Design and Testing of an Airbrake System for a Sounding Rocket

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The University of Georgia's International Rocketry Engineering Competition (IREC) Team is developing a robust airbrake design for use on the 2025 competition rocket. A significant portion of the score consists of achieving apogee at 10,000 feet. This research delves into the design, analysis, integration, manufacturing, and control theory for the airbrake system. An analysis of the airbrakes will be performed by using analytical calculations along with FEA and CFD simulations. By using an altimeter to measure altitude and an IMU to measure acceleration, we will derive velocity to determine the extent to which air brakes must be deployed to create a calculated drag force for the determined apogee. The input of the altimeter along with the response measured from the IMU is used in a Model Predictive Controller (MPC). The output determined by the controller then actuates the airbrakes system through a servo with physical constraints and costs represented in the control system. We intend to perform analyses to prove that this system is effective in controlling apogee during ascent and can be implemented on future competition rockets.

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I. Nomenclature

A = cross sectional area, in^2
C_d *= drag coefficient*
C_p *= center of pressure, in*
C_g *= center of gravity, in*
v = velocity, ft/s
h = altitude, ft
r = radial displacement, in

II. Introduction

The University of Georgia's Rocketry Team designs and manufactures high-power rockets for the International Rocket Engineering Competition (IREC), an annual competition with multiple divisions for students. This competition allocates a large proportion, about a third, of points to the ability of the rocket being as close to a certain apogee as possible – with our division having a target of 10,000 feet. Because of the importance of hitting the competition's target apogee, teams implement several different systems to decrease the margin of error as much as possible. When deciding how to approach the competition, it was better to design a rocket capable of overshooting the targeted apogee and implement an airbrakes system that would introduce enough drag to reduce the rocket's apogee to exactly 10,000 feet.

Airbrakes are active control systems that dynamically adjust to real-time data. They use extendable petals to create drag and precisely manage the rocket's altitude. Introducing drag is in line with the goal of decreasing velocity in the coasting phase of the rocket to reach the designated target altitude. The factors of importance in airbrakes are maintaining stability, fast extension, and the introduction of ample drag.

The proceeding entries showcase the design and manufacturing process, electronic implementation, and simulation of the airbrake system on the 2025 University of Georgia IREC rocket

III. Mechanical Design

To begin the design process for the airbrakes, we first had to consult several different deployment mechanisms to see which one would be able to maximize the deployed airbrake area and the rocket space given. We did not choose to do a flap design due to the compromise in the structural integrity of the airframe. We instead opted for a petal design that linearly extends out the air brakes that would rely on a single motor to actuate 3 petals simultaneously. We developed concepts for a linear and exponential deployment design, with the exponential design being based on a curved link design and the linear using an expanded pulley as shown in Figure 1 and Figure 2, respectively.

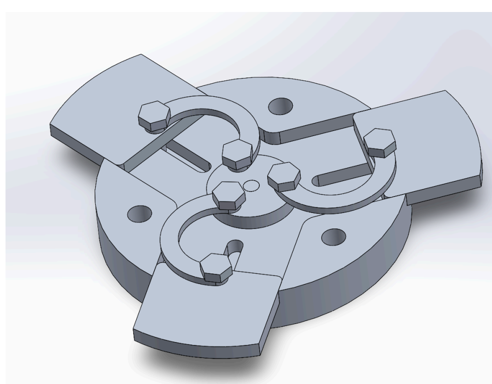


Figure 1: Initial Exponential Actuation Design

When designing the curved link as shown in Figure 1, we had a couple of constraints affecting our design. Due to the rocket diameter being 5 inches, we were unable to make the links completely straight to achieve an ideal extension, which resulted in this curved link design to accommodate the space constraints. This change resulted in an exponential actuation path rather than linear. This way we were able to maximize the area that the petals protruded as much as possible, up to a distance of 1.5 inches, as compared to the straight link distance of 1 inch. Another drawback of this design is the friction generated, as the plates would have to slide between two walls as well as on a guide, which created a lot of undesirable friction. This friction combined with the 46 lbf experienced by each petal would require a more powerful servo than the linear actuation design, thus increasing the cost significantly. Also, all the extra material in the exponential actuation design made it rather heavy, which is undesirable when attempting to achieve 10,000 foot apogee. The cost, weight, and difficulty to program an exponentially actuating design led us to choose the expanding pulley design, shown in Figure 2.

