support structure is expected to remain on the outside of the wind tunnel in most cases.

Chapter 6 | Product Realization

6.1 | Changes to the Design Objective

Certain changes to the original design objective have been made after a discussion between Dr. Doig and the team. The scope of the final product has been modified to only incorporate the axis design and function, eliminating the need to design, manufacture and test an airfoil enclosure shell for the section of operating inside the wind tunnel. This adjustment resulted in different changes to the manufacturing and testing plans, cost, as well as to the final design of the device.

6.2 | Cost Report

The budget of was originally set to under \$2500, the original design plan was expected to meet this budget guideline. However with the new design and

6.3 | Manufacturing Processes

The manufacturing processes taken to build the 3 axis traverse utilizes machining and welding. A significant number of parts were machined by the team using stock steel and aluminum ordered through McMaster Carr and Online Metals. Some parts were chosen to be sent out to be creating using waterjet cut by WaterJet Central in Paso Robles.

Waterjet cutting uses a high pressure water or water mixed with an abrasive material to cut metal. The decision to use this method for certain parts is due it ability to make very precise and high precision parts. This method allows for intricate shapes and cuts yet the largest advantage is the lack of high temperatures. The major waterjet cut part is the vertical component of the z-axis which acts as the mounting plate between the mechanism for the z-axis motion and the horizontal arm extending into the wind tunnel. This part can be seen in Figure 39. The parts sent to be waterjet cut are noted in the BOM (Appendix K), drawings for these parts can be seen in Appendix L.

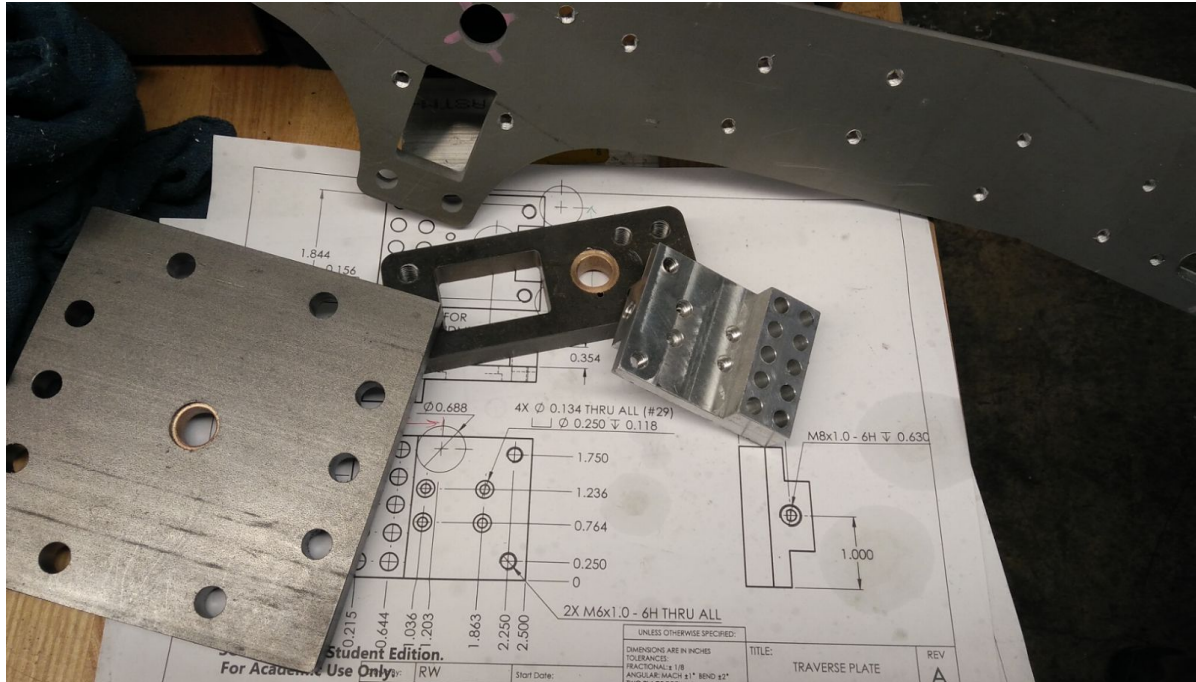


Figure 39

Figure 39 shows a number of Waterjet Cut parts made by WaterJet Central ready to be post processed.

The parts that were machined in house using the resources of the Mustang '60 Shop and the Aerospace Hangar can be seen in the BOM (Appendix K). The lathe was used to machine circular parts which only included 3 components of the assembly. The lead screw used to drive the x-axis was turned and faced to length using the lathe spinning at slow speeds since the screw extends out from the headstock due to its length. This required the extended end to be supported by a member of the team using a wooden block, a standing single roller, and cardboard to hold the screw in place. This was required so that the screw did not whirl around unrestricted which would result in warping and bending the screw as well as a significant safety hazard. This manufacturing process can be seen in Figure 40. The rest of the parts manufactured by the team were done using the mill in both Mustang '60 and the hangar, one of these parts is shown in Figure 41 as the motor mount for the z-axis drive system. The tombstone was also modified using the mill in order to cut out a space for the drive shaft, this is depicted in Figure 42.

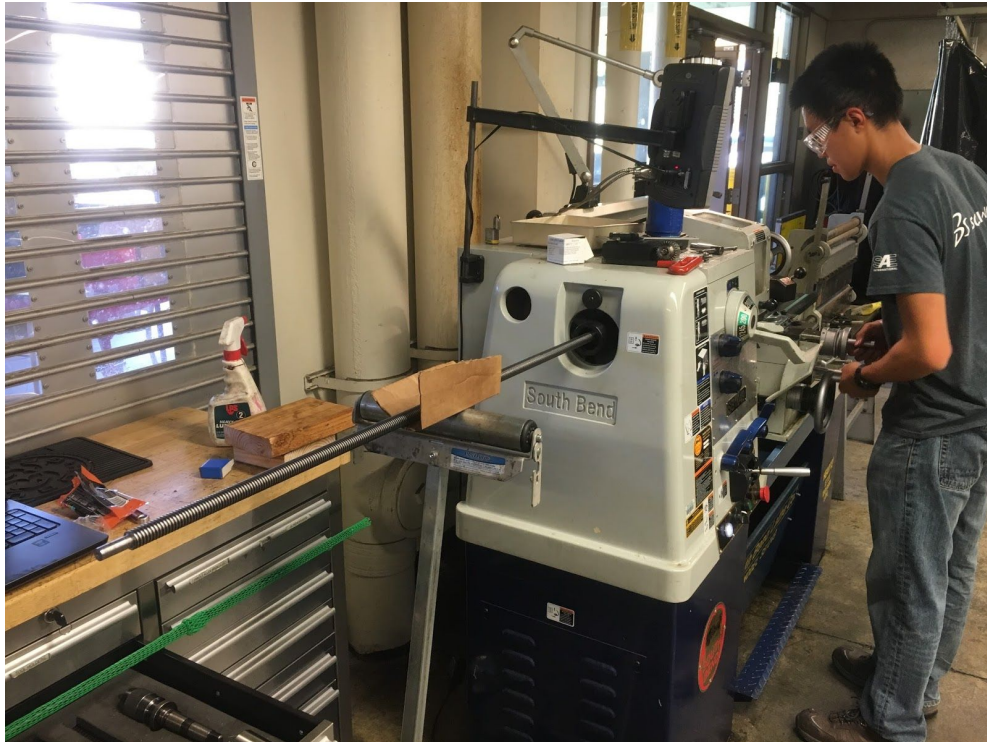


Figure 40

Figure 40 shows the lead screw being turned on a lathe in Mustang '60 by Rick and Mel(not shown, photographer). The extended section out of the headstock is being supported by the standing roller.

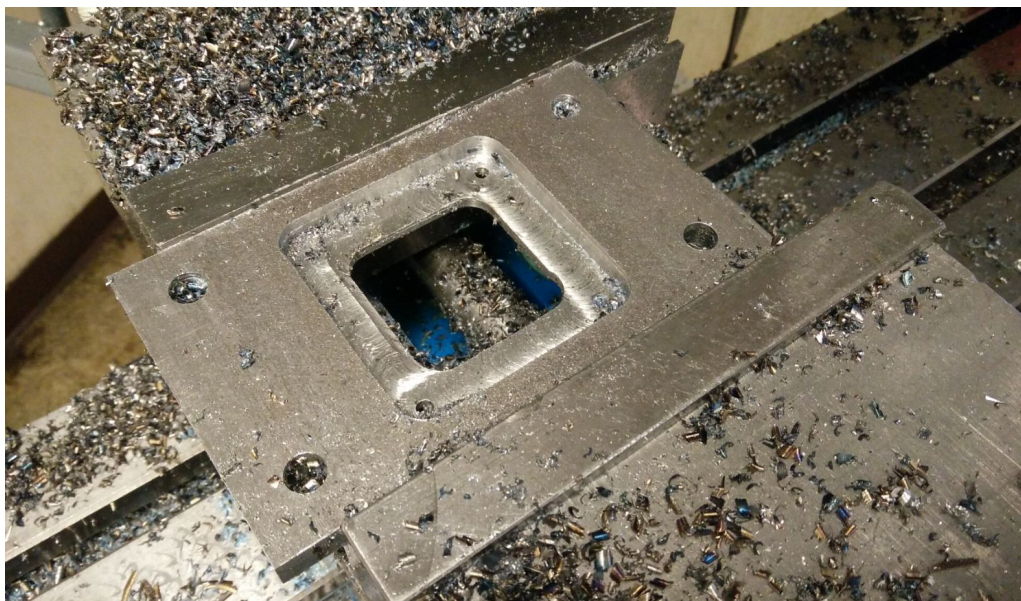


Figure 41

Figure 41 shows the motor mount being machined from aluminum on the mill in Mustang '60.



Figure 42.

Figure 42 is a photo of the tombstone being machined to create a hole to for the drive shaft done on a mill in the Aerospace Hangar.

TIG welding was used on multiple different parts to permanently attach parts together. The two square spars need to be welded together. One would hold the drive shaft and the other acted as a routing cavity for the tubing. The larger spar which held the drive shaft was then welded to a base plate for the arm so that it could attach to the tombstone and connect to the motor. Care was taken when welding the plate since the increase in temperature can warp cause the bushing to warp and change the fit between the bushing and the drive shaft. This weld can be seen in Figure 43. Gussets on certain brackets were also attached using welding.

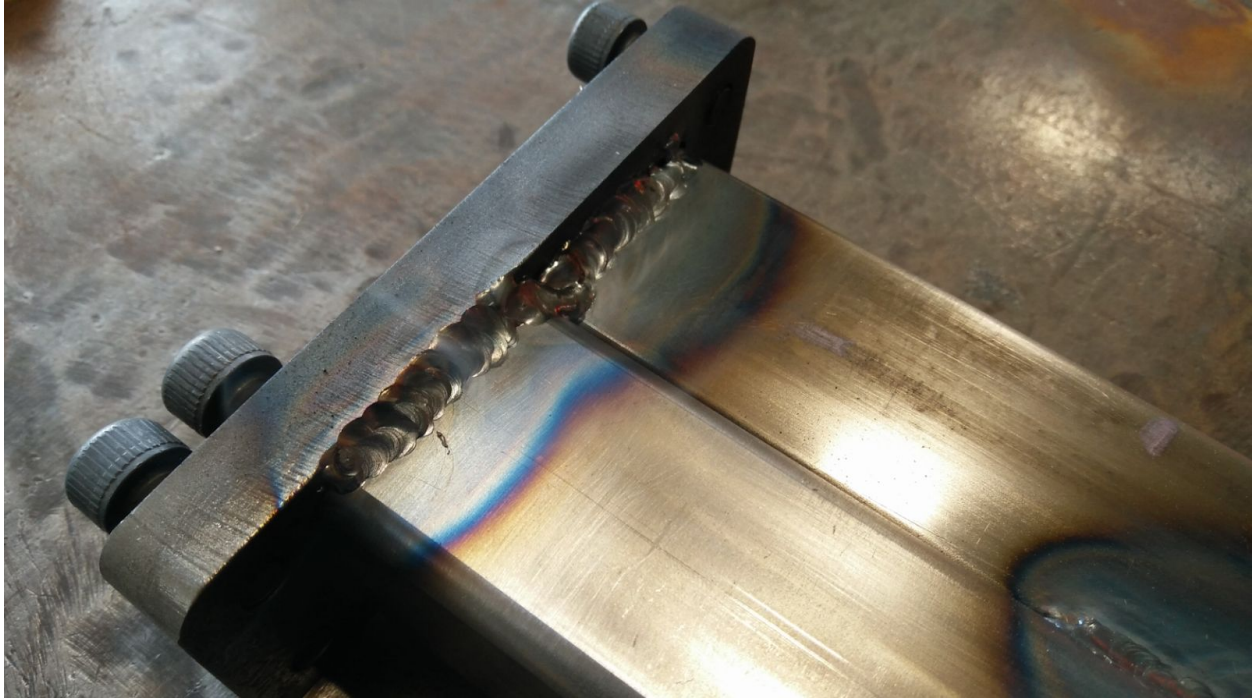


FIGURE 43

Figure 43 shows a weld done by Ricky to attach the spars to the connecting plate on the horizontal arm.

6.4 | Changes in Product

Due to an objective change by our sponsor, the scope of our project was reduced. Carbon fiber airfoils were no longer required in our design, although we wanted to make a design that could potentially be fit with airfoils at a later date. An update photo of our final design is shown in Figure 44. The support structure and linear guide rails attached to the wind tunnel structure are the large components shown in Figure 44. A lead screw (in pink) is driven by a stepper motor which moves the assembly upstream and downstream of the wind tunnel test section. The updated cantilever assembly is shown in Figure 45. This assembly remains very similar to our earlier design, but does not have the airfoil components. The stepper motor mount that drives the vertical motion also changed slightly, as shown in Figure 46.

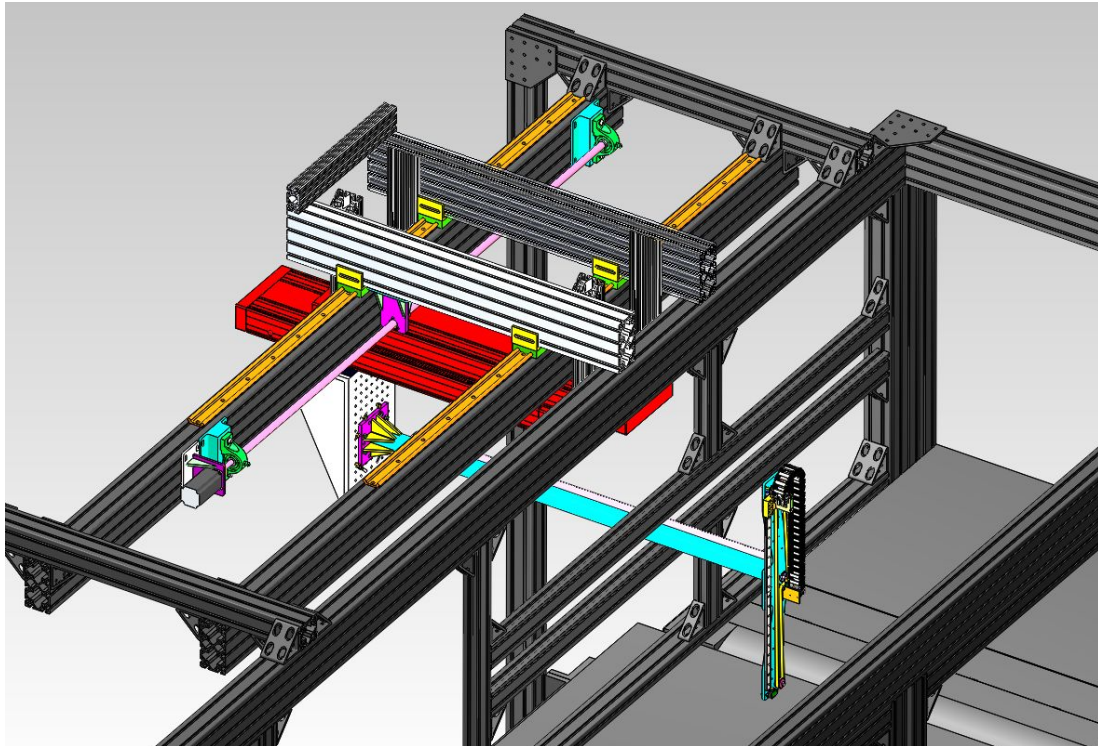


Figure 44. Updated design on wind tunnel test section. The colored parts in the picture are the new design.

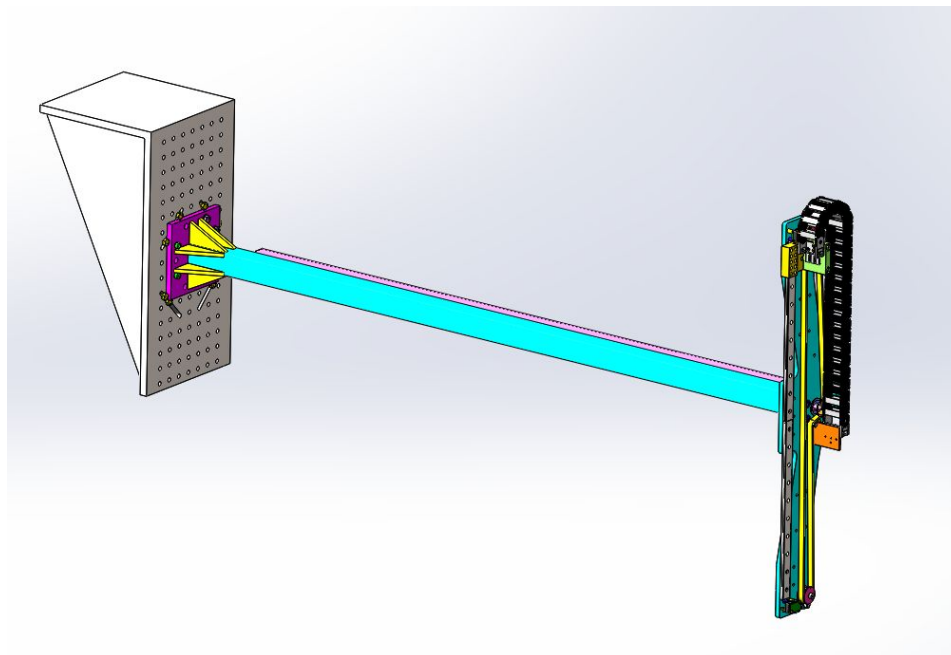


Figure 45. A “bare” arm that will allow for the wind tunnel team to design and optimize an airfoil around in future design additions.

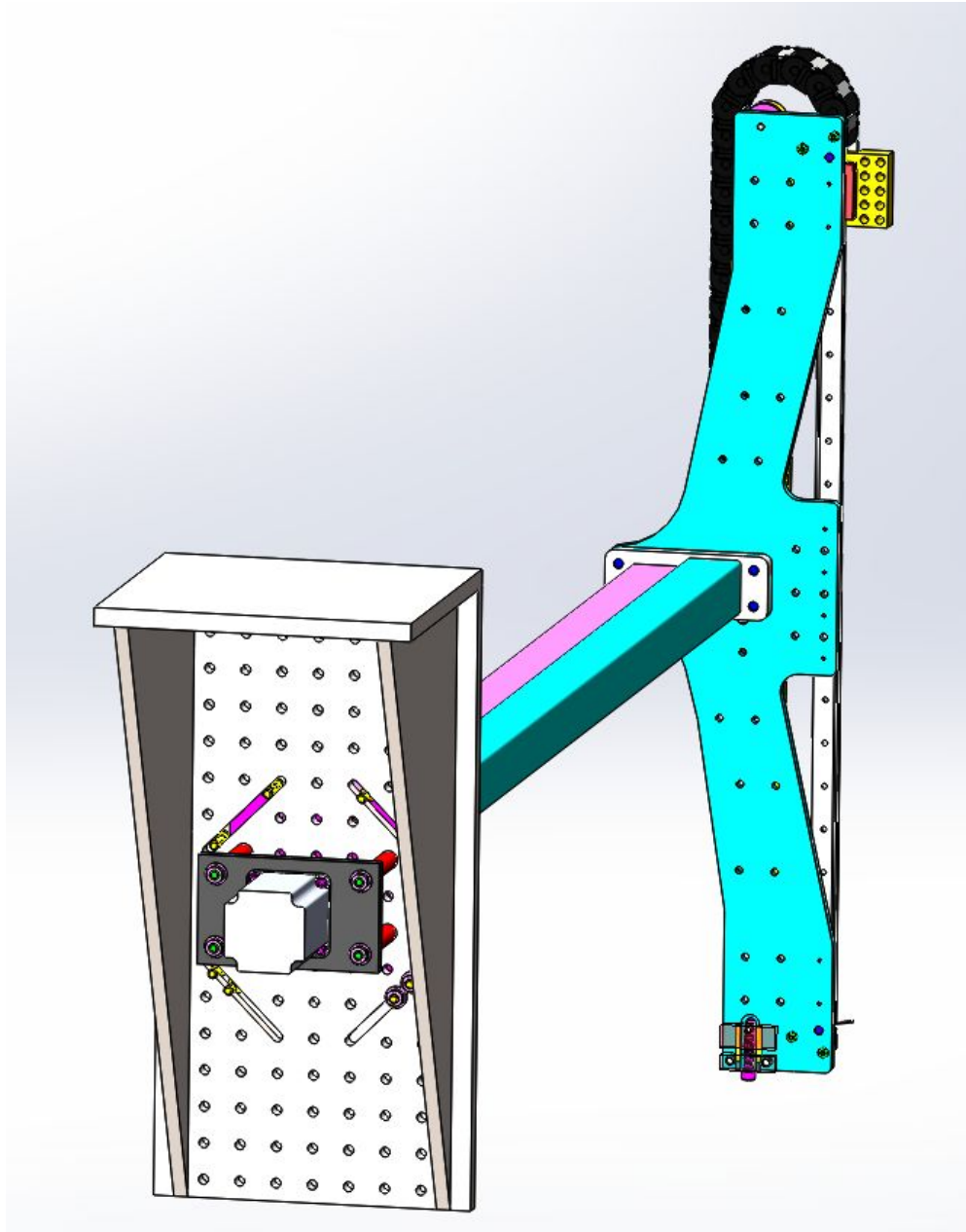


Figure 46. Stepper motor location in relation to the arm assembly.

