Plume-Surface Interactions for the Moon and Mars
Phase IV Report

Grant Brickner
Maria Ortiz
Michael Burgos
Uesli Keta
Jett Langhorn

Advisor: Nicholas Parziale
Advisor: Jason Rabinovitch

"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 many CFD (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.

Table of Contents

List of Figures

List of Tables

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 with citations

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. Alpha Prototype

The first test for the electromechanical subsystem was a test of accuracy and control. Since the linear actuator had a built-in potentiometer and limit switches, closed loop control was easily implemented. In real time, the actuator was able to move, while receiving feedback on the current position of the end effector. It quickly became apparent that the potentiometer gave different values while the motor was on and while it was off. This was determined after a series of tests ensuring a constant input voltage was provided to the potentiometer, despite clear changes in current draw. To accommodate this, potentiometer readings were given to convey the final position to the user after the motor had been shut off. During this test run, the desired end effector height was unable to be produced, however, the height measured from the potentiometer matched the actual height within 1% error. Since the goal of the project is to produce empirical data to validate computational programs, as well as provide insight into the fluid mechanics present, control of variables is significantly less important than the accuracy of measurements. In other words, the actual height of the end effector is irrelevant so long as it is measured accurately.

In addition to the accuracy of the linear actuator, the accuracy of the absolute orientation IMU sensor was tested. Shortly after beginning testing, the IMU began to experience noticeable drift. In axes of rotation perpendicular to the direction of gravity, variability of up to 3 degrees was observed within the first minute of testing. Because of this, the sensor was deemed unsuitable for measuring the angle of the plate. However, the removal of this sensor will not be a problem due to the discrete nature of the physical angle adjustment system.

While the results of testing the accuracy of control for the electromechanical subsystem were overall satisfactory, the system was ultimately too large to fit into the test section. The linear actuator was simply too large for practical use. Had this system been implemented into the final design, Schlieren imaging of the impinged flow would have been impossible. Instead, the electromechanical subsystem would have to be redesigned to incorporate smaller actuators to meet the length requirements.

The pressure transducer was integrated into the physical system and the first series of ambient tests were conducted. In these tests, the transducer was connected to a signal conditioner, which was then connected to an oscilloscope to measure and record the changes in voltage given by the sensor. For ambient testing, the transducer was sprayed with refrigerant from a "can of compressed air" commonly used to remove dust from computers. The recording was triggered when the sensor gave a reading surpassing the threshold voltage. While the data was primarily exported as a .csv file, a screenshot of the graph generated by the first ambient test is shown below (*Figure 2.1.###*).