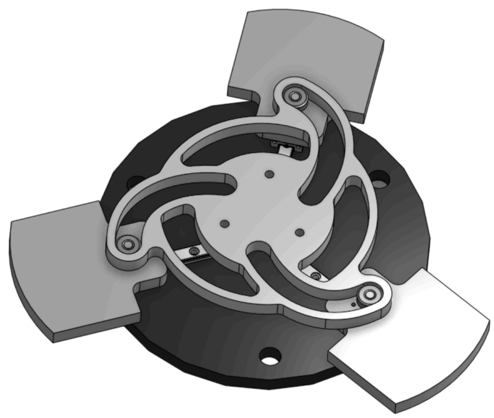


Figure 2: Initial Linear Actuation Design

With the goal of creating a design that would actuate all 3 plates simultaneously, we took inspiration from the Worcester Polytechnic Institute High Power Rocketry Club's 2024 design [1], while adapting it to fit our constraints. The main restrictions were our manufacturing capabilities (limited to waterjet, 3D printing, handheld tools, and very little machining) and the rocket's small cross-sectional area. This posed challenges that had to be considered from the earliest stages of development and would later inform our design choices.

The chosen mechanism lies between a ¼" top and bottom G10 fiberglass plate. There are three linear rails radially extended from the center of the bottom plate, which will guide the carriages and petals (extending plates) with very little resistance. These petals have a ball bearing that will slide within the actuator plate's path, and since their movement is constrained by the linear rails, they will extend radially when the plate rotates. The actuator plate revolves around the center, being actively rotated by a HPS-3518SG servomotor and supported by a bearing and shaft connected to the bottom plate to decrease axial strain on the servo.

The path that the petals follow in reference to the actuator plate is of great importance, and has been iterated multiple times. By circumferentially elongating the path, the servo must rotate more to achieve the same outward extension of the plates, increasing control and mechanical advantage. Similarly, the trajectory can be optimized to improve the plates' stability when they are fully extended. The plates are prevented from "backing out" due to outside forces when fully extended because the last portion of the actuator path is tangential to the circumference. This means that the only way to push them backward is through rotational motion, which can only be experienced through the servo. Currently, the position of the plates can be represented by the following equation:

$$r = -2(10^{-7})\theta^3 + 1(10^{-5})\theta^2 + 0.0006\theta \qquad 0 \leq \theta \leq 53.9^\circ$$

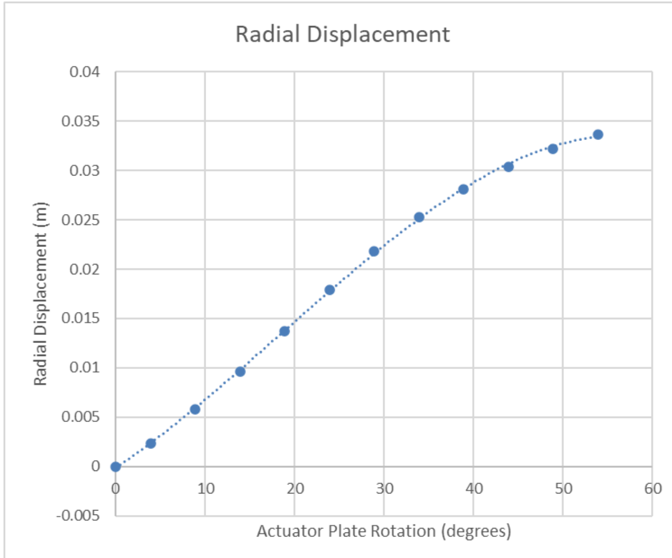


Figure 3: Radial Displacement of Petal on Actuator Plate Rotation

The displacement can be further simplified by approximating it as a linear function. This change could help aid future calculations and simplify the system, but further optimization is needed.

