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Roll Reduction System for Mid-Power Rocket

Paislee L. Adlington [1]
West Virginia University, Morgantown, WV, 26505, United States

Nathan J. Bonafield[2]
West Virginia University, Morgantown, WV, 26505, United States

Samuel E. Olsavsky[3]
West Virginia University, Morgantown, WV, 26505, United States

[1] Undergraduate Mechanical and Aerospace Student, WVU, and AIAA Student Member, 1603642.
[2] Undergraduate Mechanical and Aerospace Student, WVU, and AIAA Student Member, 1603645.
[3] Undergraduate Mechanical and Aerospace Student, WVU, and AIAA Student Member, 1400198.

The stabilization of a rocket is vital for a safe and successful flight. There are numerous techniques that can be implemented to ensure that a rocket obtains a stable flight. One such technique is to install a set of fins on the bottom of the rocket to move the center of pressure (CP) aft of the center of gravity (CG). If the fins are installed asymmetrically however, the rocket will experience roll during launch. While the roll of a rocket is a common practice to maintain stability, the rocket could stray away from its targeted flight path due to the misalignment of fins. Due to human error when installing fins, and weather conditions, the roll and stray of a rocket is much more likely to occur. To counteract this issue and understand the flight of the rocket, this research will design and implement an active stabilization system that reduces the amount of roll the rocket experiences during flight, and help the rocket maintain a vertical flight path. This system will introduce a set of four small fins near the mid-portion of the rocket that are attached to a mechanism that allows the fins to orient themselves in a manner to counteract the roll. Though adding a second set of fins near the mid-portion of the rocket adjusts the CP, these fins are small enough in size that they will not adversely affect the rocket's stability, while also being large enough to serve as control surfaces during flight.

I. Nomenclature

ASA	=	acrylonitrile styrene acrylate
B	=	rocket wing's span, in feet
CAD	=	computer aided design
C_l	=	rolling moment coefficient in the longitudinal direction
CG	=	center of gravity
CP	=	center of pressure
D	=	rocket body diameter, in feet
F	=	gravity force enacted by weights in torque test, in pounds force
lb_f	=	pounds force
L	=	lift, the resultant pressure force on a single fin, in pounds force
L_{Ref}	=	reference length used by Missile DATCOM, equal to rocket body's diameter, in feet
MAC	=	mean aerodynamic chord, in feet
PLA	=	polylactic acid
PID	=	proportional-integral-derivative
q_∞	=	dynamic pressure, in pounds per square foot
r	=	radius of torque test wheel, in inches
$R2S$	=	roll reduction system
S_{Ref}	=	reference area used by Missile DATCOM, equal to rocket body's cross-sectional area, in squared feet
T	=	torque, in pounds force inches
$°$	=	degrees of a circle

II. Introduction

The use of a stabilization system is common practice in the aerospace industry to ensure the success of a rocket's mission. An active stabilization system is able to assist the rocket in performing maneuvers during flight, maintaining a level flight path, and maintaining a stable flight while airborne. Different types of active stabilization systems include: actuated fins, gimbled nozzles, rollerons, reaction wheels, as well as many others [1]. Depending on the mission requirements of the rocket, one of the stabilization systems will be preferred over others.

When analyzing stabilization systems used in the hobby of experimental rocketry, many low-power, mid-power, and high-power rockets do not utilize a stabilization system when in flight. Experimental rockets do utilize flight computers in order to record in-flight data, such as altitude, velocity, acceleration, and pressure, but for the main purpose of separation to deploy recovery equipment, such as parachutes. Depending on weather conditions, manufacturing, and assembly of the experimental rocket, the rocket could become unstable during flight and experience either a catastrophic failure or stray away from the ideal flight path. By implementing an active stabilization system, the experimental rocket can have a greater chance of experiencing a successful flight and mission.

Previous research on this topic has been conducted in the past from different sources. One such research was conducted by Guerrero et al [2] on a control system that would serve the purpose of being able to assist a high-power rocket during launch and maintain a certain attitude throughout flight, while also being able to reach a target altitude. Throughout the research conducted, the team analyzed how a set of four actuated fins would be able to assist the high-powered rocket and be able to stay within 5 degrees from the vertical axis of the launch. The team also did an analysis on the system's ability to eliminate roll throughout flight. Though the system never flew on a high-powered rocket at the time of the research, different theoretical tests were conducted, including the step response of the rocket, finite element analysis, Digital DATCOM for different aerodynamic coefficients, computational fluid dynamics, and flight dynamic calculations. From their results and conclusions, it was determined that the system is statically and dynamically stable for flight, and can achieve the target altitude. The research conducted by the engineering team at Santa Clara University was used as reference in the analysis and design of the stabilization system being conducted for this project. However, the main focus of this project is to observe and record data as to how reducing the amount of roll a mid-power rocket experiences affects the flight and performance of the rocket.