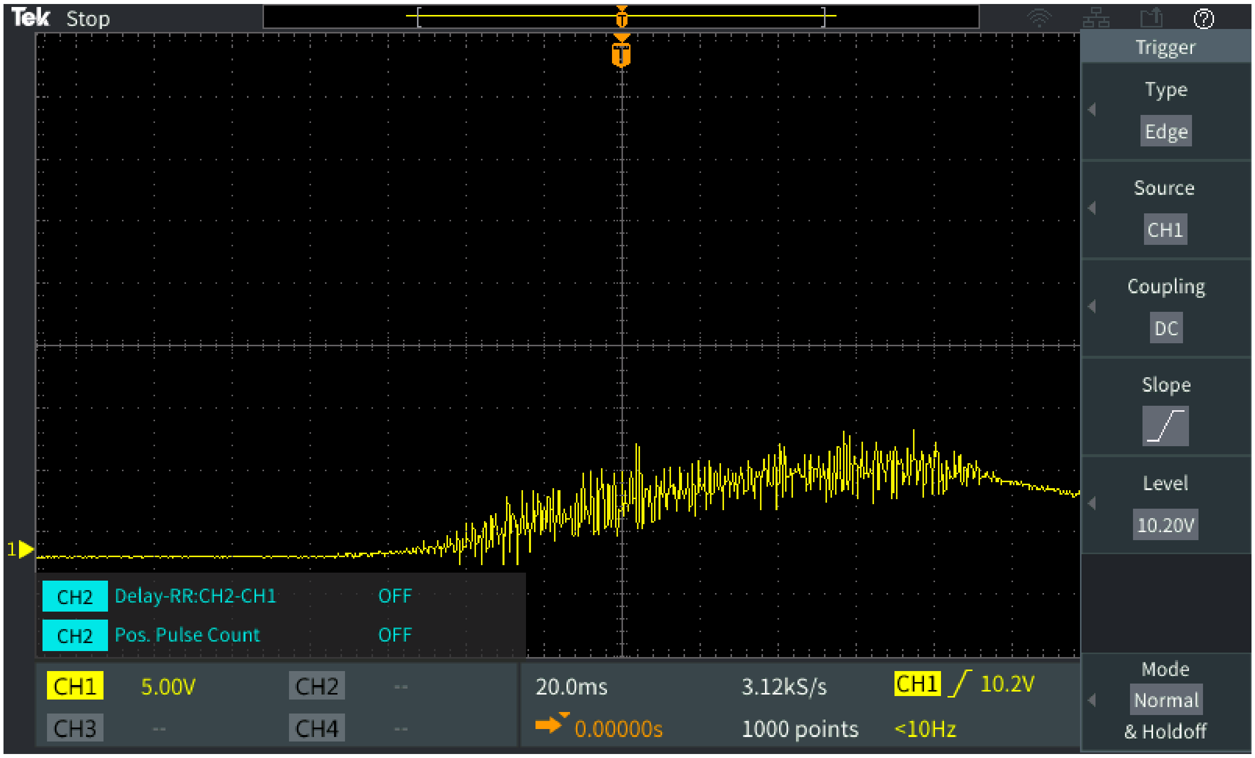

Figure 2.1.1: The raw signal from Ambient Test 001 is shown.

The graph shown above (*Figure 2.1.1*) displays a number of system characteristics. First and foremost, it appears that the sensor is working as intended. There is a low signal until the sensor is shot with compressed air, during which a higher, oscillatory signal is displayed. However, after the sensor is no longer experiencing a burst of compressed air, the signal seems to remain high. This is because the sensor is a piezoelectric crystal, meaning that it will produce a signal similar to a resistor-capacitor circuit. This implies the presence of an intrinsic time constant for charging/discharging electricity. For this specific sensor, the time constant is roughly 200ms. Since the sonic flow is not expected to develop into steady state until about 170ms, the data must be processed to resolve these hardware issues. It is also worth noting that the compressed air can exit nozzle area was quite small, and the entire surface area of the PCB was not being used to the degree that it would be in our actual testing in the future. Data processing techniques such as spectral analysis will be studied in the following phase.

Due to the constraint of not being able to access the test section chamber in the shock tunnel, the team was unable to perform structural tests and analyses. This is a priority going into the development of the Beta prototype, as the group will be able to finally test the entire system in March once the graduate students are able to free up space. Structural components and parts however have been in development since the alpha prototype was finished, which are touched on in the next section of this report.

2.2. Beta Prototype

The structure of the alpha prototype has been changed in order to both accomadate the changes in the electromechanical system and limited space and viewing angles inside the hypersonic shock tunnel test section. Originally, the alpha prototype included two nearly identical square plates. One plate connected to the impingement plate and the other that connected to the electromechanical system to lift the impingement plate. These plates were then going to be fastened together. However, it was quickly determined that having two of these plates was redundant and only added unnecessary weight for the electromechanical system to overcome. Instead, one plate would be remachined to serve both roles as the mounting point of the impingement plate and the connection to the electromechanical system. This would also serve the benefit of providing a better viewing angle of the impingement plate within the tunnel by decreasing the maximum height of the alpha prototype.

As previously mentioned, the original linear actuator that was being used was too big for the shock tunnel test section, and so the team decided to use a stepper motor that was purchased earlier in the fall. For the electromechanical system to work without physical interference, a new part needed to be designed to allow the impingement plate to translate up and down the stepper motor's lead screw. It was also at this point where the team decided to replace the current square plate being used to hold up the impingement plate with the other square plate that was used by last year's senior design group. The location of the holes on the new plate influenced the design of the new connector piece that was modeled.