$$r = 0.00070\theta, \qquad 0 \leq \theta \leq 53.9°$$

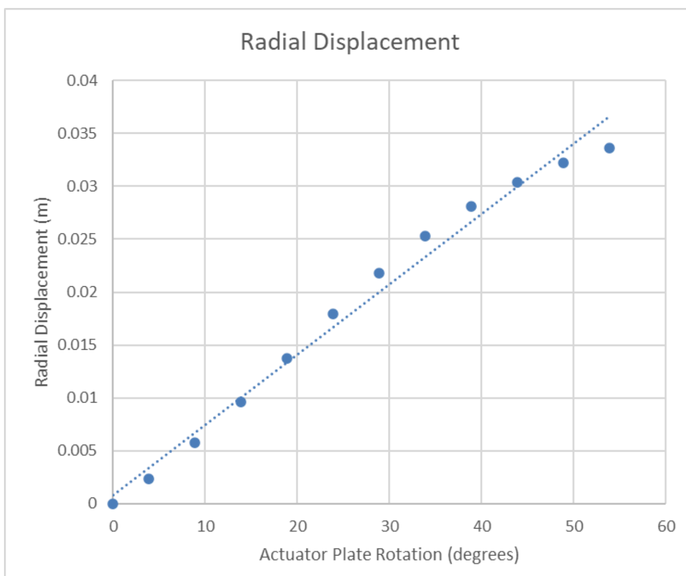


Figure 4: Simplified Radial Displacement Based on Actuator Plate Rotation

There were some early concerns surrounding the stress that the airbrakes would be subjected to. The rail carriage was identified as the critical component, however, upon static structural simulations in Ansys Mechanical, it was found that the maximum stress was of around 2.32 Kpsi. This value would result in a safety factor of 15 when using the 35 Kpsi yield point for Aluminum 6061 given by the supplier. Although this safety factor may appear unnecessarily large, it must be noted that it is only a reflection of its behavior until material failure, and the carriage may stop sliding before that due to the increased frictional force. In the airbrake's case, the carriage's sliding capabilities are of extreme importance, and since these are harder to predict, will require further testing.

To facilitate manufacturability, all the plates were designed to be completely cut in the waterjet. It must be noted that a recessed pocket might have to be milled in the actuator plate's center for the center bearing to lie, since it requires a tighter fit. The center of the plate can be easily indicated due to its geometry, making this a suitable adjustment for the team's capabilities.

IV. Control System Design

The design and architecture of the model predictive controller in the control system used for the actuation of the air brakes relied heavily on interpreted values and simulations gathered by CFD. This section will cover the construction, analysis, and testing of the theoretical Model Predictive Controller (MPC) that the air brakes system will use to reach a defined setpoint for altitude in feet. Analysis and testing are all done within Matlab's Simulink program with the use of both the Control System and Model Predictive Controller Designer packages.

The team's first task was to define the variables of flight and generate a model that could interact with these variables in a meaningful way through the use of a 'u' variable, representing the actuation of the air brakes and resulting drag. This variable is output by the MPC controller and input into the plant, which uses a state-space model to predict how the current state may change in the future.

The state-space model used to represent the air brake system was developed to model the state of the rocket with varying levels of drag being induced by the air brakes. We defined the system in terms of the state variables altitude (h) and velocity (v) in order to capture the system as a whole. Because the state-space vector is represented by altitude and velocity, modeling the changes in these variables with respect to time is necessary. The change in altitude is equal to the current velocity (which we approximate to linearize our system), but the change in velocity is more complex. For the change in velocity we consider both gravity and drag of the rocket into the equation, however, we additionally consider the drag of the airbrakes and its relation to 'u'. Therefore, our final state-space equation can be modeled as:

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{2m}\rho v C_r A_r \end{bmatrix}\begin{bmatrix} h \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{2m}\rho v^2 C_b A_b \end{bmatrix} u + \begin{bmatrix} 0 \\ -g \end{bmatrix}, \dot{y} = [0\ 1]\begin{bmatrix} h \\ v \end{bmatrix} + [0]u$$

For simplicity, the rounded edges of the flat plates are averaged into a larger rectangle whose area is related to the radial displacement previously calculated in Section III, Design. Based on the force of drag equation and the rocket having a known mass after the burnout of the motor, our team was able to directly relate the actuation of the plates to a determinable change in acceleration the plates would cause. With reference points set in the controller for constant values of 10,000 feet and 0 feet/second velocity, the model aims to minimize the difference between the data created from the plant and the reference values given.

