Group 2 Technical Report for AE199 Fall 2024

Maximizing Performance Stability Through Aerodynamic Precision: A Technical Exploration of Rocket Design and Fabrication Methods

Written by: Zihao Lian

Mission Statement:

This report, created for AE199, details the design, analysis, and fabrication of a model rocket estimated to reach an apogee of 655 feet. Our mission is to design, analyze, and fabricate a model rocket that demonstrates the principles and integration of aerodynamics, stability, and precision learned in the course. Through research and literature reviews, we aim to apply theoretical concepts to practical challenges while fostering teamwork and problem-solving skills shown by the construction of our rocket. By adhering to professional standards and embracing the skills taught to us, we strive to advance our understanding of rocketry and lay a strong foundation for future engineering endeavors.

I. Introduction

A. Project Goals

The goal of our project is to design and construct a model rocket that achieves the highest possible apogee while maintaining good stability, all within the constraints of our materials and design specifications. Throughout the process, we aim to apply the technical and hands-on skills taught throughout the course and apply various analysis and fabrication methods to achieve a successful project outcome

B. Team Goals

Our team’s primary goal is to deepen our understanding of rocket design and fabrication processes while constructing the best rocket possible. This includes refining our technical skills, learning from challenges from the design and fabrication process, and adhering to high standards of precision to achieve our project goals. By doing so, we aim to develop a comprehensive understanding of both theoretical concepts and practical applications in rocketry.

C. Team Approach

To achieve our objectives, we conducted extensive research on how professional teams, such as from Spaceport and IREC America competitions, design and build their rockets. With a focus on maximizing performance through aerodynamic precision in the fabrication of our rocket, we prioritized precision and thoroughness in every step of the construction process to ensure the rocket's components were aligned and assembled accurately. This approach was essential for validating trajectory predictions made using OpenRocket and for ensuring stable flight dynamics.

D. Project Outcomes

Overall, our project demonstrated strong execution, particularly in the fabrication and assembly stages. While we did not have the opportunity to launch the rocket, all components appear properly aligned and constructed as intended in the design phase, and our OpenRocket simulations show a stable trajectory flight. This suggests that the rocket would perform well in flight, meeting the goals of stability and apogee optimization as predicted from our Open Rocket data. Ultimately, this project reflects the importance of precise fabrication and evidence-based decision designing in achieving successful outcomes.

II. Literature Review

E. Topic of Interest

Our group has decided to focus on researching the aerodynamics and the importance of the proper fabrication of rocket fins. This topic is particularly relevant to our rocket project because fins directly impact performance, stability, and trajectory accuracy. During the presentation portion of the class, I don't think this topic was given enough emphasis despite its critical role in the final performance of our rocket. Additionally, the reason we believe this issue is significant is because the fabrication process of the rocket plays a critical role in its performance during launch. Even with a flawlessly designed rocket in OpenRocket, meeting all optimal criteria categories such as stability and apogee, any lack of precision in its construction can lead to inaccurate trajectory readings. Since rocket fins are one of the most impactful components towards rocket trajectory, we decided to focus our research and fabrication geared towards maximizing aerodynamic performance through precise fabrication of the fins.

F. Sources of Resources

To address the significance and issue of rocket fins and deepen our understanding of how they affect aerodynamic performance, we divided our research into two parts. First, we reviewed technical reports from professional and academic rocket teams, including UIUC's ISS Spaceshot [1-3] and Spaceport America competition teams [4-7], to identify best practices for fin design and fabrication. These resources offered us insight and ideas into how other teams designed and constructed their fins using tools like alignment template and 3D printed jigs. Second, we investigated technical aspects of fin alignment and the aerodynamic impact through peer-reviewed articles and specialized databases to synthesize a more theoretical and technical understanding of why fin alignment is critical to stability.

G. Summary of Findings and Conclusions

The aerodynamics and alignment of rocket fins are essential in ensuring stable flights and best performances according to trajectory predictions. Properly aligned fins ensure the center of pressure remains behind the center of gravity, a critical balance necessary for maintaining stability during flight [8]. When fins are misaligned, this equilibrium balance between the COP and COG is disrupted which in turns to aerodynamic inefficiencies such as increased drag and potential structural failure. Misalignment can also result in flutter oscillation during flight due to the action of aerodynamic forces that stress the fins, causing potential consequences such as the fins falling off or the rocket tipping over [9].

From the first part of our research, we learned that fabrication and installation practices are very important in regard to the effectiveness of rocket fins. Research, including technical reports from Spaceport America teams [4-7] and UIUC's ISS Spaceshot [1-3], shows that professional teams often use tools such as 3D-printed alignment jigs and CAD-designed templates to ensure precision during fin assembly. The 3D-printed jigs are particularly effective in maintaining the required 90-degree spacing between fins, reducing human error, and ensuring symmetrical aerodynamic forces and flux. Similarly, CAD-designed templates aid in precise fin slot cutting, minimizing discrepancies that could arise from manual methods.

Materials and reinforcement techniques during the fin fabrication also play a vital role in fin stability. Many teams employ epoxy for bonding and reinforcement, complemented by fiberglass filets and layups for added strength. For instance, Team 124 [1] applied a multi-layer carbon fiber layup with cross-ply fiber orientations to significantly enhance rigidity and structural integrity. Surface preparation techniques, such as sanding and cleaning with acetone, improve the bond between the fins and the rocket body for durability and to minimize any detachment due to high aerodynamic loads. Reports highlight that symmetrical fin alignment not only reduces drag but also prevents instability caused by the unevenness of the resultant aerodynamic forces. For example, when the fins are equidistant and properly aligned, the COP stays centered relative to the rocket's vertical axis, contributing to smooth and predictable flight dynamics. Moreover, this accurate alignment minimizes the chance of flutter and reduces random errors due to mass or thrust eccentricities, which might otherwise destabilize the rocket.

Additionally, the second part of research here highlights that accurate fin alignment is critical for achieving stable flight by ensuring the center of pressure remains behind the center of gravity. Misaligned fins disrupt this balance, leading to multiple instability points, such as aerodynamic instability, flutter, and structural failure. Reports such as the UVIC Rocketry Report [10] emphasized that symmetric and well spaced fins also minimize drag, balance aerodynamic forces, and ensure predictable flight dynamics. Furthermore, if the rocket fins are not spaced evenly across the circumference of the body tube, it will result in the center of gravity and pressure to not be exactly in the middle of the rocket, potentially causing the rocket to flip and steer off the projected trajectory path. Our research articles also explain how misaligned fins not only risk causing flutter but also lead to uneven flux distributions, where differences in airflow across the fins result in imbalanced aerodynamic forces [9]. This imbalance can cause the COP to shift unpredictably relative to the COG, leading to potential instability and aerodynamic inefficiency. Excessive fin flutter could also potentially lead to complete failure of the fins and them falling off mid flight, which is caused by excessive external forces like wind. If the fins aren’t exactly parallel to the direction of travel, it introduces another force, causing the flux through the fins to increase and could lead to aerodynamic forces acting on the rocket in other directions.