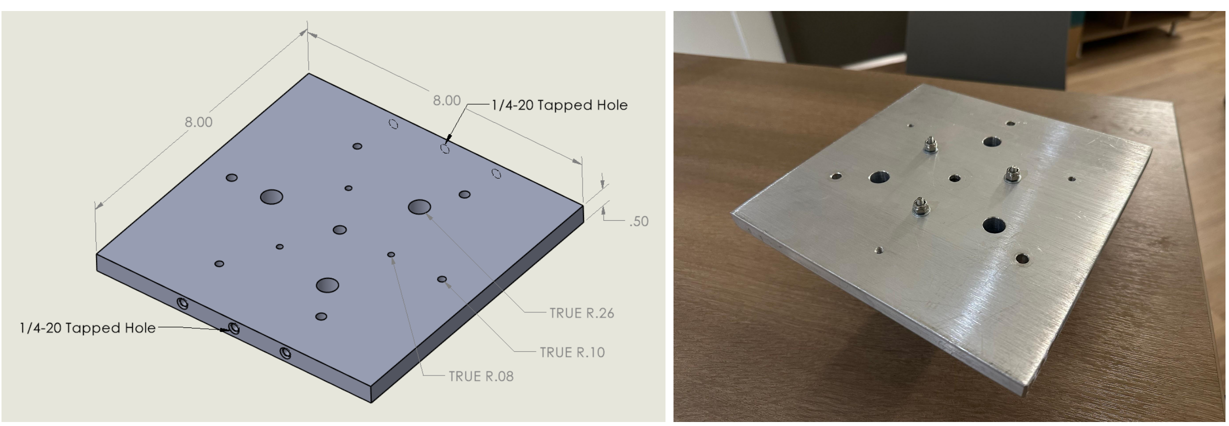

Figure 2.2.1: New Square Base Plate

This plate was chosen because along with the threaded holes that are necessary for our optical mount connections, the three larger holes can potentially be used to further secure the new connection piece. Regarding the design of the connector piece, there were three main design factors that had to be considered. First, the connection holes had to line up with the plate holes. Secondly, there had to be a cavity within the part to allow the stepper motor's led screw to travel inside of it. Thirdly, the bottom of the connection part had to be compatible with the brass nut that came with the motor. The final design is as shown below:

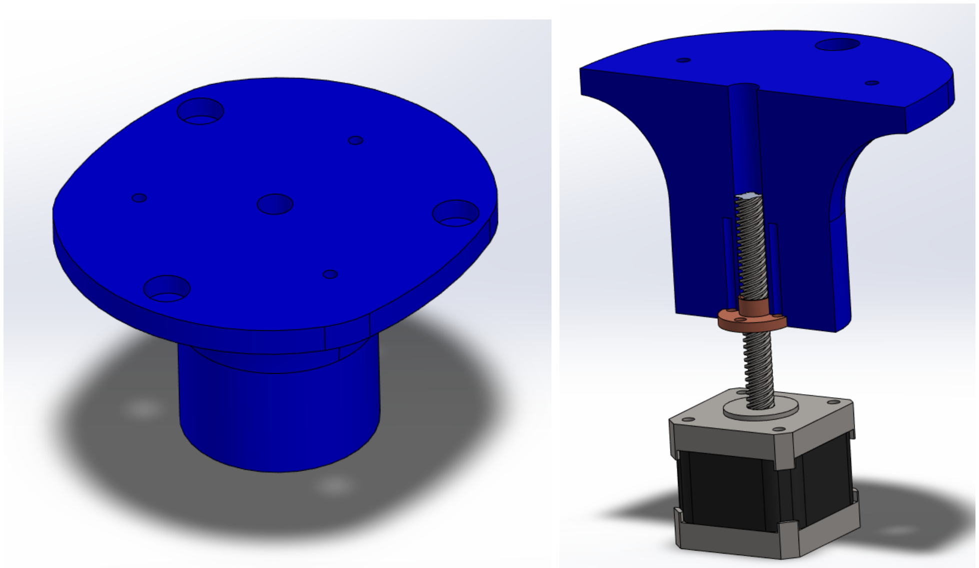

Figure 2.2.2: Motor-Plate Connection, Part Section View Showing Lead Screw Travel Space

Once printed, the part was fastened to the square base plate with anti-vibration nuts to limit vibrations as much as possible, as that was an issue that last year's group struggled with. If additional stability is required for the connection between this part and the plate, cylindrical pegs can be printed or machined and placed into the three larger holes that are shared by both the part and the plate.

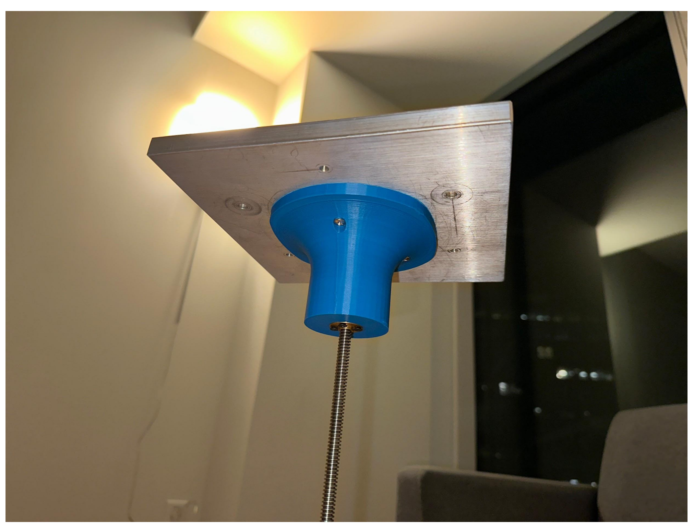

Figure 2.2.3: Printed and Assembled Motor-Plate Connection

In regards to overall changes from the alpha prototype, the current angle adjustment piece has undergone some small dimensional changes, and optical risers have been implemented to provide additional support to the plate system. While the stepper motor and connection part have been added, the connection between the stepper motor and the test section plate will have to be iterated further as the group looks to machine a new plate to allow the assembly to have a better fit in the chamber.