In the analysis of this research and design, a Roll Reduction System (R2S) is going to be created to assist a mid-powered rocket during flight. The R2S serves the purpose of reducing the amount of roll a mid-power rocket experiences during flight, while also recording data as to how the rocket is oriented from its designated flight path from launch. A set of four actuated fins located near the mid-point of the rocket are installed for the purpose of being able to reduce the roll the experimental rocket experiences throughout flight. A series of tests and analyses are conducted to determine the success of the R2S relating to the torque that the servo motors are able to produce, the torque needed during flight, the deflection rate of the servos, the theoretical performance of the mid-power rocket, and the response of the system when installed in the electronics bay of the mid-power rocket. By conducting these tests and analyses, conclusions will be able to be made to determine if the system will be successful when flown on a mid-power rocket. If the R2S is able to pass these tests, further tests will be conducted and recorded when the system is flown on a mid-power rocket, such as the orientation of the rocket throughout flight, how well the fin actuators perform when under load, the stability of the rocket throughout flight, and the maximum altitude reached by the rocket when the system is activated.

III. Methodology

A. Computer Aided Design (CAD)

The Roll Reduction System serves as one of the main flight computers during the launch of the mid-power rocket. Due to this, the control system had to fit within the airframe of the rocket. The mid-power rocket that the R2S will fly on has an inside diameter of 2.95 inches, and a length of 42 inches. From these dimensions, the maximum diameter of the electronics bay is 2.95 inches, and it was determined that the length of the electronics bay would be 4.95 inches. In order for the R2S to operate properly, numerous components must be able to fit within the electronics bay. These components include: 4 SG90 Micro Servo Motors, an Arduino Nano, an MPU 6050 gyroscopic sensor, a 9V battery, and a Stratologger CF Altimeter. From knowing the limiting dimensions and which components need to fit inside the electronics bay, the design could be created.

For the design of the electronics bay, it was separated into two components: a bay for securing the servo motors, and a bay for securing all other electrical components. The servo bay was designed to properly secure the four servo motors in place so that they would not shift their position during flight. The other bay would house the Arduino Nano, MPU 6050 sensor, power supply, and Stratologger CF Altimeter. A set of four slider mounts was created to sit within this bay so that each component could be secured and separated from one another. Within each slider is a cutout design that will allow for proper wire connections between the different components. Once assembled, a top cover was created to fully enclose the electronics bay. The finished design of the electronics bay with the electrical components can be viewed in Fig. 1. To determine if the design of the electronics bay would work properly, the different components were created using additive manufacturing techniques for rapid prototyping.

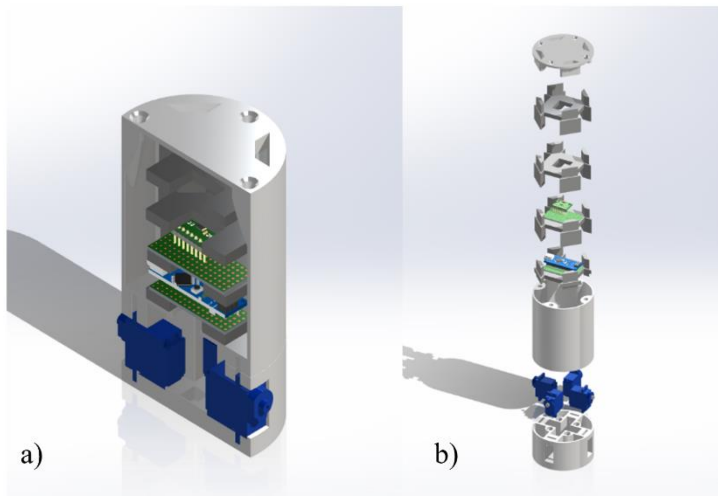

Fig. 1 a) Cross section of fully assembled CAD of the R2S; b) Exploded view of the electronics bay.