III. Ideation

H. Openrocket Design and Selection Process

Initial Decision Matrix Methods:

To determine our rocket's measurements to maximize performance, we decided to conduct a decision matrix using two main criterias: stability and apogee. Given our constraints such as maximum number of fins and total length of the rocket, we decided to experiment from two different ways. The first factor that would determine the final "score" of our rocket is the total length, which is composed of both the length of the body tube and the nosecone. The second factor that would determine our final rocket is the number of fins. In table 1 below, we've kept the number of fins constant at 3 for designs 1 through 3 and kept the number of fins constant at 4 for designs 4 through 6 while changing the body tube and nose cone length proportionally.

Link to spreadsheet:
https://docs.google.com/spreadsheets/d/1fK4K558kYYaVec8r--mvY7CyVipvbDxjURZYBviTfO0/edit?usp=sharing

A	B	C	D	E	F	G	H	I	J	K
	Body Tube Length	Nosecone Length	Number of Fins	Center of Pressure	Center of Gravity	Stability	Apogee	Stability Score	Apogee Score	Weighted Final Score
Design 1	28	4	3	22.127	14.44	1.83	687	7.44	10	32.32
Design 2	32	6	3	26.807	17.008	2.33	576	8.56	8.384279476	34.06427948
Design 3	36	8	3	31.486	19.9514	2.85	483	4.4	7.030567686	20.23056769
Design 4	28	4	4	23.551	14.718	2.1	655	9.6	9.534206696	38.3342067
Design 5	32	6	4	28.49	17.312	2.66	551	5.92	8.020378457	25.78037846
Design 6	36	8	4	32.429	19.84	3.24	464	1.28	6.754002911	10.59400291

Table 1: The output data for when different number of fins and total lengths were changed

After experimenting with the corresponding body lengths to nose cone lengths for each respective number of fins, we needed to find a way to compute a "score" in order to easily determine which design was the best based on the highest "score." To do this, we first assigned scores to each design's stability and apogee values.

Stability Score Methodology:

For stability, the formula we came up with is:

$$\text{Stability Score} = 10 - 4 \times (|(2.5 - Stability) - (Stability - 1.8)|)$$

The reasoning behind this was we know the ideal stability is between 1.8 and 2.5. Therefore, the ideal stability would be exactly the average of 1.8 and 2.5 of 2.15. Our goal was to assign the highest scores to stability values closest to this midpoint. To achieve this, we calculated the deviation from the midpoint using the expression ∣(2.5−Stability)−(Stability−1.8)∣, which measures the total deviation from 2.15 and approaches zero as stability gets closer to this ideal value. We applied absolute values to ensure that deviations on either side of the midpoint were treated equally.

Finally, we subtracted this deviation from 10 to create an inverse scoring system, where values near the midpoint yield higher scores. The factor of 4 essentially further scales the deviation, allowing the scores to be more spread across our scoring range of 0-10. This approach results in a stability score that ranges from 0 to 10, prioritizing designs with stability values closer to the ideal range.

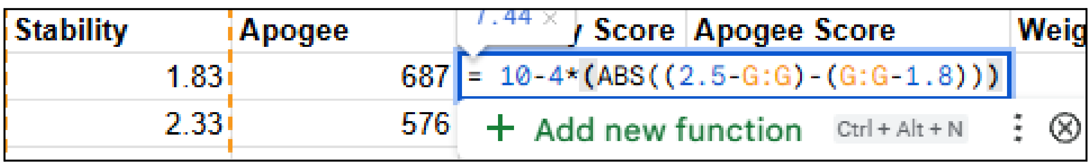


Figure 1: The google sheets equation entered for the entire row to automatically calculate the stability score for all designs

Apogee Score Methodology:

To evaluate the apogee of each design, we created a scoring equation that assigns higher scores to designs with apogees closer to the datum we set of 687 feet since that was the highest apogee out of any of our initial designs. We then computed a way to compare each design’s apogee to that datum value. The formula we used to calculate the apogee score is The formula for calculating the apogee score is:

$$\text{Apogee Score} = \frac{apogee}{687\ feet} \times\ 10$$

In this equation, we divide the apogee for each design by the datum value of 687 feet and then multiply by 10 to scale the score to a range from 0 to 10. This scaling allows us to directly compare apogees across designs, with a score of 10 representing a design with better apogee values while lower apogees receive proportionally lower scores.

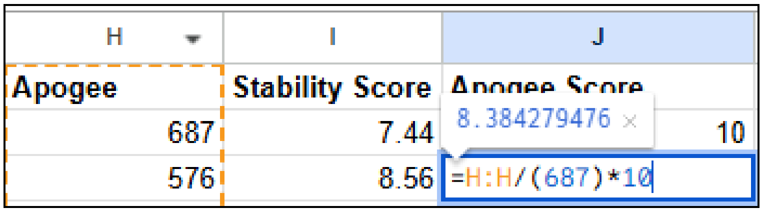


Figure 2: The google sheets equation entered for the entire column to automatically calculate the apogee score for all designs

Final Score Methodology:
To determine the final score for each design, we combined the stability and apogee scores where we weighted stability more heavily to reflect its greater importance in the design of our rocket. Specifically, we multiplied or scaled the stability score by 3 and added it to the raw apogee score. This approach allowed us to emphasize stability as a more important factor for our final design, which we considered to be three times as important as apogee in selecting the optimal design.

Secondary Decision Matrix Methods:

Based on our data in Table 1, we observed that as the total rocket length increased, both stability and apogee scores tended to decrease. With two datasets to compare, one for designs with 3 fins and one for 4 fins, we entered a second phase of analysis to determine which configuration would be best on average for our final rocket. While the 3-fin designs technically scored higher on average, we chose to proceed with the 4-fin designs due to knowing that more fins typically provide greater stability, though with increased drag. Given that our final scoring methodology prioritized stability over apogee, we opted for 4 fins as the optimal choice.