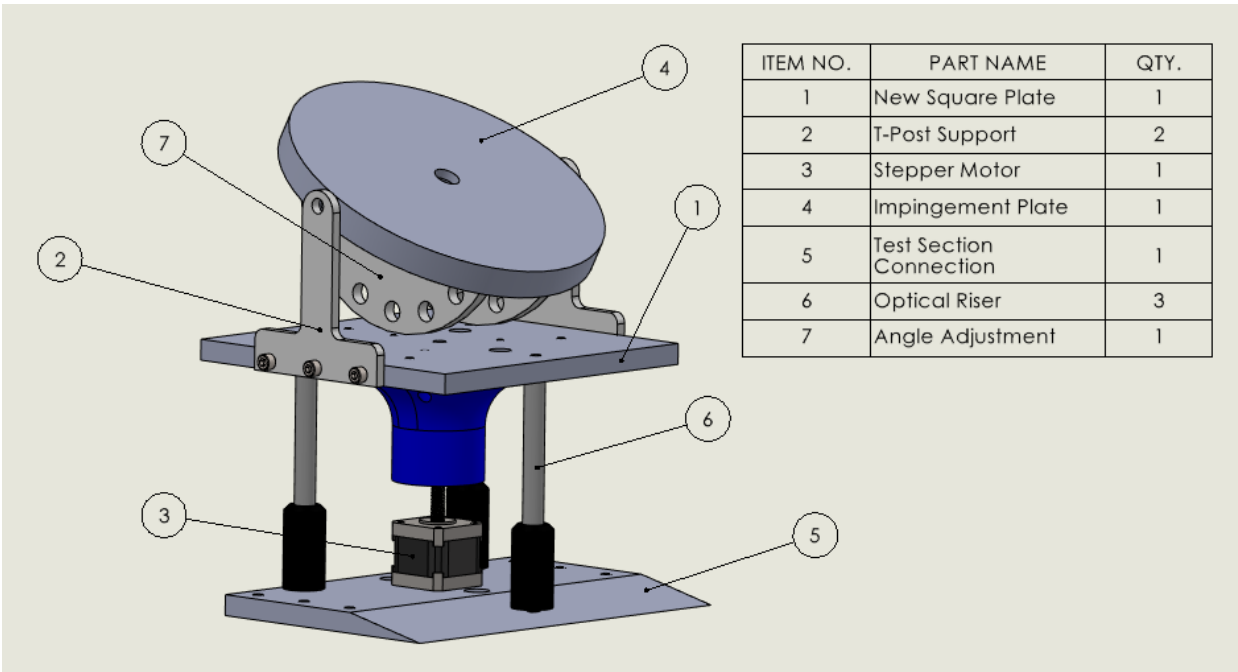

Figure 2.2.4: Post-Alpha, Pre-Beta Assembly

A major obstacle that must be overcome in the beta prototype is the limited space currently available within the hypersonic shock tunnel test section. Currently, and for the foreseeable future, the team doing ongoing funded research in the lab has a project that must take priority within the tunnel. While we have been given access to the tunnel, it is not our lab. Our prototypes must fit in a specific part of the tunnel test section without interfering with their project in order for us to collect the necessary data. This will require remachining of the base plates of the current alpha prototype in order to remove excess material that interferes with the other project in the lab.

The top priority part to be remachined is the tunnel mount which serves as both the connection to the hypersonic shock tunnel test sections and the base of the entire experimental set up. This part must be capable of securely mounting to the existing holes of the test section without interfering with the current projects that are in the test section. In addition, this part must allow for the stepper motor of the electromechanical system to be mounted securely. This part is anticipated to be the most challenging to produce because of the necessary constraints surrounding it. It may also require the purchase of new material. Through the beginning stages of this project, the team considered that future expenses would be needed as more information was gathered. This led the team to limit their initial spending in the interest of being able to pivot their design as needed down the road. Currently, the team has enough budget to machine the necessary parts for the beta prototype, but additional funding may be required to fully implement the design.