Z-axis Traverse Arm Assembly

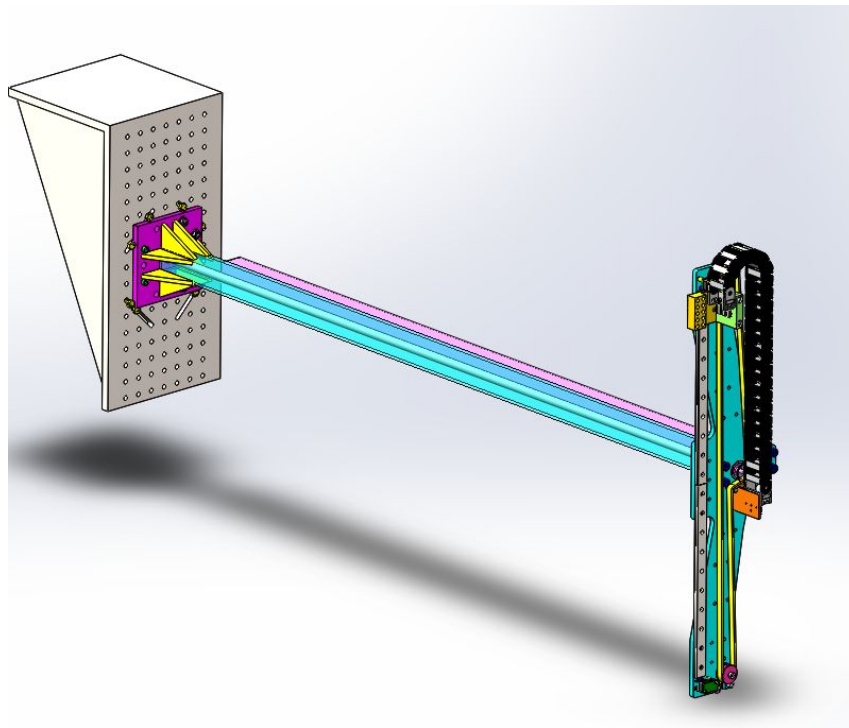


Figure 47. Z-axis Motion Drive Mechanism

A waterjet-cut 6061 aluminum plate, shown in Figure 47, will be used to mount the linear slide and carriage, pulleys, and the vertical airfoil shell. Minimal post-machining is required for the waterjet part: reaming and tapping holes.

The yellow carriage block will be machined on the manual mill, and is used for an attachment point to the probe mount assembly.

Figure 48 shows a brace assembly with linear slide that allows the probe mount to move up and down inside the test section. The carriage is attached to a timing belt pulley which is controlled with the z-axis motor attached to the tombstone. Included on one of the parts in the brace assembly are dozens of mounting holes for future use, should they be needed. Figure 49 shows the locations of these mounting holes. Figures 50 and 51 show how the updated assembly assembles. The main attachment involves M6 screws. Screws are used for non-permanent fastening, as the assembly will need to be removed from the tunnel from time to time.

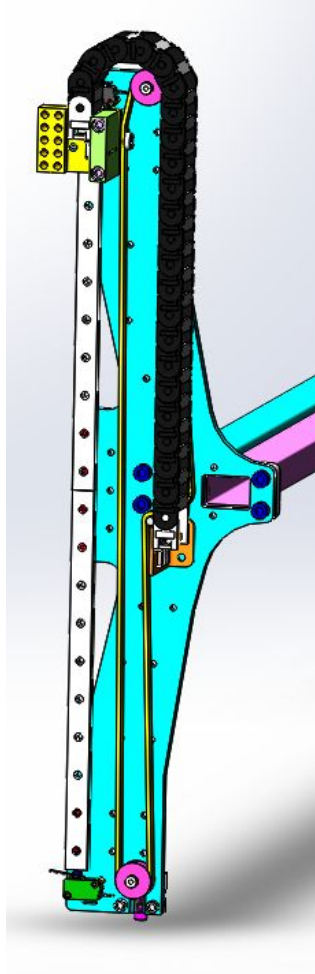


Figure 48. Linear motion assembly for vertical motion.

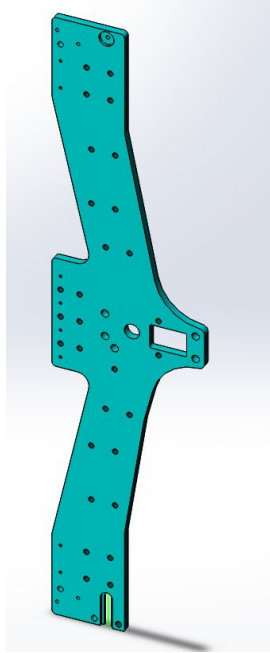


Figure 49. Dozens of M6x1.0 tapped mounting holes on the z-axis assembly plate will be available for future mounting of airfoil shells or accessories.

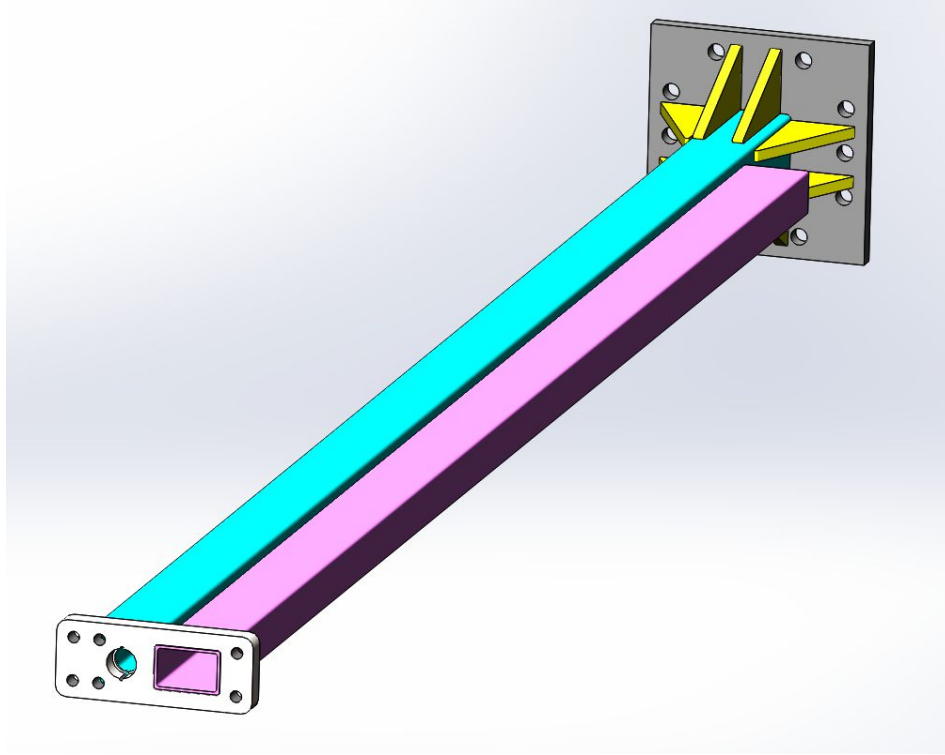


Figure 50. The horizontal arm which holds the z-axis assembly is made of welded alloy steel tubing and plate. The pink rectangular tube allows for pressure tubing and wiring to be routed safely through the arm and to the probe mount carriage.

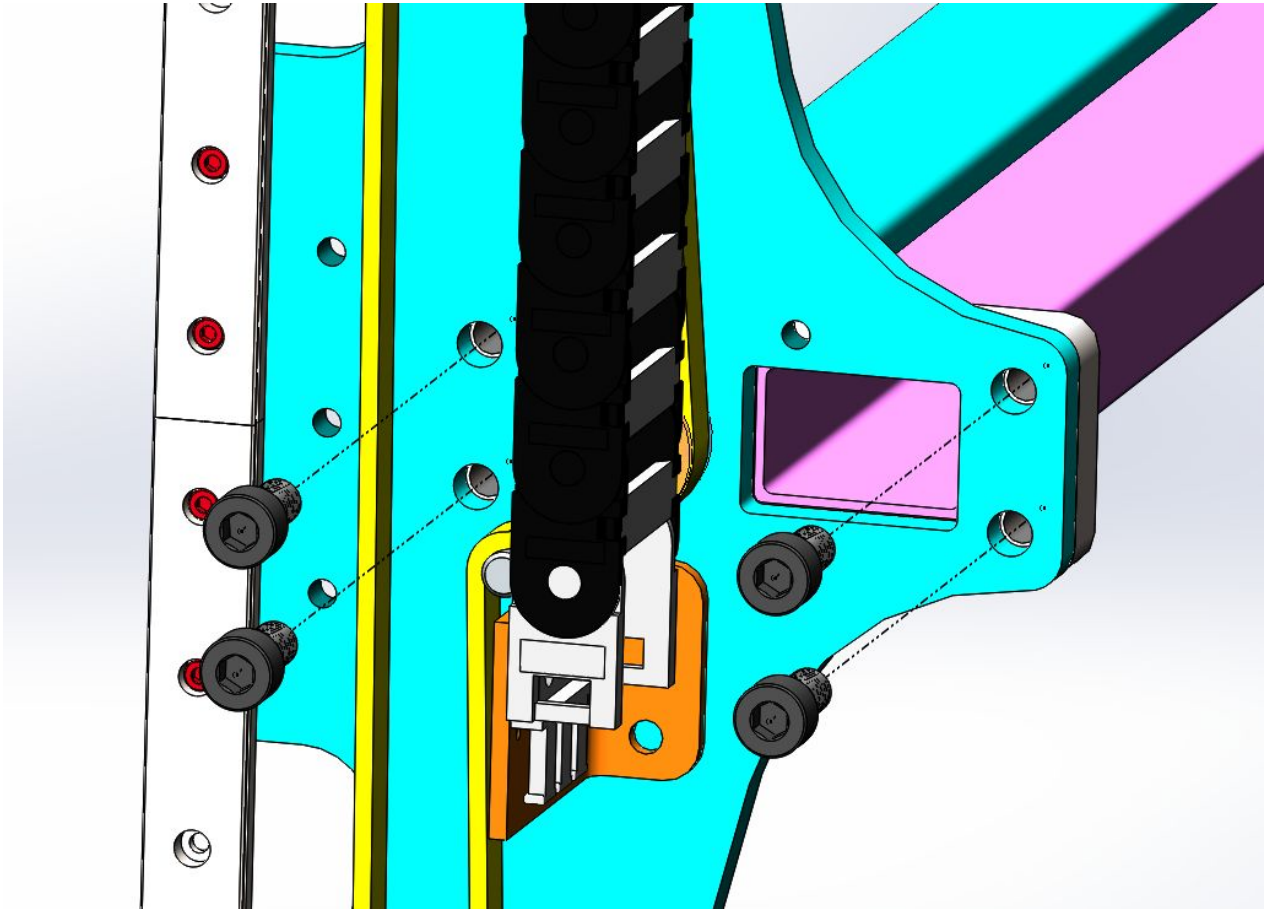


Figure 51. The z-axis assembly is attached via four socket head cap screws, directly to the horizontal arm.

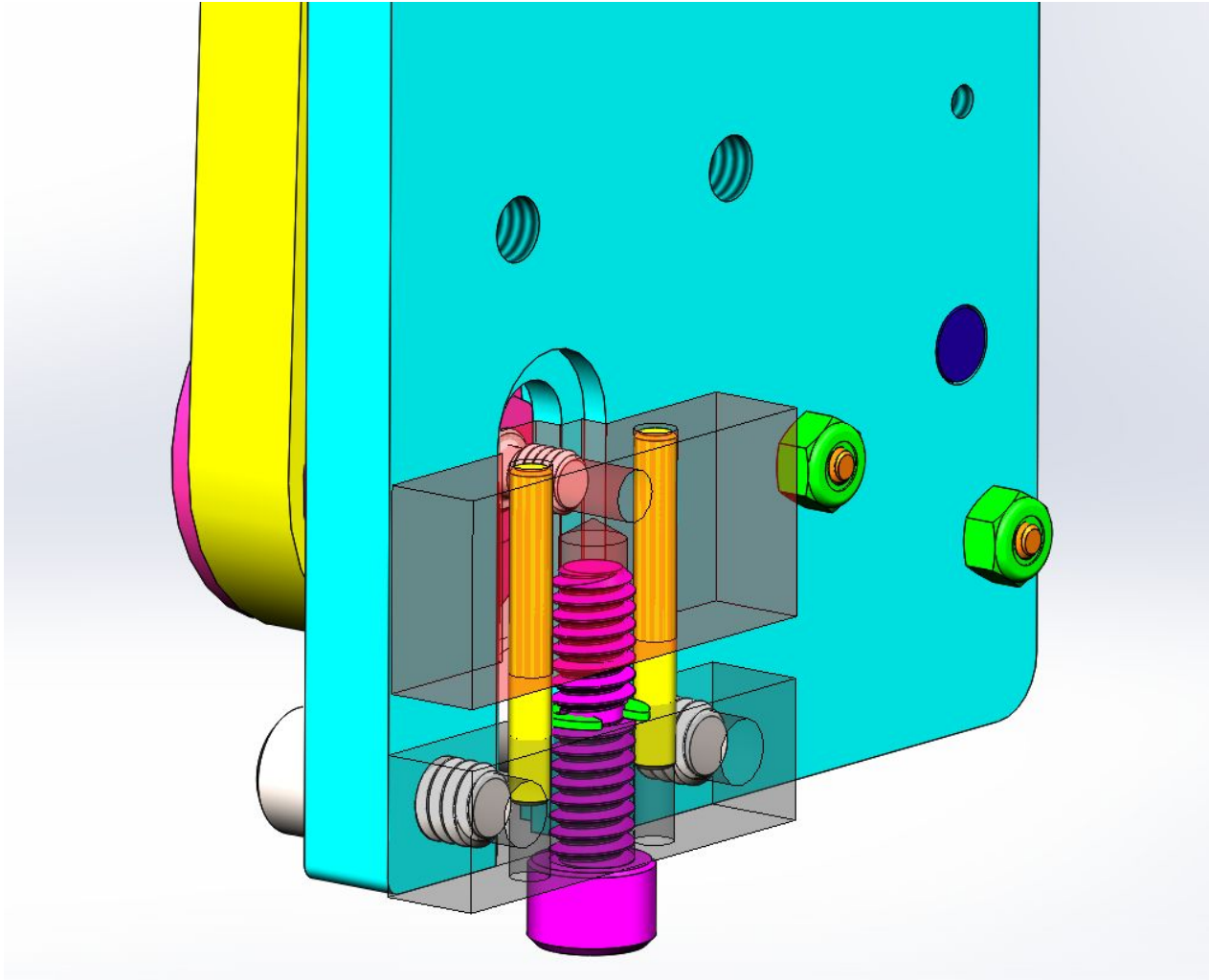


Figure 52. A timing belt tensioning mechanism. This will be used to remove slack from the timing belt. Threading in the captive (pink) socket head cap screw will tighten the belt. A small groove will be machined into the screw for a c-clip which keeps the screw from falling out. Two dowel pins keeps the assembly from bending.

Z-axis Probe Mount Design

For the Z-axis the stepper motor attached to the tombstone spins a shaft that is positioned through the length of the horizontal arm section, the shaft is then attached to a pulley system and will drive the timing belt which the probe is attached to. This can be seen in Figure 52.

The components shown in Figure 53 attaches to the vertical pulley system and acts as a universal mount. The component has holes that can interface with probe mounts that will be 3D printed by a technicians using that wind tunnel. The universal mount allows the

technicians to create probe mounts of any size and shape so they can tailor the mounts to their specific measurement applications.

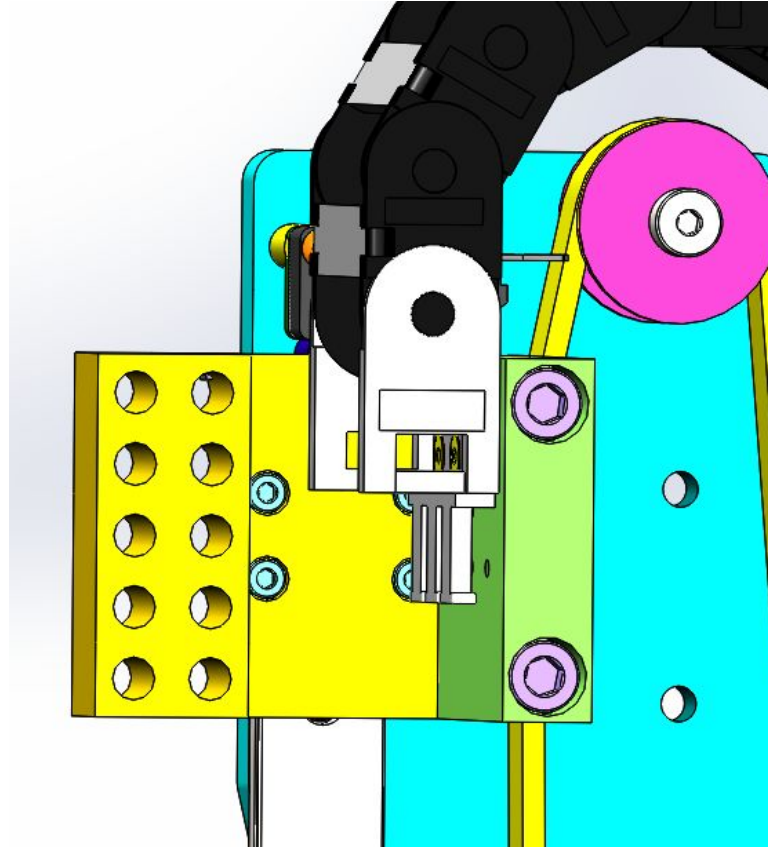


Figure 53. The Traverse plate (in yellow) for the probe mount to attach to and slide along the vertical rail system. A drag chain (in black) keeps wiring and tubing from kinking.

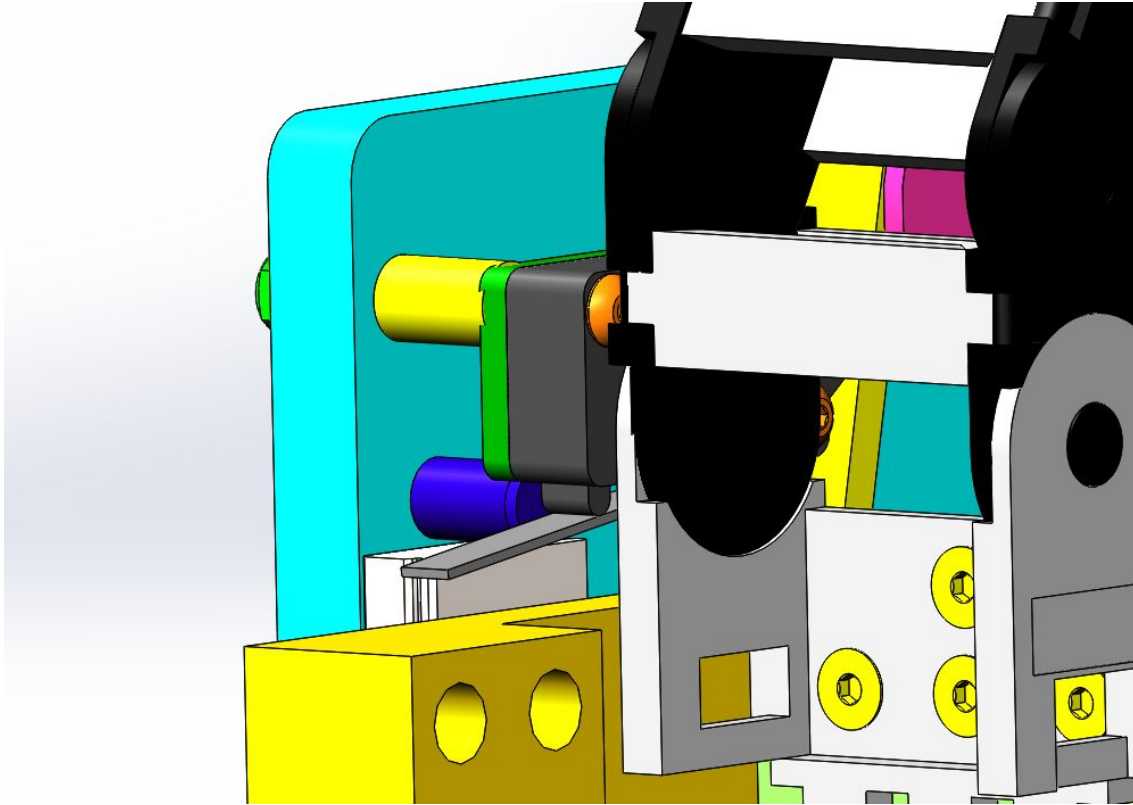


Figure 54. A limit switch at the end of the linear guide rail allows for accurate zeroing of the carriage. As an additional safety measure, dowel pins (shown in purple) will be pressed into the mounting plate as hard stops for the carriage to prevent it from over traveling.

The drawings for all these z-axis components can be found in Appendix L.