With the 4-fin setup established, we then focused on analyzing various combinations of body tube and nose cone lengths. Initially, we only tested paired values (e.g., a 28-inch body tube with a 4-inch nose cone). Furthermore, looking at our data from Table 1, it shows that body tube lengths of 28 and 32 inches yielded higher stability and apogee scores. Therefore, we decided to test these body tube lengths in combination with three nose cone lengths of 4, 6, and 8 inches to conduct a more thorough analysis using the same methodology as the first method. The below table (table 2) shows our results.

	Body Tube Length	Nosecone Length	Center of Pressure	Center of Gravity	Stability	Apogee	Stability Score	Apogee Score	Weighted Final Score
Design 7	28	4	23.551	14.718	2.1	655	9.6	9.534206696	38.3342067
Design 8	28	6	25.339	15.597	2.32	593	8.64	8.631732169	34.55173217
Design 9	28	8	27.126	16.511	2.53	532	6.96	7.743813683	28.62381368
Design 10	32	4	26.702	16.502	2.43	611	7.76	8.893740902	32.1737409
Design 11	32	6	28.49	17.312	2.66	551	5.92	8.020378457	25.78037846
Design 12	32	8	30.278	18.163	2.88	496	4.16	7.219796215	19.69979622

Table 2: Our secondary analysis data for different nose cone lengths corresponding to a 4 fins and a body tube length of 28/32 inches.

Final Decision Conclusion:

Based on our data from both table 1 and table 2, it's clear that the design with the highest final score of 38.33 was the design 4/7 with a body tube length of 28 inches, a nose cone height of 4 inches, and 4 fins. This design also scored the highest for stability based on our criteria and weight of importance for stability, scoring a 9.6. This near 10 value suggests that it is very close to the ideal stability rating of 2.15. Additionally, except for our datum apogee of 687 feet, this design also had the highest apogee of 655 feet. Therefore, this will be the final design (figure 3) we will move forward with to the build phase.

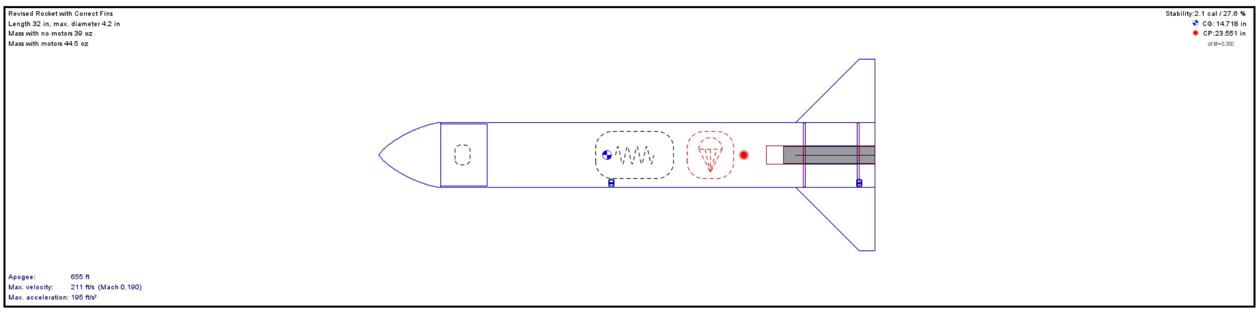
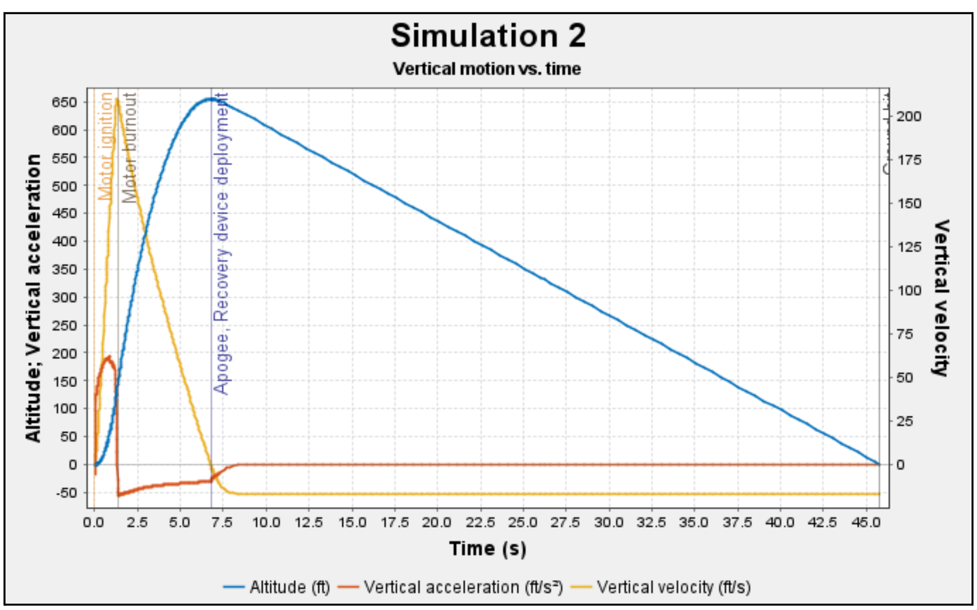
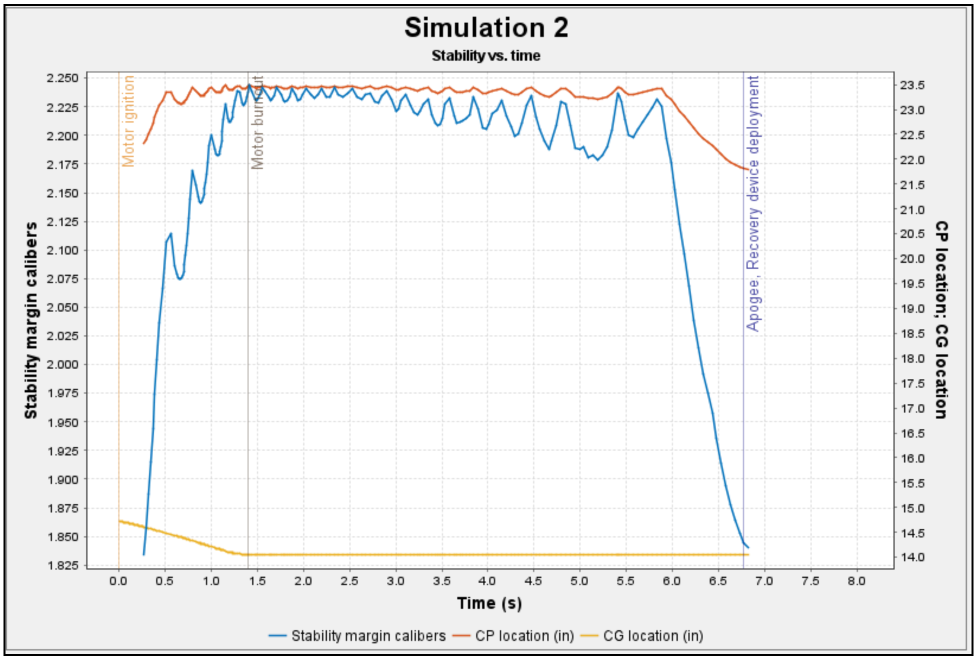