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

The above equation is how the force of drag is calculated both for the rocket and the airbrakes system. In the real system, the total acceleration is available through an IMU, and after being projected to the vertical axis, will be converted to the drag equivalence with the only unknown being the drag of the rocket's body. An ideal version of the air brakes plates will be used with velocity and air pressure input into the equation available from a barometric pressure sensor, with velocity being derived through sensor fusion between the IMU and the barometric sensor, capable of outputting altitude based on environmental conditions.

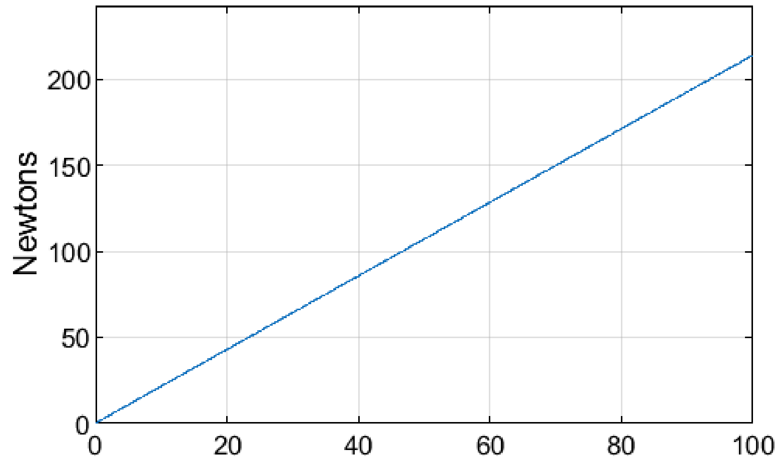
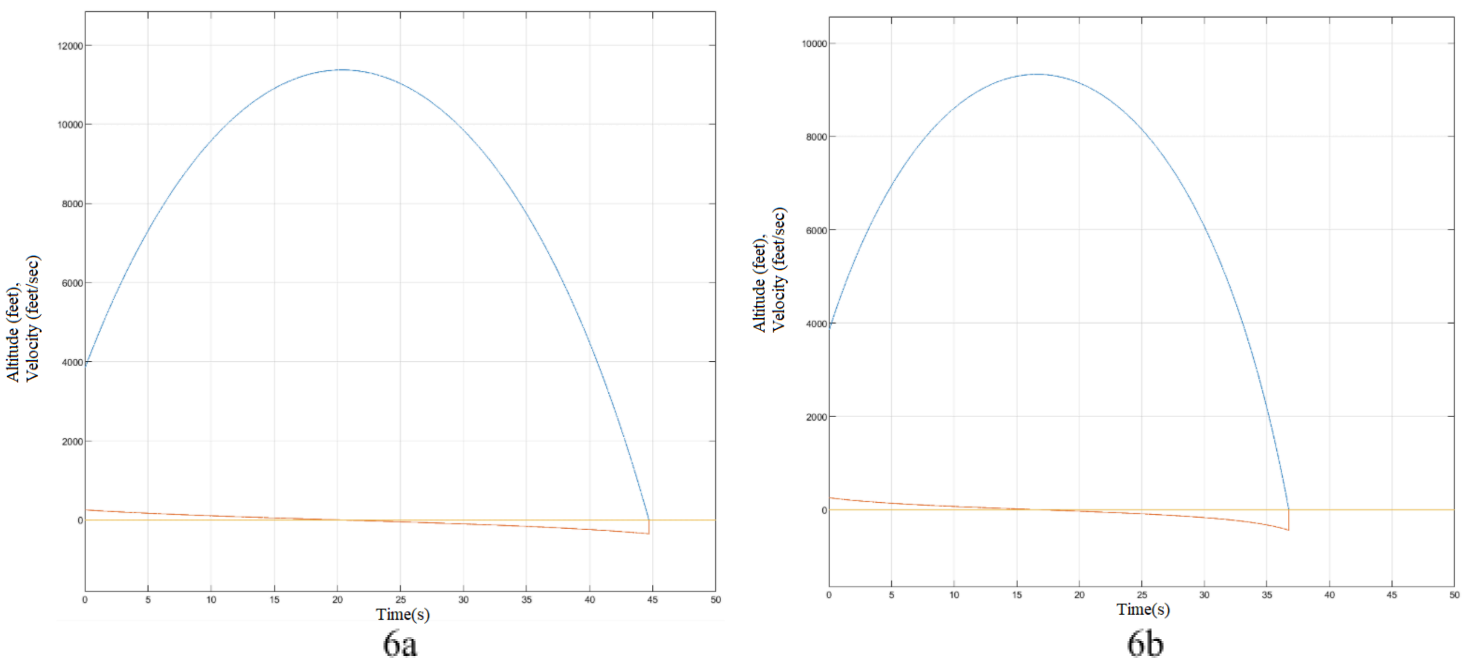