6.5 | Electrical and Controller Design

The electrical considerations were dependant on the the motor and hardware design. After the motors were decided on, the next step was to choose motor drivers and a robust controller that could integrate into Labview with ease. The motor drivers are CWD556 Stepping Motor Drivers from Circuit Specialists, these are 2-phase digital stepper drivers with internal PID control and automatic microstepping from full step to 52,100 steps per revolution. These drivers required 24-50 volts each so a 36volts 8.5amps single switching power supply with three parallel outputs powers both stepper motor drivers. This allowed automation control for the vertical (Z-axis) and the horizontal length (X-axis) while still allowing the use of two of the previously used ISEL linear driver motors for compound motion horizontally through the cross section.

For the controller, a basic Arduino Uno will be receiving commands from a computer running the Labview program. A serial to USB cable double as the Arduino 5V power supply and sends the Labview commands from the interface. Outputs on the Arduino are wired to the pulse

+/- and the direction +/- terminals on both motor drivers. Additionally the limit paddle switches on the vertical arm are wired into the board for logic control of software stops and zeroing position.

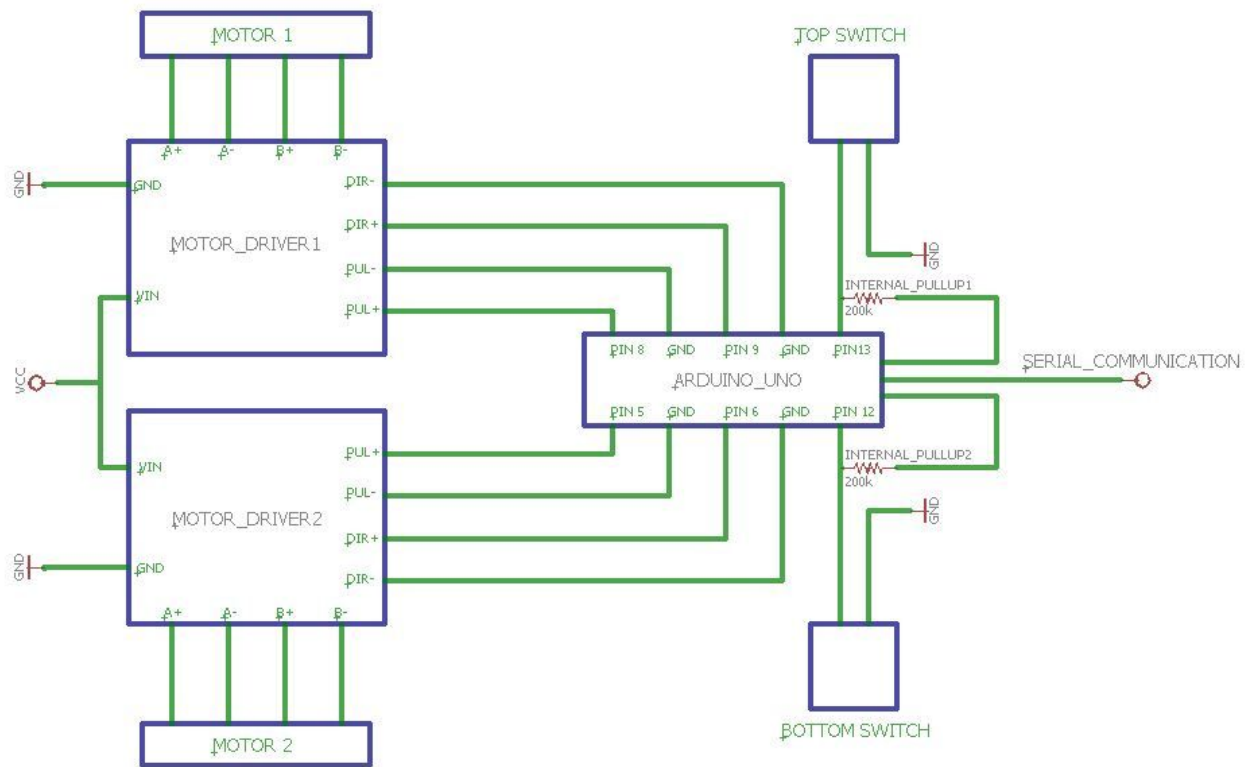


Figure 55 - Wiring Schematic and Electronics Diagram

Here is a simplified visual schematic of the motors, drivers, controller and switches.

6.6 | Software design

The software was designed using LabView, this program utilizes a built in and adaptable user interfaces for a wide variety of external hardware, controls and sensors. The main controller panel (Figure 56a) shows instructions on running the program. It also has start/stop buttons, various presetting constants and adjustable inputs for the motors and requirements. The block diagram (Figure 56b) runs the code to configure the arduino and begin sending control instructions. Note that this setup is an example of the software that can be used, but the users will make their own interface in LabView based on their desires.

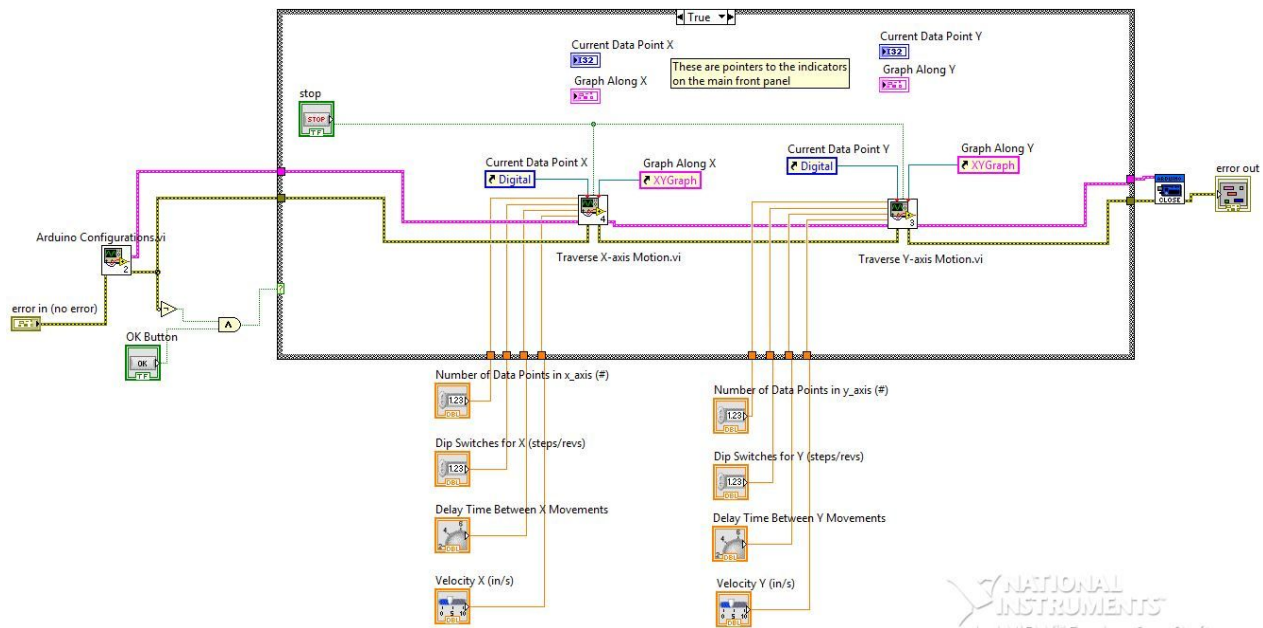
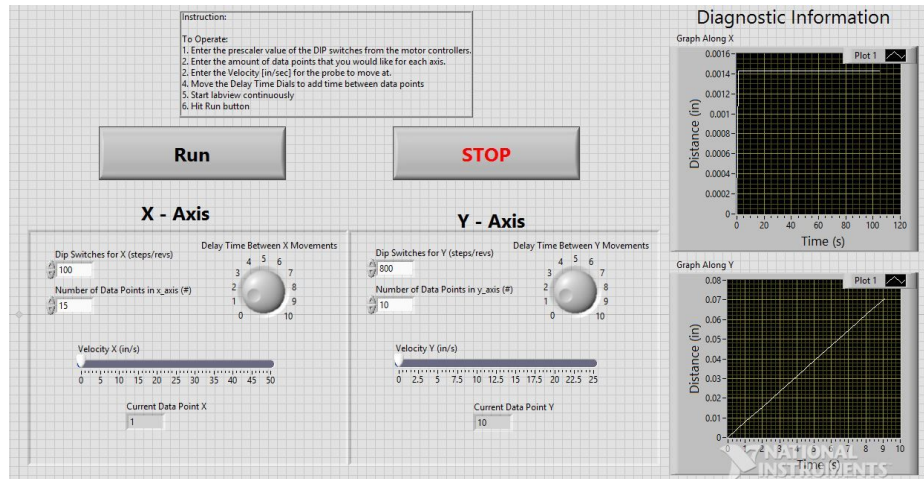


Figure 56. LabView interface: a) The Front Panel and main user interface, b) the main block diagram for running the code.

6.7 | Future Manufacturing

A small design could be made on the horizontal arm to further improve performance. The steel shaft that runs through the horizontal arm to drive the z-axis pulley currently spins on oil-impregnated bronze bushings. It would be nice to be able to grease the bushings periodically for machine maintenance

to minimize wear on components. In order to accomplish this, a simple thru hole with a tapped zerk fitting will allow for greasing of the bushing with a grease gun.

Additionally, drag chains should be incorporated into the x and y-axis, to improve cable management. Brackets can be manufactured out of sheet metal and attached to the current 80/20 aluminum tubing structure, and all wiring for the stepper motors and motor drivers can be routed through them.

Chapter 7 | Design Verification Plan

7.1 | Test Description Plan

Once the device is completely assembled, the team must verify that the constructed device meets the specifications set out by the customer. The development of the Design Verification Plan (DVP) is used to help the team determine critical areas and plan accordingly on how to control those areas in the case of failure or non-compliance. The tests are created through expansion of the consumer specifications for the design. These tests range from a simple pass/fail through inspection or measurements of size to testing for pressure drops due to the entire system inside the wind tunnel. The DVP shows the specific values for which the team will test for. The following is a list of the tests that the team will be conducting:

External Airfoil Properties

Test #1-5: These three tests include the length and weight of the two vertical and horizontal airfoils. The two airfoil shells will be manufactured by Dr. Doig's Experimental Aerodynamics class to test for aerodynamic properties. Once these airfoils have been tested and approved, the team will measure its physical properties; length, thickness, and overall weight of the shells. The thickness of the vertical airfoil is to be no more than 4" and between 23"-25" long, and the horizontal no more than 3" thick and between 44"-46" long.

Internal Airfoil Components

Test #6: This criteria tests the adjustability range of the pulley system located inside the vertical airfoil. This pulley adjustment will allow for changing the tension in the belt. Although, this tension does not matter, the belt needs to remain in tension so that it will operate efficiently and effectively. The adjustment allows for compensation of any initial belt stretching. The adjustability range between the pulleys will be 2" to 3".

Test #7: Drive shaft deflection will be tested outside of the assembly but simulating working support conditions. The deflection of the drive will be measured at the location where it is assumed to have the highest deflection. This deflection is to be less than 3mm.

Test #8: Cable interference requires the team to observe the device in full motion range as it operates realistically. This test will be a mere observation/inspection test to see if the cables and tubes get caught in any type of pinch points.

Test #9: The clearance inside of the the vertical airfoil is already expected to be quite low since the shape is designed to be as thin as possible. Thus the allowable minimum clearance is 0.1”.

Motion Range

Test #10-11: Vertical range of motion is required to be equal to or exceed 18”. This will be measured as the vertical motion is activated. Vertical motion speed will then be determined and this is to be between 0.5-2in/sec as operation range.

Test #12-13: Horizontal range of motion is required to be equal to or exceed 35”. This will be measured in the same matter as the vertical motion and the speed should also be within the same range of 0.5-2in/sec.

Test #14-15: X axis, down the length of the wind tunnel, motion range is to last least cover 65” down the length of the section at a speed of between 0.5-3in/sec.

External Support

Test #16: The power screw that will be used to provide the x-axis motion is mounted at two locations: at the opposite ends of its length. The deflection will be measured at the location of where it is calculated to be the highest. This deflection is not to exceed 7mm.

Test #17: Alignment between the two supporting brackets at each end of the power screw must be measured to ensure that it does not exceed 0.5” difference between the two ends. This category also includes alignment of all the support brackets between all the connected parts. Misalignment is to be no more than 0.5” in all areas.

Test #18: Exposed sharp edges and corners will be chamfered, filleted, deburred or sanded down to ensure that these points do will not cause injury, Pinch points will be covered with a housing.

Test #19: The rotating drive shaft for the z axis drive is located approximately 5ft of the ground

Overall Performance Criteria

Test #20: Probe Deflection will be measured at the tips of the measurement probes at maximum test speed (MTS), which is 125 mph. This deflection is not to be greater than 3mm. This deflection is very difficult to predict since it depends on both the stiffness of all the internal components and the stiffness of the carbon fiber airfoil itself.

Test #21: Flow disturbance of the device will be measured by observing the pressure drop in the tunnel as a result of the device obstruction the flow. This pressure drop is to be no more than 5 psi at MTS.

- Test #22: Test section cross section coverage of the probe is to be approximately 80% of the overall cross section. This will be determined by operation the device though maximum motion range in all three axes.
- Test #23: Repeatability of the device will be measure by setting a location of the device then moving it away and back again. The device should come within 2mm of the position it was at previously.
- Test #24: Assembly/Disassembly time will be estimated as the team assembles and disassembles the device multiple times. This time should be between 30 to 45 minutes, although this is not a strict requirement.
- Test #25: The overall cost of the device is to be no more than \$2400. This cost is estimated in a previous section of this report and will be revisited again as parts are ordered.

7.2 | Test Results

As mentioned earlier in this report, our sponsor agreed that the objectives of our project needed to be changed, as the project scope was too large for a single team to complete in the time period of our senior project class. As a result, we did not manufacture the carbon fiber components of our design, and thus did not have to test any specifications related to these particular design features. The tests that are no longer relevant due to objective changes are noted below. The final Design Verification Test Chart can be found in Appendix N.

Appendix N shows the results of our extensive design testing. An accompanying note is provided in this chart so as to discuss the test results. As noted in its legend, the table is color coded to show the results of our testing. The green colored cells indicate a test that has been fully passed when measured against our specifications. The yellow colored cells indicate that a test's results are acceptable. This result can occur in the table for two different sets of tests. For test six, it was determined after the pulley components were built that a belt adjustability of two to three inches is not necessary, and our range of one-and-a-half inches is acceptable for a functional design. Test twenty-five is also marked as acceptable, because although this project was slightly over budget, our sponsor notified us that he would allow us to go over budget slightly to complete our design. Any tests in which we have failed the criteria would be marked in red in the table of Appendix N. Note that there were no valid specifications that were directly not met, so none of our tests were failed.

Blue cells in Appendix N are no longer applicable tests for our design. This is because certain design objectives were removed by our sponsor. As a result, the tests involving the dimensions of the airfoil components, exposed components, and flow disturbance no longer need to be validated. Also, it was determined that measuring the deflection of the probe during wind tunnel operation was too dangerous, so we were not required to perform that test. External airfoil properties testing has become Not Applicable in the testing method since there is no long an airfoil to test. Internal clearances between the internal driving mechanics and parts and the airfoil has also been marked Not Applicable in the testing chart since there is no longer an enclosure around the mechanism and therefore no clearances or interferences to be measured. As part of a safety check list, it was specified that there was to be no rotating section below a specified

height, however since there is no airfoil covering the z-axis assembly, the belt drive is considered to be an exposed rotating system. This specification was made with having a shell in mind therefore the safety test for rotating system exposure is deemed Not Applicable. All other rotating systems are either above the specified safety height or shielded by other parts in the assembly. Probe deflection and flow disturbance were two key specifications noted by Dr. Doig, however due to the elimination of the external airfoil, the system will clearly have a higher than expected flow disturbance due to a number of different geometries exposed to the wind flow that would trip the boundary layer. After discussions with Dr. Doig, this test was marked Not Applicable since without the airfoil shell flow disturbance is expected to be high due to the increase in volume of parts inside of the wind tunnel when compared to the old Excalibre Beam. It was originally planned that the team would design a probe holding device which was described in Chapter 5, however Dr. Doig deemed this part unnecessary since they did not want to be limited by the design and instead asked for a mounting plate where they would be able to 3D print parts that would hold measurement devices and mount the parts to the plate. This plate design is previously described in Chapter 6 as part of the final product description.

Chapter 8 | Future Considerations and Recommendations

A future consideration to build onto the design is to create the airfoil shell which was previously part of the original plan. After some discussions with certain individuals who regularly work with the wind tunnel, it has been considered that this airfoil shell may not be necessary. An airfoil addition would make the arm more aerodynamic, but putting on a shell covering would further increase the volume of the obstruction placed inside the wind tunnel. Depending on whether the arm alone has a significant enough impact on the test results inside the wind tunnel, an airfoil shell could do more harm than good.

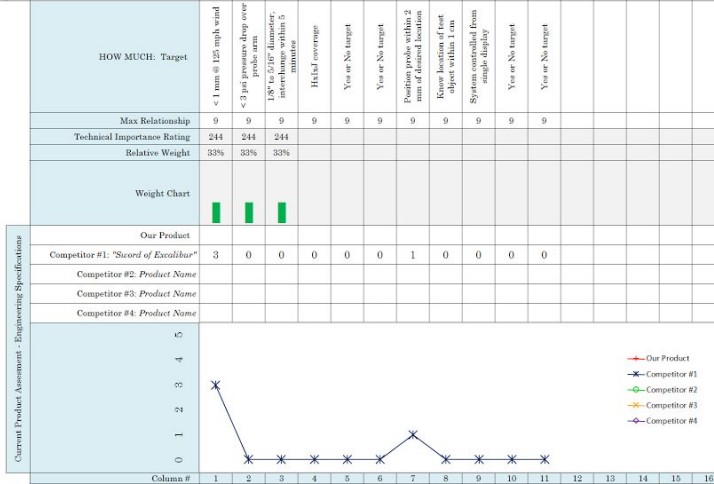
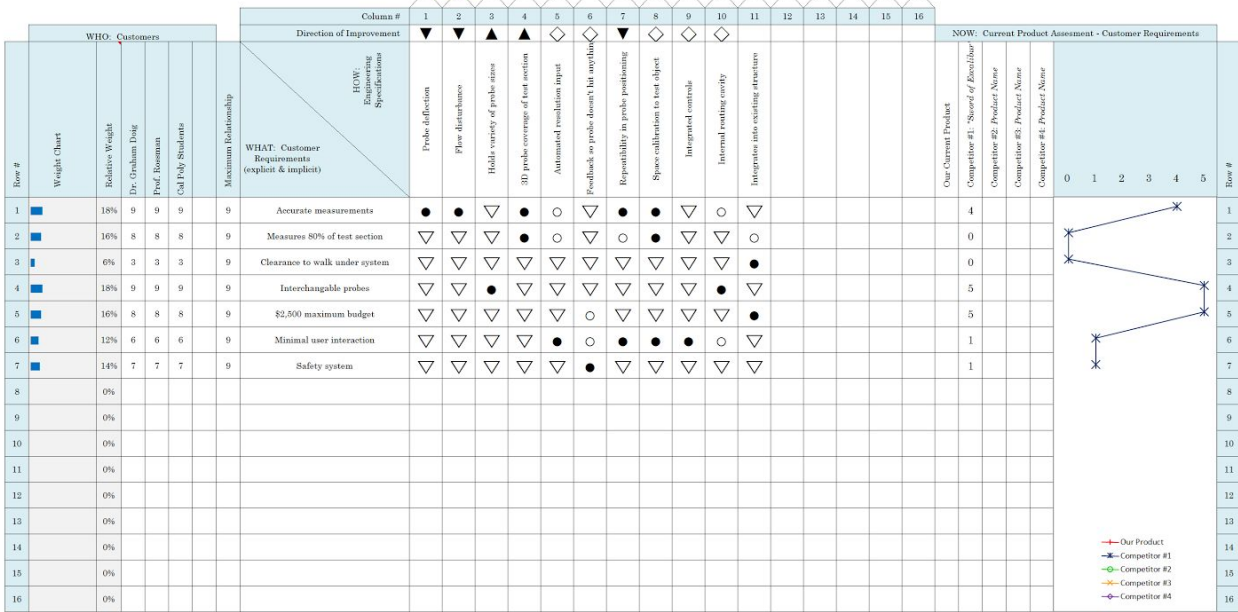
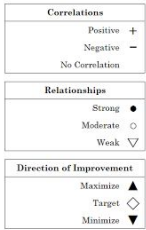
It can be seen from the development of both hardware and software that the modularity of the system allows for upgrades that could potentially increase accuracy or precision if necessary. This can be done through changes with the motor, motor drivers, timing belt, power screw or the existing ISEL motors. The software design has been developed so that it is user friendly for those who merely want to utilize the wind tunnel and device through the LabView user interface and it can also cater to those who are more experienced with LabView and electronics so that internal code and motor driver settings can be change to produce the desired performance level.

