# Stevens Institute of Technology

# Plume-Surface Interactions for the Moon and Mars
# Phase III Report

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"I pledge my honor that I have abided by the Stevens Honor System."

*Project Website*

## Abstract

Plume surface interactions (PSI) studies the environment that is created from rocket plumes. When a rocket is attempting to land on a surface such as the Moon or Mars, the exhaust interacts with the ground in a very violent manner by launching particles of all sizes as well as heating them up. Two of the biggest issues caused by this interaction are the potential damage that can be caused to the ship as well as the lack of visibility caused by the dust. There have been manyCFD (computational fluid dynamics) models created to try to accurately portray this problem, however there is little experimental data available for comparison.

The goal of this project is to create an experimental setup that produces a high-speed flow at conditions similar to that of the Moon (~340m/s in a vacuum), as well as design a plate that will act as the surface of the Moon. The plate will also be adjustable, allowing for multiple "landing angles" to be tested. Using various sensors, data can be collected about the flow acting upon the plate. Schlieren imaging techniques will also be employed to study the flow. The data gathered from the experimental setup will be used to compare to available CFD models to verify their accuracy. This will ideally allow for accurate flow modeling to be done without the need for experimental verification or wind tunnels in the future.

Understanding the plume surface interaction will allow for safer landings for spacecraft as well as more complex landing sequences. Apart from space applications, this research can also be used to safely land helicopters and planes into areas with a high volume of small particles or uneven terrain such as deserts and mountains.

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# Introduction

## 1.1. Problem Statement

This project will provide a new way of understanding the interactions responsible for many of the issues current air and spacecraft experience during landing sequences. Because of the high importance of any data collected, the experimental setup design needs high measurement accuracy and consistency. The design must be compatible with the existing high-speed shock tunnel's parameters and available space. While staying within the tunnel's allowed parameters, the apparatus should be adjustable in terms of height and plate angle. Pressure sensors will be used to record data and must be compatible with the apparatus as well as the shock tunnel. The setup must be able to withstand the large expected force loads due to the high-speed flow acting on the plate. This requires strength of any joints implemented as well as overall quality of materials. The setup should be able to collect a wide range of high-quality and consistent data. Adjustability within the setup, for example adjustable heights and angles, will contribute to this goal.

## 1.2. Literature Review

A large portion of the literature review consisted of the report regarding the pre-existing experimentation performed last year (Daigle et al., 2022). From this report came detailed explanations of the work done to date for this project and the ending points the previous team reached. It also allowed insight into where the previous team felt they went wrong and what needed to improve in future developments. Since the team had access to the final experimental setup model from the previous team, the report provided insight into how the model was developed and what the expectation was for their work.

Many of the concepts, assumptions, and equations present in this report were verified through the review of several respected educational texts, including *Hypersonic and High Temperature Gas Dynamics* (Anderson 2000), *Modern Compressible Flow: With Historical Perspective* (Anderson 2021), and *Introduction to Flight* (Anderson 2022). Also referenced was the educational text *Fluid Mechanics* (Kundu 2015).

Another work referenced in relation to this project was *Numerical Analysis of Supersonic Impinging Jet Flows of Particle-Gas Two Phases* (Zhang 2020). The paper explored research goals very similar to those of this project. The paper also aimed to study the interaction between supersonic jets, or plumes, and the ground surface below any landing craft in question. Their research focused more on the numerical and CFD (computational fluid dynamics) modeling side of things. They developed working CFD models to better understand the behavior of impinging jets with varying particle sizes included. Some experimental work was done for comparison and validation but not enough to entirely validate the models in question. It was concluded that the CFD models showed theoretically accurate particle-laden flow behaviors.

# Methodology

## 2.1. Project Overview

Through phase III of the project, the primary needs and specifications of the design remained largely unchanged. The designed apparatus must provide a solution to the height and angle adjustments of the plate and allow for the integration of a pressure sensor into the impingement plate. As can be seen below, the selection criteria remains the same as the previous phase, however the team thought of a new idea to actuate the plate using a stepper motor. Both the old selection criteria (*Figure 2.1.1)* and the new selection criteria *(Figure 2.1.2)* can be seen below.

| | A | B | C | D |
|---|---|---|---|---|
| | Previous Year | Linear Actuators | Actuating Nozzle | Actuating Base |
| **Selection Criteria** | **Concept A** | **Concept B** | **Concept C** | **Concept D** |
| Height Elevation | 0 | 1 | 1 | 1 |
| Angle Adjustment | 0 | 1 | 1 | 1 |
| Pressure Sensor Compatability | 0 | 1 | 1 | 1 |
| Remote Height/Angle Adjustment | 0 | 1 | 1 | 1 |
| Joint Stiffness | 0 | 0 | -1 | -1 |
| **Pluses** | 0 | 4 | 4 | 4 |
| **Sames** | 0 | 1 | 0 | 0 |
| **Minuses** | 0 | 0 | 1 | 1 |
| | | | | |
| Net | 0 | 4 | 3 | 3 |
| Rank | 3 | 1 | 2 | 2 |
| | | | | |

*Figure 2.1.1: Concept Selection Criteria Phase 1*

| | A | B | C |
|---|---|---|---|
| | Previous Year | Linear Actuators | Stepper Motor |
| **Selection Criteria** | **Concept A** | **Concept B** | **Concept C** |
| Height Elevation | 0 | 1 | 1 |
| Angle Adjustment | 0 | 0 | 0 |
| Pressure Sensor Compatability | 0 | 1 | 1 |
| Remote Height/Angle Adjustment | 0 | 0 | 0 |
| Joint Stiffness | 0 | 0 | -1 |
| **Pluses** | 0 | 3 | 3 |
| **Same** | 0 | 2 | 1 |
| **Minuses** | 0 | 0 | 1 |
| | | | |
| Net | 0 | 2 | 1 |
| Rank | 3 | 1 | 2 |

*Figure 2.1.2: Concept Selection Criteria Phase 3*

After some debate on whether the team should use stepper motors or a linear actuator.. The team decided it was best to use a linear actuator for two reasons. The first was that the linear actuator could hold a load of 1000N, which is far more than needed for our purpose. The second reason is that the stepper motors start to vibrate a lot as the height is extended which would make stabilizing the system more difficult than it already is.