Figure 3: The Openrocket design for our final rocket design that we will be moving forward with

I. Expected Rocket Performance



Graph 1: Vertical Motion vs Time Data



Graph 2: Stability vs Time Data

Our OpenRocket simulation predicts an apogee of 655 feet, reached in 6.71 seconds, with a maximum vertical velocity of 209.68 ft/s occurring at motor burnout at 1.4 seconds. This implies that our model rocket achieves its maximum speed shortly after launch, while the motor is providing thrust, and continues to coast upward under inertia until it reaches its peak apogee.

Additionally, as shown in Graph 2, the center of gravity (COG) consistently remains above (closer to the nose cone than) the center of pressure (COP). This alignment is a critical indicator of the rocket's stability and suggests a stable flight trajectory. When the COG is ahead of the COP, the rocket tends to self correct during flight if it deviates from its intended path and essentially prevents the rocket from flipping.

The stability graph further illustrates a stable flight trajectory by showing a relatively consistent average stability margin of 2.2 calibers after motor burnout during the rocket's sustaining phase. This consistent margin after burnout indicates that the rocket maintains its stable aerodynamic properties throughout its flight to apogee, ensuring a reliable close path to the simulation.

J. Recovery System Schematic

Our rocket's recovery system is designed to safely bring the entire rocket back to the ground after reaching its max apogee of 655 feet. As depicted by graph 1, the recovery system deploys at 6.78 seconds, which occurs 0.07 seconds after it reaches 655 feet. The system works by using an ejection charge to push the nose cone off and deploy the parachute. As the rocket ascends and reaches apogee, the motor's built-in delay charge activates after burnout. This delay is timed so the ejection happens when the rocket is nearly motionless at its peak height, minimizing stress on the overall system and preventing shift in stability. Once the delay charge burns through, it ignites the ejection charge which creates an immediate buildup of gas pressure inside the body tube. This pressure is what ejects the nose cone out of the body tube and has the parachute deployed. The nose cone is connected to the rocket body with a shock cord, thus the entire system stays attached during the recovery phase. The parachute is tied to the shock cord closer to the nose cone with a butterfly knot. When the nose cone is ejected, it pulls the shock cord and parachute out of the body tube. As the parachute unfolds, it slows the rocket's descent, ensuring it comes down gently and intact.

IV. Execution

K. Fabrication Plan and Procedure

Nose Cone Construction:

With the nose cone dimensions determined based on our method analysis, the next step was to transform the digital model into a physical nose cone. We began by exporting the nose cone design from OpenRocket as an OBJ file and then opened it in NX to convert it into a CAD format. From there, we imported the CAD file into Ultimaker Cura to prepare it for 3D printing. Since the nose cone's head has a larger diameter than the shoulder, we needed to add tree supports during 3D printing to ensure proper slicing and prevent the head from collapsing during 3D printing.

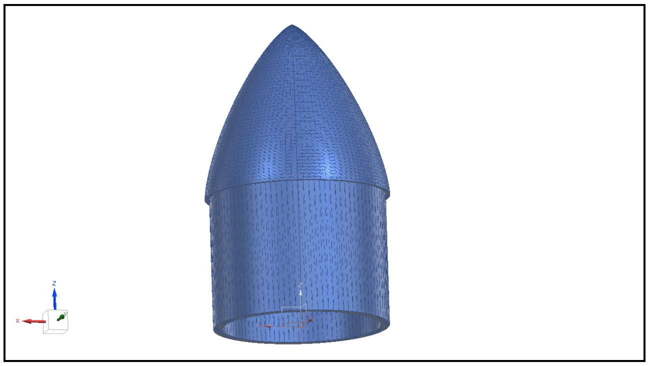


Figure 4: 3D image of the nose cone in NX imported as an OBJ from Open Rocket

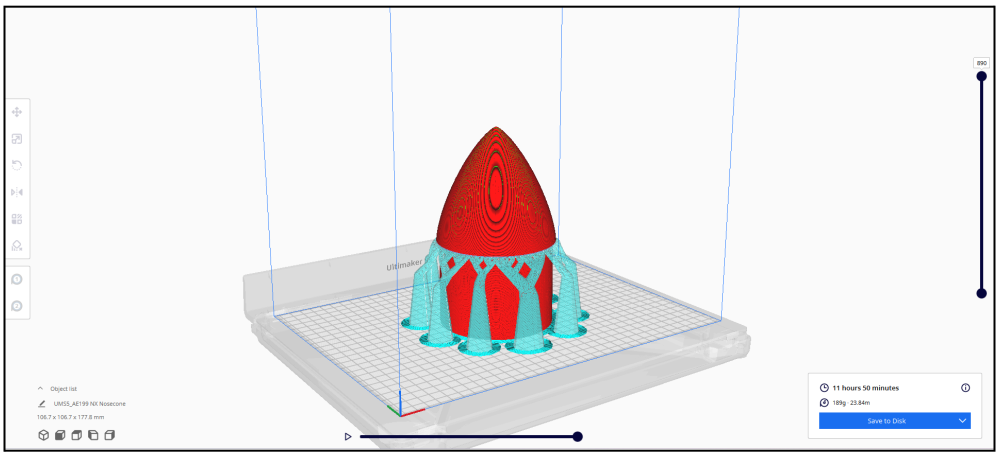


Figure 5: The Nose Cone as an STL file on Ultimaker Cura with tree supports

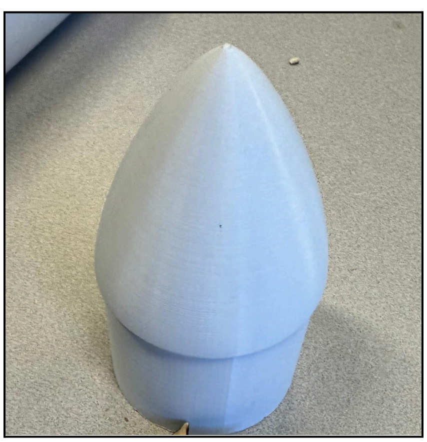


Figure 6: The 3D printed Nose Cone after taking off the tree supports

Centering Ring and Motor Tube Construction:

Our rocket uses two centering rings for the motor mount and a shock cord (the yellow string in Figure 7) that measures three times the length of the 28-inch body tube. To position the centering rings correctly on the motor mount tube, we first determined the spacing between the rings and from the ends of the mount, accounting for rail button placement needing to be below the bottom centering ring as well. Based on our OpenRocket design in Figure 3, the bottom centering ring is positioned 1 inch above the rocket's base. Using our fin tab height of 3.375 inches, we placed the second centering ring 3.5 inches above the bottom ring, or 4.5 inches from the base. Once the dimensions were set, we attached the centering rings to the motor mount tube along with the shock cord. To ensure the shock cord fit without pushing into the motor mount tube, we sanded a small crevice or dent in the inner edge of the centering ring. Finally, we positioned the top centering ring with its shock cord and applied epoxy along its edges to secure it to the motor mount. The bottom centering ring was purposely left unattached in order to attach the fins later on.