The electronics bay was manufactured using the Fused Filament Fabrication manufacturing method. The material chosen for the manufacturing was polylactic acid (PLA). This choice of filament type was due to its relatively high strength, low cost, and not needing any of the special properties provided by other common filament materials, such as acrylonitrile styrene acrylate (ASA), which is able to withstand ultra-violet light and has high heat resistance. To secure the different sections of the electronics bay together, M4 machine screws were utilized. The threads necessary for the use of M4 machine screws for the closure of the printed electronics bay were accomplished with heated metal threaded inserts. It was determined that heated metal inserts would be utilized compared to printing the threads necessary for securing the screws due to the heated inserts being more precise. One other concern for the printed threads was the necessary print layer orientation placing the shear force on the threads in the layer plane of the print, thus making tightening of a screw practically guaranteeing layer adhesion issues. Overall, the electronics bay printing used 254 grams of PLA, costing $4.06 overall and 11.5 hours of print time over the course of 3 days.

B. Programming

The main purpose of the R2S is to control the amount of roll the mid-power rocket experiences during flight, as well as keeping the rocket on a stable flight. In order to achieve this, a set of four actuated fins will be controlled by servo motors, which will receive signals from the MPU 6050 sensor. As the rocket rotates in a clockwise manner, the fins will orient themselves to create a torque that counteracts the clockwise roll. Similarly, if the rocket is rotating in a counterclockwise manner, the fins will orient themselves the opposite direction to reduce the roll of the rocket.

The MPU 6050 sensor is able to detect rotational velocity and inclination along the *x*, *y*, and *z axes* [3]. For the purpose of the R2S, the main data that will be utilized is the rotational velocity of the sensor along the *z-axis*, as the *z-axis* is how the MPU 6050 sensor is oriented within the electronics bay. The MPU 6050 sensor will transmit signals to the Arduino Nano as the rocket rotates during flight, and in return, the four servo motors will receive inputs to adjust the fins in either a positive or negative direction. Due to wanting to reduce major changes during flight, the servos are limited to ± *15°* for the deflection angle, regardless of the roll rate of the rocket. When the rocket is not rotating, the servos and fins will return to their initial orientation of *90°*.

IV. Results

C. OPENROCKET Simulation

To specify the characteristics of the project, OpenRocket, an opensource software used in the amateur high-power rocketry community to design and simulate rockets, was utilized to create an ideally unstable mid-power rocket to be the carrier of the R2S. OpenRocket itself primarily runs on Barrowman’s Equations that aerodynamicists and hobby rocketeers utilize to understand high-power rocket performance [4]. The calculations rooted in OpenRocket are based off a wide variety of aerodynamic principles, but the largest contributing factors to provide the most accurate data are: 6 degree of freedom flight simulation, Runge-Kutta 4 integration method, mass/moment calculations using longitudinal and rotational moment of inertia calculations to determine CG position, and quaternions for 3D rotations and rocket orientation.

General ideas for the R2S rocket design were initially discussed based on previous rocket design knowledge from experiences within WVU’s Experimental Rocketry Team. After discussing a possible rocket design, OpenRocket was used to create the dimensions of the rocket to be specially designed for the R2S. OpenRocket allowed for multiple design iterations of the rocket dubbed *‘Pivotal’* while simultaneously allowing for flight simulation based on different motor configurations. The final design created was made to be intentionally unstable to allow the R2S to better stabilize the rocket through the actuating fins during a mid-power flight on a G75-10 motor. The basic design of the rocket is a 42-inch fiberglass wound rocket with a ogive nosecone, with four fixed fins at the base, four actuated fins located near the electronics bay, and an onboard camera system to review flight footage to support other collected data. Based off of the simulation for *Pivotal*, it is expected to reach an apogee of 504 feet and Mach 0.13. *Pivotal’s* general design and planned simulation are detailed in Fig. 2.