The team also decided that it was best to split the angle adjustment and height elevations into two separate systems. The selection criteria is changed to be more suited for angle adjustment, however some elements still remain the same.

| | A | B | C | D |
|---|---|---|---|---|
| | Previous Year | Linear Actuators | "Gym" method | Serpantine Belt |
| **Selection Criteria** | **Concept A** | **Concept B** | **Concept C** | **Concept D** |
| Angle Adjustment | 0 | 1 | 1 | 1 |
| Precision | 0 | 0 | 1 | 0 |
| Pressure Sensor Compatability | 0 | 1 | 1 | 1 |
| Remote Angle Adjustment | 0 | 1 | 0 | 1 |
| Joint Stiffness | 0 | -1 | 1 | 0 |
| **Pluses** | 0 | 3 | 4 | 3 |
| **Same** | 0 | 1 | 1 | 0 |
| **Minuses** | 0 | 1 | 0 | 0 |
| | | | | |
| Net | 0 | 2 | 4 | 3 |
| Rank | 4 | 3 | 1 | 2 |

*Figure 2.1.3: Concept Selection Criteria for Angle Adjustment*

In the angle adjustment selection criteria the team was split between three designs. The first design was to use linear actuators again for the angle adjustment. This method was not very reliable as it would add a lot of vibrations to the system due to it not being connected to the flat plate. This design decision also lacks the precision needed for this experiment. The second method was to use a pin with set angles, similar to what you might see in a gym, to change the angle. This method provides a very rigid structure. Additionally, this method is very precise due to the holes being cut and measured beforehand. With this method however, the team sacrifices it's ability to remotely change the angle. The last concept is a serpentine belt idea similar to belts that are found in 3D printers. While this idea is probably the most precise, it requires a perfect setup otherwise inconsistent angles will be measured, therefore it is not as precise as the gym method. Since the system would also be using a belt, it would not be too stable. Knowing this, the team thought it was best to move forward with the gym method for angle adjustment. Upon further discussion, there is also room to improve this into a remote angle adjustment system.

## 2.2. Technical Analysis

The preliminary technical analysis was primarily focused on determining the vertical force expected to be present on the plate. In determining this force, component specifications such as motor braking force, can be determined and parts can be purchased and implemented into the final design. The initial analyses will use the schlieren images resulting from the previous year's experiments in conjunction with the governing laws of compressible flow. The specific test being referenced in the analysis is shown below (*Figure 2.2.1*). However, before the results can be analyzed, several assumptions can be made to simplify the model.

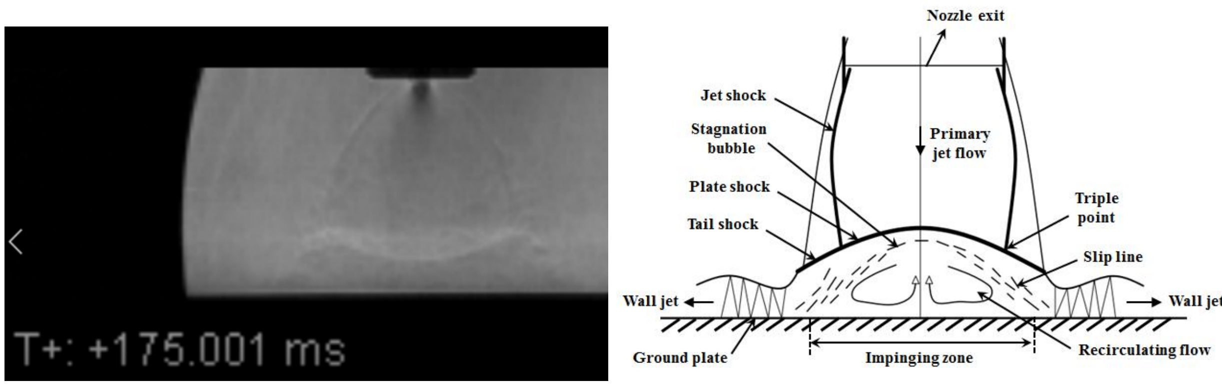



*Figure 2.2.1: The Schlieren image taken from previous testing is shown on the left (Daigle et al., 2022), in comparison to the theoretical diagram of a standard plume surface interaction shown on the right (Zhang 2020). The h/D dimensionless ratio of the test is 10.*

The first assumption is that the test section will exist at vacuum conditions. The test section is capable of reducing pressure to a tenth of a torr in the standard atmosphere. For comparison, the pressure in the test section is roughly 0.001% of atmospheric pressure. The highest pressure that is likely to exist in the shock tunnel during testing is that of the martian atmosphere, or 0.6% of standard atmospheric pressure. While this means that the test section will never truly exist at vacuum, the density of the ambient fluid should be low enough such that all contributing pressure and viscous forces are negligible. Next, it will be assumed that the flow will expand isentropically, with apparent pressure losses due only to shock. This is a standard assumption when designing rocket nozzles or other compressible propulsion systems. To simplify calculations, the flow is assumed to be bounded entirely by the apparent jet shock. Additionally, as a conservative estimate, it will be assumed that the flow stagnates entirely in the impinging zone, more clearly illustrated in *Figure 2.1.1*. Because the stagnation pressure accounts for both the kinetic and static effects of the gas, the highest pressure will exist in regions of stagnation. Finally, it will be assumed that the specific heat ratio will be independent of temperature and the reservoir will be very large. While it has been experimentally proven that the specific heat ratio is a function of temperature, changes in its value are relatively small within the expected temperature range. Additionally, the current fluid reservoir is Earth's atmosphere, so there should be no changes in reservoir fluid conditions throughout the test.