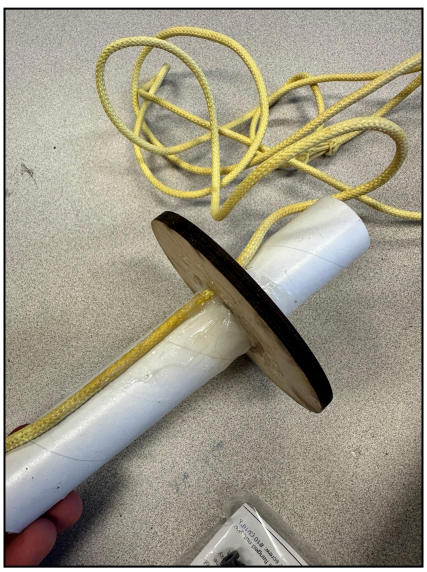


Figure 7: The top centering ring epoxied onto the inner motor mount with the shock cord

Rocket Fins Construction:

Similar to the nose cone, we began the construction of our fins by first exporting the fin design from OpenRocket into NX as a cad format. However, a pdf drawing format is needed to laser cut a part. Therefore, we needed to convert the CAD file into a 2D drawing, which the drawing function in NX did for us. From there, we exported the pdf file into adobe illustrator and laser cutted the fin.

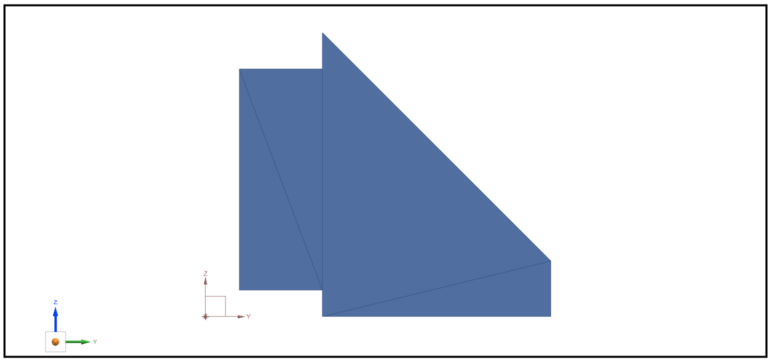


Figure 8: The NX CAD file used to convert the STL file into a 2D pdf drawing

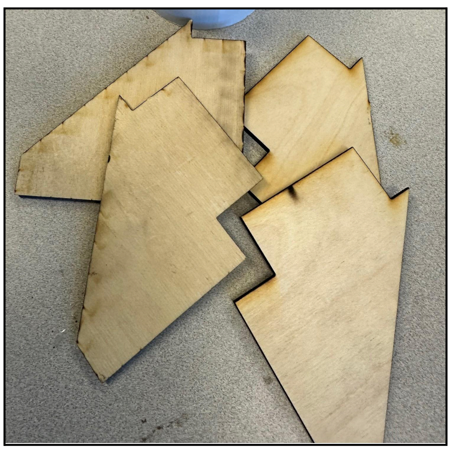


Figure 9: The result from laser cutting the fins

Integration of Fins onto Body Tube:

Method 1:
With the fins cut, we needed an effective method to integrate them to the body tube. First, we outlined the fin slot locations by wrapping a piece of paper tightly around the tube and then cutting it to exactly match the tube's circumference. This gave us a paper template of 13 inches in length. Given that the fins are ¼ inch thick, we calculated the spacing between each inner fin slot to be 2.75 inches, as (13−4×fin thickness)/(4 spaces) (see figure 10 for the paper template). After marking the spacing, we used a magnetic spirit level (Figure 11) to draw precise vertical lines for the slots, ensuring they aligned perfectly on the body tube.

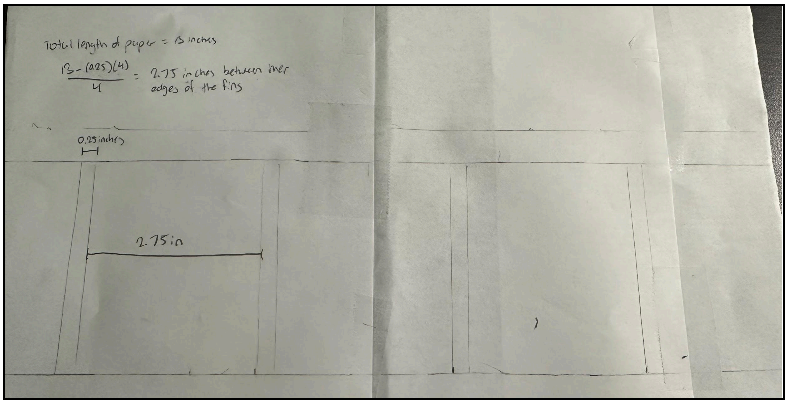


Figure 10: The 2D paper template that outlines where the fin slots will be when wrapped around the body tube

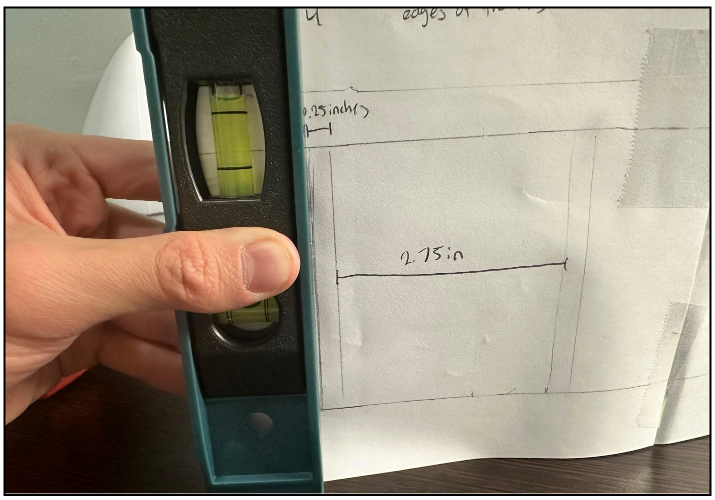


Figure 11: This figure showcases using the leveler to ensure the vertical alignment of the fin slot outline

Method 2:
Although this method seemed theoretically sound, we noticed that once the paper was wrapped around the body tube, the fin spacing didn't align perfectly perpendicular. This discrepancy was likely due to slight human error and the added thickness of the paper around the body tube. To ensure the fins would be positioned exactly 90 degrees apart, we revised our approach to drawing the outline for the fin slots.

