Senior Design- Spring 2023

Assignment 6: Project Report

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Instance 1
Hours spent: 150

Cover Photo: Wind Tunnel Team and Dr. Wout de Backer at Senior Design Showcase

UNIVERSITY OF
SOUTH CAROLINA

Revisions

Revision	Comments	Affected Pages	Date
1	First Issue	All	05/03/2023

References

Ref. No.	Title	Authors	Date

1.
2.
3.

1. Introduction

This report will examine intricate design and thorough analysis of the conceptual stage of our wind tunnel to effectively highlight the readiness for the next phase of the project. The following report will begin with multiple updates on the earlier sections of the design, starting with project management in Chapter 2 and transitioning into the requirements section in Chapter 3. Subsequently the report will enter the main section of Chapter 4 and will discuss the detailed design of the project. This will emphasize the preparedness of the wind tunnel through extensive analysis of various components of the structure and the design.

2. Project Management Update

While the project management established the early phases of the overarching design, most if not all the work done has been fluctuating with the design. This chapter will update all diagrams and charts used to organize the middle stages of the wind tunnel and how our design has developed since the beginning.

2.1 Organigram

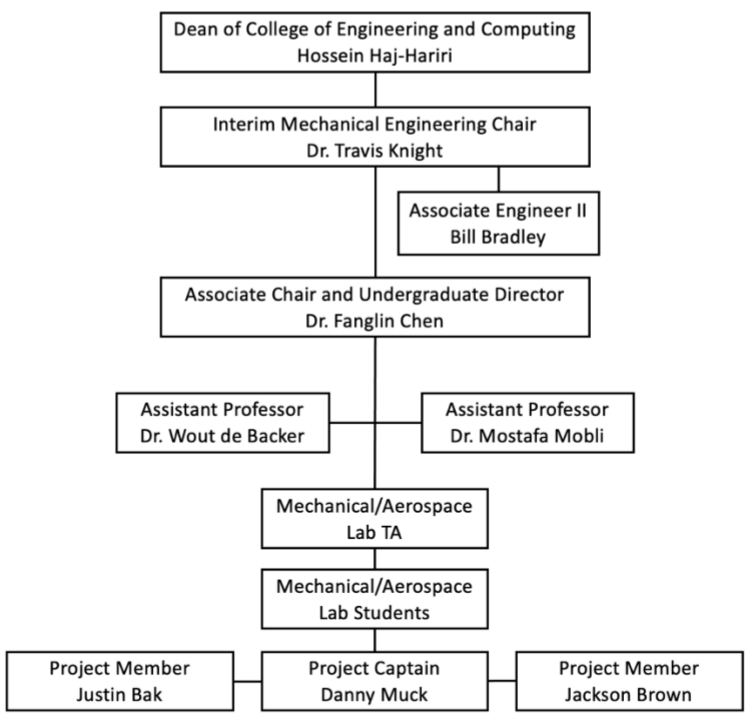


Figure 2.1: Organigram

The organigram has not changed since the initial phase of the design, and the stakeholders remain as listed. The organigram shown above represents the project management and conceptual design phase of the project, but it is important to note that the project captain for this phase for the detailed design is being led by Jackson Brown.

2.2 Project Objective Statement & Mission Need Statement

Our project objective statement is determined based on the actual objective of the project including the time and monetary constraints and what the final product will be. The project objective statement has not changed since its inception:

Our group of three students will design, manufacture, and test a low-speed wind tunnel for use by mechanical and aerospace engineering labs in about 4 months, while maintaining a budget of $1250.

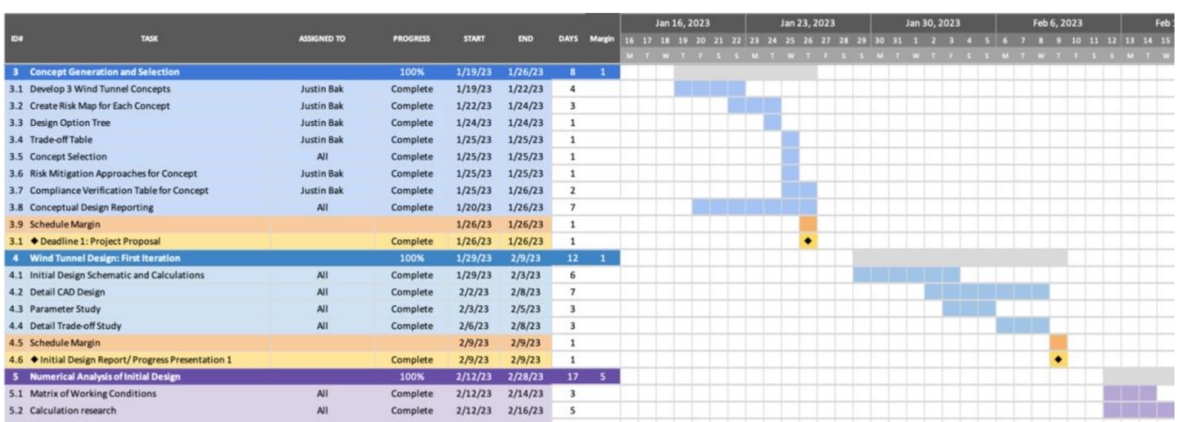
The mission need statement defines the constraints and requirements of the final wind tunnel design. This statement conveys the required specifications to any stakeholders to ensure that the final product meets the specified needs:

Maintain low speed, laminar flow (Re<5000) with heating and cooling capabilities up to 50 degrees Celsius of a 1ft x 1ft test section while also providing data acquisition for force analysis of mountable prototypes.

As the design has progressed, there have been two changes made to the mission need statement since Assignment 1. The first change is an increase in Reynolds number from a maximum of 2000 to now 5000, and the second change is a decrease in test section cross sectional area from $2\ ft^2$ to $1\ ft^2$. These alterations have been agreed upon by the stakeholders, and the design has been moving forward with these changes implemented.

2.3 Gantt Chart

The Gantt chart has been utilized throughout the lifecycle of the project and effectively organizes the major phases. Appendix 7 shows both a full-size image of the Gantt chart as well as a snippet from an earlier phase of the design:



ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	Margin
3	Concept Generation and Selection		100%	1/19/23	1/26/23	8	1
3.1	Develop 3 Wind Tunnel Concepts	Justin Bak	Complete	1/19/23	1/22/23	4	
3.2	Create Risk Map for Each Concept	Justin Bak	Complete	1/22/23	1/24/23	3	
3.3	Design Option Tree	Justin Bak	Complete	1/24/23	1/24/23	1	
3.4	Trade-off Table	Justin Bak	Complete	1/25/23	1/25/23	1	
3.5	Concept Selection	All	Complete	1/25/23	1/25/23	1	
3.6	Risk Mitigation Approaches for Concept	Justin Bak	Complete	1/25/23	1/25/23	1	
3.7	Compliance Verification Table for Concept	Justin Bak	Complete	1/25/23	1/26/23	2	
3.8	Conceptual Design Reporting	All	Complete	1/20/23	1/26/23	7	
3.9	Schedule Margin			1/26/23	1/26/23	1	
3.1	◆ Deadline 1: Project Proposal		Complete	1/26/23	1/26/23	1	
4	Wind Tunnel Design: First Iteration		100%	1/29/23	2/9/23	12	1
4.1	Initial Design Schematic and Calculations	All	Complete	1/29/23	2/3/23	6	
4.2	Detail CAD Design	All	Complete	2/2/23	2/8/23	7	
4.3	Parameter Study	All	Complete	2/3/23	2/5/23	3	
4.4	Detail Trade-off Study	All	Complete	2/6/23	2/8/23	3	
4.5	Schedule Margin			2/9/23	2/9/23	1	
4.6	◆ Initial Design Report/ Progress Presentation 1		Complete	2/9/23	2/9/23	1	
5	Numerical Analysis of Initial Design		100%	2/12/23	2/28/23	17	5
5.1	Matrix of Working Conditions	All	Complete	2/12/23	2/14/23	3	
5.2	Calculation research	All	Complete	2/12/23	2/16/23	5	
5.3	Wind and Honeycomb calculations	Jackson Brown	Complete	2/17/23	2/20/23	4	

Figure 2.2: Gantt Chart Snippet

3. Requirements Analysis Update

As the design is continuous and frequently changing, it is to no surprise that preparations around the requirements will be fluid and fluctuating as well. Identifying the requirements early aided in the preliminary stages of design, but they have been changing as our design has too. This section identifies the additions, removals, and edits to each diagram with respect to their given requirement analysis. Like Assignment 1, requirements analysis begins with a functional breakdown and functional flow diagrams, organizing the desired functions with respect to the customer. This then transitions into the list of requirements, where requirements are not only displayed but also divided into function or constraint categories. The final portion of this section will present the N^2 diagram, relating the interactions between requirements and functions, but lacking a chronological flow. The final note to make about the following sections is that all changes/additions are represented by blue text.

3.1 Functional Breakdown Structure

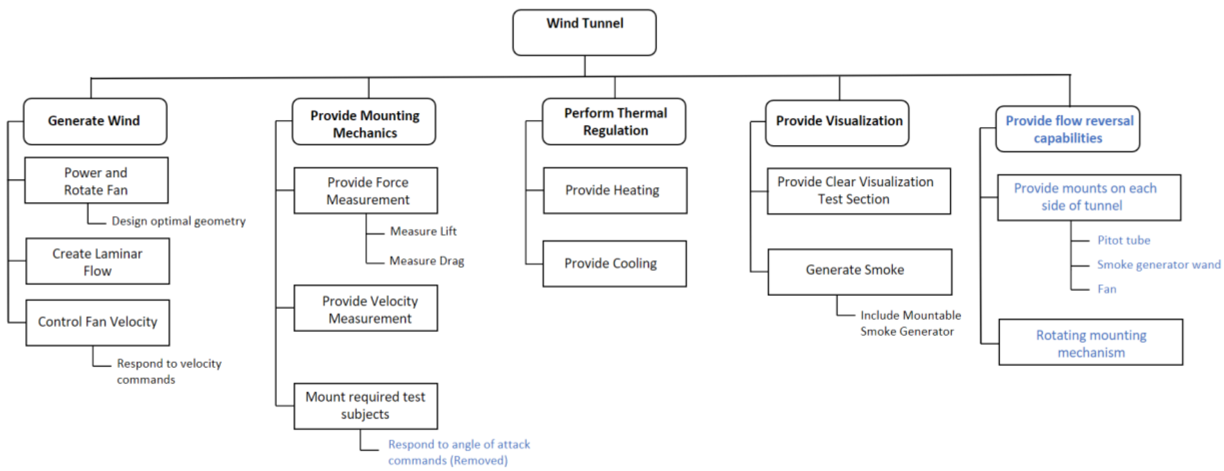


Figure 3.1: Functional Breakdown Structure

One major change was made to the functional breakdown structure and that is the integration of flow reversal into our design. These additions all relate to the ability to reverse the flow without diminishing the capabilities of our tunnel. For example, with the flow reversed, the smoke generator would be rendered useless, and the pitot tube would provide inaccurate data as the air has already passed the test subject. These mounts on each side allow the only variable changed to be the flow direction.

3.2 Functional Flow Diagram

This updated functional flow diagram introduces a new function of making tunnel adjustments prior to the initiation of any power systems. This function can be seen in 2.0 of the functional flow diagram and is entirely new since the first version of the chart. As for other minor changes to the diagram, an addition of a function relating to the heating and cooling units can be seen in the 3.0 function. The functional flow diagram is represented in Appendix 3, and a snippet can be found below:

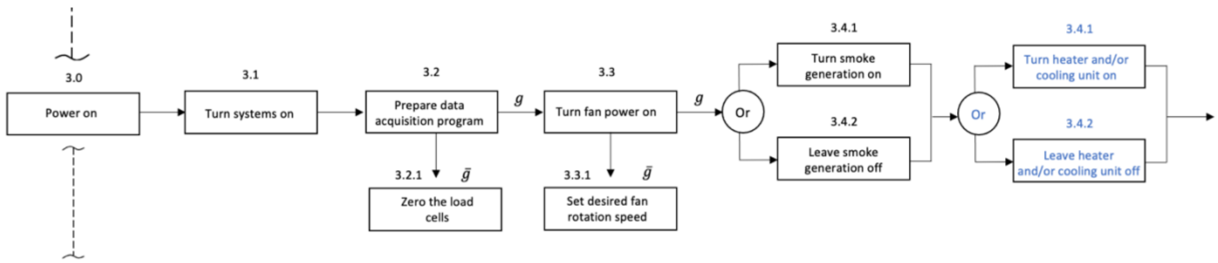


Figure 3.2: Functional Flow Diagram Snippet

3.3 Requirements Tree

The overall requirements breakdown did not experience too many changes, but the few ones can be seen highlighted in the requirements tree. Two main requirements have been updated as the Reynolds number limitation has been increased and the text section cross sectional area has decreased, as explained in Chapter 2.2 on the mission need statement. Similar to Assignment 1, the killer requirements are being indicated in red, while the secondary requirements remain black. Killer requirements were determined by how effective a failure to meet that requirement would have on the overall outcome of the project. For any section that is marked as killer, it is noteworthy that all the subsections connected are also considered killer requirements as well.

3.4 N^2 Chart

The N^2 chart has not changed since its initial creation, and all functions appropriately represent the required functions of the design. This chart can be found in Appendix 8.

3.5 Requirements Compliance

With the many requirements that our tunnel must fulfill, it is essential that we test and ensure that each aspect gets met. As explained in our killer requirements, the operational parts of our wind tunnel will be the most essential for the tunnel to be deemed successful. The primary requirement for our tunnel will be to measure the lift and drag forces on our test subject. This will be the most essential aspect to comply due to it being the whole reason for the tunnel. Other requirements such as smoke generation, heat/cooling capabilities, and speed regulation will need to be met, but those are just additions to the wind causing lift and drag. For this reason, the mounting apparatus will be focused during the testing stage to prove its compliance to the requirements. This will be done by testing on the load cells both not connected to the apparatus and connected to it. Various trials will be conducted with different weight loads to ensure accurate results. Moving forward, our requirement for 50-degree heating and cooling will be tested using a thermometer in the tunnel. These tests will be conducted individually in a controlled environment. As for the Reynolds number requirement, this is governed by the velocity of the flow and will be tested using the pitot static tube. Calculations for Reynolds number were conducted previously and confirmed fan compliance to the requirement.