Figure 5: Drag force created by air brakes plate based on deployment (percent value of 'u' from 0 to 1) at mach 0.8

As a final note for the simulations and their generated graphs, constants were assumed for complex relationships such as the coefficient of drag where lookup tables will be utilized from CFD results in implementation.



Figures 6a & 6b: Flightpath graphs with (6b) and without (6a) airbrakes fully deployed. Blue represents altitude (feet), and orange represents velocity (feet/second).

In consideration of the cost function and constraints of the MPC, very liberal values were assumed for both the speed the servo is capable of actuating the plates at, and for the prediction horizon. For the cost function of the MPC, following the general quadratic cost function:

$$J = \sum_{k=0}^{N_p - 1} [h, v_{ref} h, v_k)^{\top} Q(h, v_{ref} h, v_k) + u_k^{\top} R u_k]$$

$$where$$

$$-\ \Delta u_{max} \leq u(k) - u(k-1) \leq \Delta u_{max}$$

The maximum step size of the servo for a given time step is determined by u_{max}. Although the team is in the stage before HIL testing can be completed to verify hardware constraints of the servo, as well as any functional tests of the MPC and its interaction with the servo, such values are easy to change when needed. Sampling time of the MPC is to be determined, but due to hardware limitations on the ESP32 microcontroller implemented in the avionics bay of the rocket, the potentially slow response time of the actuating system, and generally the relatively long flight time, will be kept in the range of 0.1 seconds.

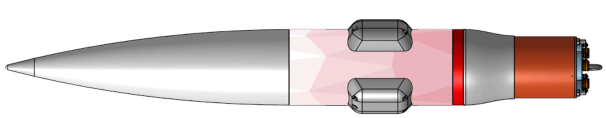
Refinements will continue to be made with the MPC and simulations covered within the section, and focus will be put into generating non-idealized versions of flight conditions, with a heavier emphasis being put on verifiable CFD data at more data points, and randomized yaw pitching to expose the MPC to different conditions and further verify its efficacy.

V. Integration

A. Rocket Overview

Per the competition rules, the rocket must contain a payload weighing a minimum of 4.4 lbs, and follow a cubesat form factor with bonus points for 3Us. The team designed the rocket with a 6" diameter forward airframe and a machined transition down to 5" for the aft airframe. The main parachute sits within the nosecone and features a 'head-end' deployment, where the body separates at the nosecone. Below the nosecone sits the payload, which includes a fuel-sloshing experiment that maps sloshing during the launch vehicle trajectory. Immediately below the payload is the avionics bay, located inside the transition. The avionics bay includes all flight-safety critical electronics, including a GPS tracker for recovery and COTS flight computers which activate charges to deploy the main and drogue parachutes, as well as the microcontroller and sensors utilized for the control system dictating the movement of the air brakes to reach the system's ideal apogee.

The transition was designed using overlapping couplers for both the 6" and 5" airframe sections, epoxied together with 3 centering rings. All airframe sections are G12 fiberglass while bulkplates, fins, and centering rings are made from G10 fiberglass. The drogue parachute is located below the avionics bay inside the aft airframe. Below the drogue and above the motor casing sits the airbrake system, including the petals, actuator plate, and avionics.