First, we drew the body tube's cross sectional outline on a flat piece of paper, again measuring the diameter to be 13 inches. We began by arbitrarily cutting one fin slot, using this as a reference point. For its vertical placement, we used the fact that the bottom of the fin is perpendicular to the body tube and aligns with the bottom of the bottom tube. We then drew a top and bottom line around the body tube based on the top and bottom positions of the fin tab. After inserting a fin into this slot, we traced its bottom outline onto the paper. Since we have four fins, we know one fin would be positioned exactly 180 degrees opposite the reference fin. To mark this, we used a ruler to draw a straight line across the body tube outline (see Figure 12).

With the two opposite fin outlines now drawn, we then located the middle point of the circle outline. Since the thickness of our fins is ¼ inch, we drew one line ⅛ inch to the right and the left of that center marking. To ensure a 90 degree angle, we used the edge of a ruler that was angled from the previously drawn lines.

With all four fin outlines completed on the paper, we transferred these positions onto the body tube by aligning the width of the ruler over each mark on the paper and drawing lines up the body tube to essentially project the outline onto the body tube's plane and guide the placement of each fin slot.

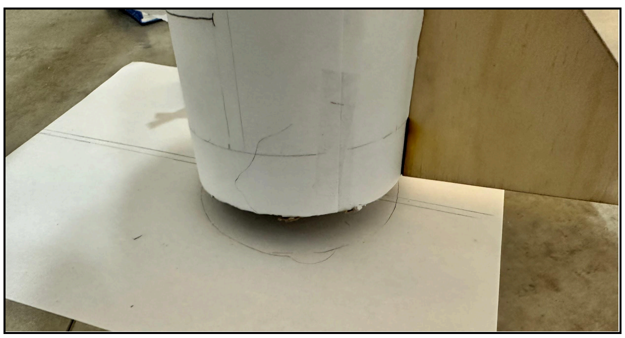


Figure 12: The image shows two of the fins and the body tube outlined on the paper

Now with all the fin slots cut out, the first step in putting the fins on was to first attach the motor mount with the one centering ring that was put together earlier. Using the fact that the bottom of the motor mount tube aligns with the bottom of the body tube, we didn't need to do any additional measurements. From there, we put epoxy on the outer edge of the centering ring, and then slid it up the body tube to its designated position. With everything positioned and outlined, the next step was to simply use a box cutter to cut out the fin slots by tracing the outline we drew previously.

After cutting out all four fin slots with a box cutter, the next step was to tack the fins onto the rocket. We began by applying epoxy to the root edge of each fin and temporarily attaching them to the inner body tube, ensuring the epoxy made contact with the tube's interior. The fins were then removed, and the process was repeated. During the second application, the fins were left in place permanently. This approach allowed the epoxy to coat the inner body tube thoroughly, which provides a stronger adhesion before the final tacking of the fins. Once the fins were put into place with epoxy, we were able to attach the bottom center ring by essentially fileting the edge of the centering ring through epoxying its edges on the inner surface of the outer body tube.

Rail Button Integration:

Once all four fins were stable, we integrated the rail buttons onto the body tube by first drawing a straight line up the rocket in order to ensure the two rail buttons were on the same as the body tube. In other words, we want the rail buttons to be as vertically aligned as possible so that the rocket will launch as straight up as possible. To do this, we first placed the bottom of the rocket on the table. We then used a meter stick to draw a line straight up while being aligned 90 degrees with the table and used a magnetic spirit leveler to ensure it was as perfectly vertical as possible. After the straight line was drawn, we simply used our OpenRocket (figure 3) to determine where our rail buttons were supposed to go. After determining the bottom rail button was 1 inch from the bottom of the body tube and the top rail button was 15 inches from the bottom of the body tube, we marked the spots with a pencil on the line we drew earlier and used a drill to make the holes (figure 13). Once the holes were drilled, we attached the rail buttons onto the rocket (figure 14).

Figure 13: Drilling the rail buttonholes

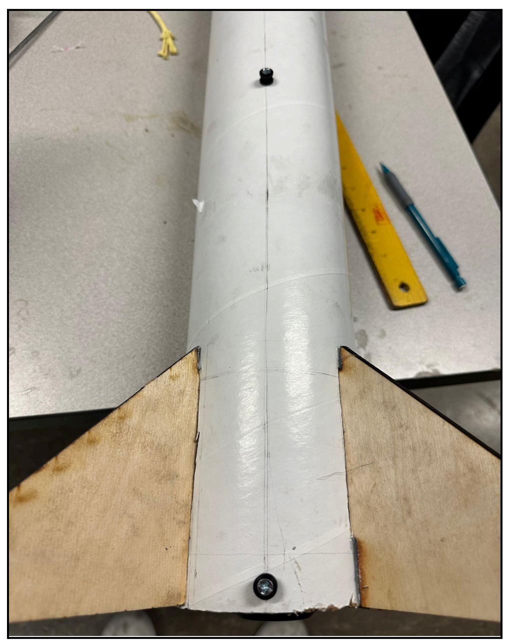


Figure 14: The completed rail buttons on the rocket on the same line of axis

Fin Fillet Process:

To create durable and aerodynamic fin filets, we began by preparing the body tube with tape, positioning it a quarter inch away from each side of the fin slots (Figure 15). This ensured that the filets would have a consistent radius of approximately 0.25 inches and kept the epoxy confined to the fins and not onto the rest of the body tube. We first applied large chunks epoxy at a time to the fin slots. Then, we shaped the filets with a curved edge popsicle stick, which allowed for a smooth and consistent filet along the length of each fin-body junction. To achieve clean edges, we carefully removed the tape within 30 minutes of applying the epoxy, preventing the epoxy from adhering to the tape and causing uneven edges and potentially damaging the cardboard body tube.