4. Detailed Design

4.1 Wind Tunnel Duct Design

Since the concept of the open return design was chosen, the design of the wind tunnel duct was broken into 4 major assemblies, The heating side duct, test section, cooling side duct, and drive section. Each assembly houses different components and were designed separately then combined for the full duct assembly.

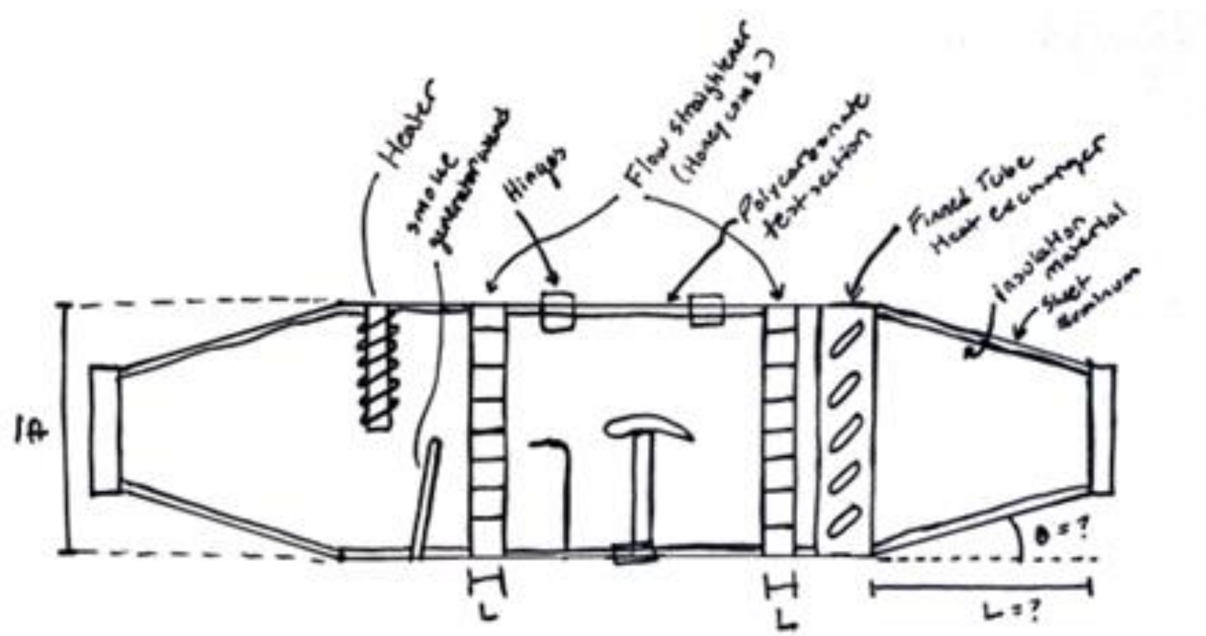


Figure 4.1: Concept Sketch of Wind Tunnel Duct

4.1.1 Heating Side Duct

The heating side duct was designed to act as an inlet for air when heating is required. Also, this section houses the heating unit, mounting for the smoke generator wand, and a honeycomb flow straightener. These systems will be discussed in more detail in the subsystems section. The actual heating duct is a 12 in by 12 in cross section duct with a length of 15 inches. The duct frame is made from aluminum bolt-together framing to create the outer structure. Each side consists of 0.025 in thick 6061 aluminum sheets which are bolted directly to the framing. The top aluminum sheet features a cut out for the heating unit to be dropped into place while the bottom sheet features a cut out for the smoke generator wand, both of which are bolted on to ensure that no air flow escapes from the duct.

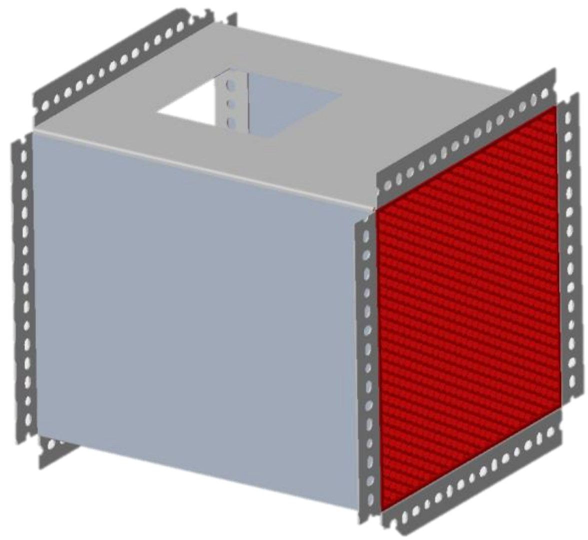


Figure 4.2: Heating Side Duct 3D Model

This duct is a constant cross-section. Our wind tunnel differs from classical open return wind tunnels which feature a converging section to increase the flow velocity according to Bernoulli's principle. This difference is due to the simple fact that the flow regime in this wind tunnel, within the test section, must be fully laminar. To ensure laminar flow in the test section, while also maintaining the required cross-sectional area of 1 ft^2, the free stream velocity must be extremely low, around 0.125 m/s. Thus, the need for a converging section is not present in this project. This was verified by testing the current wind tunnel that has been used for parts in this project. At full fan speed, the current wind tunnel produced a free stream velocity of around 1.5 m/s in the test section with a constant cross section inlet. This design also allows for ease of access to the honeycomb flow straightener which is inserted from the front of the duct.

4.1.2 Test Section

The test section is the portion of the wind tunnel where the test specimen is placed for analysis. According to the requirements, the test section had to feature a visualization panel, a test piece mounting mechanism, temperature and velocity sensors. Also, the test section was required to have a cross sectional area of 1 ft^2. The test section is made of 4 clear acrylic sheets that are 0.25 in thick. These sheets are bolted together using steel 90-degree brackets providing the main structure. This design allows for users to view the interior of the test section from any angle. The front panel features a rectangular opening where a 0.5-inch acrylic sheet is attached using steel hinges to act as a door. The door fits flush with the interior of the test section wall to maintain a smooth interior with no gaps. The door is held closed with two neodymium magnets mounted to the frame piece and the door itself. This provides easy access to the mounting arm and test section while still providing visualization from the side. The ends of the test section feature more bolt-together framing so that it can be attached to the other duct sections. The mounting mechanism and mounting for the pitot static tube will be discussed in the subsystem section.

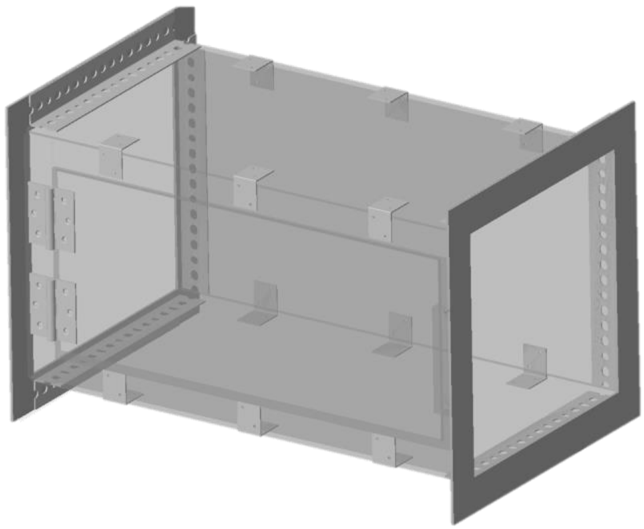


Figure 4.3: Test Section 3D Model

4.1.3 Cooling Side Duct

The cooling side duct houses the heat exchanger unit. This unit was taken from the old wind tunnel and has dimensions of 14’’ by 16’’. Because the dimensions are larger than that of the wind tunnel duct, a diverging and converging section was made to house the entire unit. This section also uses bolt together framing and aluminum sheets encasing the heat exchanger. The heating and cooling capabilities of the wind tunnel will be discussed in the subsystems section. This duct also houses a honeycomb flow straightener to improve the test section airflow when the tunnel is in the cooling configuration.

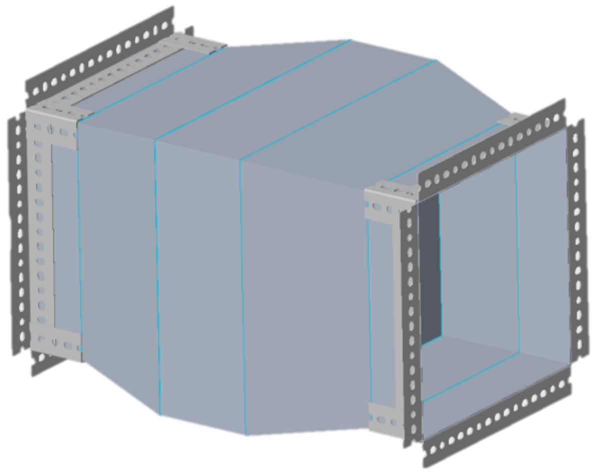


Figure 4.4: Cooling Side Duct

The smoke generator wand is also mounted on the test section side of this duct.

4.1.3 Drive Section

The Drive Section of the wind tunnel provides the free stream velocity required in the test section. According to preliminary calculations, it was found that the volumetric flow rate required in the test section must be below 20 cubic feet per minute (cfm, common fan flow rate metric). Therefore, a 120 mm equipment cooling fan was selected, which can output a maximum flow rate of 70 ft^3/min. A voltage controller is directly connected to the fan to control the speed while the pitot tube measurement is read to adjust the fan speed accordingly. To assist in slowing the fan speed and to encase the fan, a 3D printed “fan blend” was designed as a diverging section to further decrease the flow velocity according to Bernoulli’s principle.

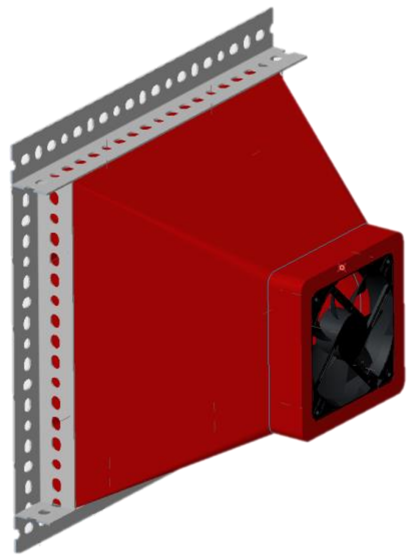


Figure 4.5: Drive Section

The fan blend is connected to the wind tunnel duct using the aluminum framing used throughout the wind tunnel duct. This entire assembly can be removed from the cooling side of the wind tunnel and attached to the heating side duct to toggle between heating and cooling the test section.

4.1.3 Mounting Mechanism

The mounting mechanism is used to hold the test specimen and hold the force sensors in the form of load cells. This mechanism consists of 1-inch-wide aluminum bars that are 12 inches in length.

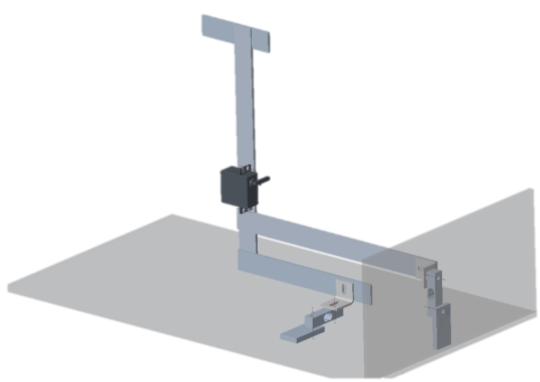


Figure 4.6: Mounting Mechanism Assembly

The vertical mounting arm holds a 20kg servo motor that attaches to the mounting arm with a pushrod. This can be controlled with a potentiometer to adjust the angle of attack of the test specimen. Two horizontal arms act as levers to transmit the drag and lift force to the load cells.

4.1 Structural Soundness

There are two main structural concerns within the design of any wind tunnel. Firstly, there are the forces that the interior of the tunnel is subject to as a result of the flow passing through. In the case of our design, the structural consequences of these forces will be negligible, as the highest flow speed expected in the tunnel is less than 1.5 m/s. Secondly, and foremost within the scope of our design, the structure below the wind tunnel must be able to hold the weight of all components.

Cost is the most significant factor in the design of the cart structure. As this structure encompasses more overall volume than the wind tunnel itself, larger parts are required to fill this space. Furthermore, the wind tunnel must be portable via wheels. As such, simplicity is prioritized in the design of the cart. The design of the cart is included below:

Figure 4.7: Wind Tunnel Cart Design

Although diagonal supports would prioritize structural stability, there is no room left in the budget at this point to justify more structural components. As such a finite element analysis is performed in Abaqus CAE to ensure that this design can hold the weight of the wind tunnel. Using this program, the weight of the wind tunnel can effectively be modelled on top of the cart using a pressure function on the top face. The weight of the wind tunnel is estimated to be 35.62 kg, as expressed in Appendix 6. Using this force analysis, we can estimate which material should be used for the top surface. In the interest of cost, the starting material chosen is plywood. One important thing to note about the analysis is that Abaqus interprets its own units. Thus, all units are converted to a standard English system, with inches as the main unit of displacement. The weight of the wind tunnel itself was modelled as a distributed pressure load on top of the table. Converting the load of the wind tunnel weight to these units results in a value of 0.0728 lbf/in^2.