Appendix A - QFD

QFD: House of Quality

Project: Cal Poly Low Speed Wind Tunnel Probe Automation

Revision: 04
Date: 2/12/2016



Template Revision: 0.9
Christopher Battles

Appendix B - Morphological Chart

Function	Means								
	1	2	3	4	5	6	7	8	9
Hold Probe	Clamp	vise	coil	cap	set screw	magnets	3D Print Hydraulic positioners	Clips	springs
High Accuracy Mount to Frame Min Deflection	Lead Screw Top supports	Servo side cross section	Stepper t-slot bars materials	Timing Belt Suspension flaps	Laser truss cross beams	Lin Bearing magnets thru flow	glue composites geared extensions	Actuators adhesion compensation	
80% Section Min Flow Dist	telescoping Air Foil Pressure trans	linkage mesh	tension cables smoke/particles	rails small size	crane floating probe	ball socket		Double airfoil	
Space Calibration	Collision switch tubes	coordinate sys	datum	gps	string pot	camera	labview stops equipment limits	switches/relays	
Feedback/Collision Internal Routing		machine zero cavities	anti backlash hooks	dead zone clips Angular extension	hard stop wireless	phys limits wire racks		Image compare	
Range extension	lead screws	belt	gearing platform		stack	chain			

Appendix C: Go/No Go

Concept	Possible Specification Violations	Go / No Go
Airfoil shaped structural members		Go
Small structural members	Internal routing cavity	Go
Rigid structure	Flow disturbance	Go
Wire probe support	Deflection	Go
Motor stack	Integration to existing structure	Go
Motor displacement multiplier	Repeatability in probe positioning	Go
Telescoping arm		Go
Scissor linkage	Flow disturbance/Stability	No
Rack and pinion		Go
Store-bought airfoil	Flow disturbance/high deflection	No
Reflective particles/Smoke + laser sensors	Cost	No
Flaps Airfoil	Software control	Go
Ridgidly mounted double airfoil	Integration to existing structure	Go
Multibar linkage		No
Ball and socket + telescoping arm	Full coverage	Go
"Snake-like" arm		No
Flexible probe mount	Deflection	Go
Camera GUI	Cost	Go

Appendix D: Pugh Matrix

Criteria / Concept	1	2	3	4	5
A	+	-	+	+	S
B	S	+	+	+	+
C	+	+	+	+	+
D	+	+	+	+	+
E	+	+	+	+	+
F	-	-	-	-	-
G	+	S	+	+	+
H	-	+	+	-	+
Sum +	5	5	7	6	6
Sum S	1	1	0	0	1
Sum -	2	2	1	2	1
Total Score	3	3	6	4	5

Criteria Description		Concept Description	
A	Small probe deflection during use	Baseline	Current probe traverse, i.e. the "Sword of Excalibur"
B	Little to no flow disturbance	1	Rigid structure concept
C	Variety of probe sizes/shapes held	2	Steel wire concept
D	Covers 80% testing region	3	Modified "Sword of Excalibur"
E	Repeatability in positioning	4	Double Airfoil
F	Cost	5	Telescoping ball-and-socket arm
G	Internal routing cavity		
H	Integrates to existing structure		

Appendix E: Weighted Decision Matrix - Minimal Deflection

Matrix for: Minimize Deflection

Design Criteria	Cost	Manufacturing Time	Stability	Complexity	Analysis	Size	Overall Satisfaction
Concepts	0.05	0.05	0.3	0.25	0.15	0.2	1
Support Beams	8	8	7	7	7	4	6.1
	0.4	0.4	2.1	1.75	1.05	0.8	
Cross sections (I-beams)	7	8	8	7	6	6	6.65
	0.35	0.4	2.4	1.75	0.9	1.2	
Materials Selection	6	8	7	8	9	9	7.65
	0.3	0.4	2.1	2	1.35	1.8	
Flaps	8	7	8	5	4	8	6.2
	0.4	0.35	2.4	1.25	0.6	1.6	
Composites	6	6	9	7	7	7	7.2
	0.3	0.3	2.7	1.75	1.05	1.4	
Compensation	10	10	4	7	7	10	6.5
	0.5	0.5	1.2	1.75	1.05	2	
Springs	8	8	4	7	7	9	6.2
	0.4	0.4	1.2	1.75	1.05	1.8	

Appendix F: Weighted Decision Matrix - Motion Drives

Matrix for: Motion Drives							
Design Criteria	Cost	Number of Parts	Durability/Life	Precision	Complexity	Space Requirements	Overall Satisfaction
Concepts	0.08	0.1	0.15	0.2	0.2	0.27	1
By hand	10	10	7	1	5	5	
	0.8	1	1.05	0.2	1	1.35	5.4
Motor stacking	7	6	8	6	7	2	
	0.56	0.6	1.2	1.2	1.4	0.54	5.5
Rack and Pinion	8	7	6	9	8	8	
	0.64	0.7	0.9	1.8	1.6	2.16	7.8
Timing belt	6.5	6	5	8	7	6.5	
	0.52	0.6	0.75	1.6	1.4	1.755	6.625
Chains	5	6.5	6	5	7	8.5	
	0.4	0.65	0.9	1	1.4	2.295	6.645
Angular extender	8	8	9	3	7	1	
	0.64	0.8	1.35	0.6	1.4	0.27	5.06
Gear transmission	0	0	0	0	0	0	
	0	0	0	0	0	0	0
Magnet	0	0	0	0	0	0	
	0	0	0	0	0	0	0
Telescopic	4	4	5	8.5	4.5	9	
	0.32	0.4	0.75	1.7	0.9	2.43	6.5
Linear Actuators	3	8	6	9	7	8.5	
	0.24	0.8	0.9	1.8	1.4	2.295	7.435

Appendix H: Detailed Supporting Analysis

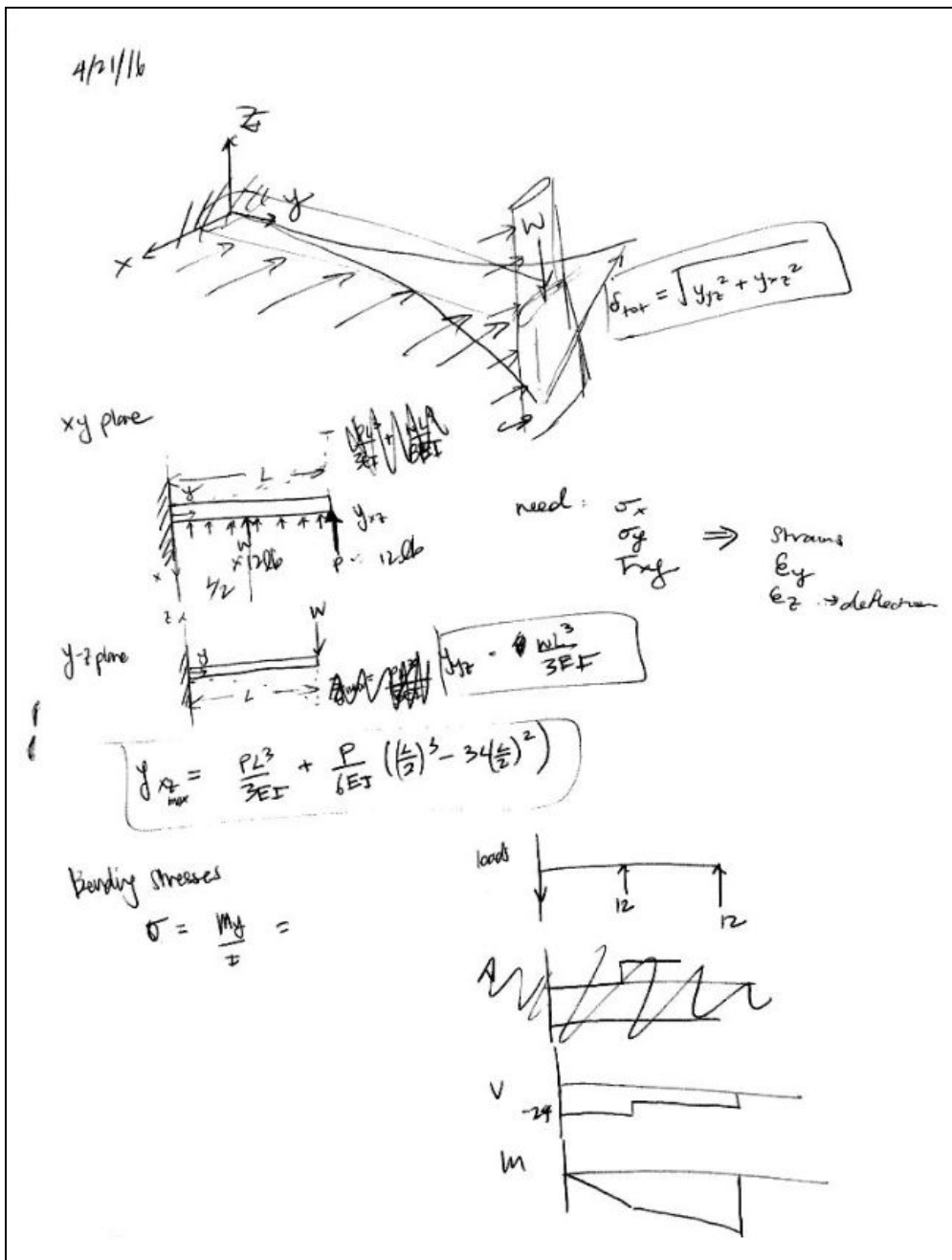


Figure H1. Static deflection of airfoil wing due to weight of the arm and aerodynamic drag force.

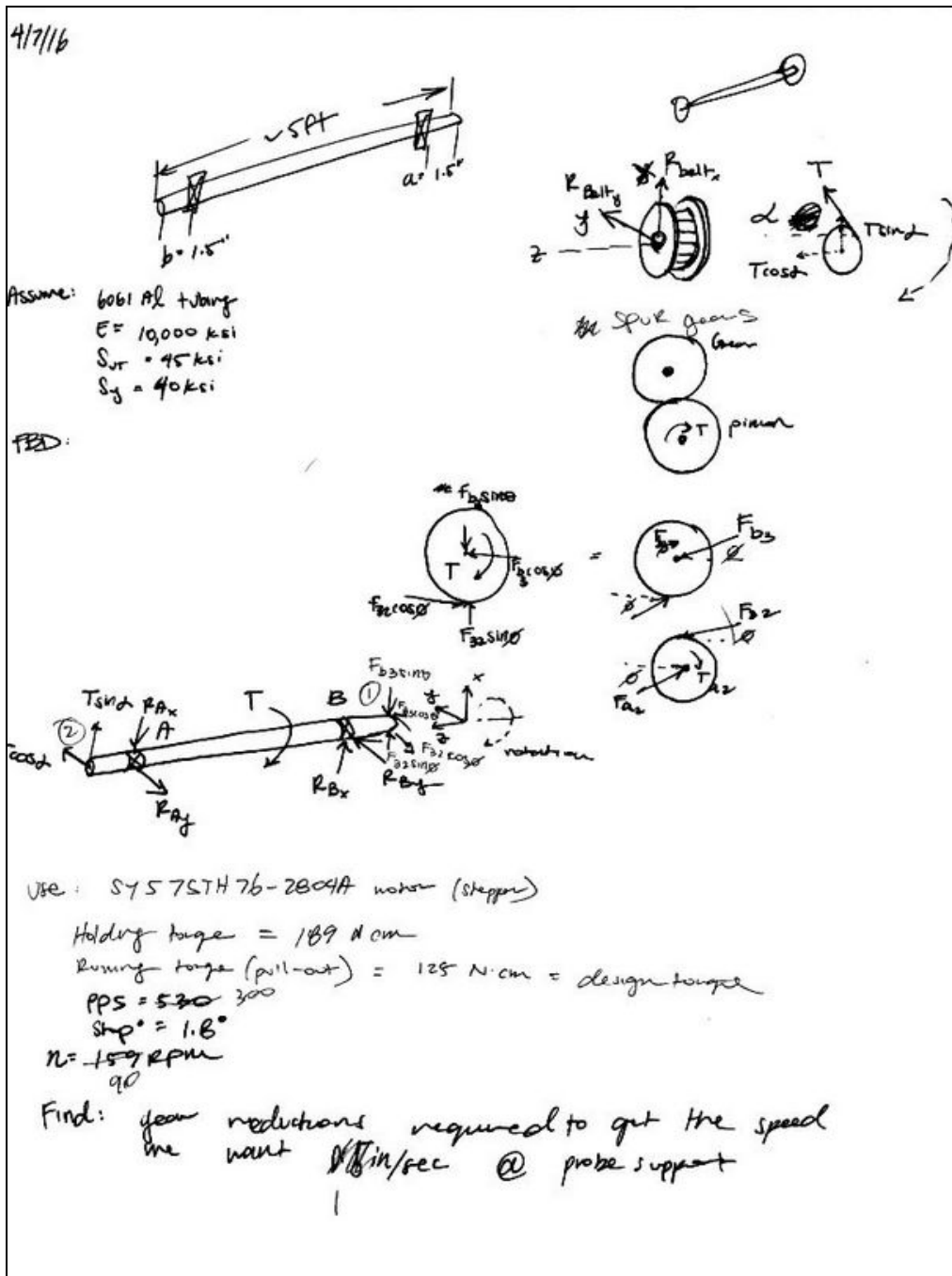


Figure H2. Pulley force analysis.

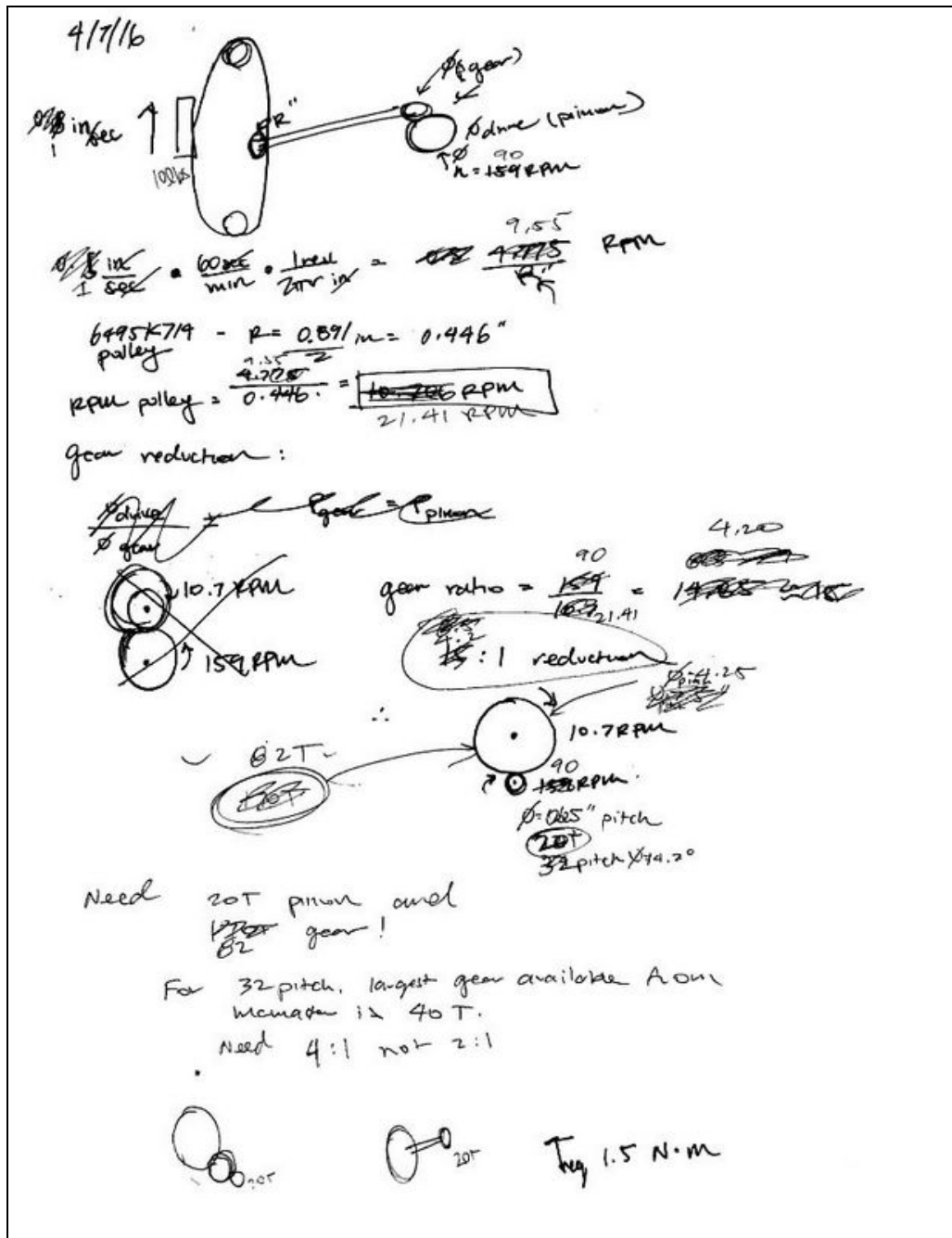


Figure H3. Pulley force analysis continued.

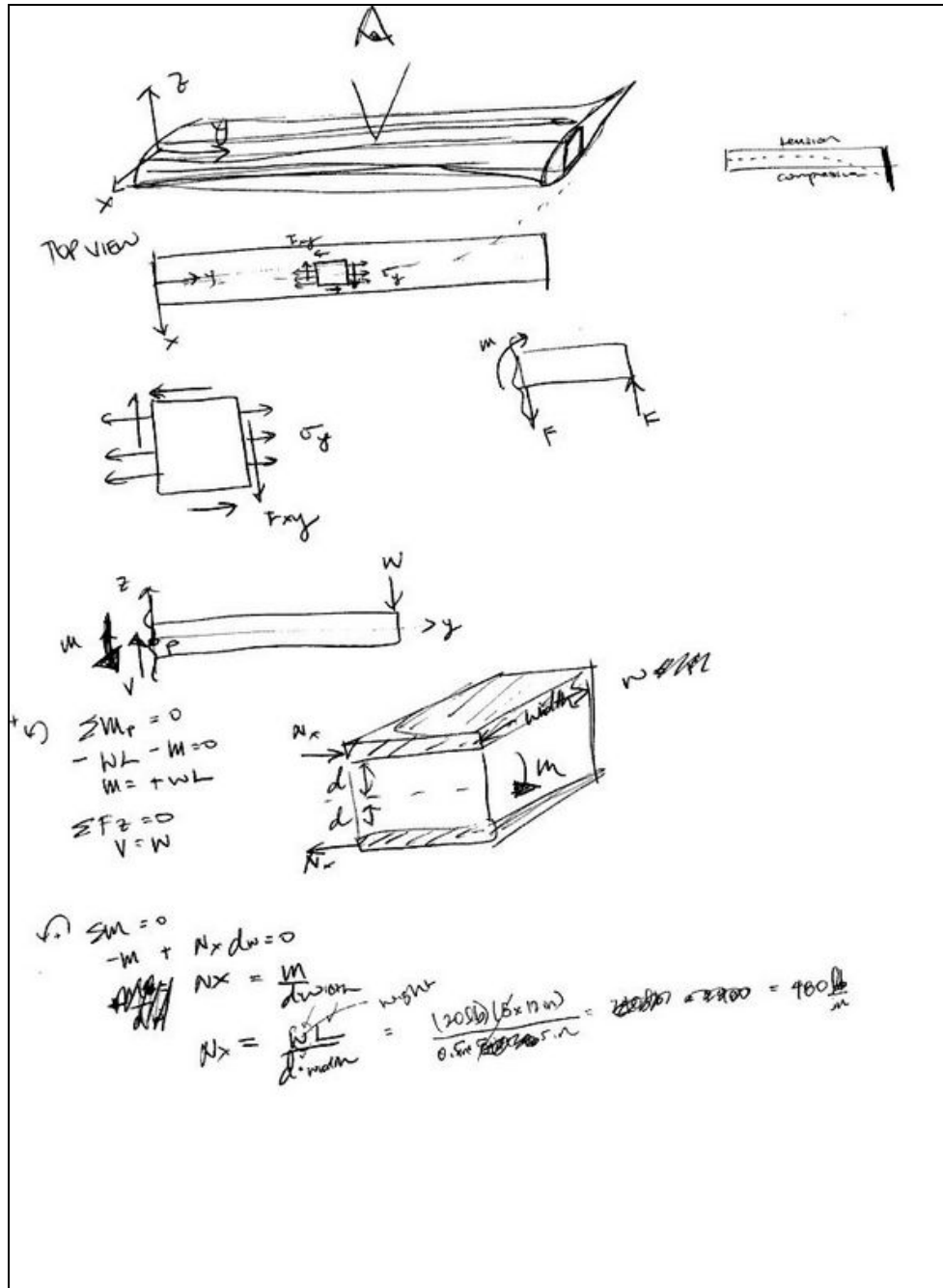


Figure H4. Spar tube calculations.

5/3/16 Carbon analysis continued

Assume: psmds - A basis Factor of safety, AS4/3501-6 UN1

Allowable line load/ply

$$N_{ia} = E_1 E_{ic} \cdot t_{ply} \cdot 0.80$$

$$= (2086) (0.012) (0.002) (0.80)$$

$$= 1000 \frac{lb}{in}$$

$$N_x = \frac{1200 \cdot 0.012}{1" \cdot 1.5"} = 800 \frac{lb}{in}$$

$$\# plies = \frac{1200}{800} = 1.5 \Rightarrow \text{use 2 plies}$$

Find deflection w/ 2 ply laminate

Stress state



$$\sigma_x = \frac{M_y}{I} = \frac{(1200 \text{ in} \cdot \text{lb}) (0.06 \text{ in})}{3.186 \text{ in}^4} = 250 \frac{lb}{in^2}$$

Have $\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \Rightarrow \text{want } \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}$

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = [S] \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}$$

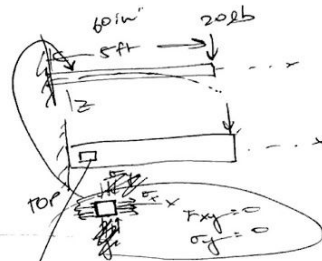
$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = [S] \begin{Bmatrix} 250 \\ 0 \\ 0 \end{Bmatrix}$$

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} 1.25 \cdot 10^{-5} \\ -3.75 \cdot 10^{-6} \\ 0 \end{Bmatrix}$$

$$\epsilon_x \cdot \text{length} = (1.25 \cdot 10^{-5}) (60 \text{ in})$$

$$= 0.00075 \text{ in}$$

$$\frac{lb}{in^2}$$



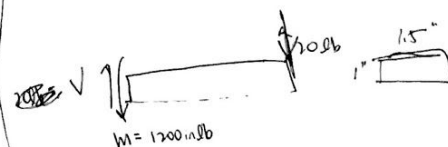
$$N_{xy} = N_{ip} = N_{ip}$$

$$\# 45^\circ \text{ plies} = \# -45^\circ \text{ plies}$$

$$\frac{N_{ip}}{N_{ia}} = \frac{N_{ip}}{N_{ia}}$$

$$N_{xy} = \frac{2086 (60 \text{ in})}{1.5 \text{ in}^2} = 800 \frac{lb}{in}$$

$$\# plies = \frac{800 \frac{lb}{in}}{(0.002) (0.012) (0.80) (1000)} = 17.23$$



$$M = 1200 \text{ in} \cdot \text{lb}$$

$$V = N_{xy} \cdot 1.5 = 0$$

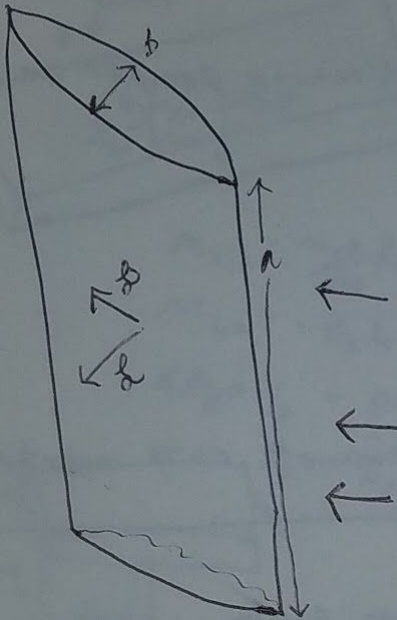
$$N_{xy} = \frac{V}{1.5}$$

$$N_x W H = M$$

$$M = N_x W H = M$$

Figure H5. Spar tube calculations.