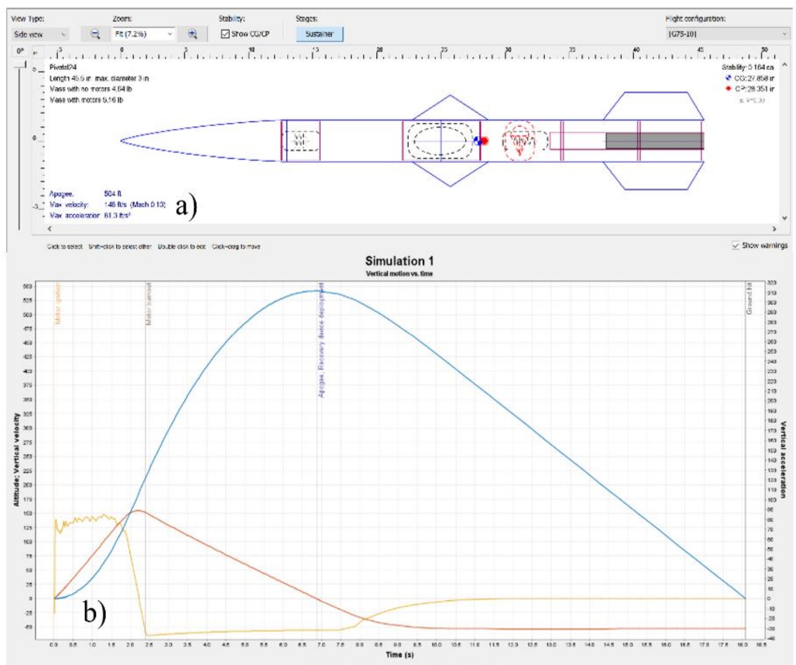

Fig. 2 a) OpenRocket Design for Pivotal rocket; b) Simulated flight for Pivotal on a G75-10 motor.

D. MISSLE DATCOM Analysis

One other analysis conducted was by using an additional piece of software to help simulate the rocket and R2S while in flight. The software that was utilized was Missile DATCOM. This software allowed for the modeling of the rocket and its testing conditions using an ASCII text file with a .dat extension. Data collected from Open Rocket was used to help build the simulation within Missile DATCOM, such as the location of the expected CG and the predicted fight speed envelope. The output files were then used to generate how Missile DATCOM viewed the rocket to verify that all the input parameters were correctly uploaded to the program, as shown in **Error! Reference source not found.**.

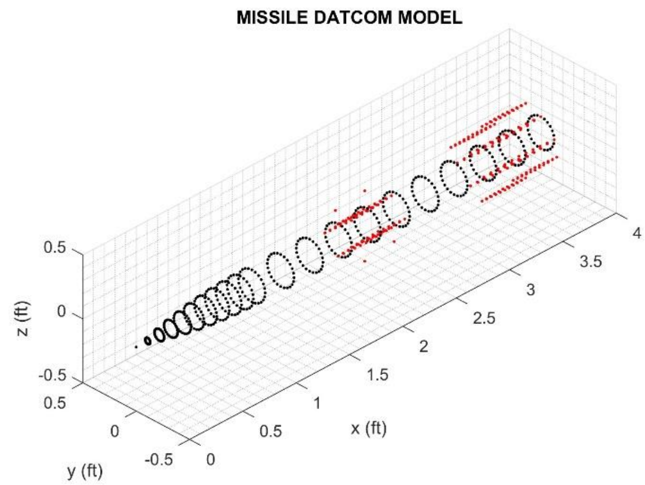

Fig. 3 Simulated rocket model as seen by Missile DATCOM

After the rocket was simulated in Missile DATCOM, information was outputted providing aerodynamic data about various flight conditions. The data that was of main interest was the rolling moment coefficient in the longitudinal axis of the rocket at varying deflection angles, and how the orientation of the rocket would change at different angles of attack. The angle of attack of the rocket is defined as the resultant velocity vector of the air when side winds and rocket. The lift for each fin was calculated by using the rolling moment coefficient given by DATCOM and the equation shown in Eq. 1. The torque generated by each fin onto the servo motor was calculated by multiplying the lift generated by the distance from servo motor's rotational axis, due to the lift acting a quarter of the way through the mean aerodynamic chord (MAC) for a delta fin. The equation that was utilized for the applied torque can be found in Eq. 2. Using these equations, the torque generated by each fin at different angles of attack was plotted and can be seen in Fig. 4. From the analysis and calculations, it is determined that a deflection angle of 10° generates a higher torque than any other deflection angles at low angles of attack. This trend changes once the angle of attack surpasses 3°, in which a deflection angle of 15° generates a greater torque. The maximum torque that is generated on the rocket from the simulation is 0.005903 $lb_f \cdot in$, which occurs when the rocket is at an angle of attack of 6° and the deflection angle of the fins is at 15°.