The next step of the procedure is to mesh the assembly locally, creating finer meshes in areas expected to cope with the highest amounts of stress. In accordance with this, a local edge seed was created along the perimeter of the tabletop. In addition, a local seed was created along the intersection of the caster and the framing. The subsequent mesh appears below:

Figure 4.8: Meshed Cart Assembly

Once the mesh was addressed, the boundary conditions were applied. A visualization of the load and boundary conditions is presented below:

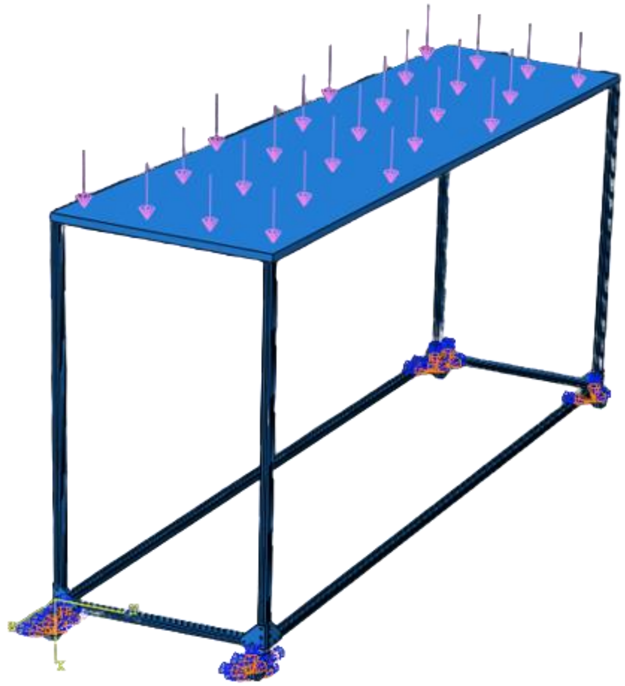


Figure 4.9: Load and BC of Cart Model

As the material of the countertop is the main structural concern, the visualization results only include the countertop. The first test conducted is of 15/32" plywood on the top of the cart. The results of the initial test are displayed below:

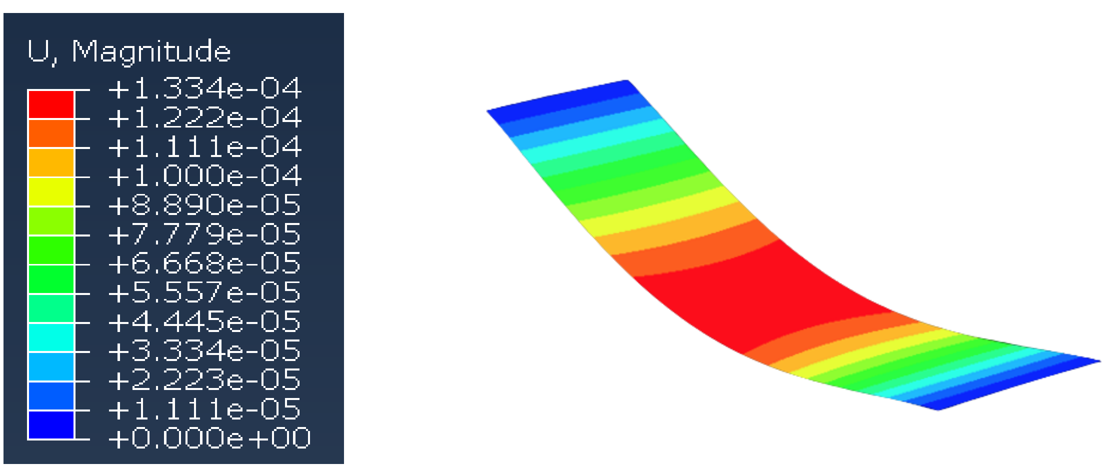


Figure 4.10: 35/32" Thickness Displacement Results

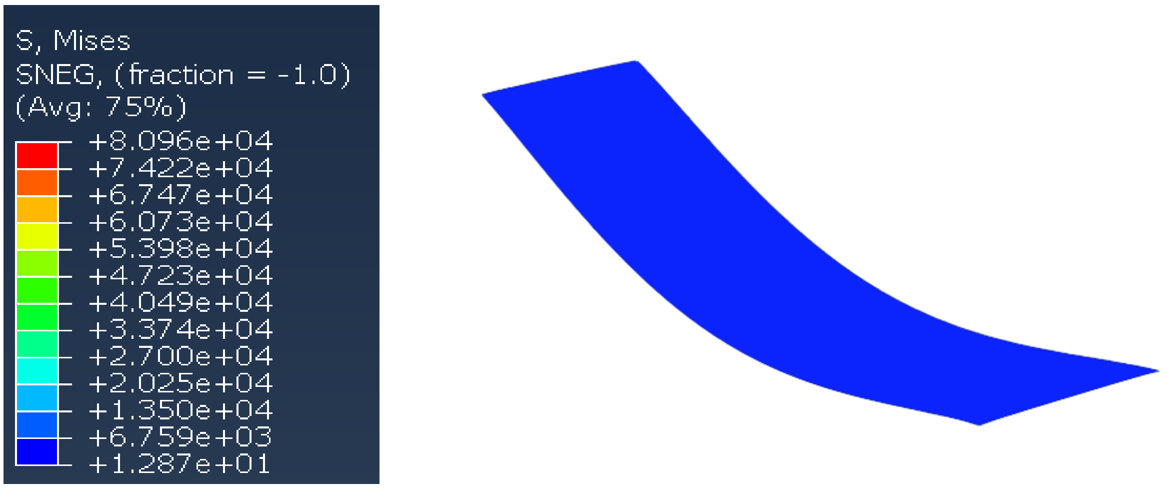


Figure 4.11: 3/16" Thickness Stress Results

The initial test resulted in the cart being subject to 12.87 lbf/in^2 of stress along the entire surface of the countertop. Additionally, the countertop experienced 1.33 x 10^{-4} inches of displacement in the center of the cross section. A second test was performed under the same conditions to understand the results of increasing the thickness of the top sheet from 15/32" to 23/32". The results of the 23/32" thickness test are below:

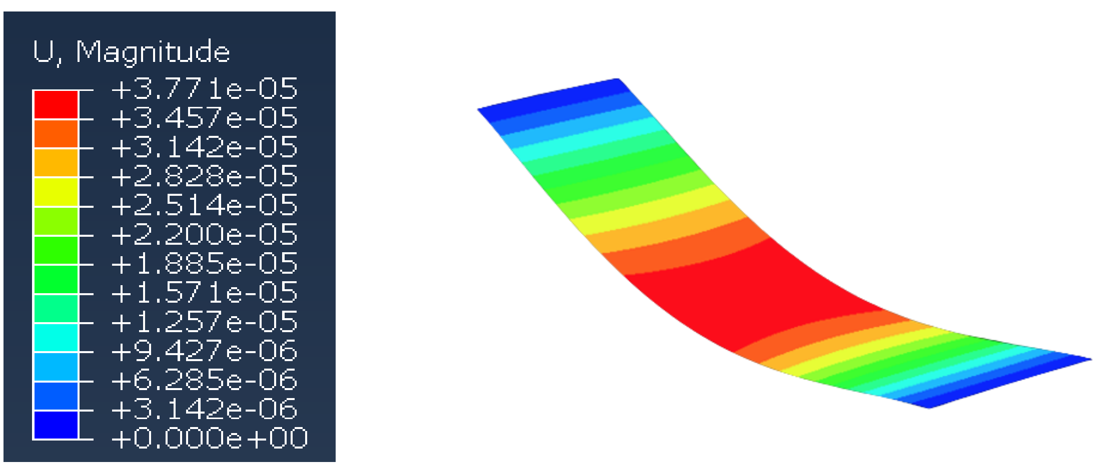


Figure 4.12: 23/32" Thickness Displacement Results

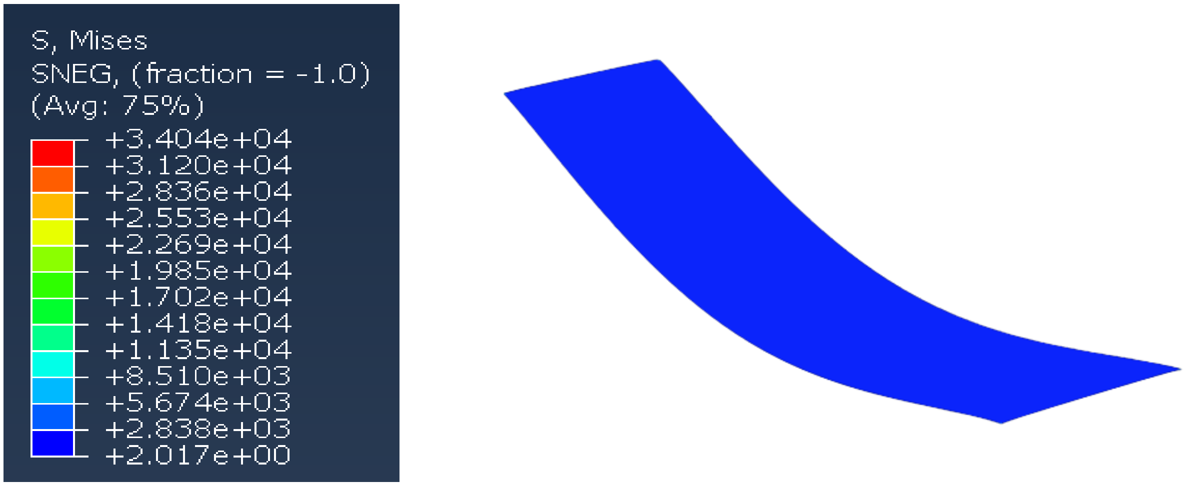


Figure 4.13: 23/32" Thickness Displacement Results

In comparison to the initial loading test, the 23/32" thick countertop experienced a stress of 2.02 lbf/in^2 around the longer edges of the plate while a displacement of 3.77 x 10^{-5} in is present in the middle of the plate. Although the 23/32" thick plate performed better under the load, this is deemed unnecessary as the 15/32" performance is acceptable and costs less. Therefore, the 15/32" plywood is selected for design.

4.2 Airflow performance

One major concern in the design of our wind tunnel is airflow performance. As evident in our mission need statement, the flow must remain laminar under a Reynold's number of 5000. In Chapter 4.1, we mention that laminarity is established through duct geometry as well as flow straighteners. While the flow straighteners are useful in this aspect, the positive geometry acts as a wall which the flow hits directly. This causes a pressure drop in the test section. Thus, pressure drop calculations were performed to determine the geometry of the flow straightener. The main equation used in determining this geometry is as follows:

$$\Delta p = f_d * \frac{\rho}{2} * v^2 * \frac{L}{D_H} \quad [4.1]$$

As the velocity and density of the flow are known, f_d is the parameter that must be found to solve for the optimal length to diameter ratio. This parameter is a friction coefficient and can be found through the Moody Diagram shown below:

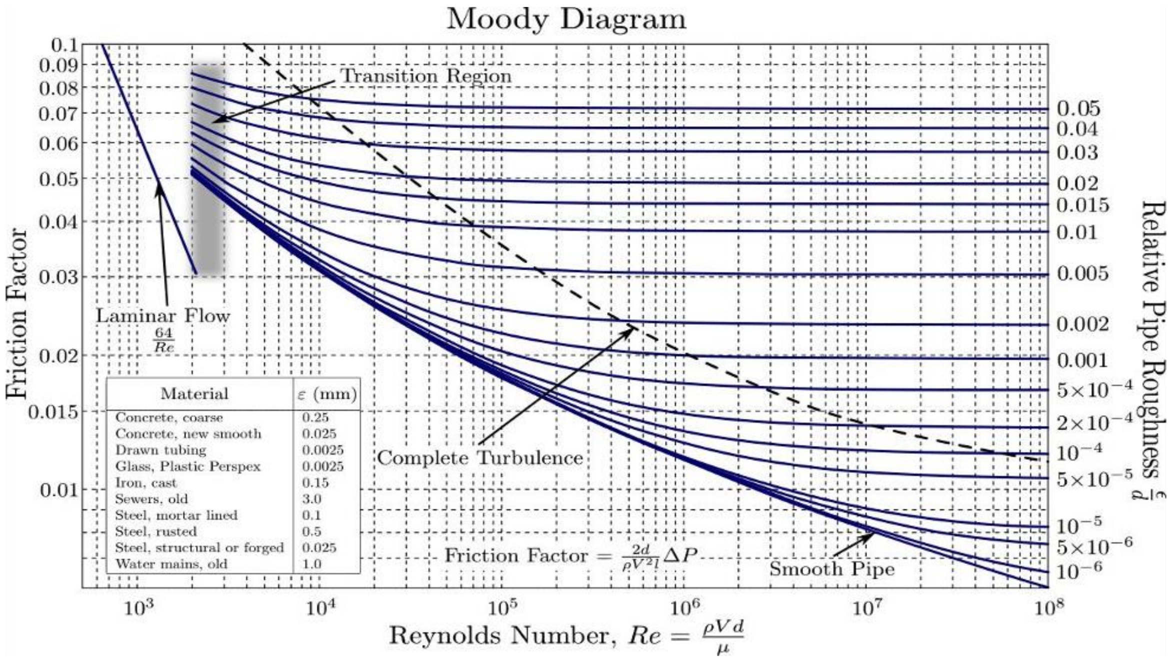


Figure 4.14: Moody Diagram

Although the goal of the design is to achieve laminar flow in the test section, it would be an oversimplification to draw from the laminar flow region in the moody diagram. Instead, the region which reflects the highest allowable Reynold's number in the test section is used. From this region, we turn our attention to the table in the lower left corner to determine the strain value of our material, which is the numerator of the relative pipe roughness. As we plan to 3D print the flow straightener, the Plastic Perspex value of 0.0025 is chosen. Then, setting the characteristic length equal to one inch, a friction factor of 0.032 is found.

According to *Fundamentals of Wind Tunnel Design,* research suggests that an optimal length to diameter ratio for an average honeycomb lies between 7 and 10 [2]. Using this range in tandem with the information found previously, the average pressure drop was found to be 0.001632 N/m^2. This value will be considered in the fan volumetric flow rating to ensure that the requirements are met in the test section. Ultimately, the equivalent diameter of each hexagon in the honeycomb is about 1 inch.

4.3 Subsystems

4.1.1 Control and User Interface

The fan speed as stated in the drive section is controlled using a DC fan controller with an integrated potentiometer. The angle of attack of the mounting arm is controlled via a separate potentiometer connected to an Arduino Mega microcontroller. The angular position of the servo and force measurement values are shown on the LCD screen which is also connected to the Arduino. Appendix 10 shows a detailed schematic of the Arduino architecture.

4.1.2 Heating and Cooling

The heating and cooling units are adapted from the old wind tunnel. These units are coupled through a single breaker and the heater can be toggled on and off as needed. The heat exchanger is connected to a refrigeration loop which is used to cool the air flowing through the heat exchanger. The temperature within the test section is monitored using the pitot-static tube which includes an onboard thermocouple.