Theoretically, as gas enters the test section at sonic speeds, the gas will expand. To conserve the mass flow rate throughout the system, as the gas expands and decreases in density, its velocity will increase. This means that although the fluid will be exiting the nozzle at Mach 1, it will almost certainly make contact with the plate at a significantly higher velocity in terms of both speed and Mach number. However, since isentropic expansion is assumed, the speed of the fluid can be calculated using typical rocket nozzle equations. The purpose of a rocket is to manipulate the properties of the fluid by geometrically constraining its flow. However, if the geometry of the flow is known, then those same equations can be manipulated to yield the properties of the fluid. To determine the amount the fluid flow area expanded, the Schlieren images can be analyzed. Since the height of the nozzle with respect to the base is known, the number of pixels can be counted and a relative length scale can be calculated. Following this procedure, the fluid was determined to have expanded to a diameter of 1.198 inches (*Figure 2.2.2*). Note that the diameter of expansion is taken before the tail shock.

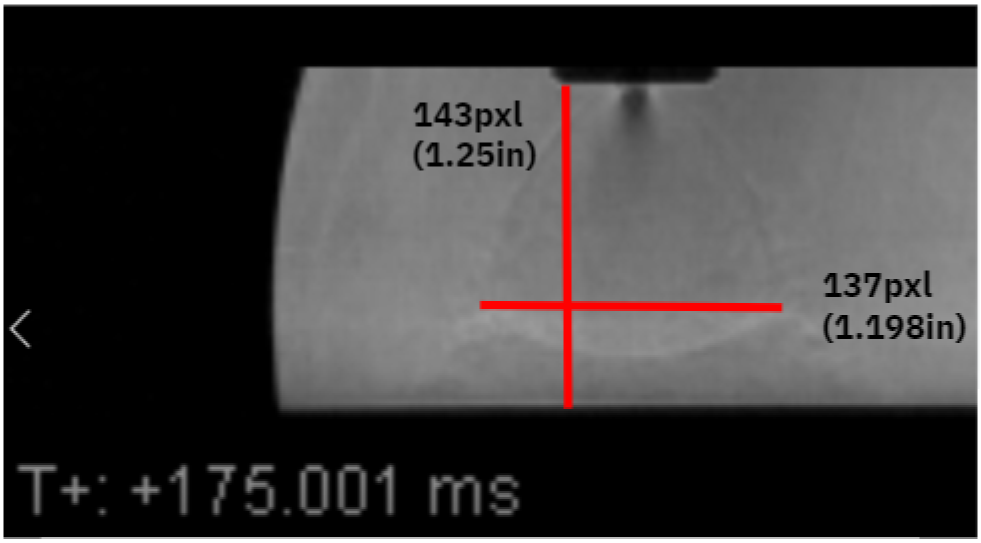



*Figure 2.2.2: The previously described Schlieren image with pixel counts as well as a length scale is shown.*

With the diameter calculated, using the following equation (*Equation 2.2.1*), the mach speed can be determined.

$$\frac{A_e}{A^*} = \left(\frac{\gamma+1}{2}\right)^{-\left(\frac{\gamma+1}{2(\gamma-1)}\right)} \frac{\left(1+\frac{\gamma-1}{2}M_e^2\right)^{\left(\frac{\gamma+1}{2(\gamma-1)}\right)}}{M_e}$$

*Equation 2.2.1: The isentropic relation between Mach number and expansion ratio is shown.*

After determining the mach speed, the stagnation pressure present on the plate can be calculated. Because the reservoir is assumed to be very large, the stagnation pressure can be assumed to be equal to the static pressure. Therefore, using atmospheric pressure as the reservoir stagnation pressure, the plate stagnation pressure can be calculated from the relation shown below (*Equation 2.2.2*).

$$\frac{P_{t1}}{P_{t0}} = \left(\frac{(\gamma+1)M^2}{(\gamma-1)M^2+2}\right)^{\left(\frac{\gamma}{\gamma-1}\right)} \left(\frac{\gamma+1}{2\gamma M^2-(\gamma-1)}\right)^{\left(\frac{1}{\gamma-1}\right)}$$

*Equation 2.2.2: The normal shock relation between Mach number and stagnation pressure is shown.*

A MATLAB script was generated utilizing the relations described in *Equation 2.2.1* and *Equation 2.2.2*. The results of the script were compared to the results obtained from the Virginia Tech Compressible Aerodynamics Calculator. The results from both the online calculator (*Figure 2.2.3)* and the MATLAB calculator (*Figure 2.2.4*) are shown below, with identical values highlighted in identical colors.

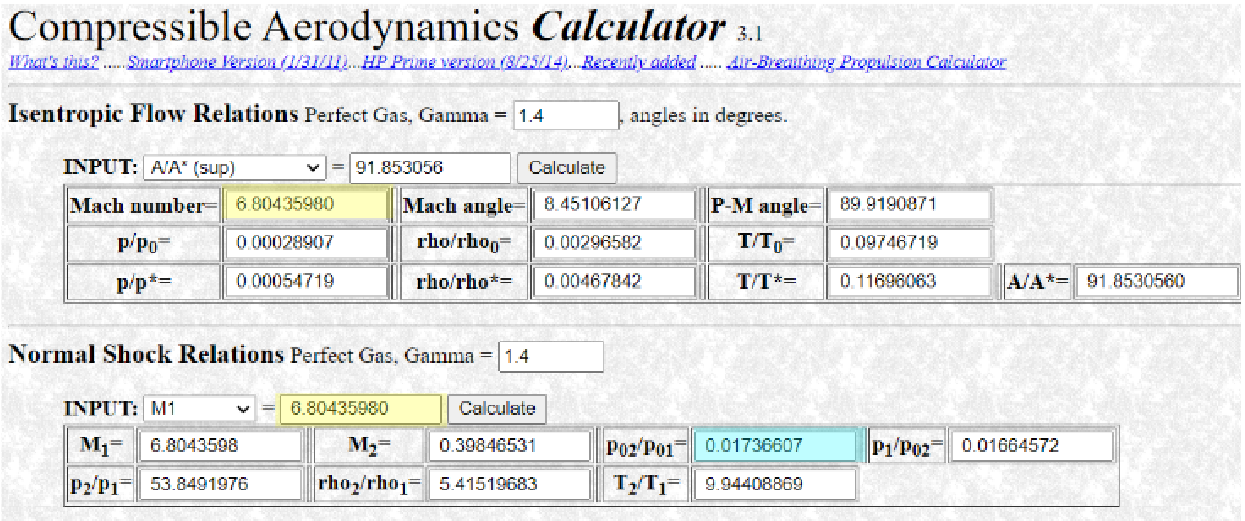



*Figure 2.2.3: The results of the Virginia Tech Compressible Aerodynamics Calculator are shown. Mach number calculations as well as stagnation pressure ratios are highlighted correspondingly.*