Appendix I: Airfoil Fluid Analysis



$$D = \frac{1}{2} \rho U^2 A_p C_D = \frac{1}{2} (1.20 \frac{\text{kg}}{\text{m}^3}) (55.88 \frac{\text{m}}{\text{s}})^2 (0.78 \text{ m}) (0.13 \text{ m}) (0.89) = \frac{169 \text{ N}}{169 \text{ N}}$$

$$L = 0$$

If air foil is at 3° angle to air stream:

$$D = \frac{169 \text{ N}}{169 \text{ N}} \cos(30) = 168 \text{ N}$$

$$L = \frac{169 \text{ N}}{169 \text{ N}} \sin(30) = 8.84 \text{ N}$$

\Rightarrow lift caused by possible misalignment of airfoils
not substantial force

Appendix J: Drive Motor Torque Calculation

TORQUE REQUIRED FOR X-AXIS POWER SCREW DRIVE

POWER SCREW 3/4 - 7 ACME & PLASTIC NUT

$$LEAD = 0.143"$$

$$\phi_m = 3/4"$$

$$f_p = 0.4 \rightarrow \text{ESTIMATED STEEL PLASTIC FRICTION}$$

$$T_R = \frac{F d_m}{2} \left(\frac{L + \pi f d_m}{\pi d_m + f L} \right)$$

$F \Rightarrow$ FOR ON NUT, USUALLY THIS IS W, WEIGHT OF OBJECT BEING RAISED SINCE T_R IS TORQUE TO RAISE A LOAD VERTICALLY

F IS NOW FORCE THAT THE POWER SCREW NEEDS TO OVERCOME WHEN TRYING TO MOVE THE SYSTEM HORIZONTALLY

$$\therefore F = f_R W$$

WHERE f_R IS FRICTION COEFFICIENT BETWEEN CARRIAGE & LIN. RAILS WHICH SUPPORTS THE WEIGHT OF THE STRUCTURE
 $f_R \approx 0.3$ RAILS ARE DESIGNED BE EXTREMELY LOW FRICTION.

W IS SUPPORT SYSTEM WEIGHT

$$W = 200 \text{ lbf} \rightarrow \text{MOTORS} + \text{AIRFOIL} + \text{T SLATS}$$

$$T_R = n f_R \frac{W d_m}{2} \left(\frac{L + \pi f_p d_m}{\pi d_m + f_p L} \right) \quad n \rightarrow \text{SAFETY FACTOR 2}$$

$$= 2 \frac{(0.3)(200 \text{ lbf})(.75)}{2} \left(\frac{.143 + \pi(.4)(.75)}{\pi(.75) + 0.4(.143)} \right)$$

$$= 20.24 \text{ in-lbf}$$

$$= 20.24 \text{ in-lbf} \times \frac{16 \text{ oz}}{1 \text{ lbf}}$$

$$= 324 \text{ oz-in}$$

$$\boxed{T_R = 2.3 \text{ N.m @ } S.F. = 2}$$

SELF LOCKING CONDITION POWER SCREW

$$\pi d_m f_p > L$$

$$\pi(.75) \times .4 > .143$$

$$.942 > .143 \quad / \rightarrow \text{SELF LOCKING}$$

Appendix K: Bill of Materials

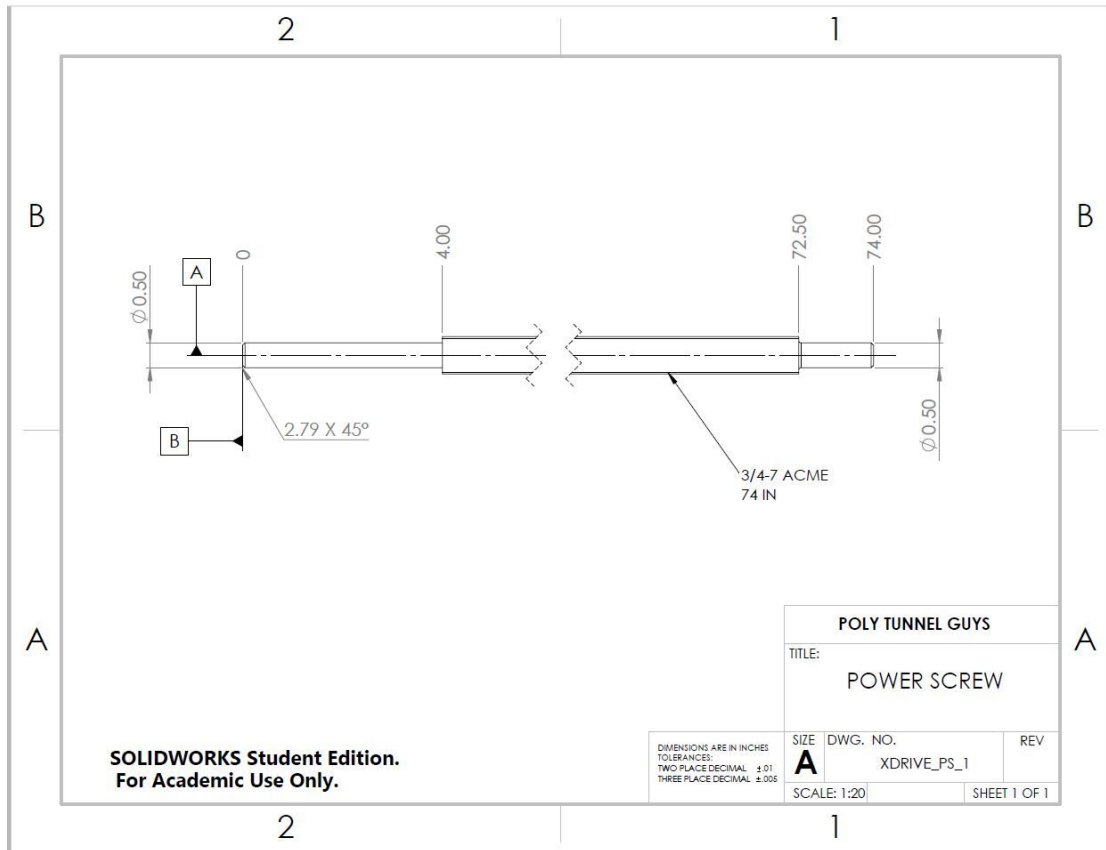
Description	Quantity		Cost	Extended Cost
Timing Belt XL Series 3/8" width	5	feet	2.97	14.85
XL Series Pulley 1.12" OD	3	each	14.68	44.04
1/4" x 3/4" Long Shoulder screw 10-32 Thread	2	each	9	18
M8x1.25 Low Profile SHCS 10mm length	1	10/pack	6.38	6.38
5/16" thick x 1.5" width x 1ft 6061 Bar	1	each	4.06	4.06
1/2" thick x 1.5" width x 1ft 6061 Bar	1	each	6.71	6.71
1/8" Dia SS Dowel Pins 1" length	1	25/pack	7.15	7.15
1/4-20 Black Oxide SHCS 7/8 length	1	each	–	
External Retaining Ring 3/16 shaft	1	100/pack	3.99	3.99
18mm Wide Linear Guide Rail 300mm Long	2	300mm/each	231	462
M3x0.5 SHCS 8mm length	1	100/pack	4	4
18mm Guide Rail Carriage	1	each	97.02	97.02
M3x0.5 SHCS 6mm length	1	50/pack	5.66	5.66
Snap Together Hose Carrier 3ft	3	feet	63.42	63.42
Drag Chain Mounting Brackets	1	2/pack	11.4	11.4
1.5" x 1 ft x .125" thick Low Carbon Bar	1	feet	2.97	2.97
M6x1.0 SHCS 10mm Length	4	each	–	
M3x0.5 Black Oxide Flat Head 12mm length	1	100/pack	5.38	5.38
1/2" x 1.75" x 6" 6061 Plate	1	each	4.69	4.69
M6x1.0 SHCS 45mm Length	1	10/pack	5.52	5.52
M8x1.25 Black Oxide SHCS 18mm Length	1	25/pack	4.28	4.28
1" x 2.5" x 2ft	1	each	38.74	38.74
4130 .063" Thick 6"x12" sheet	1	each	18.39	18.39
M6 dowel pins 16mm length	1	10/pack	5.92	5.92
10-32 Set screw	1	25/pack	3.64	3.64
Nema 23 Motors	2	each	23.89	47.78
Stepper Motor Drivers	2	each	49	98
Power Source	1	each	69	69
USB to A-B cable	1	each	1.95	1.95
Arduino Uno	1	each	24.95	22.39
limit switches	4	each	1.5	6
Motor Flex Shaft Coupling	1	each	71.14	71.14
1/2" OD x 60 Long 1045 Black Oxide Shaft	60	inches	35.13	35.13
1.5"x1.5" x .125 wall 6ft long	6	feet	35.36	35.36
3/8" Thick 5" width Carbon Steel Plate	1	feet	30.11	30.11
1" x 1.5" x .065" wall Hot Rolled A513 Rect. Tube	4	feet	8.12	8.12
1/2" Oil Embedded Sleeve Bearing	6	each	1.37	8.22
4-40 set screws 3/8 length	1	10/pack	4.59	4.59

3/8" Thick x 5" Width x 1ft 6061 plate	1	each	16.82	16.82
.500" OD .125" wall x 3ft 4130 Tubing	3	feet	27.97	27.97
1/4-20 x 4.5" length SHCS	1	5/pack	8.26	8.26
1/4-20 Flange Nut	1	100/pack	6.52	6.52
1/4" OD x 3/4" Shoulder 10-24 thread	4	each	0.95	0
10-24 flange nut	4	each	3.7	14.8
3/8" thick x 6" x 6" low carbon steel plate	1	each	21.06	21.06
3/4"-7 x 7' ACME Leadscrew	1	each	176.47	176.47
Flange Nut	1	each	31.21	31.21
Linear Rail	1	each	283.01	283.01
Linear Carriage	4	each	59.81	239.24
5/16-18 T-Slot Threads	50	each	0.24	12
5/16"x5/8" T-Slot Mounting Bolts	50	each	0.32	16
M6 LowProfile SHCS x 16mm length	4	25/pack	8.89	8.89
6063 AL U channel 1/4 thick	4	feet	62.15	62.15
Helical Shaft Coupler	1	each	49.62	49.62
Steel Ball Bearings	2	each	66.98	133.96
Steel Stock 1.5x5x1ft	1	each	95.38	95.38
Steel Stock .25x4x6	2	each	9.94	19.88
Gusset	16	each	3.5	56
Motor Mounting Plate	2	each	17	34
Motor Mounting Bracket	2	each	20	40
Mount Bridge Base	2	each	16	32
Mount Bridge Base	2	each	30	60
Pulley Brace	1	each	115	115
U Channel Spacer	10	each	5	50
Vertical Wing Attach Plate	2	each	30	60