4.1.3 Smoke Generator/Pitot-Static Tube Mounting

The smoke generator and pitot static tube are mounted to the wind tunnel duct using a 3D printed block that holds four magnets, these magnets are used to connect the mounting block directly to the wind tunnel duct. This also allows for quick swapping of the smoke generator wand and pitot static tube to the opposite side of the duct to change from heating to cooling configuration.

4.4 Budget Breakdowns

The following breakdowns represent the three components of finances, weight, and power, respectively.

4.4.1 Financial Breakdown

Our financial breakdown can be seen in its entirety in Appendix 11 in the Bill of Materials (BoM), highlighting every aspect to our design, including in house materials obtained from the old wind tunnel or scrapped. As you can see in the BoM, the total cost for our project has totaled up to $1053.78, which can be compared to the estimated cost seen in Figure 4.15.

Item	Group	Cost $	Cost %
Clear panel	Visualization	66.08	6.2707586
smoke generator	Visualization	50	4.7448234
Visualization group total		116.08	11.015582
Heater	Thermal	0	0
Heat exchanger	Thermal		0
Thermal group total		0	0
Tunnel walls	Structural	344	32.644385
Entry Hatch	Structural	30	2.84689404
Support legs	Structural	150	14.2344702
Misc.	Structural	150	14.2344702
Casters	Structural	75	7.1172351
Structural group total		749	71.0774545
Fan	Airflow	100	9.4896468
Honeycomb	Airflow	0	0
Variable speed controller	Airflow		0
Airflow group total		100	9.4896468
Load cells	Data acquisition	88.7	8.41731671
Pitot-static tube	Data acquisition	0	0
Data acquisition group total		88.7	8.41731671
	Total Cost	1053.78	

Figure 4.15: Preliminary Budget Estimation

Prior to the second progress presentation, a preliminary budget estimation was organized to get a solid idea of the total price our tunnel would cost. In addition to that, the goal was to assist with the creation of the BoM by determining the top priority parts, and how cautious our group would have to be when purchasing the items. From the preliminary cost estimation, it was clear that the structural group would take up a solid chunk of the cost, and this is certainly evident in the BoM.

4.4.2 Weight Breakdown

The next step of the design is to determine the weight breakdown of the wind tunnel. The center of gravity is useful in determining where the highest load will occur on the cart that the wind tunnel is placed on. The cart is symmetrical, so we can find the centroid as half of the base and height of the top cross section. The weight breakdown of the wind tunnel consists of 17 groups, as expressed in Appendix 6. These groups are visualized in the diagram below:

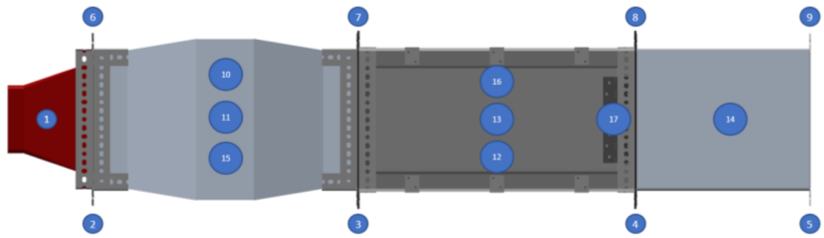


Figure 4.16: Wind Tunnel Center of Gravity Breakdown

The groups indicated in Figure 4.16 relate to components of the wind tunnel. The weights of these components are used in the equation below to find the center of gravity:

$$COG = \frac{(\Sigma W_{element} \Sigma x_{element})}{\Sigma W_{element}} \quad [4.2]$$

Using equation [4.2], the center of gravity was found to be 2.46 ft back from the beginning of the fan mount, longitudinally. This would place the center of gravity approximately at the flow straightener section on the cooling side of the test section. This center of gravity does not deviate exceedingly from the longitudinal midpoint of the wind tunnel.

4.3.3 Power Budget

Our wind tunnel is connected directly to external power while in use. The heat exchanger and heating unit from the original wind tunnel are coupled into a 240 V AC power unit. Thus, the only known power source on the University of South Carolina campus like this is in the basement where the original wind tunnel is located. This is one of the constraints that the power budget induces.

As for the rest of the electrical components, such as the fan, a 12 V DC power supply can be used. This power supply can be found virtually anywhere; however, an extension cord may be required to achieve the required distance from the power source and the electrical components of the wind tunnel.

4.5 Risk Map

The updated risk map appears in Appendix 9. Many of the risks are included from the initial risk map created for the design; however, the definition of such risks differs from their original meaning. For example, the 'Fan Power' risk used to relate to the fan not having a CFM rating high enough to supply proper velocity into the test section. Now, the risk relates to the ability to integrate the fan output to the power source while maintaining variable fan power.

We have constructed methods to mitigate the risk of the most likely and most severe problems. The problem with the highest established severity and probability is the force acquisition failure. This is due to the number of elements associated with the success of the force acquisition system. The mounting mechanism must promote accurate force readings for the load cells, the servo must operate, and the wiring must function. As such, the force reading will take precedence over other components once all parts arrive. Furthermore, testing dates for the data acquisition system have been set in the Gantt Chart.

Other probable and severe risks include the achievement of laminar flow in the test section as well as temperature control. Considering laminarity, the honeycomb flow straighteners have been included on both sides of the test section to achieve redundancy. When the flow is being pulled through the heating side of the duct into the test section, it will pass through the flow straightener. The same is true for when the fan is blowing the flow through the cooling side of the duct. Temperature control is something that our team has had to work around, considering we are taking the heat source and exchanger from the original wind tunnel in the basement. During preliminary tests, both the heating and cooling capabilities worked. To deal with this risk, testing dates have been established in the Gantt Chart.

5. Manufacturing Approach

Following the periodical acquisition of parts, the assembly of the tunnel could begin. Although, prior to the arrival of new parts, the old tunnel could first be disassembled appropriately. An image of the old tunnel can be seen below in Figure 5.1.

Figure 5.1: Previous Tunnel Prior to any Disassembly

This old tunnel was very valuable to our design, as there were crucial aspects that were able to be harvested from it such as the heater, the heat exchanger, the electrical system, and even the whole cart. The first step in the manufacturing phase was to disassemble this old tunnel, leaving only the parts that were necessary when the actual assembly of our tunnel was ready to begin. Figure 5.2 highlights the removal of the important components, and Figure 5.3 displays all the parts that were harvested and will be included in the new tunnel:

Figure 5.2: Removal of Significant Old Tunnel Components

Figure 5.3: Remaining Components to be Implemented into Design

This step of utilizing the old tunnel was completed shortly prior to arrival of any parts but was done to ensure that when parts would arrive, the manufacturing phase would be ready to begin. Manufacturing of the arriving parts began with the assembly of the three main sections of the tunnel, the heating section, the test section, and the cooling section. Prior to these being assembled, the sheet metal and the polycarbonate sheets needed to be measured and cut to the appropriate lengths. Cutting of these was accomplished in the machine shop, utilizing the table saw, sawblade, shear machine, and hole puncher. All tasks were assisted by Bill Bradley. Once these had been cut, the assembly of the tunnel was accomplished through L shaped brackets, nuts, and bolts. The assembly of the heating section and test section can be seen in Figure 5.4 below:

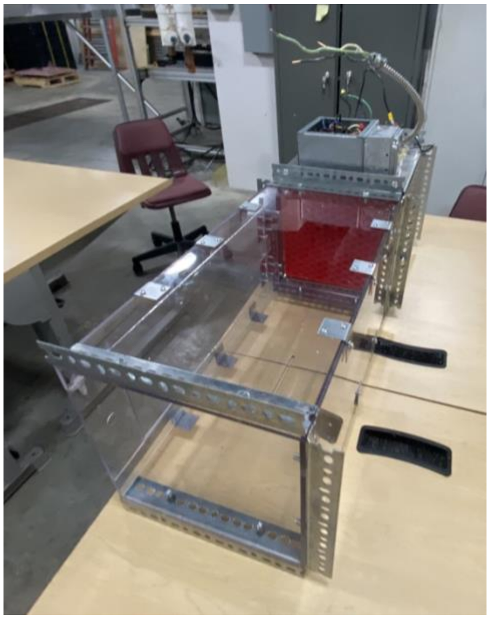


Figure 5.4: Heating Section and Test Section Assembly

Other work that was necessary to reach the step shown above would be drilling holes into the polycarbonate for the corner brackets to assemble the test section. Also, the wiring was attached onto the top of the heating section, as well as the heater which was attached with two sets of nuts and bolts. The honeycomb mesh is able to slide in and out of the cooling section and did not have to be secured.

Now that those two sections of the tunnel have been assembled, the trickiest section of the cooling side was ready to be put together. This side required the most intricate of cutting and assembly due to the odd size of the heat exchanger that did not match the 1 ft x 1 ft size of the rest of the tunnel. While the initial plan was to construct a converging diverging section to build around the excessive cross section of the heat exchanger, the design evolved into maintaining the 1 ft x 1 ft area by not utilizing the outer sides of the cooling section. This was determined to be not only simpler to manufacture, but also material efficient and did not impact the flow requirements. Now that the third section had been completed, the structural part of the tunnel was ready for assembly.

Another significant portion to our design was the fan mount apparatus, which was 3D printed and manufactured. This print was tricky due to its size and time necessary to print, but once it was complete it was nearly ready for addition to the tunnel. The two steps that needed to be completed were to Dremel the corners for the fan to fit, and then to attach the L shaped brackets. The holes on the mount were precisely placed during the print, so the brackets were easily attached. The Dremel tool was necessary until the fan was able to fit, and that concluded the work done for the mount.

Figure 5.5: Fan Mount with Fan Attached

While the tunnel was being put together, another aspect of the design that was being manufactured was the leg assembly. While the initial design intended to use all the t-slotted framing to accomplish this support for the tunnel, the design was shifted to utilizing the legs from the old tunnel and extending it using the T-slotted framing. This can be seen in Figure 5.6, which is a picture of the whole tunnel assembled on top of the legs.

Figure 5.6: Final Wind Tunnel Design

The extension of the legs can be seen on the left side of the tunnel, with the T-slotted framing providing the extra support necessary. The T slotted framing came with all the accessories necessary for assembly, but the holes at the end of the bars needed to be tapped to size M6 to connect them to both the wood planks at the top and the cart base at the bottom. This was done in the machine shop. Furthermore, the T-slotted framing had to be cut to the necessary lengths using the saw machine.

The final major step for assembly was both the mounting mechanism as well as the undercarriage which contained the mounting mechanism. The undercarriage was made with excess wooden planks and excess T-slotted framing, which were tapped on both ends of the bar to the same size of M6. The mounting mechanism was attached directly onto the undercarriage, and this was done so that the load cells had a fixed position to record accurate displacement measurements. With the mounting mechanism attached to the undercarriage, and the undercarriage attached underneath the top level of the table, the assembly was complete. This can all be seen in Figure 5.7. Prior to the attachment of this undercarriage, a hole must be also cut into the tabletop for the mounting apparatus to fit. This hole can be seen from the bottom in Figure 5.7 but also from the top in Figure 5.8.

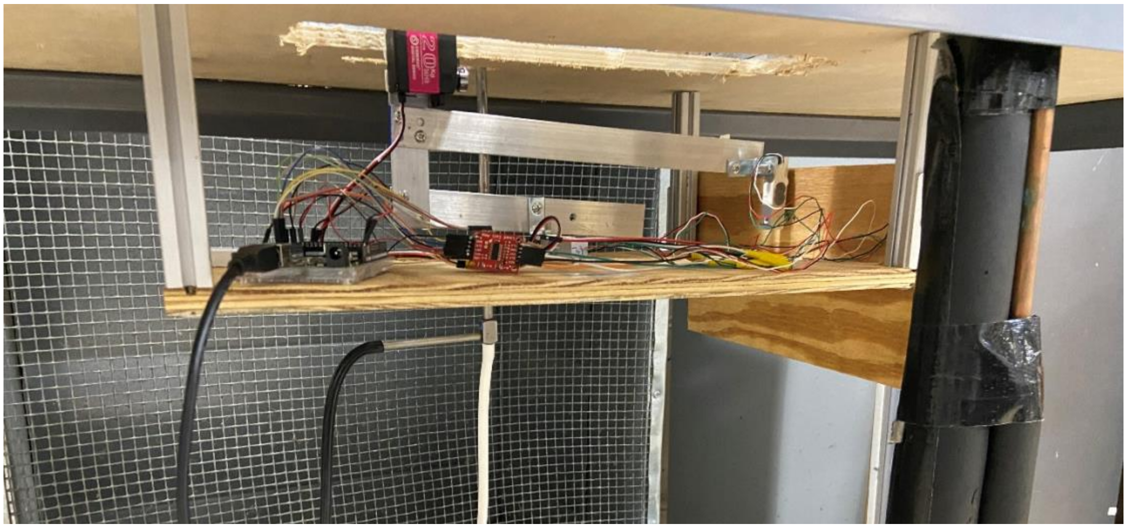


Figure 5.7: Undercarriage and Force Acquisition

An additional manufacturing step that was completed following the demonstration was the mount for the test subject. This can be seen below in Figure 5.7. The mount has a cylindrical piece that allow for the mounting of items similar to the large functional tunnel that is in the wind tunnel room of 300 Main. The cylinder has a diameter of 13.5 mm, so to 3D print any airfoil desired, simply extrude a hole into the wing so that it can be mounted appropriately. Also, there was a bit of manufacturing to the pitot tube, and that was mainly through the magnets. The approach taken for the pitot tube was to glue a small plate to the tube about halfway down, to which magnets were glued into. Furthermore, a similar plate with magnets was also glued to the bottom of the test section. What this allows is for the pitot tube to be disconnected, rotated 180 degrees, then reattached. This allows for airspeed measurement for both forward flow and reversed flow.