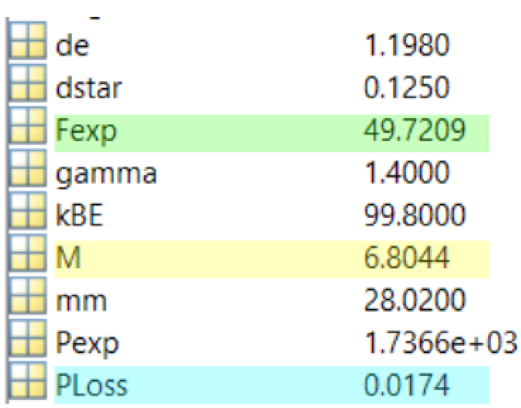



*Figure 2.2.4: The results of the MATLAB calculator are shown. The same highlighting convention from Figure 2.2.3 is shown.*

After validation of the MATLAB calculator, the expected force on the plate was determined to be roughly 50N. Additionally, the expected pressure was determined to be roughly 174Pa.

## 2.3. Engineering Design

After assessing the force exerted by the flow from the nozzle onto the plate, components needed to be selected that could withstand this force. Because the plate and other primary structural components would be salvaged from the previous team's design, which was proven to stand up to testing in the tunnel, this primarily pertained to the sensing and actuation subsystems. The pressure sensor provided to the team was a model 106B52 ICP Pressure Sensor from PCB Piezotronics. According to the listed specifications from the distributor, the maximum pressure for this model is 345 kPa which is well above the predicted 174 Pa exerted onto the plate by the team's technical analysis. The resolution of the sensor is .13 Pa, so this sensor was deemed viable for the purposes of this experiment.

The components for the actuation subsystem needed to be able to withstand the anticipated force of the flow from the nozzle as well as the weight of the impingement plate and other components above it. Originally, the team intended to use one or multiple stepper motors to adjust the Impingement plate vertically. This type of motor was selected based on their low cost, but it was determined that the original motor would not be strong enough to lift the plate assembly and withstand the load. The team turned to using a heavy duty linear actuator salvaged from the ABS Makerspace. The maximum load of this particular actuator is 1000N with a 4" stroke which is ideal for the range of heights that the team intends to experiment with. It was decided that based on technical analysis, the team would move forward in designing with this actuator in mind for the alpha prototype.

Due to the nature of this project, the materials and designs are not intended to be mass produced. Therefore, their environmental impact is negligible. Therefore, the team was free to choose components and materials that best met the needs for the design. In most cases, components were recycled from the previous team in order to remain within the budget for this project and cut down on machining time.

## 2.4. Alpha Prototype

Because the proposed model will consist of multiple subsystems, several alpha prototypes were created to demonstrate the functionality of each subsystem. The first prototype is a demonstration of the electromechanical subsystem. The primary goal of this prototype was to showcase the ability to precisely and accurately control the position of the end effector on the given motor. By doing so, it can be ensured that the height and angle of the plate will be able to be reliably controlled. The alpha prototype consists of a linear actuator equipped with a built-in potentiometer, driven by a L298 H-bridge motor controller, connected to an arduino. The arduino is in turn connected to a computer. When first turning on the arduino, it will establish a serial communication with the computer. When prompted, it will begin calibration, moving the end effector to the furthest position and then to the closest position. The purpose of this is to determine the minimum and maximum potentiometer readings. Because the potentiometer reading is subject to inconsistencies in the signal, as well as imperfections in the wire and circuitry, base measurements are taken to account for any errors in the physical system. The user is then prompted to enter a distance in thousandths of an inch. After the request is completed, the linear actuator will move to the desired position, and then enter a braking mode. For consistency purposes, the measurement is then reported back to the user so that the user is aware of any errors in distance. While the measurement of the position of the end effector has been proven to be accurate to one hundredth of an inch, the distance actually traveled is consistently shorter than the desired distance. This is not a huge problem, because the user is still made aware of the actual distance, meaning there should be no inconsistencies when validating CFD models. In addition to this, the absolute orientation IMU sensor was successfully interfaced with the arduino. This also communicates to the computer via serial connection. However, the precision of the IMU sensor is questionable. It is unclear whether or not the sensor can be fixed to give an acceptable error margin, but as the structural system stands now, it may ultimately be unnecessary. The current electromechanical design and linear actuator are shown below (*Figures 2.4.1 - 2.4.2*).