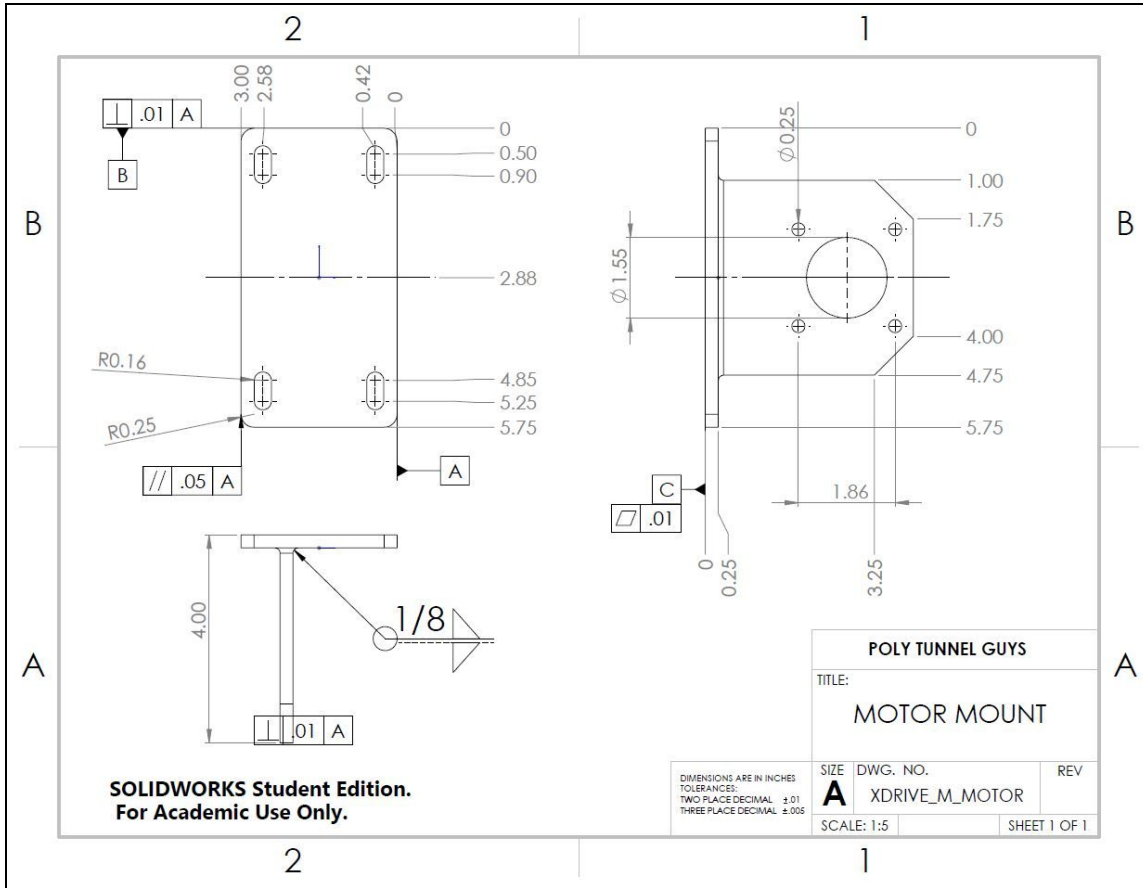
Total: \$2946.24

Appendix L: Part Drawings

Appendix L1: Power Screw Machine Ends



Appendix L2: Motor Mount



POLY TUNNEL GUYS

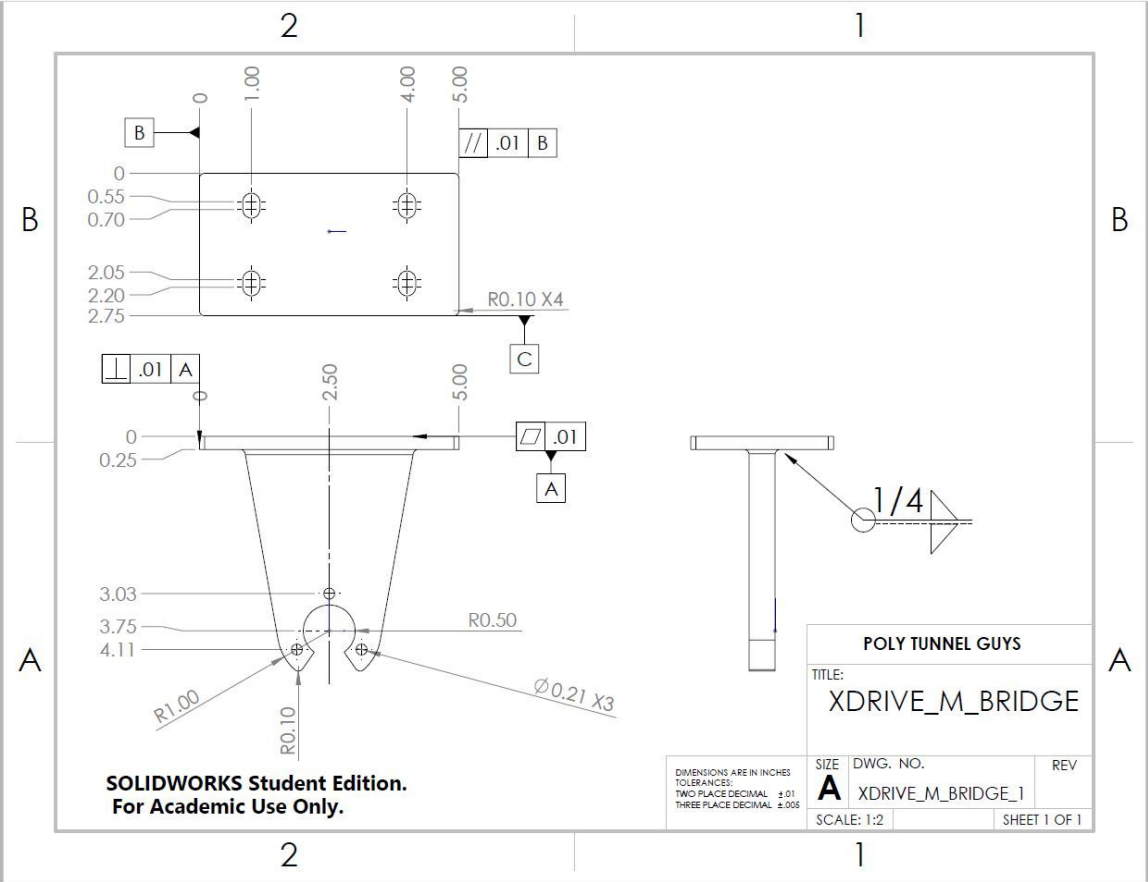
BEARING MOUNT

SIZE A DWG. NO. XDRIVE_M_BEARING_1 REV

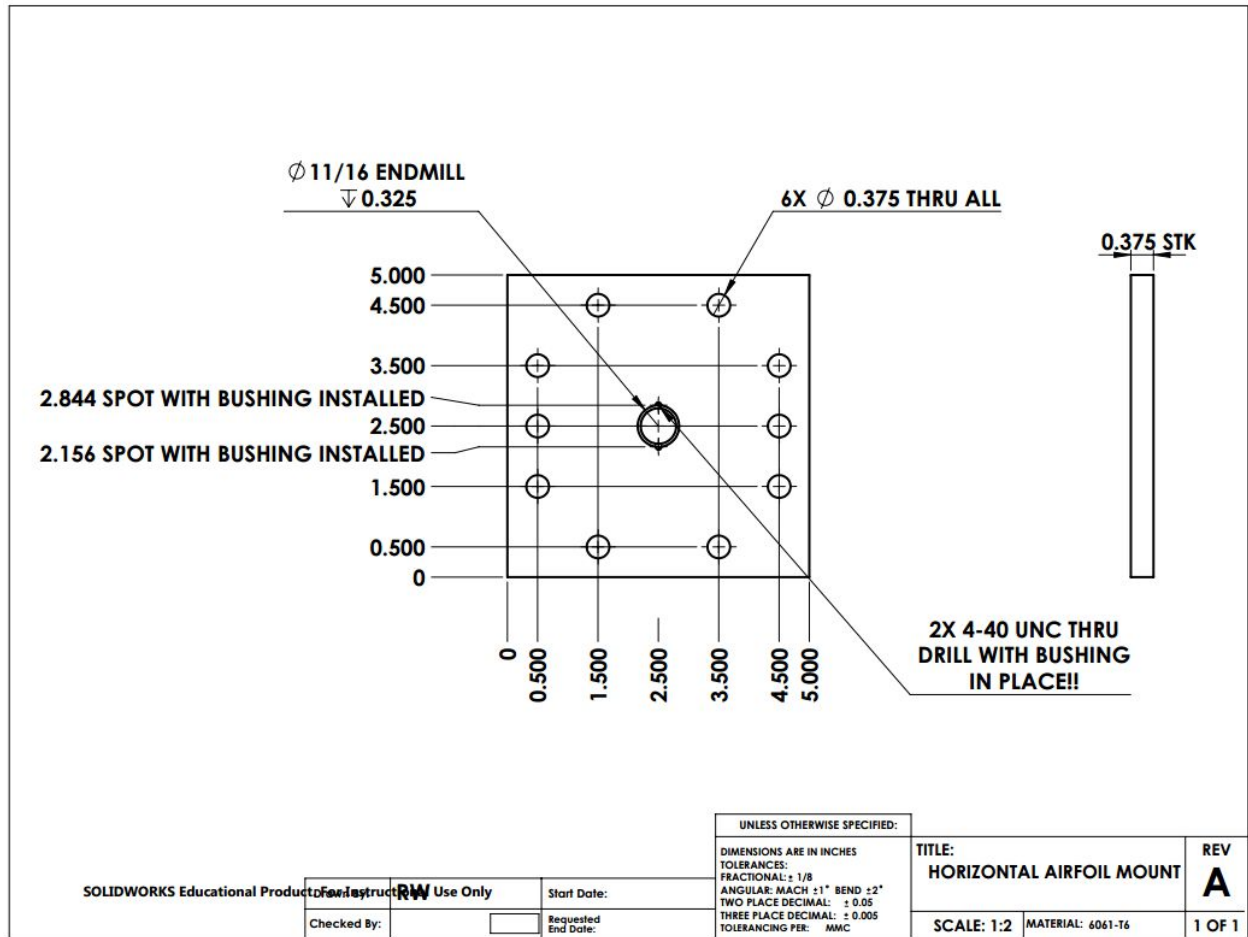
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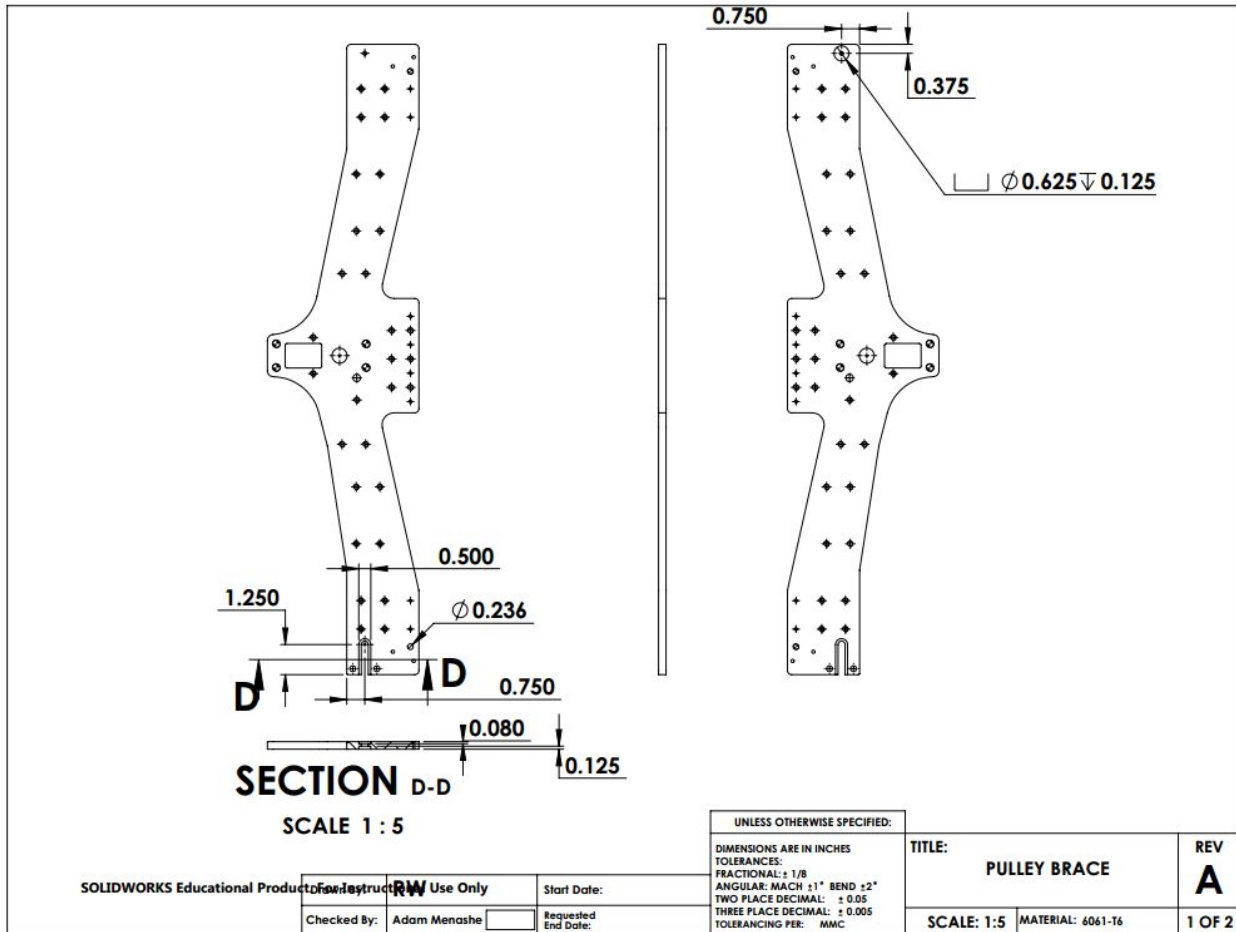
Appendix L4: Mount Bridge

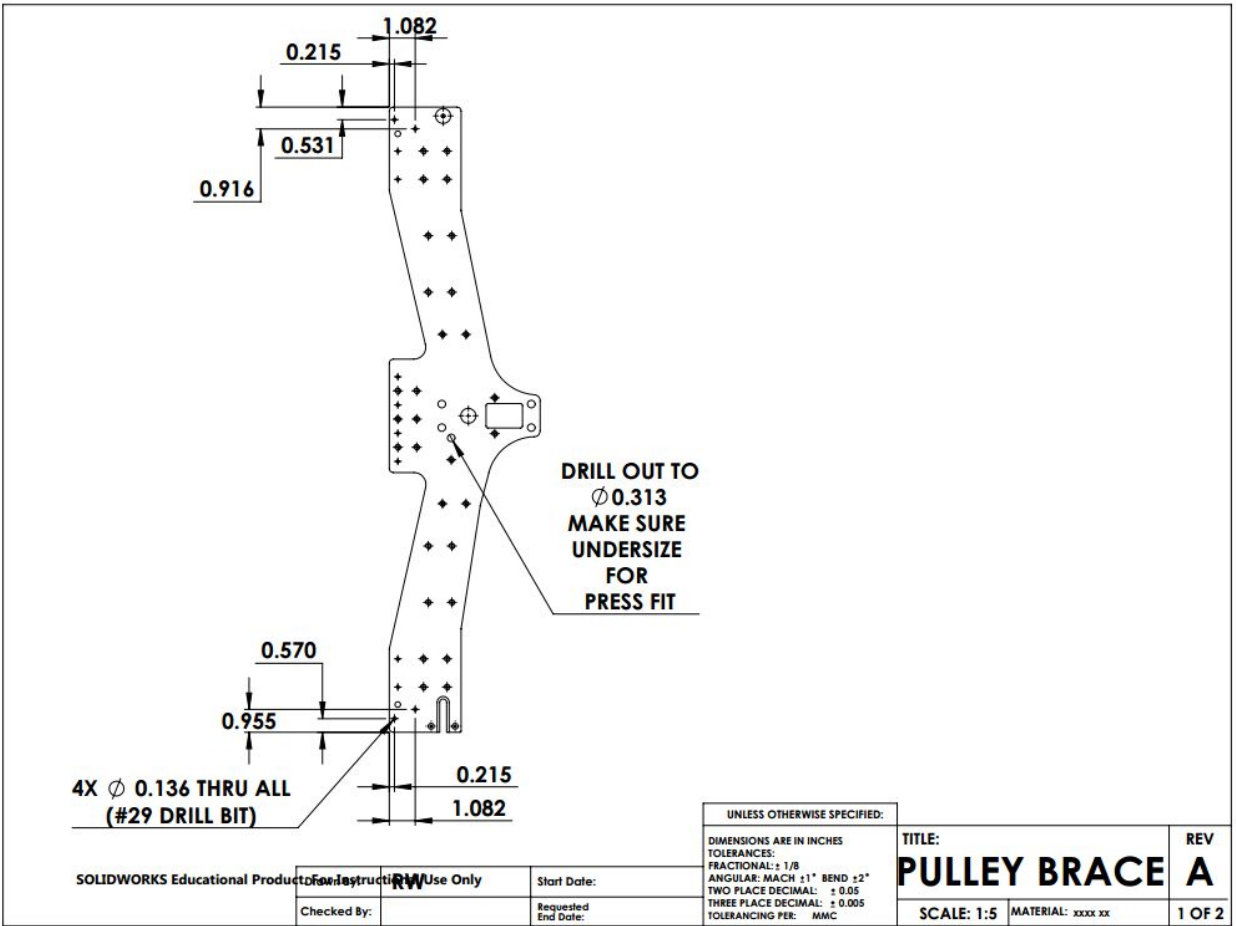


Appendix L5: Horizontal Airfoil Mount

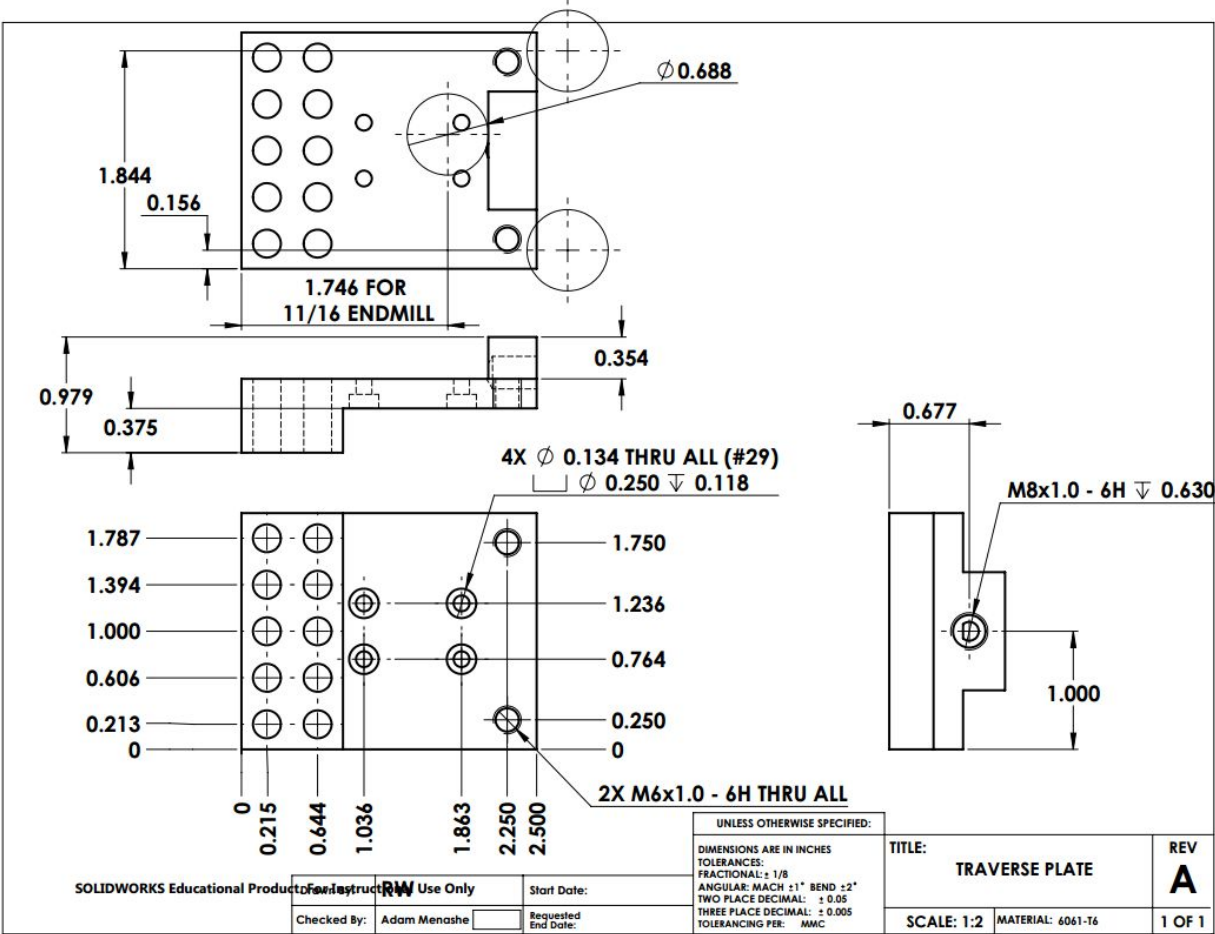


Appendix L6: Pulley Brace Plate

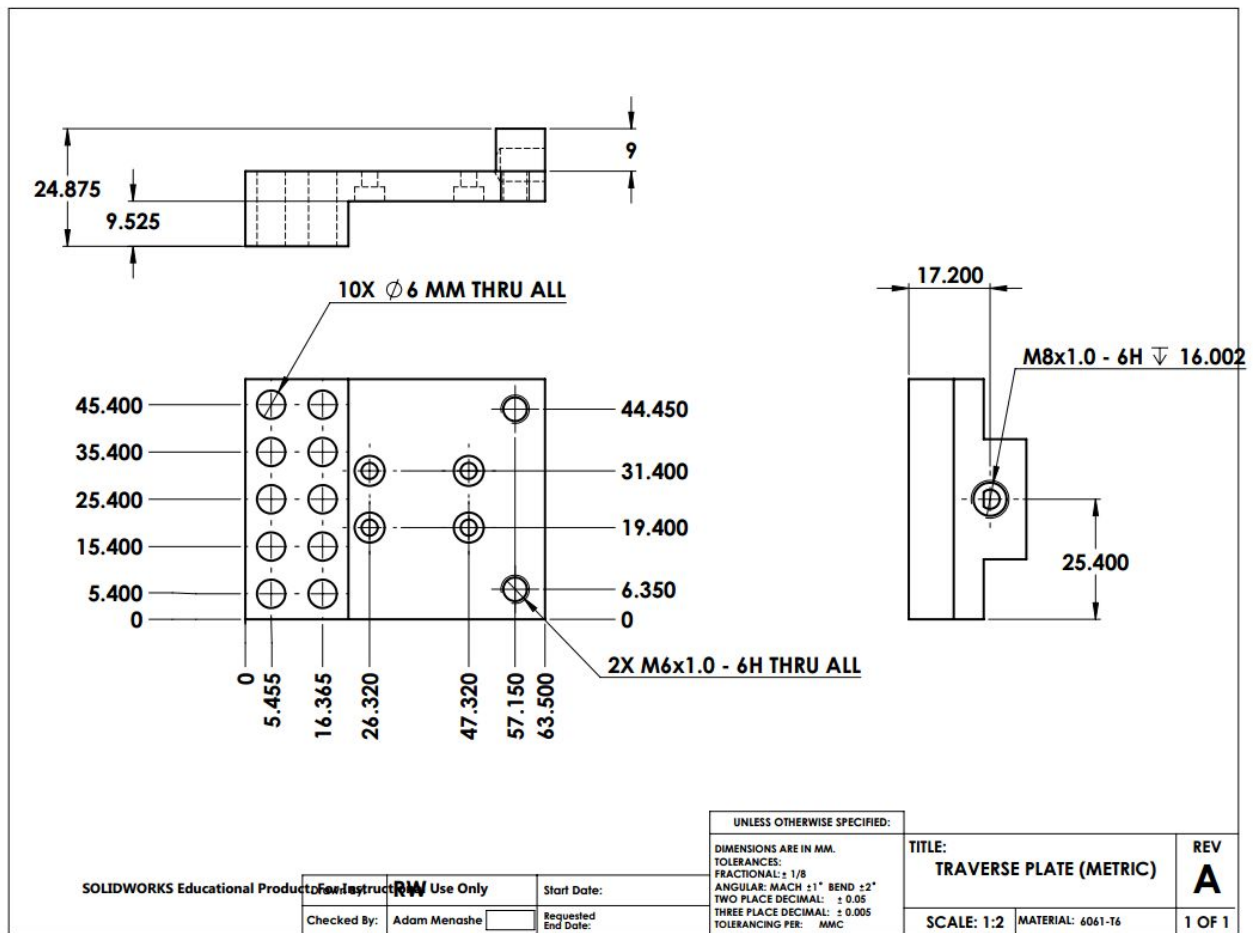




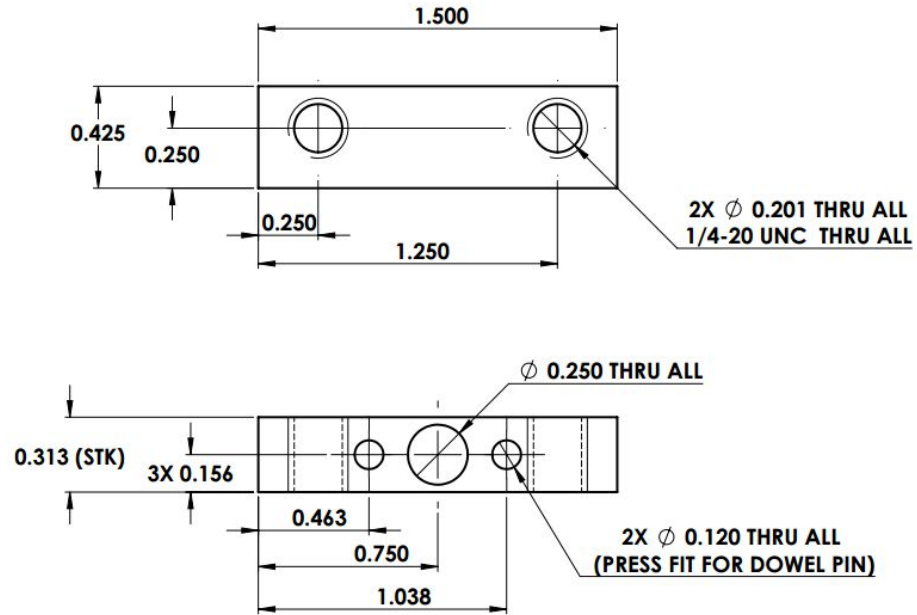
Appendix L7: Traverse Plate



Appendix L8: 3D Printed Probe Holder Required Specs



Appendix L9: Belt Tension Block



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Checked By:

Start Date:

Requested End Date:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: $\pm 1/8$
ANGULAR: MACH $\pm 1^\circ$ BEND $\pm 2^\circ$
TWO PLACE DECIMAL: ± 0.05
THREE PLACE DECIMAL: ± 0.005
TOLERANCING PER: MMC

TITLE:

BELT TENSION BLOCK

REV

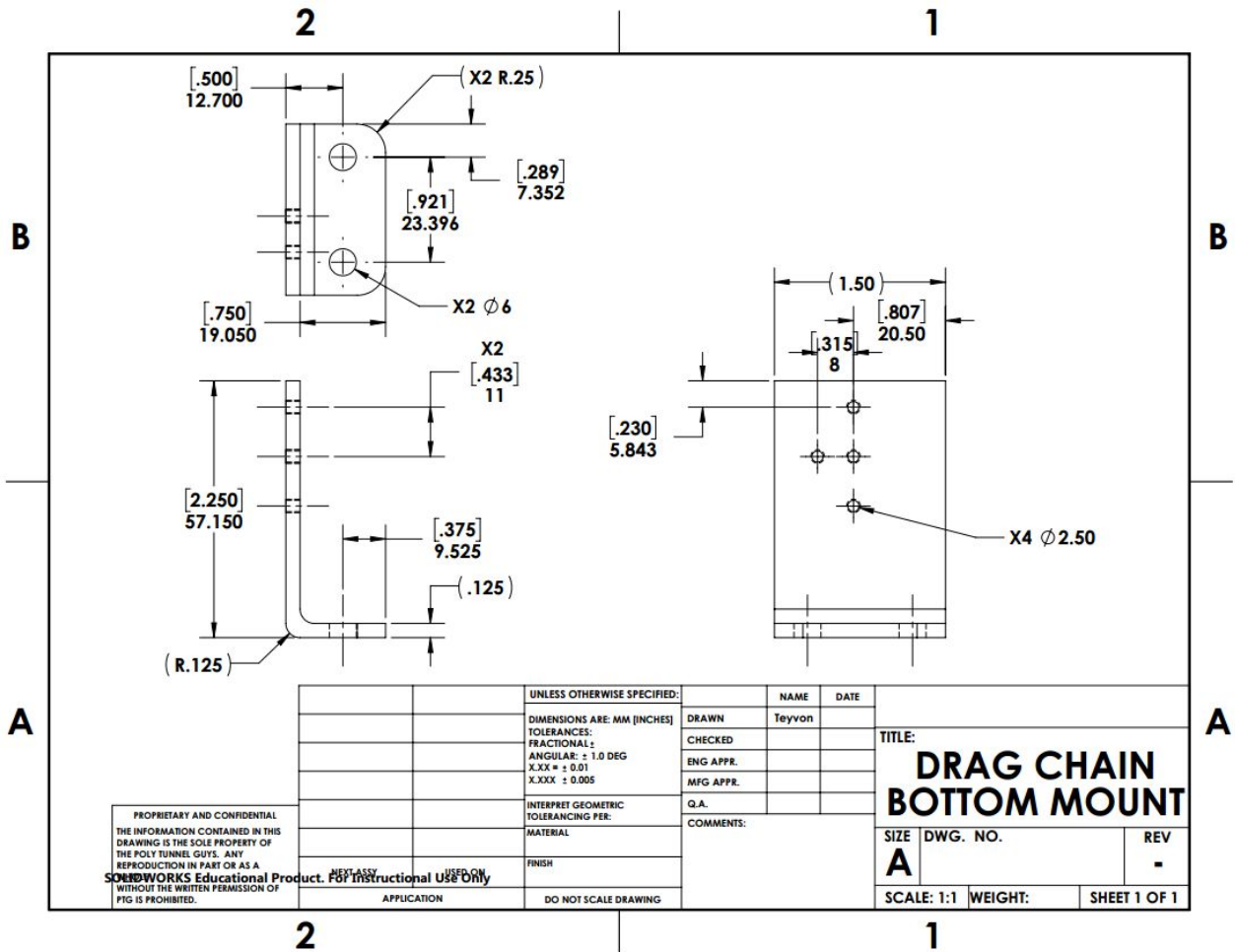
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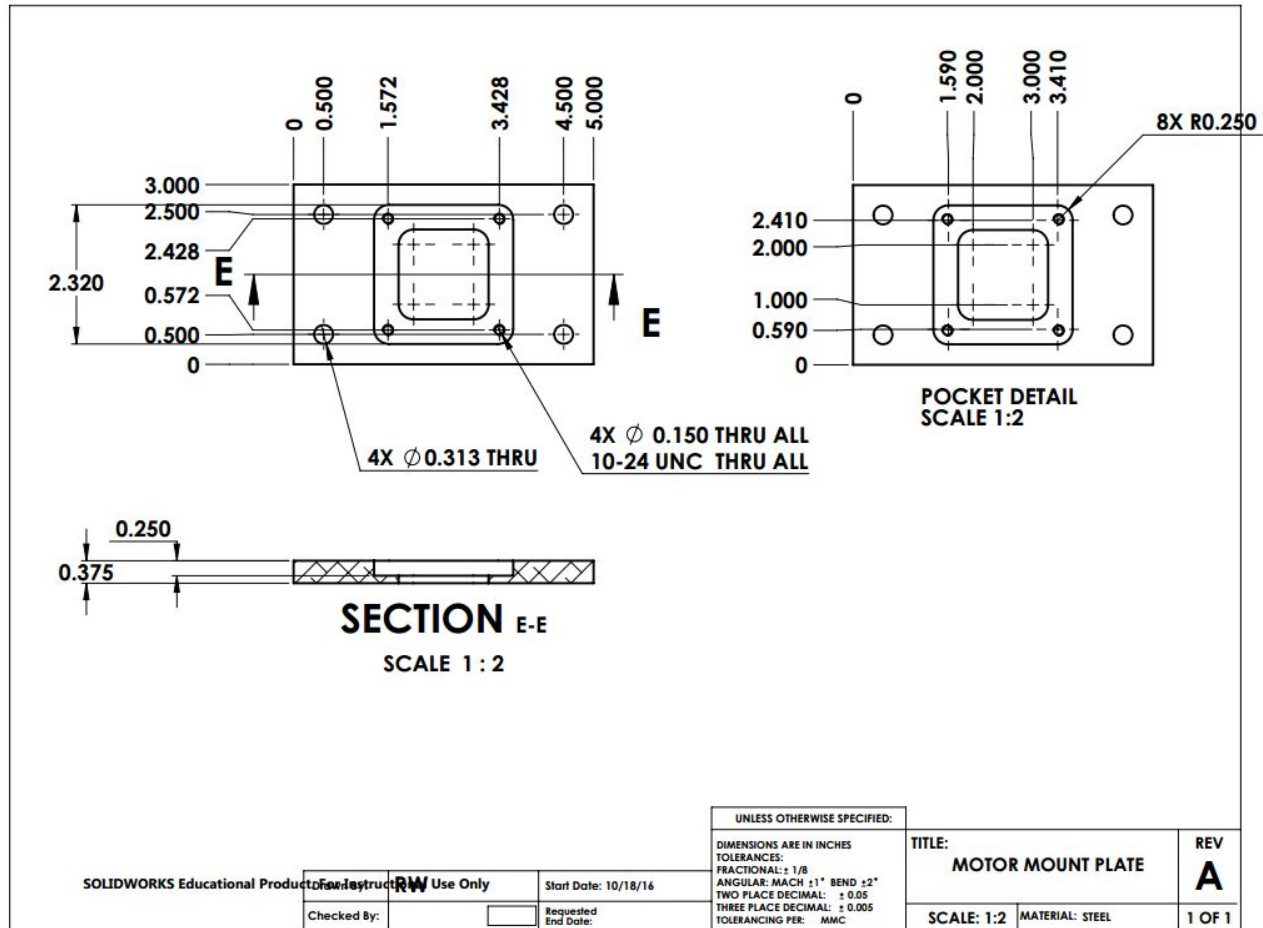
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1 OF 1

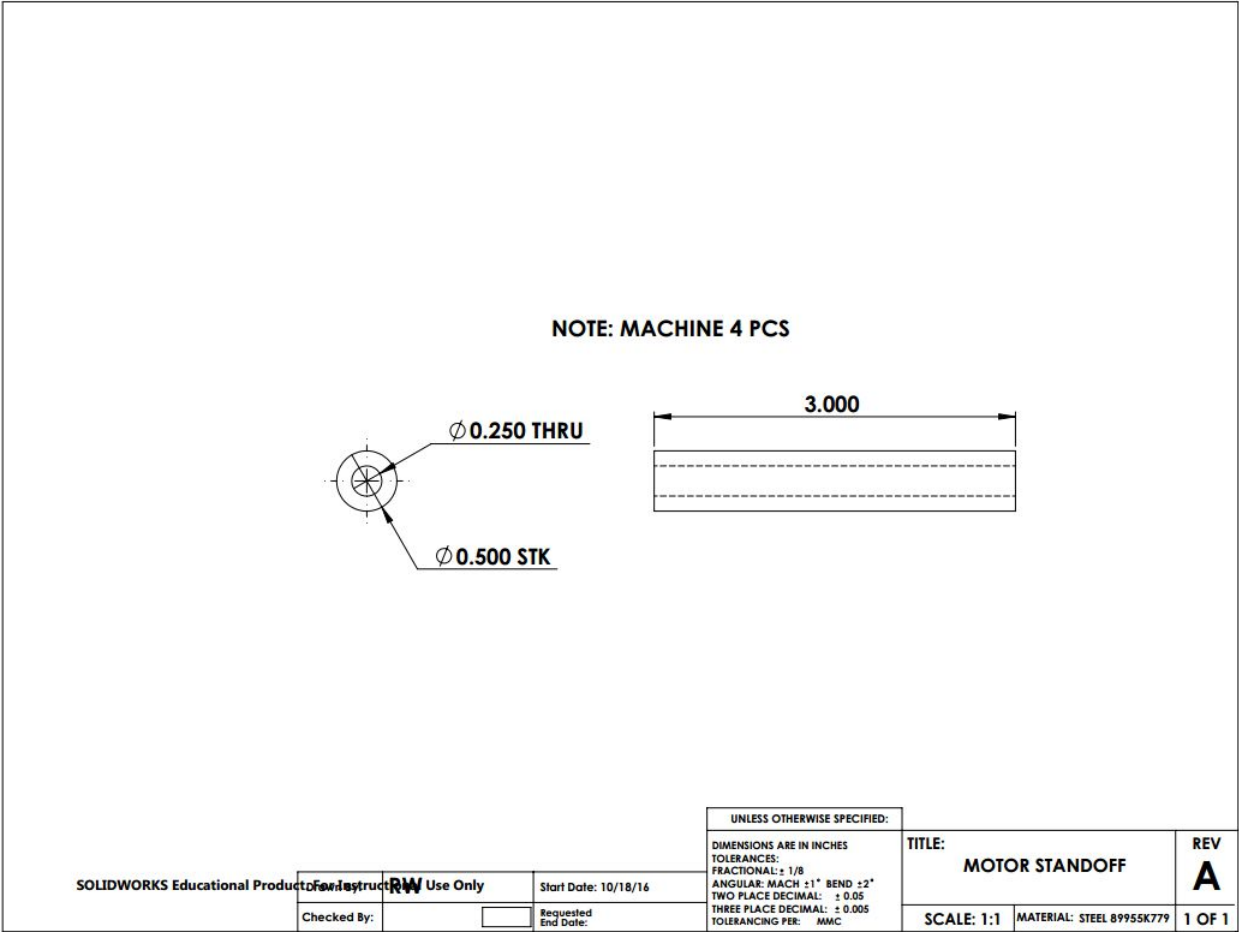
Appendix L10: Drag Chain Bottom Mount



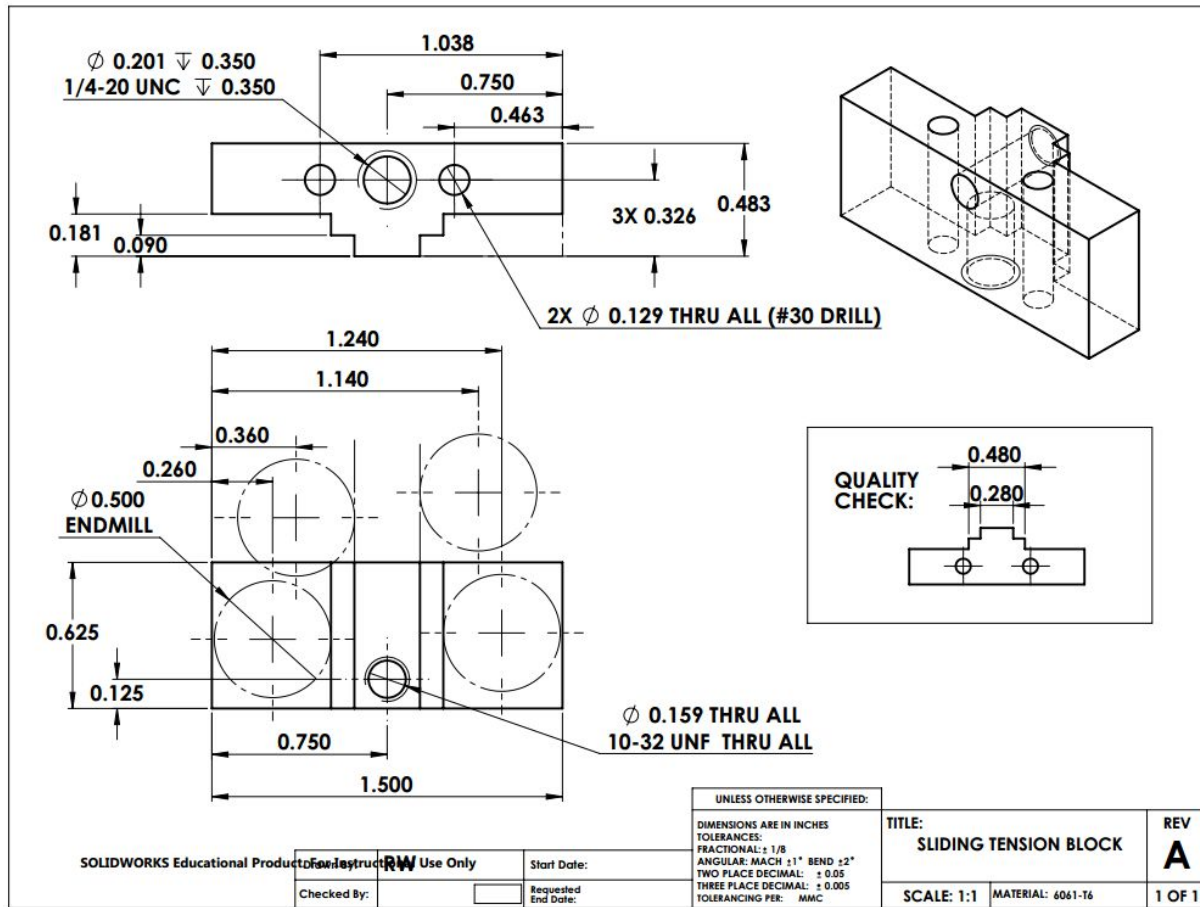
Appendix L11: Motor Mount Plate



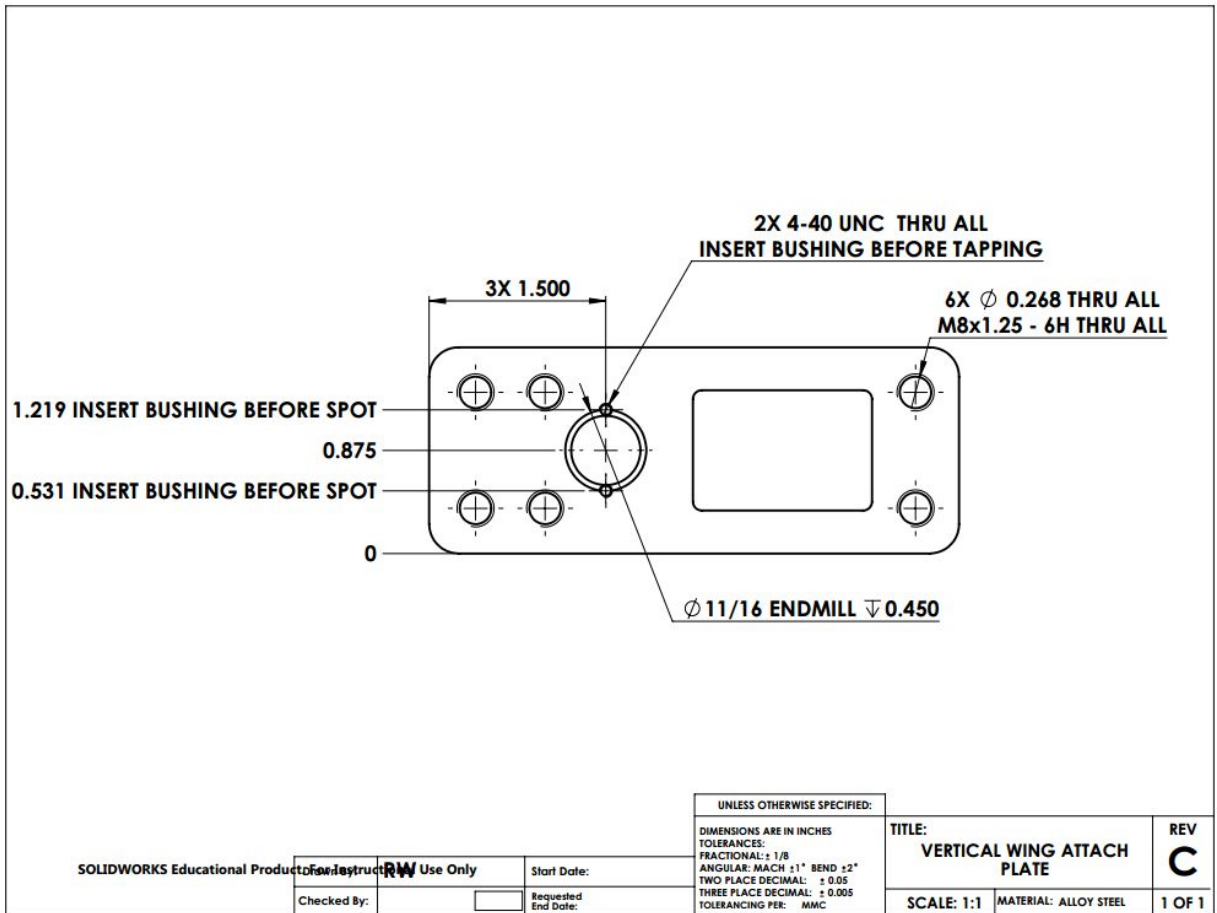
Appendix L12: Motor Standoff



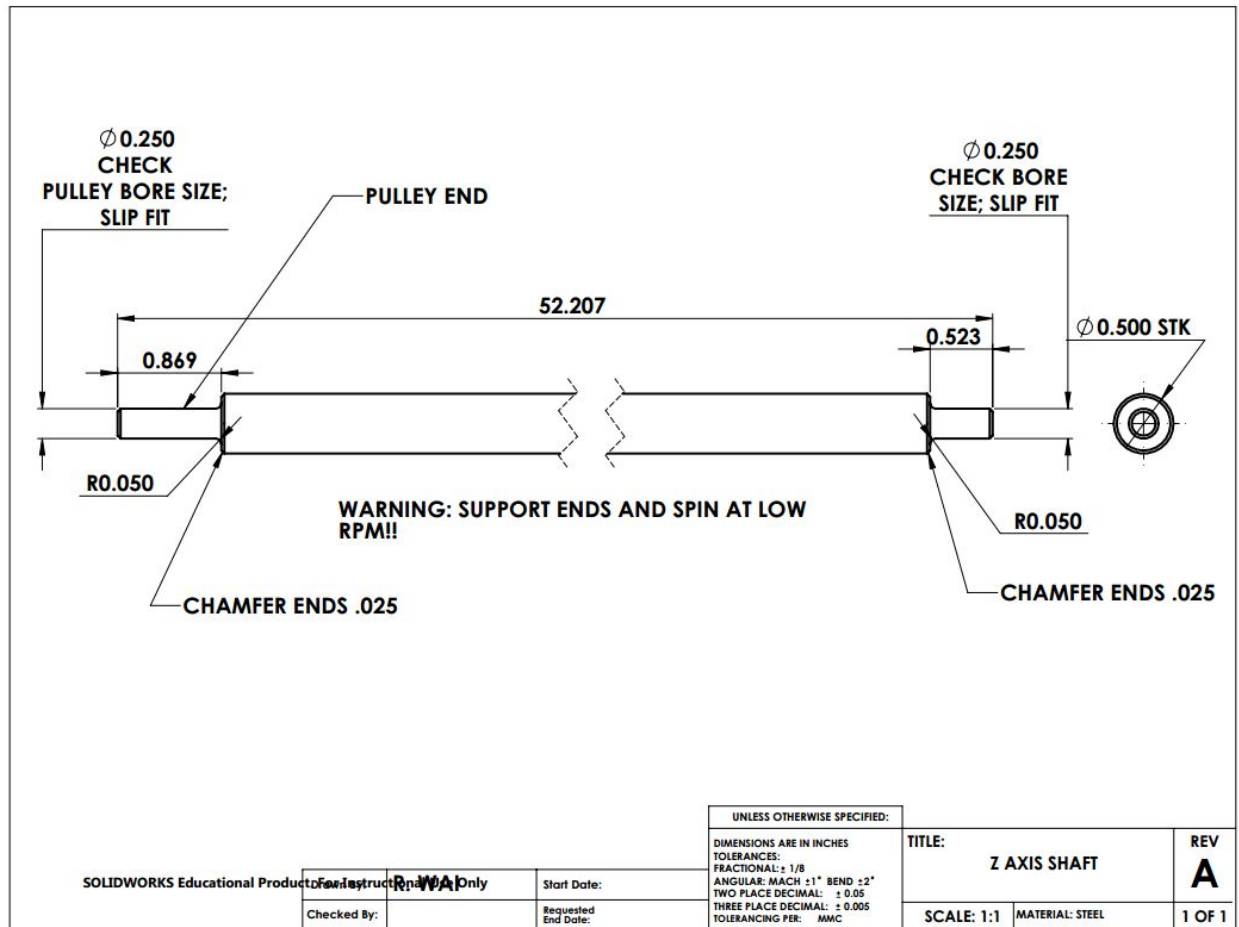
Appendix L13: Sliding Tension Block



Appendix L14: Vertical Wing Attach Plate



Appendix L15: Z-Axis Shaft



Appendix M: Failure Mode and Effect Analysis

System

Subsystem

Component

Model Year(s)/Vehicle(s):

Core Team:

Potential Failure Mode and Effect Analysis (Design FMEA)

Design Responsibility: Ricky wai

Key Date: 4/5/2016

FMEA Number:

Page 1 of 1

Prepared By:

FMEA Date (Orig.) 4/5/2016

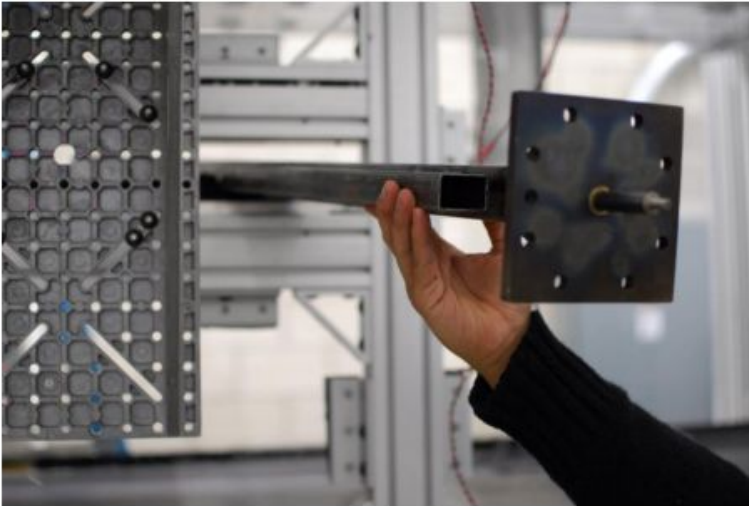
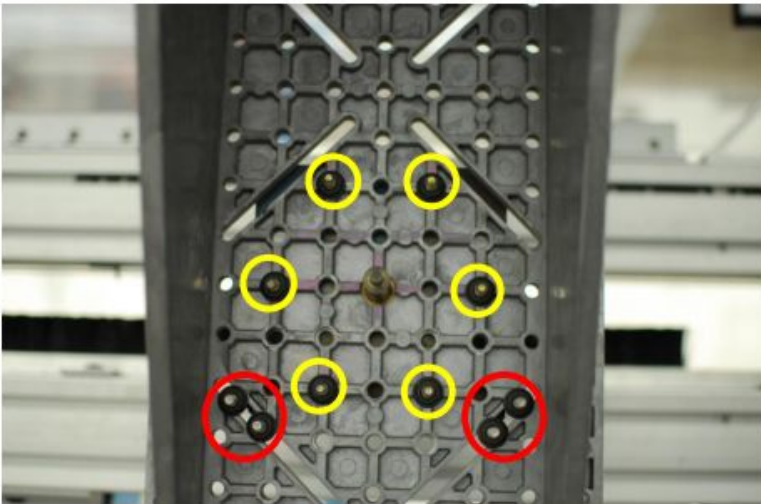
Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	S e v	Potential Cause(s) / Mechanism(s) of Failure	O c c u r	C r i t	Recommended Action(s)	Responsibility	Action Results			
									Actions Taken	S e v	O c c u r	C r i t
Timing belt	Belt slips/ breaking/ Stretching	Loss Components inside the verticle section	3	Time/Usage	2	6	Accessibility for maintainance to replace	Teyvon				
Linear rail mounting plate	Bolts come loose	z-axis falls apart	4	Vibration in the structure	2	8	Design for tight bolt fights high stregh material for high tightening torque	Ricky				
Wing T joint	Deformation/Bending	Misalignement of the Vertical section	4	High wind forces	1	4	over design with safety factor	Ricky				
Drive shaft	Deformation,Bending	Misallignment and failure of Z drive	4	Excess loading, unpredicted loading on the shaft	2	8	Over design with safety factor, isolate all loads to mounting points	Ricky				
	Bearings wear	Notchiness, loss of accuracy	3	Time/Usage	1	3	Replace every 12 months	Mel				
External Supports	Misallignment	Wing section is not perpendicular to test section	4	Bolt wear/deform position	1	4	Design accurate mounting points for locating the support	Mel				
	Deformation	Structure falls apart	5	High stress points	1	5	High safety factor on support beams	Mel				
Airfoil Structure	Crack/ Break/ Deformation	Loss of integrity in the structure	5	Airfoil breaks due to stresses incurred by the loads	3	15	Multiple layers of fiber on the foil shell and testing	Zander				
Connections	Kinks and bends in wires	Inaccurate data or inability to aquire data	3	Sharp bends and pinch points in the structure as it operates	3	9	Inspection during testing operation to determine pinch pointsand modify if necessary	Teyvon				
Linear Rails External	High friction	May cause problems to driving motor	2	Motor stall	2	4	Warning to keep rails clear and clean	Zander				