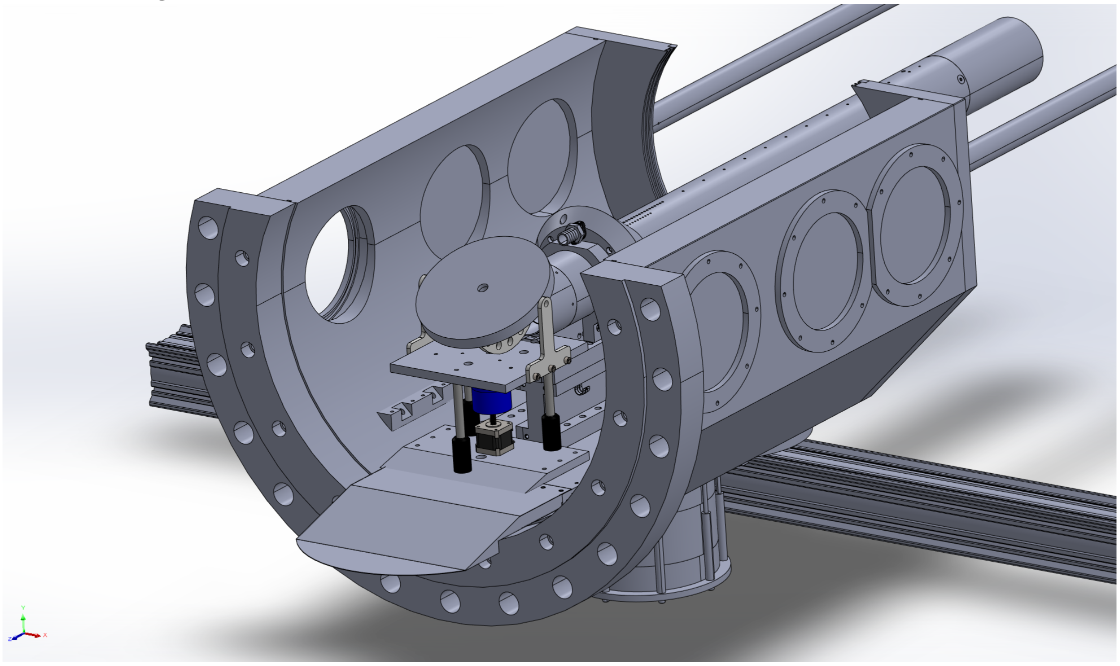

Figure 2.2.5: Current Assembly Lacking Space in the Test Section

The second priority part to be remachined is the square plate that will connect the impingement plate to the electromechanical system. This will only require six holes to be drilled into the plate. The team already has all of the necessary dimensions and drawings for this operation because it was already done on the previous identical plate. This part along with the tunnel mount must be completed in time to be tested in March as soon as space becomes available in the shock tunnel.

Another part that the team plans to machine for the beta prototype are the t-posts that support the impingement plate and allow it to be rotated to different angles. Currently, these parts are 3D printed for the alpha prototype and are beginning to show sins of light wear. The team believes that reinforcing this component for the beta prototype will be necessary. Additionally, the stepper motor lead screw will need to be reduced by more than half its current height to about two inches to accommodate the test section window for imaging, as well as to reduce vibrations that the mechanical system will experience during testing.

Because the stepper motor is replacing the linear actuator in the electromechanical design, the entire wiring schematic needed to be updated. This new schematic is shown below (*Figure 2.2.6*).

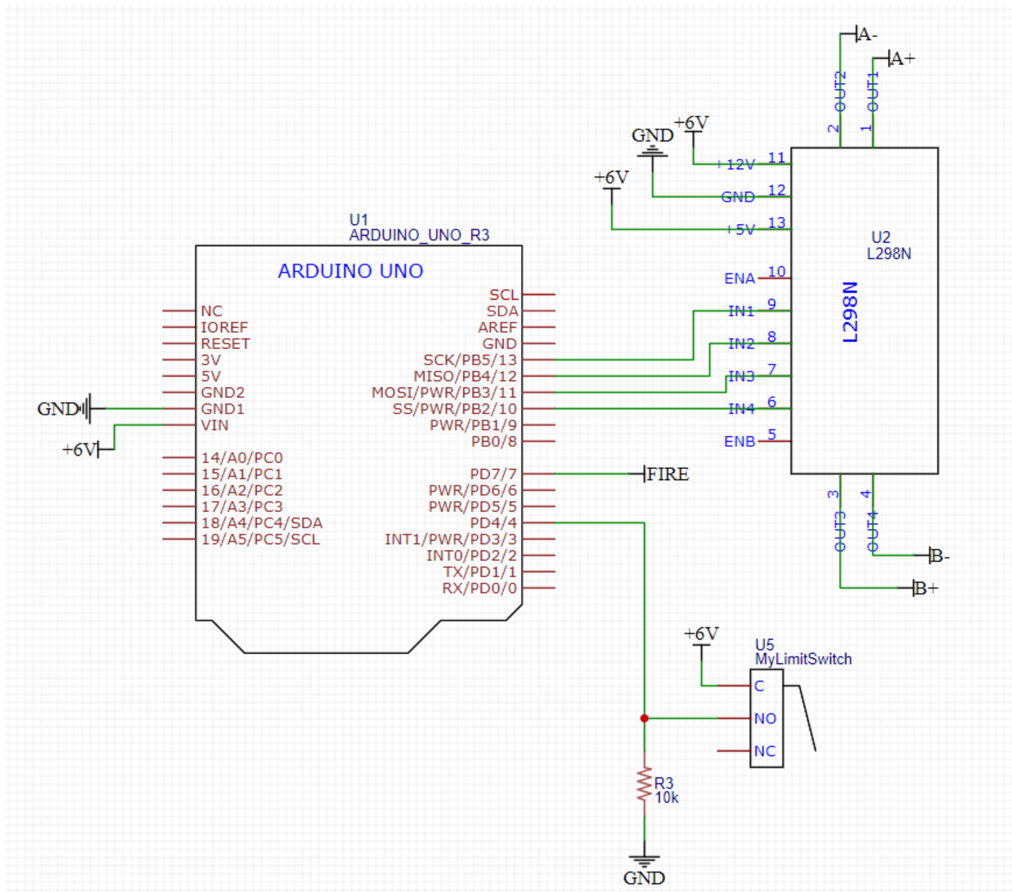

Figure 2.2.6: The updated schematic for the new electromechanical system is shown.