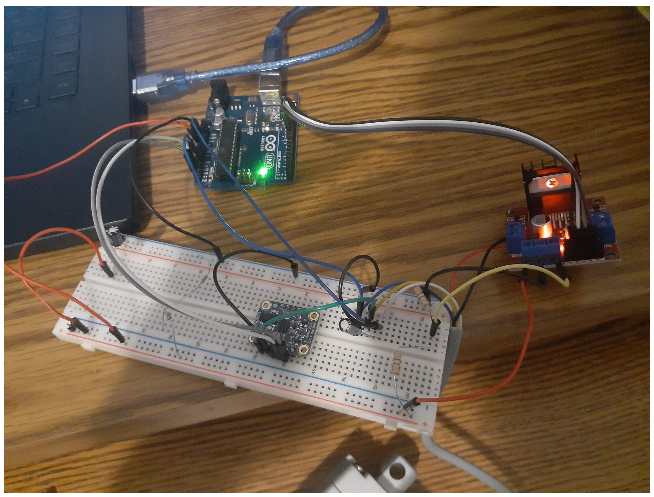


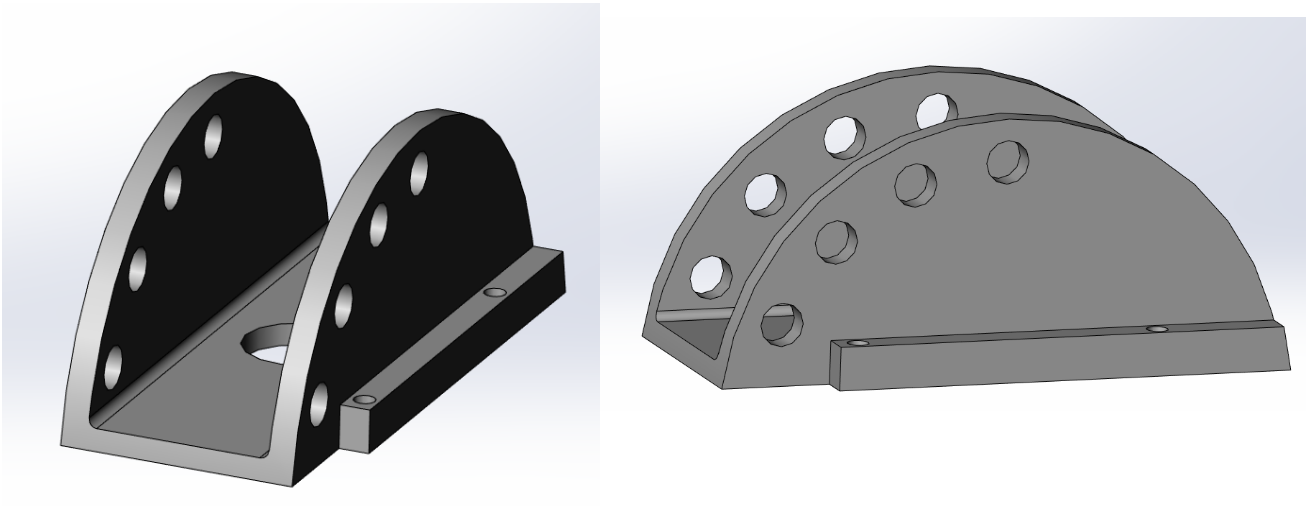
*Figure 2.4.1: The electromechanical alpha prototype is shown without the linear actuator.*

*Figure 2.4.2: The linear actuator used in the electromechanical prototype is shown.*

The second subsystem focused on mechanically changing the angle of the plate and accommodating the Piezotronic pressure sensor. Utilizing the different shaped aluminum plates that the group was able to receive from last year's project, as well as the 3D printers present on campus, the group was able to come up with a way to manually adjust the main impingement plate's angle. The design mainly draws inspiration from standard gym bench equipment, as seen in Figure 2.4.3. This adjustment system functions off of a machined piece containing many holes, each of which correspond to bringing the bench to a specific angle for the user. The user pulls out a pin, adjusts the bench angle to their liking, and then reinserts the pin into their desired angle's hole, holding the bench in that position.

*Figure 2.4.3: Design Inspiration*

The same methodology was used when designing the main angle adjustment piece that attached to the impingement plate. Given that the desired angle range for measurements was between 20°-70°, the holes on the piece were assigned in order to allow the plate to rotate from its original 90° orientation to 67.5°, 45°, and 22.5°. The part also included 3 mounting holes to line up with the already existing 0.25-20 screw holes on the plate, and a circular cutout was made in the center of the part to account for the pressure sensor connection and wiring.



*Figures 2.4.4: Plate that is going to hold the pin*

In order to hold the plate in place at a given angle, small L-brackets were modeled and 3D printed to restrict the pin from moving side to side, as well as T-shaped posts to hold the impingement plate up (Figure 2.4.8). Additionally, in order to accommodate these new parts, the aluminum plates from last year's project required machining. This involved drilling two sets of three 0.25-20 holes to allow the T-shaped pieces to screw into the bottom square plate, as well as two threadless holes on the impingement plate that allowed for rotation and also served as a connection to the T-shaped pieces.