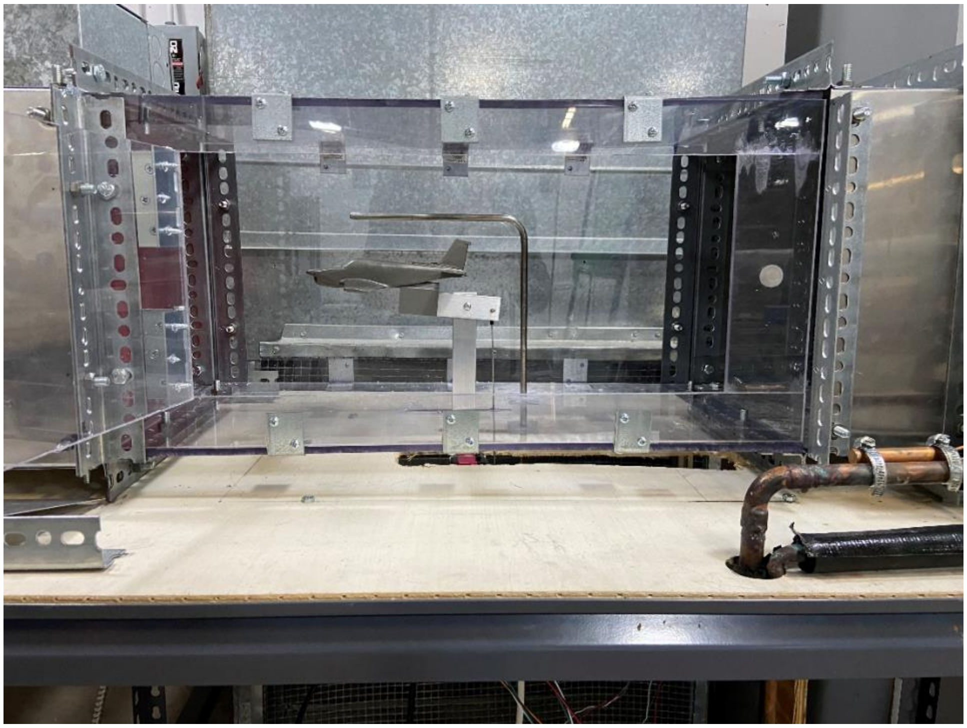


Figure 5.8: Test Section, Revealing Mounting onto Apparatus

6. Standards, Codes, and Regulations

Standards are technical definitions which are not enforceable by law, but rather simply voluntary. Despite this, it is still expected to perform tasks under this practice to ensure the safety and stability of the system. There were not too many standards for the wind tunnel to comply with, but two examples would be the noise and the NEMA rating. The noise level must comply with the standard from The Department of Labor Occupational Noise Exposure Standard of less than 115 dB for 15 minutes or less. Not only does the tunnel not generate that excessive dB level, but it also will most likely not need to be run for 15 minutes. Furthermore, as an extra precaution there will be earplugs located in the wind tunnel room. As for the NEMA rating, which falls under the rating of 1 since the tunnel will not only not experience liquids, but it also will not operate under conditions of heavy dust, lint, and/or fibers.

Unlike standards, codes are enforceable by law and are mandatory to be followed, so they govern the whole process and drive the design. One main association that guided our design and safety precautions would be the NFPA (National Fire Protection Association). Under this association would be the basic NFPA codes and standards, which are in place to represent all fire hazards. There are more than 300 codes and standards representing various risks, and one of these that our tunnel must have adhered to would be NFPA 90B, emphasizing requirements for warm air heating and air conditioning through ducts, two components to our design.

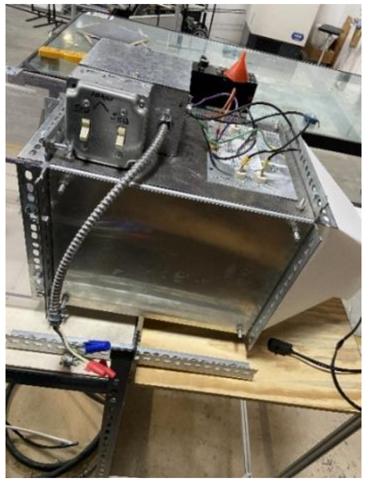


Figure 6.1: Section of Electrical System

Furthermore, another one of the codes under this association that our group had to follow when operating would be the NEC (National Electrical Code) for safe electrical installations. This code goes under the title of NFPA 70 and represents the foundation for safety with respect to electrical design, installation, and inspection. While most of our electrical work had already been designed and installed, it was still essential for the previous wiring to be inspected and confirmed. Some examples of codes that our project did not have to adhere to would be the IBC (International Building Code) and FBCA (Federal Food, Drug, and Cosmetic Act), which are self-explanatory.

Regulations are like codes in the fact that they are also enforceable by law, as they stem from an order from the government. While there are multiple regulations that involve flying that we do not have to pay attention to such as EASA and the FAA, there are still some significant ones such as OSHA (Occupational Safety and Health Administration). This regulation was significant primarily through the manufacturing process and emerged mainly during the machine shop. While we are students and not employed for the university, the regulations must still apply to ensure safe working conditions.

7. Product Performance Evaluation

7.1 Compliance Verification Table

The compliance verification table is an important tool in terms of keeping on track with the requirements of the project. The updated compliance verification table can be found below:

Table 7.1: Compliance Verification Table

No	Requirement	Means of Compliance	Status
1	Time	Gantt Chart, Meeting Minutes	Complete
2	Laminarity	CAD Files, CFD Reports, Testing	Complete
3	Structure (Test Section Area)	CAD Files, CAD Drawings	Complete

4	Heating Capabilities	Lab Tests, Analysis	Complete
5	Data Acquisition	CAD Files, Lab Tests, Analysis	Complete

The five requirements are derived directly from our project objective statement and mission need statement. In the 'Means of Compliance' column, we have included approaches to ensure that these requirements are fulfilled.

For instance, the second requirement of laminarity was first estimated using a computational fluid dynamics analysis using the honeycomb structure. From this, the velocity in the test section was estimated and the flow was visualized. Once the structure itself had been built, we used a flowmeter to test the velocity in different areas of the test section. Uniform values for velocity ensured that laminar flow had been achieved.

7.2 Requirement Satisfaction

Given the provided requirements and considering the variation to said requirements as the design progressed, it can be concluded that most of the requirements have been met, with some outlying aspects.

The requirements that have been satisfied were accomplished through intricate planning and sticking to the designs that were initially generated. There were certainly some regions of the final product that strayed from the preliminary design, but none of these alterations affected the ability to comply with all the given requirements. Requirements that were met include completion on time, total cost under the budget of $1250, a test section cross sectional area of 1 ft x 1 ft, force analysis of lift and drag along with mounting capabilities, cooling, flow reversal, and finally visualization. There are other sub requirements that have been met such as ease of mobility, airspeed acquisition, fan velocity control, and more. All of these were monitored throughout the semester to ensure functionality and satisfaction of requirements.

7.3 Requirement Non-satisfaction

While there are many aspects of the tunnel that can be deemed satisfactory, there are certainly some that do not fulfill the requirements. The main two requirements that are not currently met are the Reynolds number of up to 5000 and heating ability up to 50 degrees Celsius. Both are not necessarily extremely difficult fixes, but regardless they restrain the tunnel from meeting all requirements. Starting with the Reynolds number, this requirement is not met due to the simple reason of not having a powerful enough fan. The fan that was ordered does not generate enough fan power to create the airspeed necessary, thus depriving the Reynolds number of reaching appropriate levels. One potential solution to this issue would be to implement the fan from the old tunnel, which is significantly more powerful than the current one. This fan was utilized for data acquisition and has proved it can generate the airspeeds necessary. Since the fan from the previous wind tunnel uses an A/C blower fan motor typically seen on HVAC units. A common solution to adjust the CFM or RPM of the fan motor is to use resistors in series with the fan circuit to limit the amount of current going through the motor. This is typically achieved using proprietary fan control PCBs that are manufactured by HVAC companies that typically use these blower fan motors for circulating hot air in a system. The blower motor used in the previous wind tunnel has a 115 VAC connection that does not have resistors built-in, thus driving the requirement for an external circuit. Based on the testing conducted using the PWM computer fan, it is apparent that the RPM of this fan, while theoretically being sufficient for the test section, is not enough to overcome the very significant pressure drop across the wind tunnel duct, heater, honeycomb, and heat exchanger. Also, the small size of the fan and the length of the diffuser used caused significant boundary layer separation, further decreasing the airspeed through the test section. This is a major issue because, based on the research we conducted, there are only a few fans that can realistically meet the flow speed and size requirements necessary. These include the AC blower fan (used in the old wind tunnel), Large DC radiator fans with relatively low CFM and little fan control options, and PWM fans that offer great speed control but lack the required power to meet the requirements. Therefore, it is suggested that the old fan, or a similar off the shelf blower motor be used for the wind tunnel, while utilizing a PCB with resistors to control the fan speed. A PSC blower motor such as the 4-speed, direct drive blower motor by Marathon could be a good option as it can be directly connected to a 24V PSC fan control board.

Figure 7.1: Marathon PSC Blower Motor, 4 speed

As for the heating capability, this was not met because the heater unfortunately stopped functioning shortly before full assembly was complete. The assumption is that the electrical aspect of the heater blew a fuse or short circuited. Regardless of the unknown cause, its lack of functionality deems the requirement unsatisfied. Future work necessary to get the heater up and running again would most likely include rewiring of the system, hopefully only the wire that caused the error. Given these two additional changes to the current design of the tunnel, it could be concluded that the tunnel is fully operational.

Another less significant requirement that has not been met would be the smoke generation, which could not be met due to inability to locate smoke generator wand. All components for creating smoke are available and stored in the undercarriage of the tunnel, but the wand is simply missing so that requirement could not be met. The items currently available to us are shown below in Figure 7.2. To fix this issue a wand would have to be purchased, preferably from AEROLAB, which is where the rest of the smoke generation set originated from.

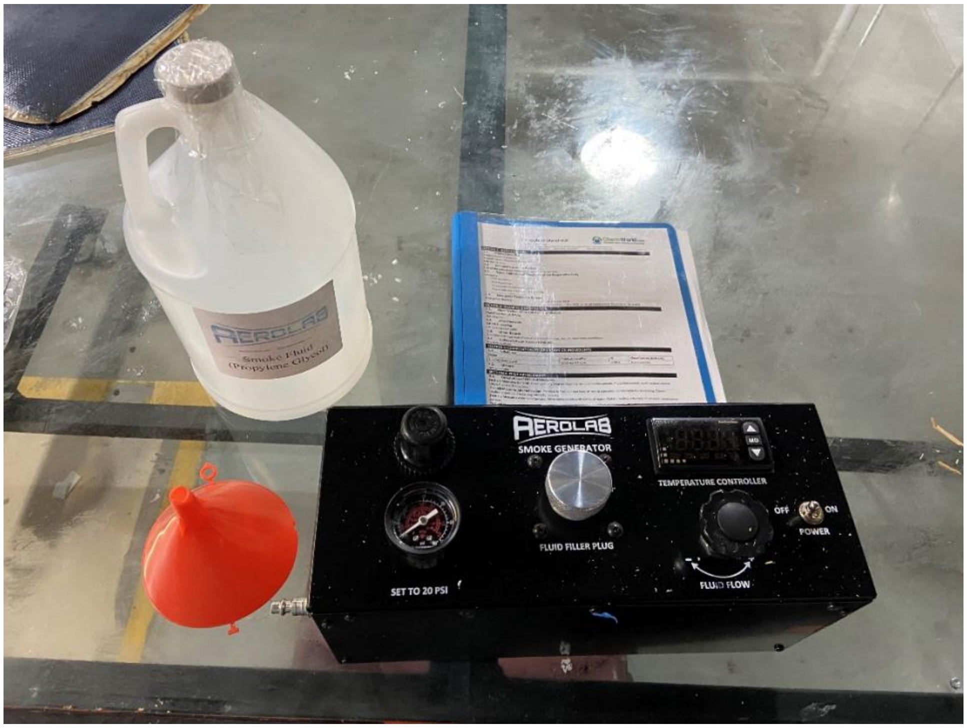


Figure 7.2: Available Smoke Generation Instruments

7.4 Future Improvements

From an outside perspective, there are several components to the design that could be improved and would be implemented to benefit the overall performance of the tunnel. As discussed previously, the two primary components that would improve the tunnel to full functionality would be a more powerful fan and a repair of the heater. Given similar resources, it could be concluded that a full redesign of the legs could have been implemented to improve the visual appeal of the design. The resources required would have been available, but the team decided to take a different route to ensure structural stability as well as improve time management.

8. Broader Impacts

8.1 Immediate Impact

As detailed in our organigram, the immediate stakeholders of this project are Aerospace and Mechanical Engineering students and teaching assistants. The ultimate goal of this project was to create something that can be used in the future for students in a lab setting. The University of South Carolina currently has a wind tunnel capable of high speeds, data acquisition, and variable angle of attack. However, our team plans to make use of the low Reynolds number capabilities along with the heating and cooling capabilities of our tunnel to deviate from the testing normally conducted on the existing wind tunnel. For instance, utilizing the cooling capabilities of the wind tunnel allows students to test flow behaviour at equivalent altitudes, in accordance with the table below:

As detailed in our organigram, the immediate stakeholders of this project are Aerospace and Mechanical Engineering students and teaching assistants. The goal of this project was to create something that can be used in the future for students in a lab setting. The University of South Carolina currently has a wind tunnel capable of high speeds, data acquisition, and variable angle of attack. However, our team plans to make use of the low Reynolds number capabilities along with the heating and cooling capabilities of our tunnel to deviate from the testing normally conducted on the existing wind tunnel. For instance, utilizing the cooling capabilities of the wind tunnel allows students to test flow behaviour at equivalent altitudes, in accordance with the table below:

Table 8.1: Altitude vs. Flow Parameters [8]

Geo potential Altitude above Sea Level	Temperature	Acceleration of Gravity	Absolute Pressure	Density	Dynamic Viscosity
- *h* -	**- *t* -**	**- *g* -**	**- *p* -**	**- *ρ* -**	**- *μ* -**
(m)	***(^oC)***	***(m/s^2)***	***(10^4 N/m^2)***	***(kg/m^3)***	***(10^{-5} $N\ s/m^2$)***
-1000	21.5	9.81	11.39	1.347	1.821
0	15	9.807	10.13	1.225	1.789
1000	8.5	9.804	8.988	1.112	1.758
2000	2	9.801	7.95	1.007	1.726
3000	-4.49	9.797	7.012	0.9093	1.694
4000	-10.98	9.794	6.166	0.8194	1.661
5000	-17.47	9.791	5.405	0.7364	1.628
6000	-23.96	9.788	4.722	0.6601	1.595

Hopefully, our wind tunnel will be able to impact students early into their aerospace engineering tenures at the University of South Carolina. We envision the wind tunnel being employed in vital aerospace engineering courses such as AESP 265: Intro to Aerodynamics of AESP 361: Aerospace Lab I. Our team believes that our low-speed wind tunnel is an effective method for demonstrating the fundamentals of aerodynamics.