Because the stepper motor does not have a potentiometer built in, new sensors for greater control were implemented. The beta prototype utilizes the fact that a stepper motor will operate in discrete steps. The exact position of the end effector will not be measured throughout the tests. Instead, the motor will retract until it reaches its "zero position" in which the limit switch is pressed, providing a reference point for the position of the end effector. After touching this reference point, the arduino will calculate the number of steps required to move the end effector to the desired position. As a means of checking the position being tested, the stepper motor will move back to the reference position, counting the steps required to reach the reference as a means of position verification. Both the Arduino and stepper motor will be powered by an external 6V power supply. When the test is ready to begin, the channel flagged "FIRE" will receive 5V, turning on the relay of the electro pneumatic system and beginning the recording of the oscilloscope and schlieren camera.

One of the uncertainties of the beta prototype is the specific sensor that will be used to study the sonic flow. While the current sensor (PCB) showed promising results in the Alpha prototype testing, there were significant issues, namely the time constant of the hardware being shorter than the desired testing time. If this issue cannot be resolved in post-processing, an absolute sensor (Kulite) may be necessary. This sensor is an absolute pressure sensor, so it has limitations on the maximum pressure it can handle, but should be more appropriate for the application. However, implementing this sensor would mean machining another plate as well as creating a new signal conditioning system. Additionally, this new sensor is more expensive than the current one. For the time being, the Beta prototype will include the use of the PCB sensor until it is deemed completely inapplicable and it can be reasonably assumed that the Kulite sensor can be implemented without risking damage to the hardware.

Another uncertainty in the Beta prototype is the use of the specific motors currently in place, as well as the use of 3D-printed PLA. This is because none of the aforementioned parts have undergone a simple vacuum test yet. The nature of 3D-printed PLA components is that even with a 100% infill during the printing process, the material is susceptible to separation over time. Under vacuum conditions, the concern is that the printed layers will separate and the component will no longer be viable, especially if there are any errors during the printing process or undetected air pockets within the material. While functional under ambient conditions, the behavior of the motors and their internal components is unknown under vacuum conditions. It is also unknown how all of the components used will behave together under these conditions, namely the amount of vibration that will occur under the force of the sonic jet. Vibration control is critical to this research, so this is being taken into account with the design of each new component, but until testing can be done, there is no definitive answer for the design's validity. Following the completion of the first vacuum condition testing series, the appropriateness of these materials and components will be better understood and adjustments will be made before finalizing the model design.