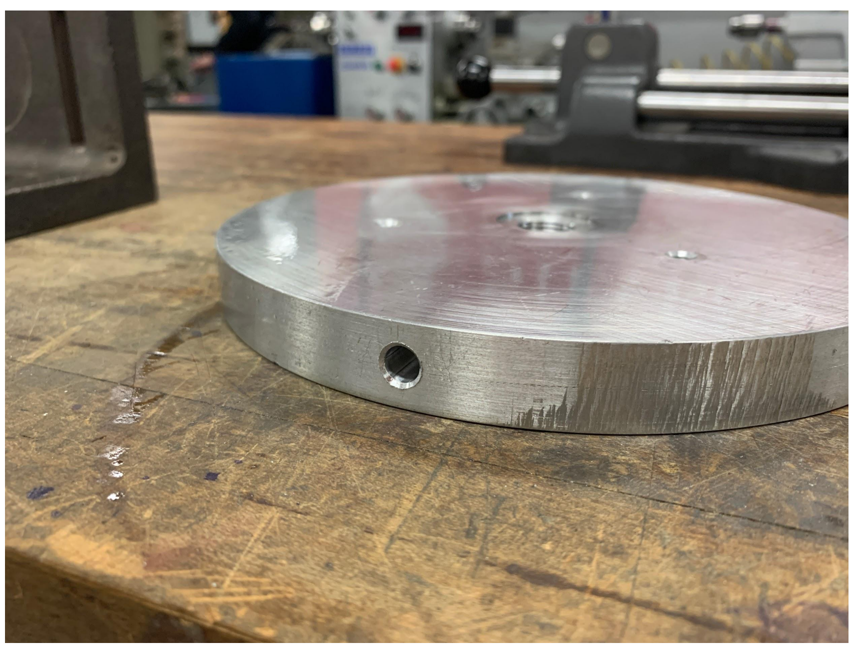
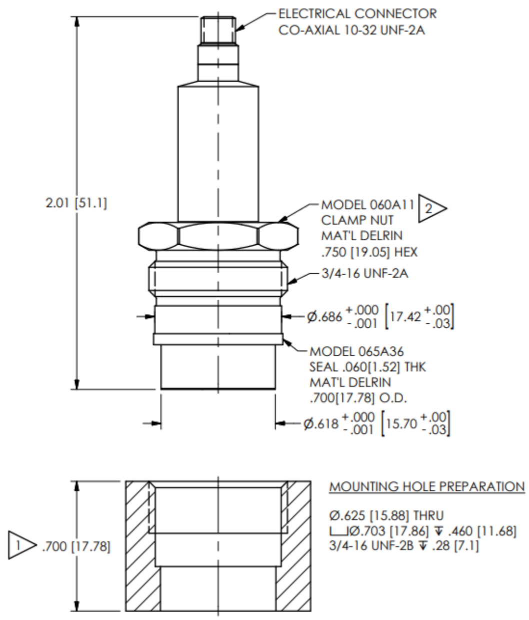
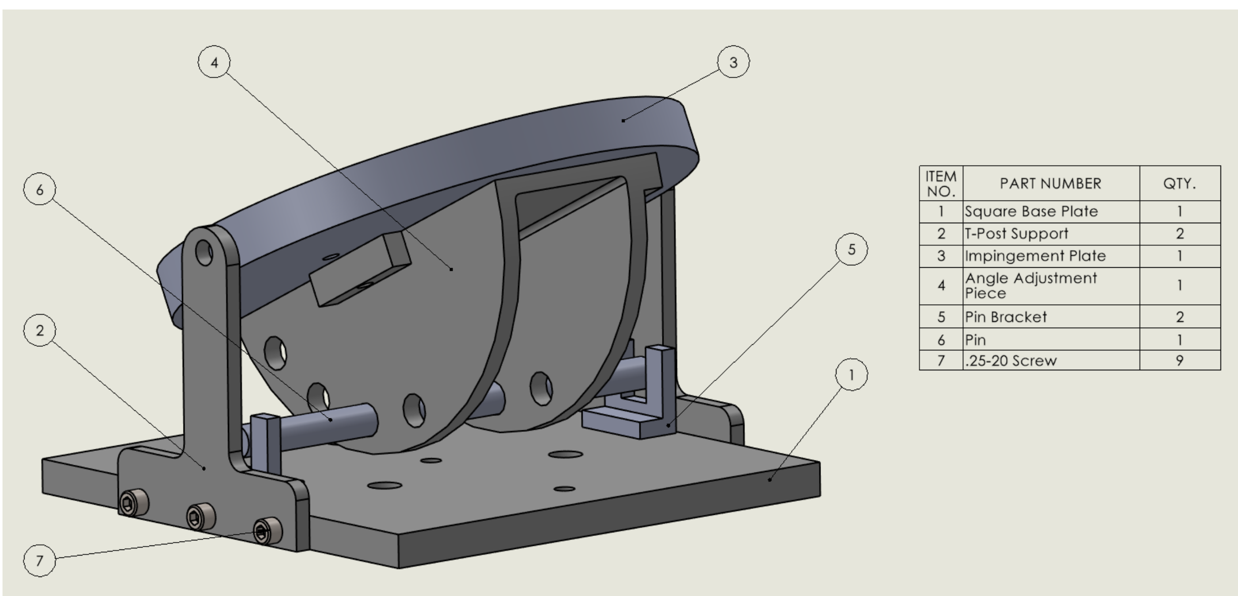


*Figure 2.4.5: Side holes on the impingement plate*

Because adding pressure sensors to the plate was one of the group’s most important goals, the most significant machining done was the drilling of the hole for the Piezotronics pressure sensor in the middle of the impingement plate.

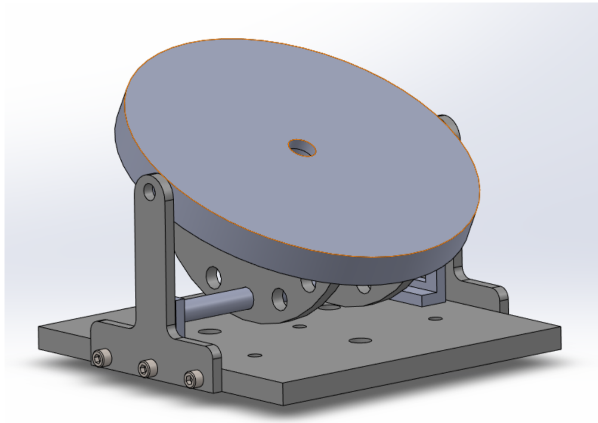
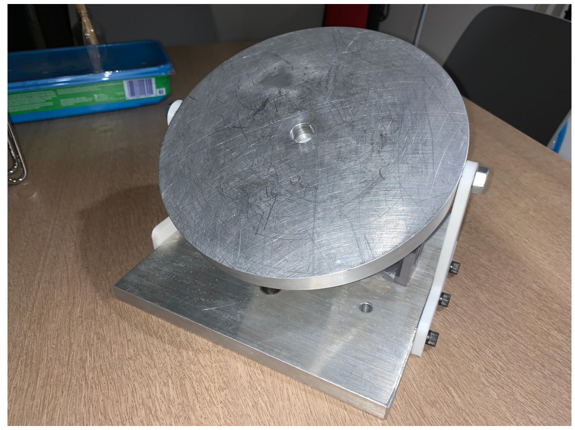
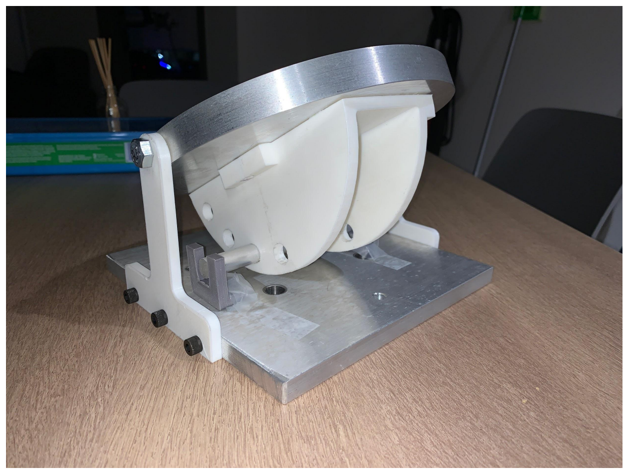