8.2 Societal, Political, and Ethical Impact

Aside from the local impact at the University of South Carolina, our team hopes that other students and interested parties take action in the education of aerodynamics inherent within the scope of our project. Our project is evidence that it is possible to create a low-speed wind tunnel capable of heating, cooling, force acquisition, and variable angle of attack for under $1250. Perhaps universities that run a similar senior design program will see a need for a product such as ours and implement a similar project into their course. Furthermore, external parties with a budget of around $1250 can build upon our design, and possibly improve on what we have accomplished in this project. In a similar fashion, politicians may see what we have done with our constraints and find that our wind tunnel provides a solid education of aerodynamics. As a popular topic amongst politicians in the technology sector is sustainability, they may decide that an understanding of aerodynamics can lead to less fuel used in aircrafts, and in turn, less carbon emissions. Ultimately, our team believes that the wind tunnel we have designed will leave a positive impact on those who have read this report.

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[8] *U.S. standard atmosphere vs. altitude*. Engineering ToolBox. (n.d.). Retrieved May 3, 2023, from https://www.engineeringtoolbox.com/standard-atmosphere-d_604.html

Appendix 1: Meeting Minutes

Team Meeting

Date: 22nd of February 2023, Time: 11:00 am, Location: Dr. Mobli's Office

Submitted by Justin Bak

Attendance:

USC	Present	Customer	Present	Leads	Present
Danny Muck	X	Dr. Mobli	X	Justin Bak	X
Jackson Brown	X				

Agenda:

- Project Updates
- CFD Discussion
- Bill of Materials
- Lab Tunnel Walkthrough
- Upcoming Deadlines
- Closing Updates

Meeting Minutes:

Project Updates:

- Reynold's Number requirement changed from Re 2000 to Re 5000
- Test Section changed from 2 x 2 ft to 1 x 1 ft

CFD Discussion:

- 3D Analysis 2D Analysis
- Find pressure drop
- Find length of convergent/divergent section

Materials Discussion:

- Aluminum vs. PLA for honeycomb structure
- Aluminum used for main body
- Polycarbonate used for test section
- Allocation of funds reserved for force measurement

Lab Tunnel Walkthrough:

- Fan measured 1 x 1 ft
- Heating/Cooling Element need to be manufactured around
- Test Section velocity 1.5 m/s

Upcoming Deadlines:

- Progress Report 2
- Bill of Materials

Closing Updates:

- Meeting Adjourned at 12:05 pm.

Action items:

- Research must be performed to determine pressure drop in the test section
- Create multiple CFD Model to test geometries
- Gather list of materials and major components

Team Meeting

Date: 1st of March 2023, Time: 11:00 am, Location: Dr. Mobli's Office

Submitted by Justin Bak

Attendance:

USC	Present	Customer	Present	Leads	Present
Justin Bak	X	Mostafa Mobli	X	Danny Muck	X
Jackson Brown	X				

Agenda:

- Approval of meeting minutes of 02/22/2023
- Roughness/Pressure Drop Discussion (velocity not constant) L/D: 7-8
- Increase/Decrease length as needed (stack cylinders)
- Orders in by next week?
- Next Step: Fan Analysis
- Add Brackets to BOM
- Determine Geometry Define Links

Meeting Minutes:

Approval of meeting minutes of 02/22/2023:

- Approved

Updates from Jackson Brown:

- Initial duct geometry created in Creo Parametric 8.0

Updates from the Justin Bak:

- 3D CFM Meshing issue

Updates from Danny Muck:

- BoM in initial stages, includes 5 components

Points from Dr. Mobli:

- Assume L/D ratio of 7
- Calculate Pressure Drop
- Download slicing software [Raice 3D Pro 2]
- Switch from 3D CFM to 2D
- Access into basement gained

Upcoming Deadlines

- Progress Report 2
- CAD and CFD (Gannt Chart)

Closing Updates:

- Meeting Adjourned at 12:18 pm.

Action items:

- Conduct 2D CFD Analysis
- Continue with wind tunnel assembly
- Continue BoM

Team Meeting

Date: 7th of March 2023, Time: 11:00 am, Location: Swearingen 1D39

Submitted by Justin Bak

Attendance:

USC	Present	Customer	Present	Leads	Present
Jackson Brown	X	Dr. Mobli			
Justin Bak	X				
Danny Muck	X				

Agenda:

- Approval of meeting minutes of 03/01/2023
- Updates from Jackson Brown
- Updates from Justin Bak
- Updates from Danny Muck
- New Business
- Upcoming Deadlines
- Action items

Meeting Minutes:

Approval of meeting minutes of 03/07/2023:

- Approved

Updates from Jackson Brown:

- Idea for mounting mechanism
- Pressure-drop calculations complete

Updates from Justin Bak:

- Scrap 2D CFD Simulation (Meshing Error)
- Pressure-drop calculations complete

Updates from Danny Muck:

- BoM updated
- Servo Mechanism Proposed

New Business

- Mounting Mechanism
- Data Acquisition
- Load Cells

Upcoming Deadlines (project planning review)

- Detailed Design Report
- BoM

Closing Updates:

- Meeting Adjourned at 1:22 pm.

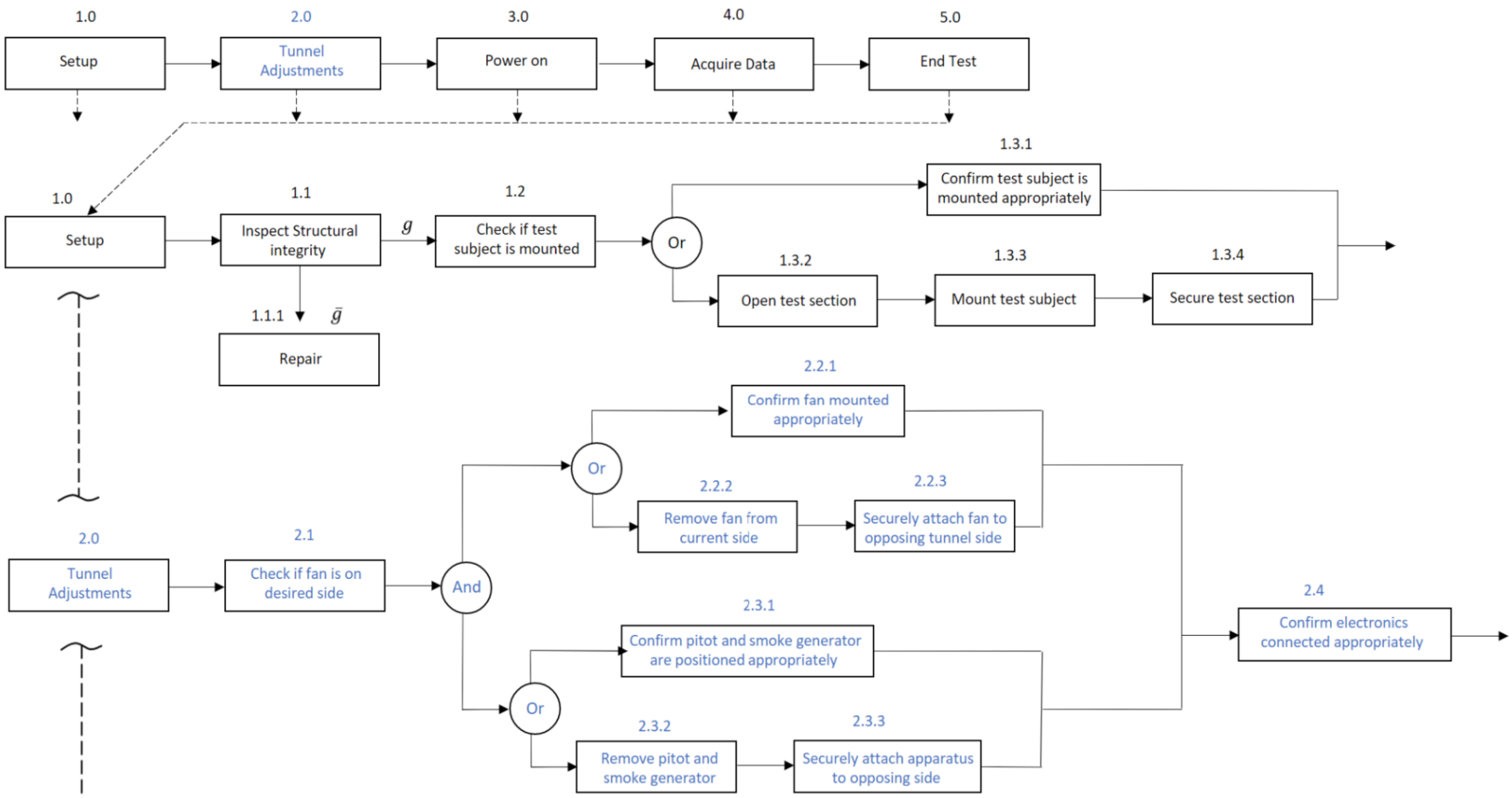
Action items:

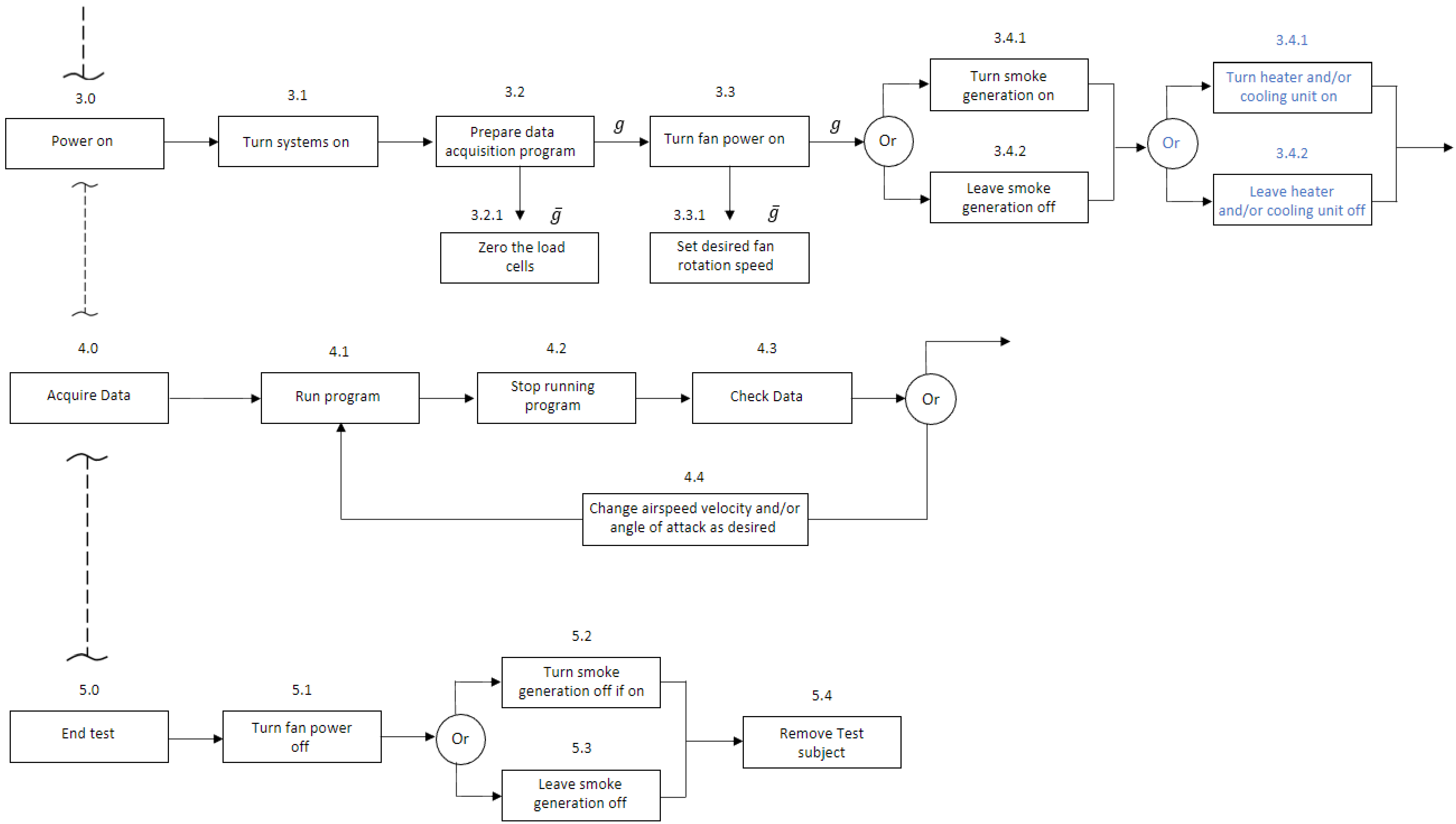
- Define mounting mechanism
- Define data acquisition
- Continue CAD Assembly
- Consider Manufacturing Methods