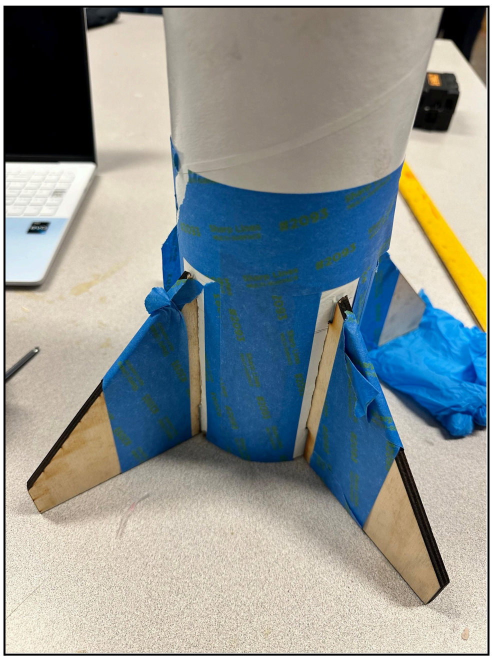


Figure 15: Fin filet tape

Shock Cord and Parachute Attachment

The final steps in the rocket construction process involved attaching the shock cord to the nose cone and securing the parachute to the shock cord. We began by using epoxy to attach the shock cord to a centering ring. We threaded the cord through the center hole of the ring, and then it was then securely glued to the other side. Once the epoxy had cured, we proceeded to attach the nose cone to the centering ring.

Using epoxy, we attached the bottom edge of the nose cone's shoulder to the surface of the centering ring that has the cord epoxied to. This attachment ensured that the nose cone would remain tethered to the rocket body during parachute deployment, ensuring the parachute to deploy effectively while preventing separation of the nose cone from the rocket body. After the nose cone was securely fixed in place, we moved on to attaching the parachute.

To secure the parachute to the shock cord, we used a butterfly knot due to its high strength and reliability. The parachute was tied at a point one-third of the way between the nose cone and the body tube, closer to the nose cone, to optimize deployment and stability during descent. These final steps ensured that the rocket was ready for a safe and controlled recovery after launch.

V. Communication

L. Expected Outcome

Our OpenRocket simulation projects that the model rocket will achieve an apogee of 655 feet. However, we believe that this estimate is likely overly optimistic due to several critical external factors not considered in the simulation such as external weather conditions and fabrication errors that could significantly influence the rocket's performance.

WEther conditions such as wind play a significant role in the rocket's trajectory and maximum altitude. The default simulation parameters on OpenRocket assume a wind speed of 4.47 mph, as illustrated in Graph 1. However, when recalculating the apogee using actual average wind speeds of 9 mph for our launch location taken from weather data, the expected apogee decreases to 625.1 feet as shown in Graph 3. This relatively large difference demonstrates the sensitivity of the rocket's performance to just a small difference in wind variations.

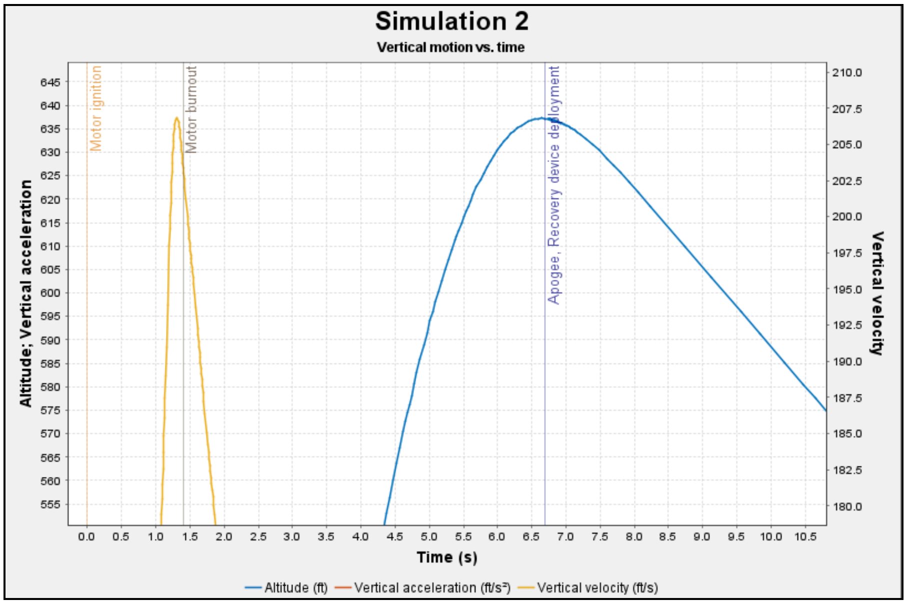
Additionally, wind speed has a considerable impact on the rocket's stability throughout its flight. Graph 4 displays stability over time using the default wind speed of 4.47 mph, while Graph 5 shows the stability data with the more realistic wind speed of 9 mph. The stability profile in Graph 4 shows fewer fluctuations and maintains a more consistent trend compared to Graph 5, where increased wind speeds result in greater variability in our stability value over time . This comparison underscores how even a single external factor, such as wind, can significantly affect rocket performance for both stability and apogee. Other external conditions, such as temperature and humidity, could also introduce further deviations but were not accounted for in this analysis.

Furthermore, it is also important to consider the limitations of the OpenRocket simulation itself. For instance, the simulation ran assumes a perfectly constructed rocket aligned with the design specifications listed out in the software when designing the rocket. In practice, however, fabrication errors inevitably occur due to human error which has the potential to significantly impact performance. Misaligned fins, improperly mounted rail buttons, or other construction defects can prevent the rocket from achieving a perfectly vertical launch trajectory. These fabrication imperfections caused by human errors further reduce the likelihood of reaching the simulated apogee.