*Figures 2.4.6-2.4.7: Pressure sensor hole & its dimensions*




| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | Square Base Plate | 1 |
| 2 | T-Post Support | 2 |
| 3 | Impingement Plate | 1 |
| 4 | Angle Adjustment Piece | 1 |
| 5 | Pin Bracket | 2 |
| 6 | Pin | 1 |
| 7 | .25-20 Screw | 9 |

*Figure 2.4.8: Angle Adjustment SolidWorks Assembly*

*Figures 2.4.9–2.4.11: Additional SolidWorks & Real World Assembly Images*

While this design is able to adjust to the angle range that was outlined by our advisor, it has some limitations and drawbacks that the team seeks to improve upon in the next phase of the project. Although it hasn't been tested in the shock tunnel test section, one main point of concern is how well the design will handle vibrations, which slightly interfere with the Schlieren imaging. Additionally, once a connection method between this plate system and the linear actuator is determined, the team will have to test and decide if more actuators are needed to provide the plate with more stability and vibration reduction, despite the fact that one actuator alone has enough thrust capability to lift the entire system. Also, 3D printed parts with lower infill like the pin brackets may fail due to rapid expansion from the sudden pressure increase in the chamber during testing. The group plans on mitigating this by machining the T-shape and pin bracket pieces out of aluminum or stainless steel, ideally stainless steel to prevent bonding to the impingement plate. Another area of improvement could be to add additional channels and brackets to stabilize the pin holding the plate's angle. The team hopes to ideally not have to go down this route by finding a way to remotely control the plate's angle as opposed to manually changing it. This could be done by replacing each side of the 3D-printed angle adjustment piece containing the angle holes with gears that would interact with a motor gear system on the square base plate right below it. These design considerations are aspects that the team will further develop in Phase IV.

## 2.5. Project Plan

While the preliminary technical analysis provides enough insight to determine part specifications, it does little to determine other variables such as Reynolds number, Knudsen number, and testing time. These variables, while not immediately required, will be useful when processing the data. Because of this, additions will need to be made to the MATLAB calculator once as experimental testing approaches.

The immediate next step in terms of the design is to incorporate the linear actuator and electrical subsystem into the mechanical subsystem. Once this is achieved, it will be possible to get preliminary data from the Alpha prototype in the shock tunnel. The team intends to begin experimenting in the tunnel and processing data within the first 1-2 months of the semester based on the lab's availability. This will require the design of additional components such as a custom mount for the actuator and a custom PCB to be purchased for the electrical components.

This preliminary testing will provide insight into multiple areas. First, it will help to highlight any design flaws that were overlooked in the Alpha prototype. One key factor will be how susceptible the plate is to vibrations during testing. Vibrations are one of the key points that the team intends to improve upon from the previous year. Being able to examine the behavior of the plate will help the team determine the best approach to dampening these vibrations.

Another area of insight will be the preliminary data collected using the ICP pressure sensor. The goal is to get reliable data using one sensor in order to justify a budget increase for the purchase of additional sensors. This also adds urgency to get the prototype ready for experimentation as the plate will require additional machining to account for an additional sensor, and further analyses will be necessary to decide on the optimal placement of the sensor.

The team also has reserved the option to iterate the mechanical angle adjustment subsystem to include electromechanical capabilities. This would be done by redesigning the printed pin locking mechanism to have teeth on its circumference that could be driven by gears and a single motor. Doing so would allow for remote adjustment and repeated tests without needing to reopen the tunnel test section as frequently. Currently, this has been tabled to allow for the team to focus on collecting as much data as possible with the current alpha prototype and assess whether or not altering this portion of the design is a priority.