$$L = \frac{(C_l * q_\infty * S_{Ref} * L_{Ref})}{4 * (\frac{D}{2} + \frac{B}{3})} \tag{1}$$

$$T = L * \frac{MAC}{4} \tag{2}$$

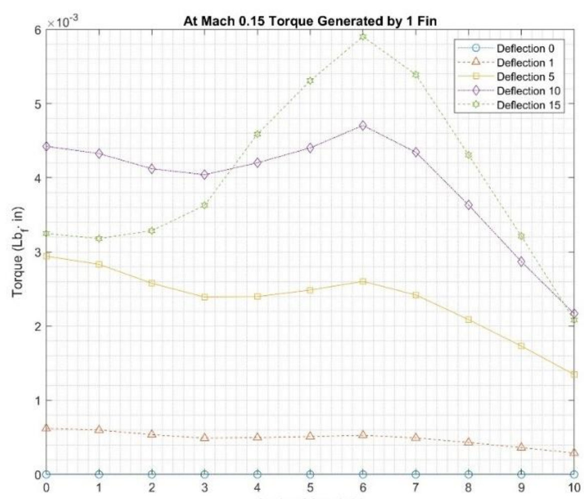

Fig. 4 Torque generated by different canard deflections at different angles of attacks.

E. Torque Test

By knowing how much torque would be generated on each fin during flight, it was crucial to determine how much torque each servo motor could generate. From the Missile DATCOM analysis, when traveling at Mach 0.15 and at the deflection of 15°, there is a maximum torque of 0.005903 $lb_f \cdot in$. Due to the analysis, the servo motors must be able to produce, at a minimum, 0.005903 $lb_f \cdot in$. To test how much torque a servo motor could produce, a wheel with a radius of 2 inches was used in addition with an added mass to determine the torque, Fig. 5. Without additional mass added, the mass holder had a mass of 56 grams. The test was conducted until failure, in which failure is defined as when the servo motor can no longer rotate to a 90° orientation, within ±5°, with the added mass components. The mass component of the torque test would increase in increments of 28 grams until failure. From the torque test, it was determined that the SG90 Micro Servo Motor is able to rotate with a total mass of 152 grams before meeting the failure criteria. Using Eq. 3, from the maximum mass of 152 grams, the SG90 Micro Servo Motor is able to produce a torque of 0.670 $lb_f \cdot in$. An additional test was conducted to determine the maximum mass that the servo motor could withstand before not being able to operate properly. From this test, it was determined that the maximum mass acting on the system was 351 grams, which resulted in the servo motor not being able to rotate. This resulted in a maximum torque of 1.5476 $lb_f \cdot in$. From the manufactures specifications for the SG90 Micro Servo Motor, the maximum torque that the servo motor should be able to produce is 2.17 $lb_f \cdot in$ [5], however that was not the conclusion that was found from the experiment. Though the servo motor was not being tested to ultimate failure, the tests that were conducted were to meet the specific design failure criteria.

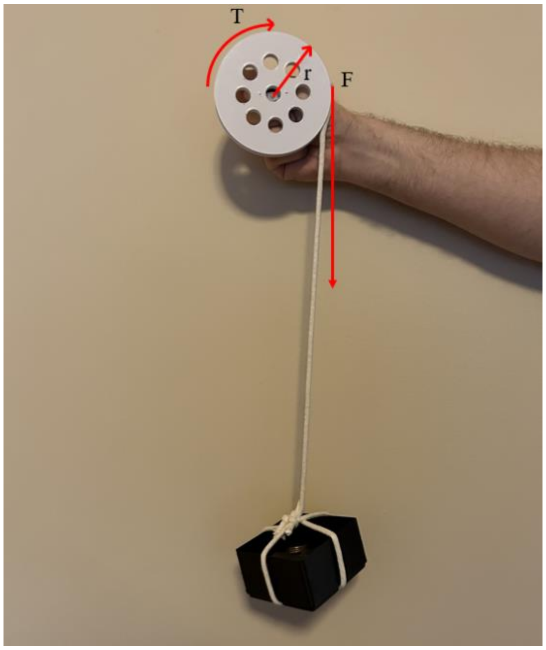

Fig. 5 Set up of how the torque test was conducted for the SG90 Micro Servo Motor.

$$T = r * F \tag{3}$$

F. Deflection Test

A deflection test was also conducted on the servo motors in order to determine the rotation speed of the motor when the fin is not under load. For this test, the servo motor would orient itself from a 0° position to a 90° position, as well as a 180° position to a 90° position to understand the full range of motion. From this test, slow motion video was utilized with the assistance of a timer to determine the deflection rate of the servo motor. After testing both orientations, it was determined that to reach the 90° position from both 0° and 180°, it takes approximately 0.25 seconds to rotate 90°. It can then be determined that the servo motor is able to perform a full rotation every 1 second.