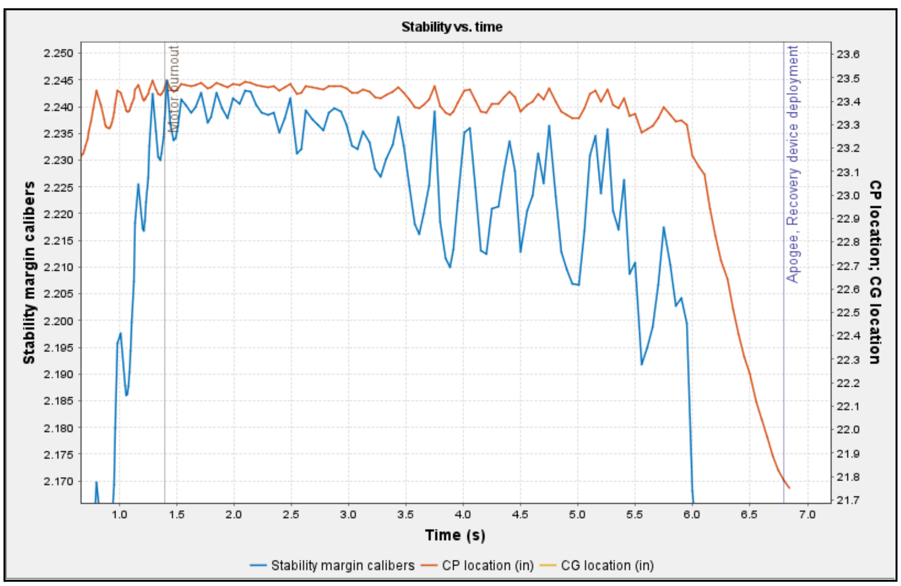
However, despite our uncertainty about the rocket achieving its optimal predicted apogee, we are confident that the rocket will still perform reliably and meet fundamental performance expectations. One main reason for our confidence is the rocket's average stability margin, which remains consistently around 2.1. Despite the greater fluctuation when introducing an external wind variable, this value still indicates a strong level of aerodynamic stability as shown in graph 5, with the center of pressure consistently behind the center of gravity through the entire flight. This alignment ensures that the rocket maintains directional stability during flight and reduces the risk of the rocket flipping or deviating too much from its predicted trajectory path. Additionally, while human error is an inherent part of manual fabrication, we took many deliberate measures to minimize its impact on the rocket’s construction as outlined in our execution report. For instance, we used a manually drawn paper fin jig and alignment template to ensure that the fins were mounted as accurately as possible. These tools allowed us to achieve precise alignment and symmetry, which are critical for maintaining aerodynamic balance and why we are confident our rocket will still perform well even with this unknown variable of human error.

Overall Assessment

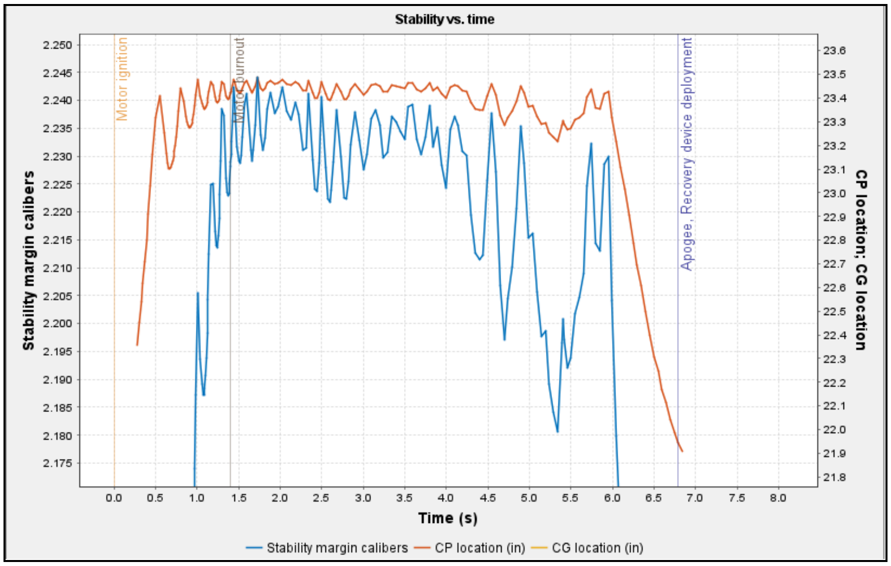
Although external factors such as wind and unavoidable fabrication imperfections may prevent the rocket from reaching its theoretical apogee, the strong stability margin and precise construction techniques give us confidence in its overall performance. These factors suggest that the rocket is likely to achieve a successful flight, meeting safety and operational benchmarks even if it falls short of the simulated optimal altitude.



Graph 3: Vertical altitude data vs time data for wind speeds of 9 mph



Graph 4: Stability vs time data with 4.47 wind speeds



Graph 5: Stability vs time data with 9 mph wind speeds

M. Project Summary

This project has provided critical insights into the design, analysis, and fabrication of our model rocket project. Focusing on maximum apogee while guaranteeing stability given constraints, we developed a systematic approach that incorporated advanced tools and methods, including OpenRocket simulations, decision matrices, and precision fabrication techniques. Even though the live launch of the rocket was not possible, the fabrication of our rocket allowed us to satisfy key design requirements and resulted in a well-constructed final product. The process also demonstrated the value of in-depth research, cautious execution, and learning in iterative steps in rocketry projects.

The final rocket design reflects a balance between theoretical analysis and practical considerations. Through OpenRocket simulations, we optimized parameters such as fin alignment, body tube length, and nose cone dimensions to achieve a stable and efficient configuration. With the trajectory readings from OpenRocket simulations, our rocket is expected to perform reliably, achieving a near-optimal apogee and demonstrating consistent stability which were major factors in our decision reasoning. Despite the lack of a launch, the fabrication process validated the design's integrity, offering promising results if we were to actually launch our rocket. Therefore, overall the rocket design did help us reach our design requirements of stability and apogee.

N. Proposal Statement

We propose implementing a 3D printed alignment jig and NX CAD alignment template for cutting and positioning rocket fin slots, increasing precise fabrication techniques and enhanced surface preparation methods to ensure accurate fin alignment; this approach will help minimize aerodynamic instabilities such as flutter and uneven flux distribution, thus improving overall rocket stability and performance.

O. Argument for Proposal

The benefits of this approach include minimizing human error, ensuring fins are symmetrically spaced, and align them precisely at 90-degree intervals, which are all essential for maintaining flight stability. With Spaceport America team reports [4-7] and also ISS Spaceshot rockets [1-3] demonstrating how the use of 3D printed alignment jigs improve durability and adhesion, we think it's important to have these good practices of fin fabrication in our class just as professional teams do. However despite the significant benefit these methods may have, there are still limitations such as human error during jig usage and reliance on tool precision were noted. Additionally, human error is still involved when using a dremel to precisely cut out the fin slots. However after evaluating many team reports, it seems that this factor is something that can't be avoided.

In conclusion, accurate fin alignment is not only a technical requirement but is also a crucial element for stable rocket performance. These findings underline the importance of both precision tools and careful execution in fin fabrication in order to maximize rocket stability during launch. Misaligned fins would cause the COP to shift unpredictably relative to the COG, leading to potential instability, aerodynamic inefficiency, and even structural failure during flight. By incorporating these tools and practices, we can significantly improve both the construction process and the rocket's overall performance.

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