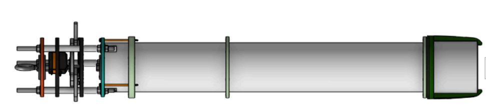


Figure 7: Rocket Assembly without Aft-end Airframe

Caliber of Stability = $\frac{|Cg - Cp|}{diameter}$

The center of gravity (C_g) is 54.3 inches from the tip of the nosecone and the center of pressure (C_p) is 66.1 inches. The top of the airbrake petals are located 57.8 inches from the nosecone. The weight of the payload in the upper airframe helps balance out the airbrake system in the aft end, creating a stability of 1.88 caliber.

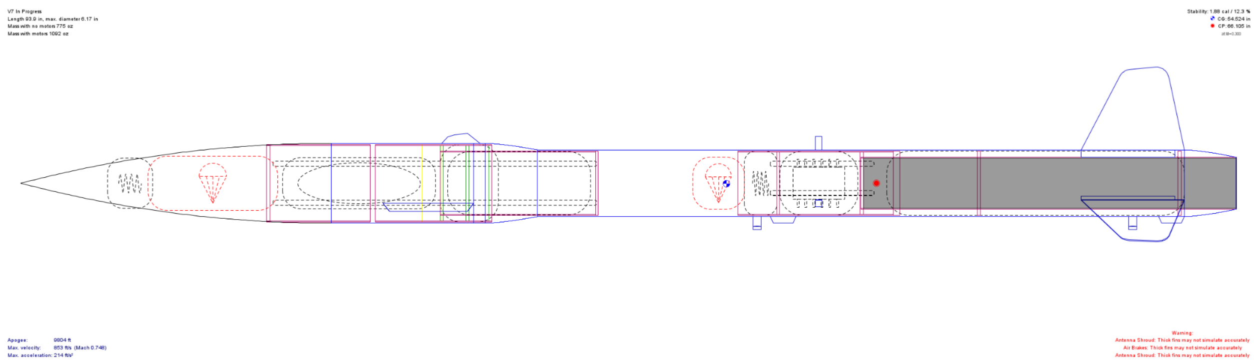


Figure 8: Open Rocket Design

B. Requirements Verification Matrix

Initial constraints and requirements for the airbrakes system required multiple design changes to sustain structural integrity and proper airflow. For example, in order to conform to requirement IV, we decided to epoxy in a coupler to thicken the airframe where the airbrake slots are located. The epoxy was used in the coupler because the slots themselves create discontinuities in the airframe, which create stress concentrations in those areas. The epoxy itself adds thickness to the airframe in addition to the coupler, which is able to provide resistance to the forces in the airframe through reinforcement. We also decided to line up the airbrake petals in the gaps between the fins to reduce airflow separation over the fins. During test launches we will be able to see how the system performs truly, but we were able to perform some subscale testing to ensure the performance of the airbrakes system. We performed stress tests with the petals, rail carriage, and actuator plate under load by applying force to the assembly equal to what we expected them to experience to ensure that these components could handle their load during deployment.

#	Requirement (The airbrake system...)	Importance	Verification
I	Shall be able to deploy and retract during flight	Medium	Embedded testing
II	Shall not impact fins by causing unstable airflow	High	CFD simulations
III	Shall increase total rocket drag when deployed	High	CFD simulations
IV	Slots shall not cause significant structural changes to the airframe	High	FEA simulations
V	Shall not weigh more than 3 lbs in total weight	Medium	Assembly testing
VI	Deployment shall be modeled and controlled from live flight data	Medium	Software testing

Figure 9: Airbrake System Requirements Verifications

C. Manufacturing and Assembly

Our biggest concerns with manufacturing materials proved to be weight and strength. We decided to go with 6061 aluminum with high strength rail carriages holding them down. All screws are rated for high strength threads, and all bulkplates are made of G10 fiberglass. These materials were specifically chosen due to their ability to be waterjet as well as handle the 46 lbf acting on the airbrakes at peak extension. Manufacturing the airbrakes required us to use the waterjet due to its ability to create precise tolerance fits, which were needed to allow for them to fit within the airframe. Other manufacturing methods available would have been costly and unable to meet the specifications of the design.