2.3. Project plan

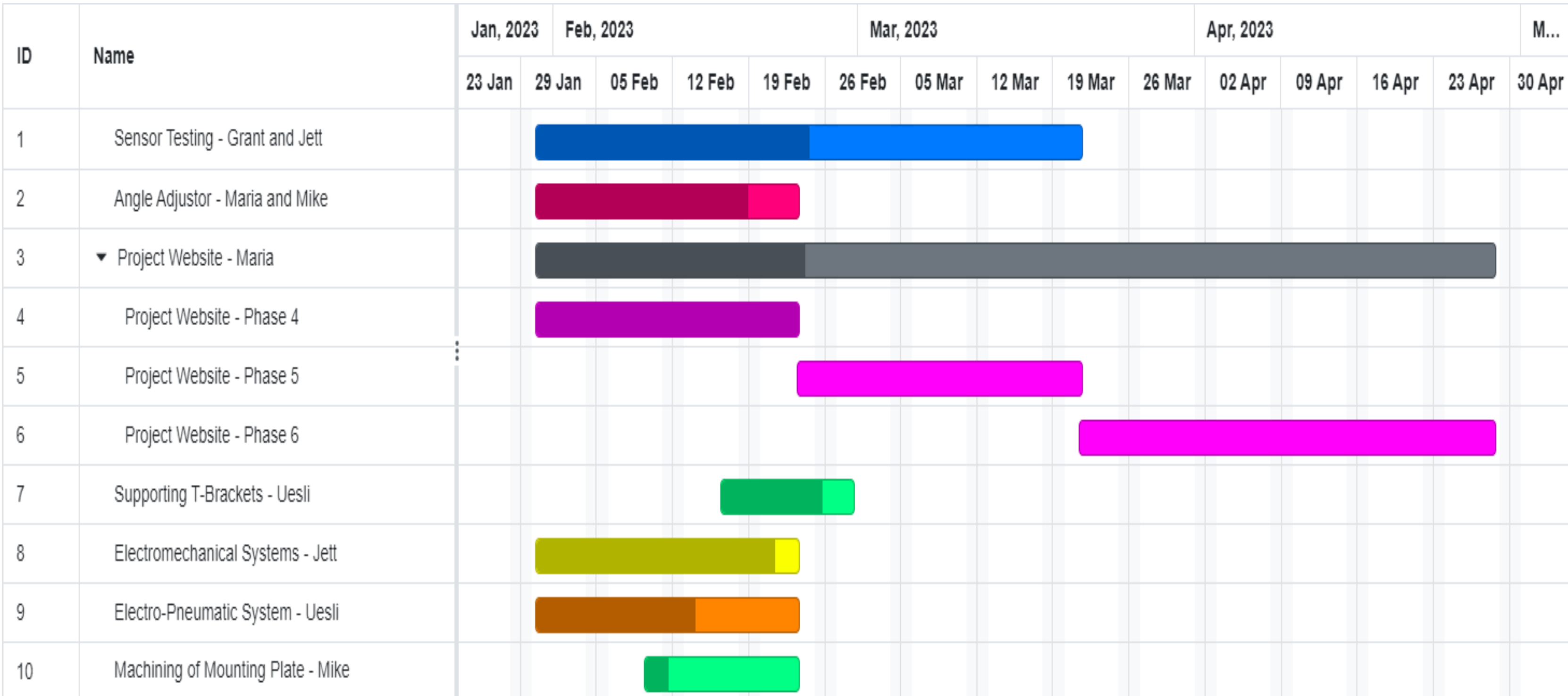

Figure 2.3.1 - Gantt Chart

Upon examination of the Gantt chart, it can be observed that Grant and Jett are currently focused on sensor testing, which comprises two distinct parts. The first part involves conducting tests under atmospheric pressure, while the second part entails carrying out tests in a vacuum. As of now, the team has successfully completed the first phase of this task and is now gearing up to commence testing in a vacuum, with the aim of optimizing the sensor data for enhanced practicality.

Meanwhile, Mike and Maria are responsible for developing the component that will enable the adjustment of the flat plate's angle. Although the design has been finalized, adjustments are needed to ensure that the screw holes on the adjuster align appropriately with the pre-drilled holes on the flat plate. This issue is due to the inadequacy of documentation and precision from the previous team. In addition to this, Maria has been assigned the task of updating the project website to reflect the latest developments in the design phase.

Uesli is working on the redesign of the supporting "T-brackets," with the goal of ensuring that they can support the pin for the angle adjuster while also allowing the plate to rotate freely while bearing its weight. Additionally, Uesli is currently working on the electro-pneumatic system, albeit with some setbacks. During testing, it became necessary to connect new equipment to the system, and the Arduino that was previously used for sending signals is no longer functional.

Jett, on the other hand, is focused on the electromechanical system, which is almost complete, with only a few adjustments left to be made. Finally, Mike is currently working on machining a new mounting plate, which is a crucial component of the overall design.

For the machining and design processes, a new piece of aluminum will need to be purchased, and a new design for the test section connection plate will need to be modeled. The adjustment piece will receive some dimensional changes, a part will be designed to hold the angle adjustment pin in place, and additionally the current PLA t-posts will have to be remodeled to provide more support and not strain as much. Once the designs are complete, the team will have to allocate time to machine these parts. If the PLA components fail during the vacuum testing that the team will perform in late February, the team will look to machine the parts out of aluminum, and make design changes where necessary. For example, if the new motor-plate connection piece fails in the vacuum, recreating that exact geometry might not be possible given the time constraints of the project. The team will work alongside the instructors in the machine shop to have all parts ready by mid to late March, as by then the test section chamber will have space to accommodate our tests. With the Innovation Expo being on April 28th, the team looks to hopefully commit the last two weeks before then to data processing. Under the guidance of the project advisors and the graduate students in the lab, the group is currently learning about the use of the fast fourier transform to better process the data from the PCB. Budgeting and prototyping expenses can be found in the Bills of Materials and Budget section below.

2.4. Bill of Materials and Budget

Due to the research-based nature of this project and current lack of an external sponsor, the available starting budget is the standard $750 available to all senior design projects. The team is working 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. A long term goal of the project, whether done by this team or by the next team to continue this work, 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. This is one example of the limitations of the team's budget with respect to their future progress. In order to continue expanding the project's scope, a future budget increase must be granted to purchase the necessary equipment, including but not limited to more sensors. After the creation and preliminary testing of the team's alpha prototype, it has been determined that several new components will also need to be machined from either existing parts, scrap materials, or newly purchased materials using the remaining budget. The team expected to have more expenses as the project progressed, as seen by their decision to limit spending up to this point. Because of this, the team has enough funds to begin machining the new components needed, but additional funding will soon be necessary to continue their progress.