Appendix 2: Design Parameters Table

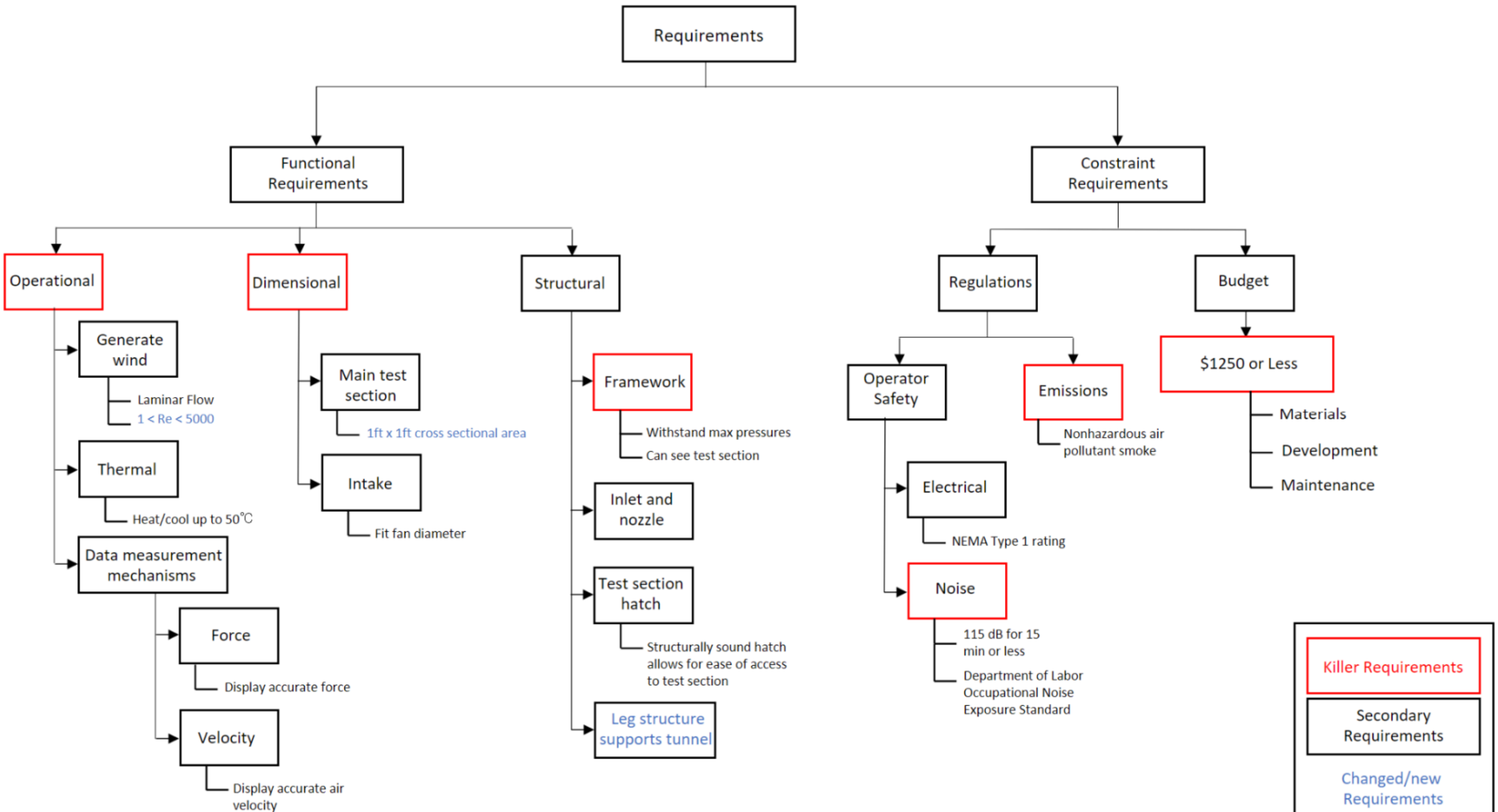
Symbol	Parameters/Characteristic	Value	Unit
A_{cd}	Area of duct material (cooling side)	2672.11	in^2
A_{hd}	Area of duct material (heating side)	1445.40	in^2
A_{ts}	Area of test section material	2473.00	in^2
R_F	CFM Rating of Noctua Fan	70.75	ft^3/min
Re_{MAX}	Maximum Reynold's Number in Test Section	5000	N/A

Appendix 3: Functional Flow Diagram

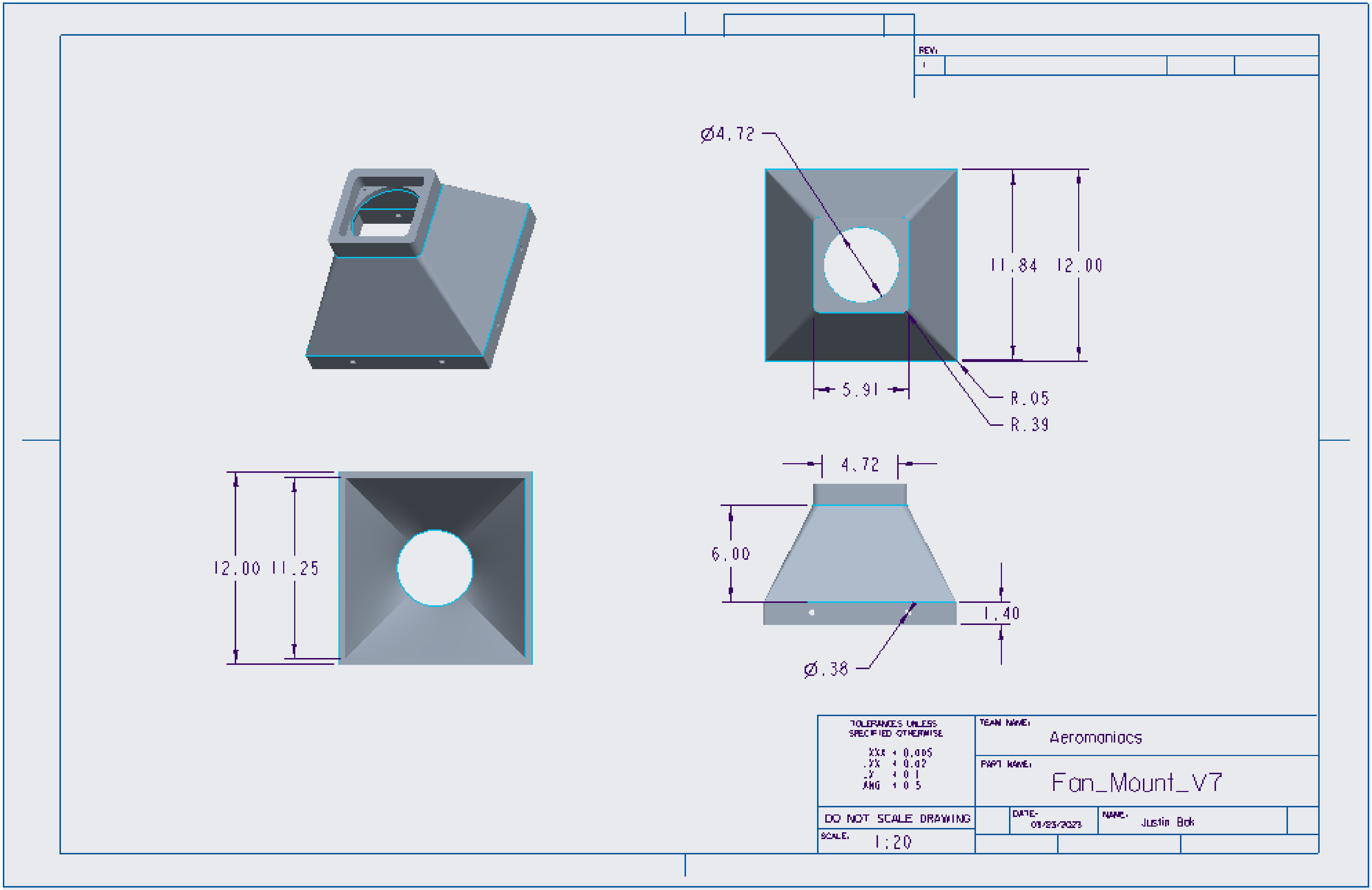



3.0
Power on
3.1
Turn systems on
3.2
Prepare data acquisition program
g
3.2.1
$\bar{g}$
Zero the load cells
3.3
Turn fan power on
g
3.3.1
$\bar{g}$
Set desired fan rotation speed
Or
3.4.1
Turn smoke generation on
3.4.2
Leave smoke generation off
Or
3.4.1
Turn heater and/or cooling unit on
3.4.2
Leave heater and/or cooling unit off
4.0
Acquire Data
4.1
Run program
4.2
Stop running program
4.3
Check Data
Or
4.4
Change airspeed velocity and/or angle of attack as desired
5.0
End test
5.1
Turn fan power off
Or
5.2
Turn smoke generation off if on
5.3
Leave smoke generation off
5.4
Remove Test subject

Appendix 4: Requirements Tree



Appendix 5: Fan Mount Drawing



Appendix 6: Weight and Center of Gravity Breakdown

Wind Tunnel Group								
Item #	Part	x-location (ft)	Quantity	Group	Volume (m^3)	Material Density (kg/m^3)	Mass (kg)	Final Weight (kg)
1	Fan Mount	0.25	2	fan-mounts	0.00259687	1400	3.64	7.27
2	L-framing (15 in)	0.5	4	duct-cooling-side	4.55826E-05	7800	0.36	1.42
3	L-framing (15 in)	2.5	4	duct-heating-side	4.55826E-05	7800	0.36	1.42
4	L-framing (15 in)	4.5	4	duct-heating-side	4.55826E-05	7800	0.36	1.42
5	L-framing (15 in)	5.5	4	duct-heating-side	4.55826E-05	7800	0.36	1.42
6	L-framing (12 in)	0.5	4	duct-cooling-side	3.64661E-05	7800	0.28	1.14
7	L-framing (12 in)	2.5	4	duct-cooling-side	3.64661E-05	7800	0.28	1.14
8	L-framing (12 in)	4.5	4	duct-cooling-side	3.64661E-05	7800	0.28	1.14
9	L-framing (12 in)	5.5	4	duct-heating-side	3.64661E-05	7800	0.28	1.14
10	L-framing (3 in)	1.5	4	duct-cooling-side	9.12E-06	7800	0.07	0.28
11	Aluminum Sheets	1.5	8	duct-heating-side	0.00007374	2700	0.20	1.59
12	Honeycomb	3.5	2	test-section	0.00072178	1400	1.01	2.02
13	Polycarbonate	3.5	1	test-section	0.00579496	1220	7.07	7.07
14	Heat Source	5	1	heating/cooling	N/A	N/A	5.00	5.00
15	Heat Exchanger	1.5	1	heating/cooling	N/A	N/A	6.80	6.80

16	L-brackets	3.5	6	test-section	1.46105E-05	7800	0.11	0.68
17	Hinges	4.5	2	test-section	1.42563E-05	7800	0.11	0.22
					TOTAL WEIGHT:	40.97	X_COG:	2.64

Cart Group

Item #	Part	x-location	Quantity	Group	Volume (m^3)	Material Density (kg/m^3)	Mass (kg)	Final Weight (kg)
1	20 mm Caster		4	framing	3.68992E-05	3400	0.13	0.50
2	T-slot 20mm (6 ft)		2	support	0.000358293	2700	0.97	1.93
3	T-slot 20mm (3 ft)		4	support	0.000179147	2700	0.48	1.93
4	T-slot 20mm (1.5 ft)		2	support	9.04676E-05	2700	0.24	0.49
5	Plywood		1	support	0.0082916	900	7.46	7.46
6	Framing Brackets		8	framing	1.02011E-05	2700	0.03	0.22
							TOTAL WEIGHT:	12.54

Appendix 7: Gantt Chart

4	**Wind Tunnel Design: First Iteration**		**100%**	**1/29/23**	**2/9/23**	**12**	**1**
4.1	Initial Design Schematic and Calculations	All	Complete	1/29/23	2/3/23	6	
4.2	Detail CAD Design	All	Complete	2/2/23	2/8/23	7	
4.3	Parameter Study	All	Complete	2/3/23	2/5/23	3	
4.4	Detail Trade-off Study	All	Complete	2/6/23	2/8/23	3	
4.5	Schedule Margin			2/9/23	2/9/23	1	
4.6	◆ Initial Design Report/ Progress Presentation 1		Complete	2/9/23	2/9/23	1	
5	**Numerical Analysis of Initial Design**		**100%**	**2/12/23**	**2/28/23**	**17**	**5**
5.1	Matrix of Working Conditions	All	Complete	2/12/23	2/14/23	3	
5.2	Calculation research	All	Complete	2/12/23	2/16/23	5	
5.3	Wind and Honeycomb calculations	Jackson Brown	Complete	2/17/23	2/20/23	4	
5.4	Results Processing	Jackson Brown	Complete	2/20/23	2/20/23	1	
5.5	Visualize and Present Results	Jackson Brown	Complete	2/21/23	2/23/23	3	
5.6	Schedule Margin			2/24/23	2/28/23	5	
5.7	◆ Simulation Report/Progress Presentation 2		Complete	2/28/23	2/28/23	1	
6	**Design Reiteration**		**100%**	**3/1/23**	**3/23/23**	**23**	**6**
6.1	Analysis of Numerical Simulation Results	All	Complete	3/1/23	3/1/23	1	
6.2	Design Modification	All	Complete	3/2/23	3/5/23	4	
6.3	Update Budget if Needed	All	Complete	3/2/23	3/16/23	15	
6.4	Weight estimation and structural simulation	Justin Bak	Complete	3/14/23	3/20/23	7	
6.5	Monitor Results	All	Complete	3/14/23	3/20/23	7	
6.6	Finalize Design	All	Complete	3/16/23	3/23/23	8	
6.7	Report of Design Changes	All	Complete	3/16/23	3/23/23	8	
6.80	Schedule Margin			3/18/23	3/23/23	6	
6.9	◆ Final Design Report		Complete	3/14/23	3/23/23	10	
7	**Component Manufacturing and Assembly**		**17%**	**3/10/23**	**3/30/23**	**21**	**3**
7.1	Draft of Bill of Materials	All	Complete	3/10/23	3/23/23	14	
7.2	Materials Procurement	All	Not complete	3/26/23	4/1/23	7	
7.3	Nozzle Assembly	All	Not complete	3/26/23	4/1/23	7	
7.3	Test Section Assembly	All	Not complete	3/26/23	4/1/23	7	
7.3	Fan/Exhaust Assembly	All	Not complete	3/26/23	4/1/23	7	
7.3	DAQ System Assembly	All	Not complete	3/26/23	4/1/23	7	
7.4	Schedule Margin			4/1/23	4/3/23	3	
7.5	◆ Progress Presentation 3		Not complete	3/30/23	3/30/23	1	