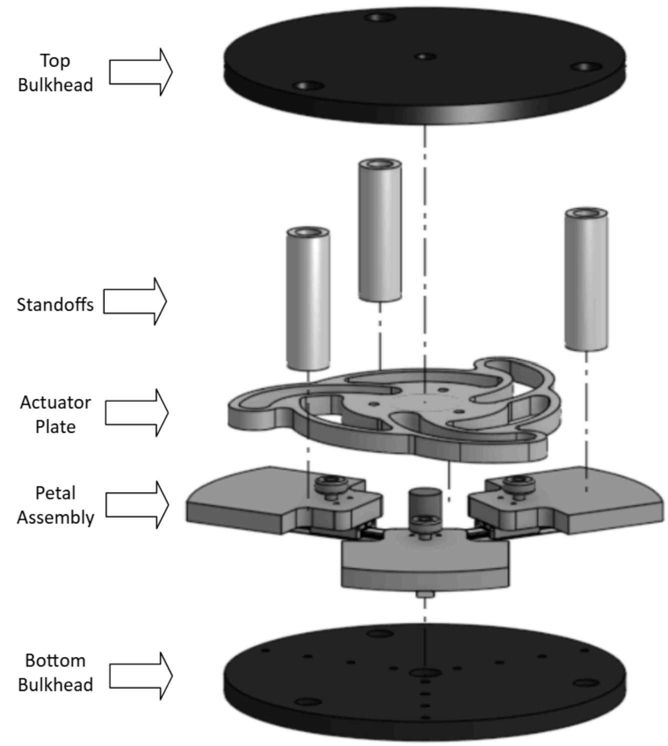


Figure 10: Exploded View of Airbrakes

Most of the airbrake system assembly will be conducted prior to launch day. The bottom bulk plate is attached to the motor casing using one bolt into the center of the casing, as well as 3 screws into t-nuts epoxied into the forward most motor tube centering ring. The bottom bulk plate will have threaded rods with standoffs installed using coupling nuts before it is attached to the motor tube and casing, and the next bulk plate will slide onto the standoffs. The middle bulk plate will have the rail, rail carriages, and petals pre-assembled using M2 screws with a tensile strength of 20 Kpsi which is well above the threshold needed to withstand shearing during flight. Once the middle bulk plate is seated, the actuator plate and bearings will slide on top and a #5 bolt will screw into the pre-threaded holes inside the petals. The petal and bearing assemblies were fit by tapping the petals and using washers to make sure only the inner race of the bearing was used and that the outer race could spin freely against the actuator plate

With the bottom airbrake assembly complete, an adequate servo was needed that could apply torque to the actuator plate against this 46 lbf pushing down on the petals during flight. By taking the maximum moment produced by the servo and ensuring it is greater than the frictional force on the rail carriage from the 45 lbf, we found a 30.4 lb*in servo was more than enough to actuate the air brakes during flight. We then attached the actuator plate to the servo and mounted the servo to the top fiberglass plate. Now, we had two halves of the air brakes and we brought them together with standoffs to ensure that the actuator plate was centered on the bearings, thus completing the airbrakes assembly.

VI. Conclusion

The airbrake system developed for the University of Georgia's 2025 IREC rocket is a crucial innovation for achieving precise apogee control. Through a well-considered design process, the team created a robust and lightweight airbrake mechanism capable of dynamically adjusting drag forces to meet the competition's target altitude of 10,000 feet. Key design choices, including a linear actuation mechanism and high-strength materials like 6061 aluminum and G10 fiberglass, ensure the system's reliability and performance.

The integration of a Model Predictive Controller (MPC) enables real-time adjustments based on live flight data, optimizing airbrake deployment to minimize apogee deviations. CFD simulations and FEA analysis have validated the aerodynamic and structural integrity of the system, while manufacturing with precision tools ensures it meets all constraints.

Although the airbrake system will soon be ready for deployment, ongoing MPC refinement and hardware-in-the-loop testing will be essential for final optimization. This work sets a strong foundation for future competitive rocketry and further advancements in airbrake technology.

VII. References

[1] Aunika Yasui, Henry Lambert, Cameron Best, and Daniel Pearson, “Team 151 Project Technical Report to the 2024 Spaceport America Cup,” pp. 28-30, 2024.