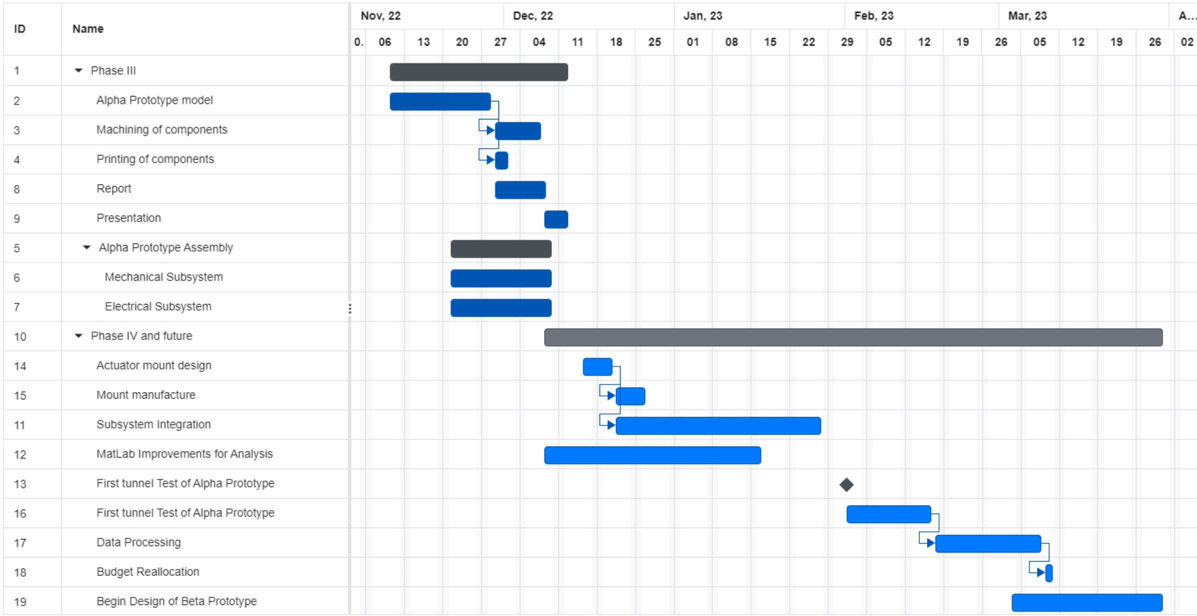



*Figure 2.5 - Gantt Chart*

## 2.6. Bill of Materials and Budget

Due to the research-based nature of this project and current lack of an external sponsor, the available budget is the standard $750 available to all senior design projects. The team aims to produce a working prototype using this initial budget in order to show the feasibility of their design and future possibilities. From there, they will look to request an increased budget in order to expand their design. One long term goal of the project is to utilize multiple pressure sensors in the experimental setup. Currently, the team has one in their possession, but each costs more than the total budget will allow. In order to continue expanding the project's scope, a budget increase must be granted to purchase the necessary equipment, including but not limited to more sensors. The first table below summarizes all purchases made to date and whether they have been received. The second table summarizes a list of all materials currently available to the team. This includes any materials and components that have been ordered, or those that were salvaged either from the previous team's project model or from other unrelated past projects.

| Item | Qty | Price/Item | Shipping | Tax | Total | Status |
|---|---|---|---|---|---|---|
| IMU Absolute Orientation Sensor | 1 | $34.95 | $13.45 | $3.21 | $51.61 | Received |
| Linear Actuator Stepper Motor | 1 | $28.77 | $0.00 | $1.91 | $30.68 | Received |
| 8 Channel Relay Module | 1 | $8.99 | $0.00 | $0.60 | $9.59 | Pending |
| 5-Pack L298N H-Bridge Module | 1 | $11.99 | $0.00 | $0.79 | $12.78 | Pending |

| | |
|---|---|
| **Total Spent** | $104.65 |
| **Remaining Budget** | $645.35 |

*Table 2.6.1 - Budget*

| Item | Qty | Vendor/Source | Notes |
|---|---|---|---|
| IMU Absolute Orientation Sensor | 1 | | Accuracy must be verified |
| Linear Actuator Stepper Motor | 1 | | |
| 8 Channel Relay Module | 1 | | Not yet received |
| 5-Pack L298N H-Bridge Module | 1 | | Not yet received |
| 8"x8" Plate | 2 | Prior design team | Custom machining done to each |
| ThorLabs Optical Post | 3 | Prior design team | |
| ¼” 20 X 1” Hex Screw | 9 | ABS Maker Space | |
| ICP® Pressure Sensor | 1 | PCB Piezotronics | Model 106B52 (English Thread) |
| ½” Granzow Solenoid | 1 | Prior design team | Model H4B19-00Y |
| 2’ of ½” Plastic Tubing | 1 | Prior design team | |
| ½” Pneumatic Nozzle | 1 | Prior design team | |
| Arduino Uno | 1 | Prior design team | |
| 4" Stroke 180 lb Thrust Heavy Duty Linear Actuator | 2 | ABS Maker Space | Available at Servocity |

*Table 2.6.2 - Bill of Materials*

### 2.7. Deliverables

Many milestones have been met along the course of this project from its start to now as the team approaches the end of Phase III. Upon beginning the project, the first goals met were to evaluate the given problem and to do as much background research and brainstorming as possible to get a head start. After obtaining a solid understanding of the project's requirements, the next deliverable was to propose several conceptual designs for evaluation. In Phase II, these conceptual designs were narrowed down to a select few which were more feasible and applicable. These designs underwent a basic technical analysis process in order to help determine which would be the best moving forward. The major milestone here was to propose two to three significant concepts in greater depth to be considered. In order to document progress, the team's initial project website was also created during this time. Moving forward into Phase III, a single design was chosen based upon the results of the technical analysis done, as previously discussed. This design was modified after further consideration and components were ordered to begin production of an alpha prototype. Now, at the conclusion of Phase III, the team has an alpha prototype ready to be presented for demonstration and proof of concept purposes.

Going forward into Phase IV and the second semester of the project, an initial testing plan will be created in order to test the basic design and functionality of the alpha prototype's design aspects. Following any initial testing and improvements, one major milestone will be to show enough success with the preliminary design to request an increase of budget in order to purchase more materials, namely pressure sensors, to increase the setup's data collection capabilities and accuracy validation.

# Conclusion

### 3.1. Results and Discussion

The team has a working alpha prototype that allows for testing to begin. This test will provide the team with data as well as help reveal some design flaws (what parts are vibrating, height clearance, etc…) Due to these design flaws there might be some inconsistencies in the data, however it does provide us with an updated range of data that the team can expect. While the prototype is complete, there is still much to be done. The team would like to combine all subsystems together into one system. The team would also like to have the angle change be remotely changed to speed up testing times. Additionally, more sensors would preferably be mounted onto the plate to allow for faster data gathering. Lastly, the team would also like to see what affects the surface finish of the flat plate has on the consistency of the results if any.

### 3.2. Lessons learned and recommendations

During the construction of the plate, the team was faced with many unexpected problems. The first being that when the plate rotates, the center of the plate slightly moves causing the nozzle not to be centered anymore. This could be fixed by adding a method to move the nozzle as plate moves or somehow mounting the nozzle to the center of the plate. Another issue is the pin used to change the angle of the plate is inaccessible with the current fastening methods. The team can drill holes to allow for access of the pin or choose a different method of mounting the plate onto the base.

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