7	**Component Manufacturing and Assembly**		**100%**	**3/10/23**	**3/30/23**	**21**	**3**
7.1	Draft of Bill of Materials	All	Complete	3/10/23	3/23/23	14	
7.2	Materials Procurement	All	Complete	3/26/23	4/8/23	14	
7.3	Nozzle Assembly	All	Complete	3/26/23	4/8/23	14	
7.3	Test Section Assembly	All	Complete	3/26/23	4/8/23	14	
7.3	Fan/Exhaust Assembly	All	Complete	3/26/23	4/8/23	14	
7.3	DAQ System Assembly	All	Complete	3/26/23	4/8/23	14	
7.4	Schedule Margin			4/1/23	4/3/23	3	
7.5	◆ Progress Presentation 3		Complete	3/30/23	3/30/23	1	
7	**Wind Tunnel Stress Testing**		**88%**	**4/3/23**	**4/13/23**	**11**	**1**
1.1	Test Assembly (w/ Test Matrix)	All	Complete	4/3/23	4/13/23	11	
1.2	Diagnose Issues	All	Complete	4/12/23	4/13/23	2	
1.3	Modify Assembly/ Fix Issues	All	Complete	4/12/23	4/13/23	2	
1.4	Re-Test Working Conditions	All	Complete	4/12/23	4/13/23	2	
1.5	Report Testing Results	All	Complete	4/13/23	4/13/23	1	
1.7	Schedule Margin					1	
1.8	◆ Wind Tunnel Demonstrations		Complete	4/13/23	4/13/23	1	
2	**Senior Design Showcase**		**33%**	**4/16/23**	**4/25/23**	**10**	**1**
2.1	Create Poster	All	Complete	4/16/23	4/23/23	8	
2.6	Schedule Margin			4/23/23	4/23/23	1	
2.7	◆ Senior Design Showcase	All	Complete	4/25/23	4/25/23	1	

Appendix 8: N2 Chart

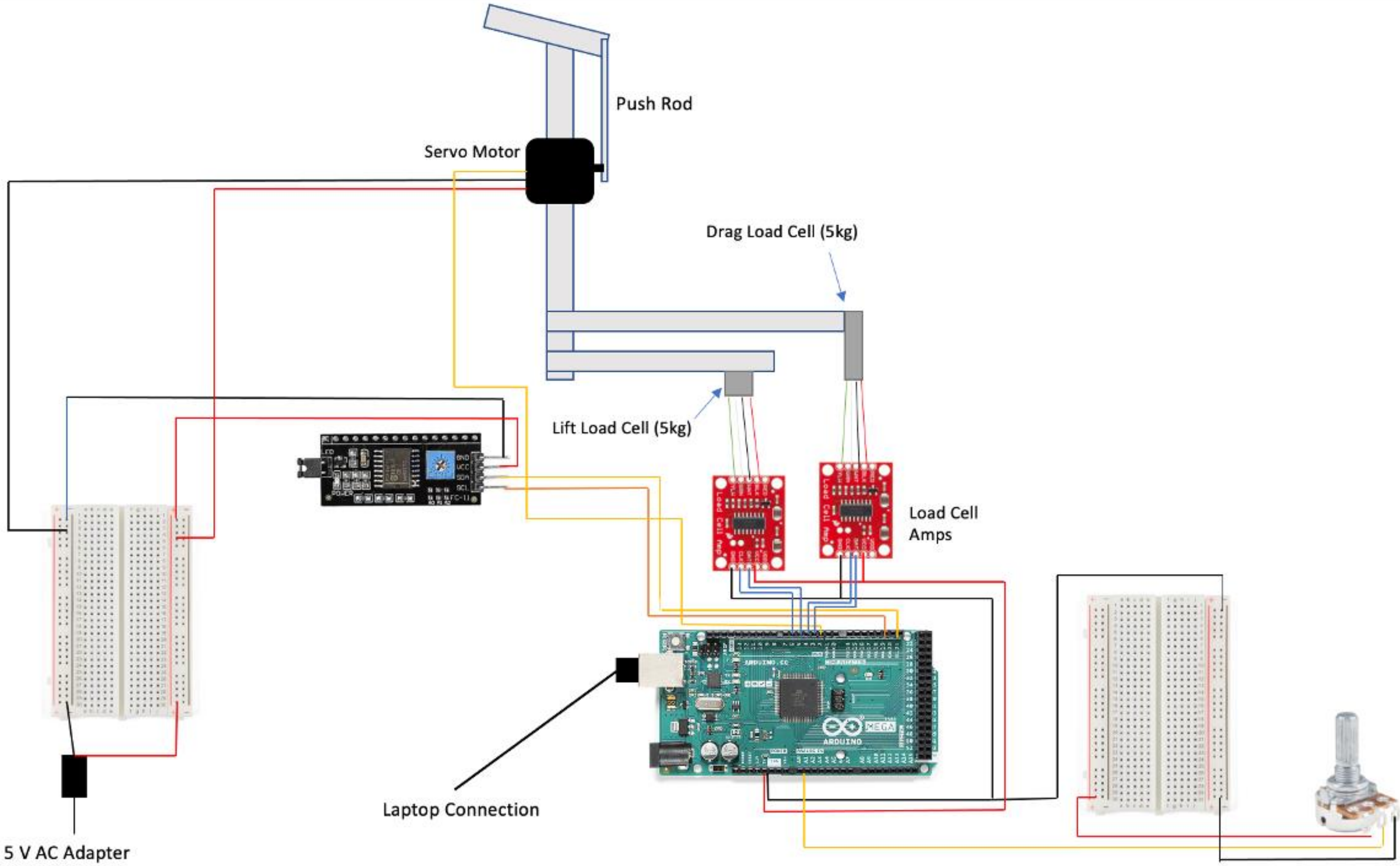
Mounted test subject	Velocity/force data Instrument response		Instrument control						
	Provide Response Data								
	Begin/end data collection	**Control Systems**	Control angle of attack	Control fan power		Control thermal systems	Control smoke generation		
			Provide Mount Mechanics						
				Rotate Fan	Accelerate airflow			Windspeed	
	Force and windspeed indicators				**Create Wind**				
						Provide thermal heating/cooling		heat and cool air temperature	
							Generate smoke	Increase air visibility	
								Control test section air features	
	Power data reponse software	Power control software	Power Servo	Power fan		Power heater/ AC	Power smoke generator		**Power**

Appendix 9: Updated Risk Map

Severity	Catastrophic	5, 14	1, 3	7		
	Major	4	9			
	Moderate	10	13	11, 12		
	Minor	6, 8	2			
	Insignificant					
		Rare	Unlikely	Possible	Likely	Almost Certain
	Probability					

1 - Laminar Flow is not achieved in the test section
2 - High operating costs
3 - Temperature control failure
4 - Reynold's Number of 2000 cannot be reached
5 - Structural Failure
6 -Noise Level
7 - Force/Velocity Measurement Failure
8 - Debris caught in fan
9 - Smoke generation not visible
10 - Fan Power
11 - Machining Issues
12 - Fastener Issues
13 - Mounting Mechanism Rotatability
14 - Fan Blend Turbulence

Appendix 10: Mounting Mechanism Control Schematic


Push Rod
Servo Motor
Drag Load Cell (5kg)
Lift Load Cell (5kg)
Load Cell
Amps
Laptop Connection
5 V AC Adapter

Appendix 11: The Bill of Materials

Column2	Part Name (as on product page)	Subcomponent	Comment	# Needed	# in Pack	Packs to order	Price Per Pack	Total	Total + Tax & Shipping	Status	Supplier
02 - WindTunnel1	T-Slotted Framing Single Four Slot Rail, Silver, 20 mm Square, Solid	5537T895	1.5 ft length	2	1	2	$9.02	$18.04	$21.23	Received by Team	McMaster-Carr
02 - WindTunnel1	T-Slotted Framing Single Four Slot Rail, Silver, 20 mm Square, Solid	5537T502	3 ft length	4	1	4	$13.10	$52.40	$61.67	Received by Team	McMaster-Carr
02 - WindTunnel1	T-Slotted Framing Single Four Slot Rail, Silver, 20 mm Square, Solid	5537T12	6 ft length	2	1	2	$19.60	$39.20	$46.14	Received by Team	McMaster-Carr
02 - WindTunnel1	T-Slotted Framing Silver 90 Degree Surface Bracket for 20 mm High Rail	N/A	N/A	8	1	8	$12.53	$100.24	$117.98	Received by Team	McMaster-Carr
02 - WindTunnel1	Stem Mount Swivel Caster for 20 mm High Single Rail	N/A	N/A	4	1	4	$13.56	$54.24	$63.84	Received by Team	McMaster-Carr
02 - WindTunnel1	Load Cell - 5kg, Straight Bar			2	1	2	$11.95	$23.90	$28.13	Received by Team	Sparkfun
02 - WindTunnel1	ANNIMOS 20KG Digital Servo			1	1	1	$15.99	$15.99	$18.82	Received by Team	Amazon
02 - WindTunnel1	SparkFun Load Cell Amplifier - HX711			2	1	2	$10.95	$21.90	$25.78	Received by Team	Sparkfun
02 - WindTunnel1	Arduino Mega 2560 Rev3			1	1	1	$48.20	$48.20	$56.73	Received by Team	Amazon
02 - WindTunnel1	Excelity AC-DC 5V 1A Power Adapter			1	1	1	$8.59	$8.59	$10.11	Received by Team	Amazon
02 - WindTunnel1	Breadboard - Self-Adhesive (White)			2	1	2	$5.50	$11.00	$12.95	Received by Team	Sparkfun
02 - WindTunnel1	Plytanium 15/32-in x 4 ft x 8 ft Rated Pine Plywood			1	1	1	$25.75	$25.75	$30.31	Ordered	Lowes
02 - WindTunnel1	Noctua NF-P12 redux-1700 PWM, High Performance Cooling Fan, 4-Pin, 1700 RPM (120mm, Grey)	N/A		1	1	1	$14.99	$14.99	$17.64	Received by Team	Amazon
02 - WindTunnel1	TeamProfitcom 4 Pin PWM Fan Extension Cable PC Fan Power Braided Sleeve Extension Cable			1	1	1	$11.99	$11.99	$14.11	Received by Team	Amazon
02 - WindTunnel1	Multipurpose 6061 Aluminum Sheet 0.025" Thick, 12" x 48"		4 x 4 ft	2	1	2	$41.64	$83.28	$98.02	Received by Team	Mcmaster
02 - WindTunnel1	IIC/I2C/TWI Serial 2004/20x4 LCD Module			1	1	1	$12.89	$12.89	$15.17	Received by Team	Amazon
02 - WindTunnel1	Multipurpose 6061 Aluminum, 1/8" Thick x 1" Wide		12 inch length	3	1	3	$2.38	$7.14	$8.40	Received by Team	McMaster-Carr
02 - WindTunnel1	Galvanized Steel Corner Bracket, 1.5" x 1.5" x 1.25"			12	1	12	$1.67	$20.04	$23.59	Received by Team	McMaster-Carr
02 - WindTunnel1	Surface-Mount Hinge with Holes, Zinc Plated Steel, Removable Pin, 3" x 1-1/4" Door Leaf			2	2	1	$10.59	$10.59	$12.46	Received by Team	McMaster-Carr
02 - WindTunnel1	Prime-Line 9019520 Sheet Metal Screws, Self-Tapping, Pan Head, Phillips Drive, #8 X 1/4 in, Zinc Plated Steel, (50-pack)			50	50	1	$9.67	$9.67	$11.38	Ordered	Amazon
02 - WindTunnel1	Prime-Line 9019111 Sheet Metal Screws, Self-Tapping, Pan Head, Phillips Drive, 6 X 1/4 , Zinc			50	50	1	$8.99	$8.99	$10.58	Received by Team	Amazon
02 - WindTunnel1	Neodymium Magnet Magnetized Through Thickness, 0.1" Thick, 3/4" OD	5862K408		2	1	2	$4.38	$8.76	$10.31	Received by Team	McMaster-Carr
02 - WindTunnel1	Acrylic Plastic Sheet 6MM (1/4") x 24" x 48" - Clear Plexiglass		24'' x 48''	1	1	1	$61.17	$61.17	$72.00	Received by Team	Amazon
02 - WindTunnel1	Neodymium Magnet Magnetized Through Thickness, 1/16" Thick, 1/8" OD		1/16" Thick, 1/8" OD	24	1	24	$0.32	$7.68	$9.04	Received by Team	Mcmaster Carr

02 - WindTunnel1	1/4-in x 2-ft Bcx Pine Sanded Plywood	2 ft x 2ft	1	1	1	$7.56	$7.56	$8.90	Received by Team	Lowes
02 - WindTunnel1	JUMPER WIRE M/M 6" 20PCS		1	1	1	$2.10	$2.10	$2.47	Received by Team	Sparkfun
02 - WindTunnel1	JUMPER WIRE M/F 6" 20PCS		1	1	1	$2.10	$2.10	$2.47	Received by Team	Sparkfun
02 - WindTunnel1	Jumper Wires Premium Female/Female Jumper Wires - 20 x 6 (150mm) (1 piece)		1	1	1	$5.65	$5.65	$6.65	Received by Team	Amazon
02 - WindTunnel1	Breadboard - Self-Adhesive (White)		2	1	2	$9.95	$19.90	$23.42	In House	Amazon
02 - WindTunnel1	Bolt-Together Framing, L-Shaped Rail, Zinc-Plated Steel, 1-1/2" x 1-1/2" Wide (***3ft Length***)	3 ft length	14	1	14	$10.77	$150.78	$177.47	Received by Team	McMaster-Carr
02 - WindTunnel1	Medium-Strength Steel Hex Nut Grade 5, 5/16"-18 Thread Size		50	100	1	$9.57	$9.57	$9.57	Received by Team	McMaster-Carr
02 - WindTunnel1	Medium-Strength Grade 5 Steel Hex Head Screw Zinc-Plated, 5/16"-18 Thread Size, 1" Long		50	50	1	$10.47	$10.47	$10.47	Received by Team	McMaster-Carr
02 - WindTunnel1	Noctua NA-FC1, 4-Pin PWM Fan Controller (Black)		1	1	1	$24.08	$24.08	$24.08	Received by Team	Amazon
02 - WindTunnel1	Coolerguys 12V Fan Power Supply, Length: 5ft, Input Power: 100-240vAC, Output Power: 12vDC Volts, Multi-Functional, Highly Compatible		1	1	1	$7.99	$7.99	$7.99	Received by Team	Amazon
02 - WindTunnel1	Multipurpose 6061 Aluminum Sheet 0.025" Thick, 24" x 24"		1	1	1	$42.36	$42.36	$42.36	Received by Team	McMaster-Carr
02 - WindTunnel1	Multipurpose 6061 Aluminum Sheet 0.025" Thick, 24" x 48"		1	1	1	$77.54	$77.54	$77.54	Received by Team	McMaster-Carr