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	Received
5-Pack L298N H-Bridge Module	1	$11.99	$0.00	$0.79	$12.78	Received
Limit Switch	1	$5.99	$0.00	$0.40	$6.39	Pending
BNC Cable	1	$11.00	$0.00	$0.73	$11.73	Pending
USB A to B	1	$4.95	$0.00	$0.33	$5.28	Pending
Printer Filament	1	$18.99	$0.00	$1.26	$20.25	Pending

Total Spent	$148.29
Remaining Budget	$601.71

Table 2.4.1 - Budget

Item	Qty	Vendor/Source	Notes
IMU Absolute Orientation Sensor	1		Accuracy has been tested and deemed inadequate for team's purposes moving forward
Linear Actuator Stepper Motor	1		Now being used as the main method of actuation
8 Channel Relay Module	1		
5-Pack L298N H-Bridge Module	1		
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	Cannot be used due to size constraints

Table 2.4.2 - Bill of Materials

2.5. 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 IV. 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. In Phase III, the team developed their alpha prototype in order to demonstrate proof of concept and to begin preliminary testing to ensure the model would function appropriately. During Phase IV, an initial testing plan was considered in order to test the basic design and functionality of the alpha prototype's design aspects. The first test was done under ambient conditions to evaluate the functionality of the pressure sensor and the team's initial data processing methods. The team was also able to determine what changes were needed in order to move forward into the next phase of testing and design alterations.

Moving forward into Phase V, the first steps will be to make the necessary changes to the current design model as detailed in the previous beta prototype discussion. Once these changes are made, the team can begin testing in the shock tunnel and collecting data to verify the validity of their design. This will be done as soon as possible, depending partly on the availability of the shock tunnel. This official testing will give the team insights into any final adjustments that should be made before finalizing the design and preparing for Phase VI and the Innovation Expo.

Conclusion

3.1. Results and Discussion

We conducted experiments on our sensor at atmospheric pressure to obtain some preliminary results. Overall this gave us valuable insight into what type of data we needed to collect in order to achieve our research objectives. We also gained a better understanding of the characteristics of the data, and how to filter it to remove unwanted noise. These insights will be crucial as we move forward with the project and begin testing at vacuum and in the wind tunnel. By building on the knowledge gained from the preliminary testing, we believe that we can achieve more accurate and insightful results in the future.

Our next step is to finalize machining of parts and to start testing our sensors in a vacuum environment. We plan to put our design in the wind tunnel to simulate high-speed conditions and study the effects of the plume on surfaces at different speeds. We aim to finetune our design to obtain results as accurate as possible and gain insights into the behavior of plumes and their interactions with surfaces.

Overall, the results of our experiments provide valuable insights into small scale plume surface interactions and demonstrate the effectiveness of our sensors in detecting plume properties. The next steps in our research will help us expand our understanding of plume behavior and surface interactions in different environments and at different speeds, paving the way for new advancements in this field.

3.2. Lessons learned and recommendations

The team's engineering advisor advised a shift in focus from the theoretical to the practical aspects of the project, which involved initiating the building phase of the design. This phase brought to light a new set of challenges that required attention from the team. However, it also facilitated a deeper understanding of the intricacies of the design process and provided a more comprehensive perspective on the project's scope and requirements.

During experimentation with the sensors under atmospheric conditions, the team gained valuable insights into the reception and filtration of data. Specifically, this phase provided a wealth of information on the nuances of data processing, including its collection, interpretation, and filtering.

Overall, the decision to shift the team's focus from theory to practice proved to be an effective strategy in navigating the project's complex design process. The building phase enabled the team to gain practical experience and identify potential design pitfalls, which informed their subsequent decision-making. Likewise, the experimentation phase deepened their understanding of the reception and filtration of data, which added an additional problem to their design approach. The results of these efforts will be instrumental in the successful completion of the project, and will serve as a valuable learning experience for the team.

References

Anderson, J. D. (2000). *Hypersonic and high temperature gas dynamics*. American Institute of Aeronautics and Astronautics.

Anderson, J. D. (2021). *Modern compressible flow: With historical perspective*. McGraw Hill Education.

Anderson, J. D. (2022). *Introduction to flight*. McGraw-Hill.

Daigle, W., Lei, L., McKenna, T., & Philippe, C. (2022, May 12). *Phase 6 Report Plume Surface Interaction Studies: Sonic Jet Impinging On A Flat Plate*. PSI Studies. Retrieved October 3, 2022, from https://sites.google.com/stevens.edu/psi-interaction-studies/home

Kundu, P. K., Cohen, I. M., & Dowling, D. R. (2015). *Fluid mechanics*.

Zhang, Yu-Xiu & Ma, & Kim, & Lin,. (2020). *Numerical Analysis of Supersonic Impinging Jet Flows of Particle-Gas Two Phases.* Processes. 8. 191. 10.3390/pr8020191.