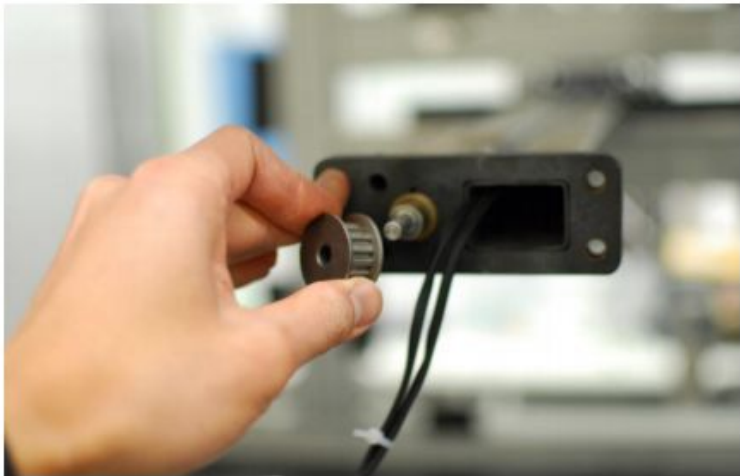

Appendix N: Design Verification Plan

Design Verification Plan								
TEST PLAN					TEST REPORT			
Category	Test #	Feature [1]	Acceptance Criteria		Test Responsibility [2]	TEST RESULTS		NOTES
			Value	Units		Test Result [3]	Pass/Fail	
External Airfoil Properties	1	Airfoil thickness: verticle	< 4	in	Ricky	Results cannot be determined due to change in objective.		
	2	Airfoil length: verticle	23-25	in	Ricky			
	3	Airfoil thickness: horizontal	< 3	in	Ricky			
	4	Airfoil length: horizontal	44-46	in	Ricky			
	5	Total airfoil weight	<15	lbf	Ricky			
Internal Airfoil Components	6	Total belt adjustability range	2 to 3	in	Ricky	1.5in	Acceptable	This acts as a system to tension the belt and after inspection and assembly does not necessarily require more than provided adjustability.
	7	Driveshaft deflection	<3	mm	Ricky	1mm	PASS	Mounted on both ends inside a horizontal structure
	8	Cable interference	N/A: Inspection		Team		PASS	Drag Chain Assembly
	9	Internal vertical structure clearance	>0.1	in	Team	No external shell, clearance cannot be assessed		
Motion Range	10	Verticle probe motion range	>18	in	Teyvon	22	PASS	Predetermined and should be according to their linear motors
	11	Verticle probe motion speed	0.5-2	in/sec	Teyvon		PASS	
	12	Horizontal probe motion range	>35	in	Teyvon	40	PASS	
	13	Horizontal probe motion speed	0.5-2	in/sec	Mel		PASS	
	14	X axis motion range	>65	in	Mel	75	PASS	
External Support	15	X axis motion speed	0.5-3	in/sec	Mel		PASS	Measured using angle of the shaft from horizontal (about 0.5 degrees)
	16	Power screw deflection	<10	mm	Mel	~5mm	PASS	
	17	Mounting alignment	<0.5	in	Mel	0.2in	PASS	Adjustiblity of mounting fixtures allows for minimizing this misallignment
Safety	18	No sharp edges, sharp points, or pinch points	N/A: Inspection		Zander		PASS	Sharp edges and points have been sanded and filed. Rotating mechanisms are either enclosed or shield by other fixtures. Verticle assembly is exposed due to objective change.
	19	No exposed rotating system under specified height	6	ft	Zander			Vertical motion system is now exposed due to change in objective: No airfoil.
Overall Performance Criteria	20	Probe Deflection	< 0.125in @ MTS		Zander		>0.125"	Arm deflection does not exceed 0.125" vertically. it is unsafe to measure the location of the probe holder when the wind tunnel is operating.
	21	Flow Disturbance	< 5 psi drop @ MTS		Team			Initial requirements in pressure drop do not apply since those were made assuming aerodynamic shell
	22	Cross section coverage	80% of cross section		Team		PASS	
	23	Repeatability	Within 2mm same position		Teyvon		PASS	
	24	Assembly/Disassembly	30-45 min		Ricky/Mel		PASS	Note Assembly/Disassembly Guide
	25	Cost	<2500	USD [\$]	Zander		Acceptable	Just under \$3000 final cost, acceptable to sponsor
PASS								
Acceptable								
Not Applicable								
FAIL								
MTS = Max Test Speed, 125 mph								

Appendix O: Traverse Arm Assembly and Disassembly Instructions

1 PROCEDURE: TRAVERSE ARM INSTALLATION

Traverse Arm Installation		
Step 1	<p>Note: make sure the shaft does not fall out of the arm.</p> <p>Insert the horizontal arm as shown. The hollow rectangular tube should be on the trailing end of the arm.</p> <p>Warning: Have a partner hold the other end of the arm.</p>	
Step 2	<p>Align the bottom corners of the square mounting plate with the four locating bolt heads on the tombstone (in red).</p> <p>Insert the six bolts (in yellow) in the locations shown and tighten the nuts with a socket and wrench.</p>	

Traverse Arm Installation		
Step 3	Remove the drive pulley from end of the traverse arm.	
Step 4	Feed the limit switch wiring through the hollow tube and attach the z-axis assembly plate with the four socket head cap screws.	

Traverse Arm Installation

Step 5

Warning: do not pull the shaft out too far out or it may fall out of the bushings.

Pull the shaft out just enough such the drive pulley's set screws can be accessed.

Reattach the drive pulley flush against the end of the shaft using a hex wrench to tighten the two set screws.

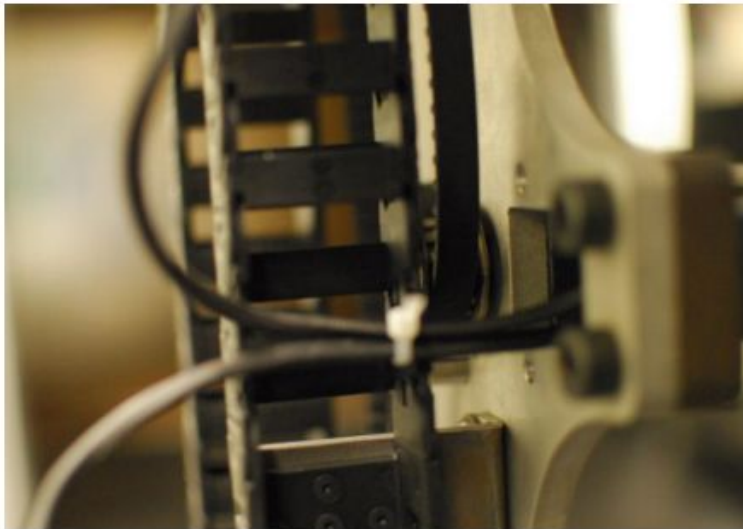
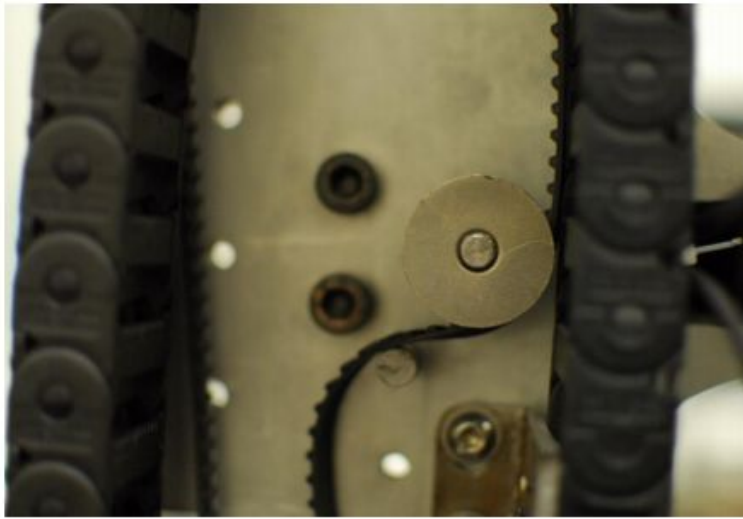



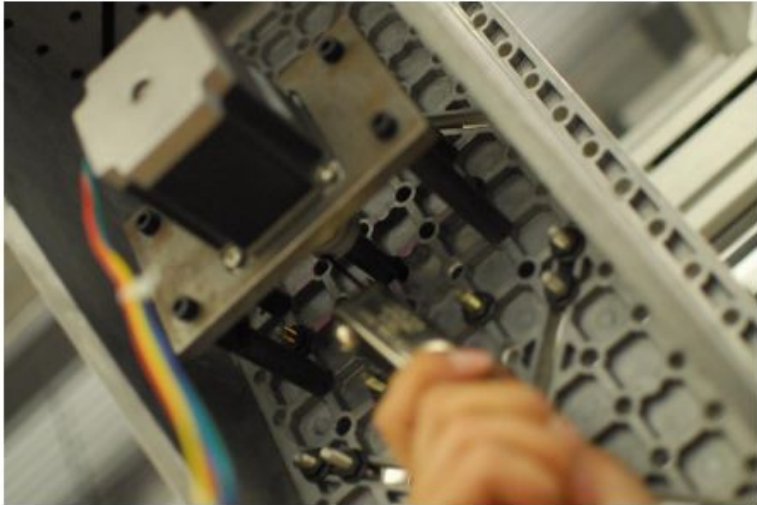
Traverse Arm Installation

Step 6

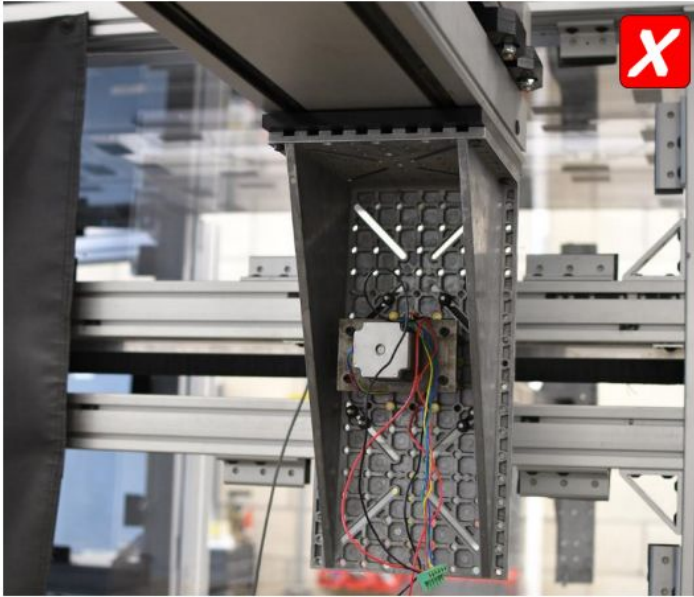
Route the timing belt around the drive pulley as shown.

Push the pulley and shaft inward until there is approximately 2 mm gap between the pulley and the aluminum plate.



Traverse Arm Installation		
Step 7	<p>Attach the bottom pulley and tighten using a hex wrench.</p> <p>Note: the current length of the belt does not require tension adjustment.</p>	
Step 8	<p>Reattach the stepper motor assembly and tighten the bolts.</p> <p>Use a hex key to tighten the shaft coupler.</p>	

1 PROCEDURE: TRAVERSE ARM REMOVAL

Traverse Arm Removal		
Step 1	Disconnect the stepper motor and carefully move wires out of the way.	

Traverse Arm Removal

Step 2

Decouple the shaft coupler on the stepper motor.

Note: there are two set screws on the shaft coupler.

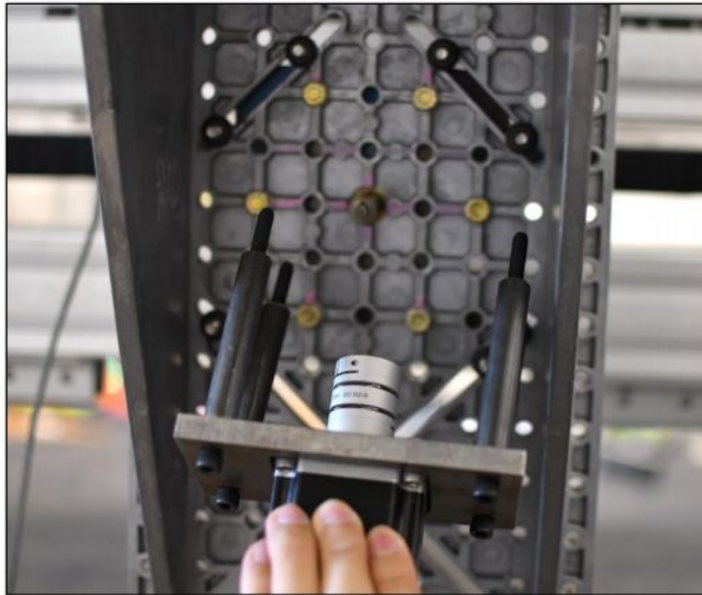
1. Loosen the set screw on the side of the black shaft using a hex wrench.



Traverse Arm Removal

Step 3

Remove motor assembly from the tombstone by unbolting the four socket head cap screws.

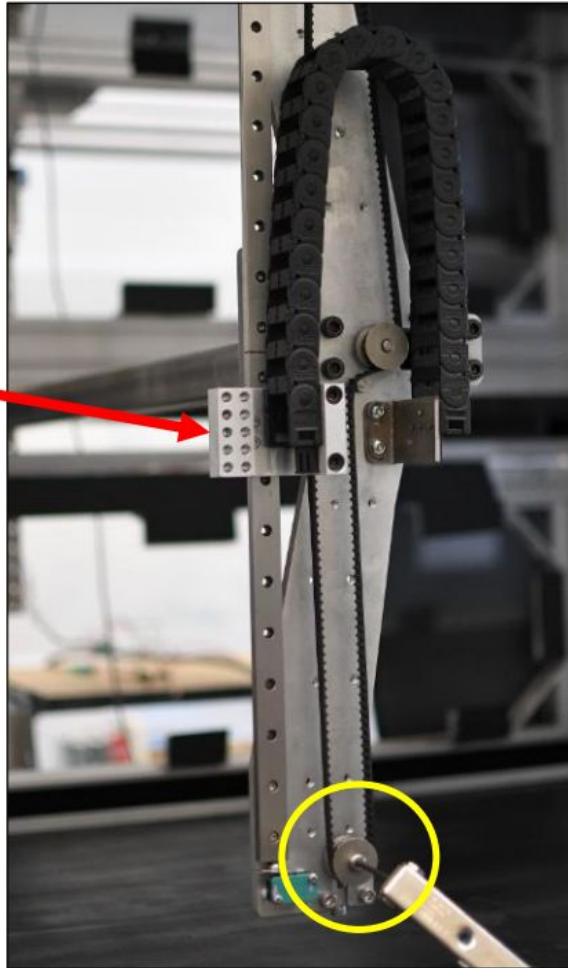


Traverse Arm Removal

Step 4

Warning: support the carriage assembly or it will slide down the linear rail.

On the pulley assembly, remove the shoulder bolt holding the lower timing belt pulley.



Traverse Arm Removal

Step 5

Gently pull the drive pulley outward just enough to access the set screws to the drive shaft.

Warning: do not pull the shaft out too far or it may fall out of the bushings.

Use a hex wrench to loosen the two set screws.

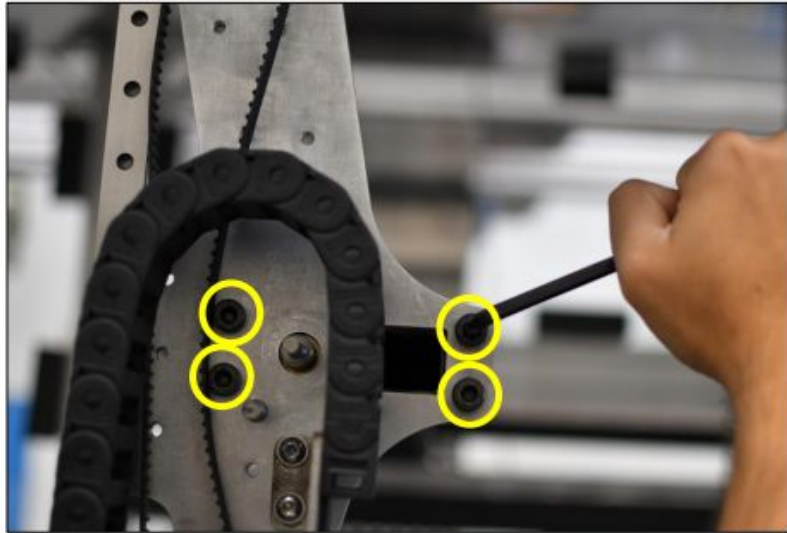


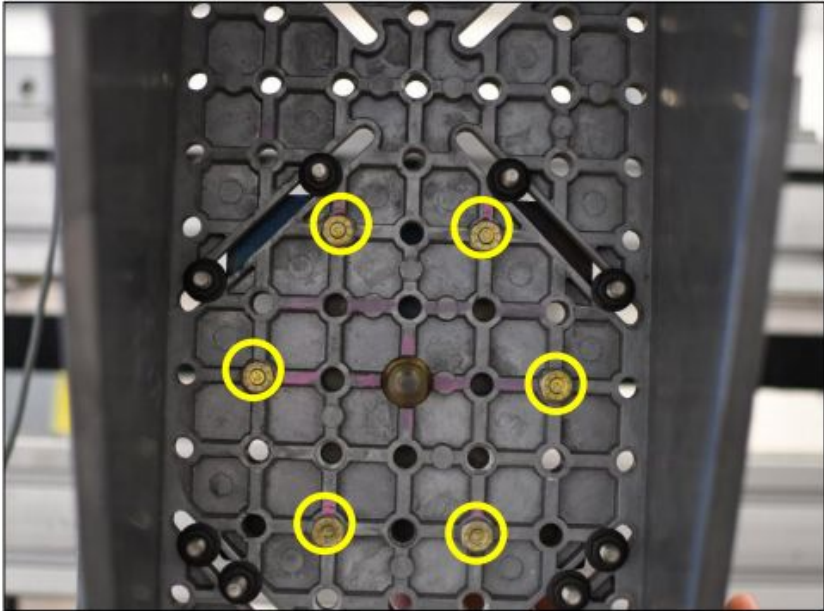
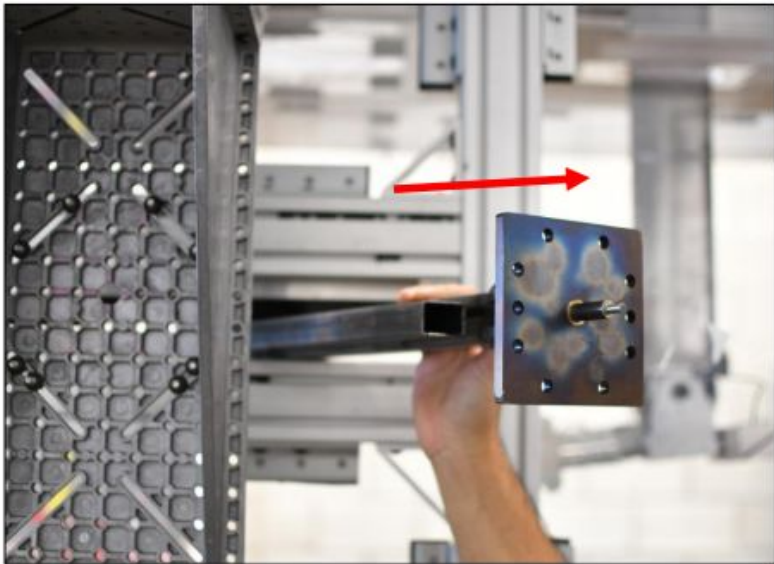
Traverse Arm Removal

Step 6

Remove the z-axis assembly by unbolting the four socket head cap screws.

Warning: have someone support the assembly before unbolting it.



Traverse Arm Removal		
Step 7	<p>Warning: have someone support the other end of the horizontal arm before removing the bolts.</p> <p>Unbolt the six bolts holding the horizontal arm to the tombstone.</p>	
Step 8	<p>Carefully remove the horizontal arm from the slot. Warning: do NOT let the drive shaft slide out of the bushings.</p>	

Appendix P: References

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