G. Integrated System Test

After performing the various test, one final test was then conducted. The R2S was fully assembled in the 3D printed electronics bay and tested to determine if the four servos rotate ±15° when the electronics bay is rotating, and return to 0° when not rotating. To conduct the test, the electronics bay was held in midair by a string, and allowed to rotate freely, Fig. 6. When the electronics bay was rotated in a clockwise motion, the fins attached to the servo motors were observed to orient themselves 15° in the direction needed to counteract the clockwise motion. As the electronics bay stopped rotating, the fins were observed to return to 0° for a short period of time. The electronics bay then began rotating in a counterclockwise direction, in which it was observed that the fins oriented themselves 15° to counteract the counterclockwise motion. From this final test, it was determined that the R2S is able to operate properly when the electronics bay is rotating.

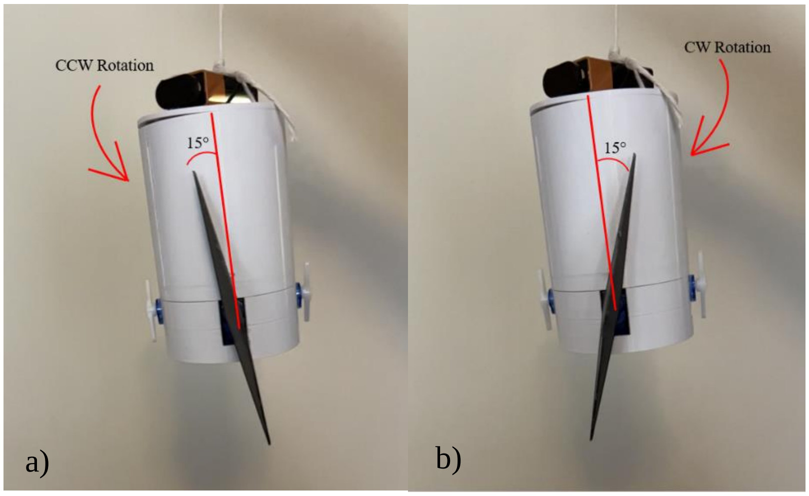

Fig. 6 a) Orientation of fin when system is rotating counterclockwise; b) Orientation of the fin when the system is rotating clockwise.

V. Conclusions

After various tests and simulations were conducted, it was determined that the Roll Reduction System that will fly on *Pivotal* will be a successful system. From the torque tests, the SG90 Micro Servo Motors are able to produce a torque of 0.670 lb_f·in, while from the Missile DATCOM analysis, it is required that the servo motors be able to produce, at a minimum, 0.005903 lb_f·in. Due to being able to complete half a rotation within 0.5 seconds, the servo motors will also be able to provide rapid responses with the change in *Pivotal's* rotation during flight. From the final experiment of testing the system fully assembled in the electronics bay, it was determined that the four servo motors are able to provide correct responses when the system is rotating. By conducting these simulations and comparing data with experimental tests, the Roll Reduction System is able to provide sufficient countermeasures when *Pivotal* is in free flight, and will be able to assist in the stabilization of the flight. In future iterations of the R2S, a new system will be tested where the fins located at the mid-section of the rocket are able to rotate to ±*5*°, ±*10*°, and ±*15*° so that the system can make smaller changes relating to the roll rate of the rocket. A Proportional-Integral-Derivative (PID) System will also be tested on the R2S in future iterations to record data as to how the rocket stabilizes as the rotation is reduced, and to make sure no over-correcting occurs. By using a PID System, further data can be collected an analyzed as to how the R2S is performing during flight.

In future work for this project, additional experiments and tests will be conducted to determine the success of the Roll Reduction System. As *Pivotal* is completed in the upcoming weeks, the R2S will be integrated into the electronics bay and fitted within the rocket for testing. Once assembled and ready for flight, *Pivotal* will be launched and reach an apogee of 504 feet with the assistance of the R2S. Numerous test flights will take place where the R2S is active and inactive to determine how the rocket performs when under the effects of the system. Additionally, test flights will also be conducted where the fins of the R2S are removed completely to determine how *Pivotal* will perform without the mid-section fins attached. If *Pivotal* is able to reach the target altitude while remaining stable during flight and reducing the amount of rotation, then the R2S will be deemed a success. If the R2S on *Pivotal* does not significantly increase the performance of the rocket, but the rocket is still able to remain stable during flight, and reach the target altitude compared to when the R2S was inactive, then the system will be deemed marginally successful. If the R2S on *Pivotal* has a negative impact on the flight, such as causing the rocket to rotate in an uncontrolled manner, then the system will be deemed a failure. As future tests are conducted, a greater understanding of how the system performs can be concluded, and adjustments can be made as necessary.

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