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Design and Development of a Model Rocket with Active Stabilization

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ABSTRACT

This work is to present the design and development of a model rocket equipped with active stabilization, aiming to improve flight stability, trajectory accuracy, and overall safety. The traditional model rocketry community has long relied on passive stabilization methods, such as fins, to ensure stability during flight. However, as model rockets become increasingly sophisticated and ambitious in their design and performance goals, the need for more advanced stabilization systems has emerged. The study begins with a review of existing passive and active stabilization techniques, including their advantages and limitations. It then focuses on the development and integration of an active stabilization system utilizing modern sensor technology, actuators, and an on-board microcontroller. This active stabilization system actively adjusts the rocket's orientation during flight, counteracting disturbances and enhancing stability. In addition to evaluating performance, the safety aspect is meticulously examined. The paper discusses the potential risks associated with active stabilization systems and outlines safety protocols adopted during the research and development process. The findings from this research provide valuable insights for the model rocketry community and inspire further investigations into advanced stabilization techniques for model rockets. This work contributes to the advancement of model rocketry technology, fostering safer and more efficient designs for future high-performance model rockets and possibly extending the knowledge to larger-scale rockets and space vehicles.

Keywords: Model Rocketry, Solid rocket motor, Avionics, Gimbal.

1. INTRODUCTION

In recent years, the field of model rocketry has experienced a remarkable evolution, driven by advancements in materials, electronics, and propulsion systems [1]. As enthusiasts push the boundaries of what is achievable in this hobby, the need for improved stability and control during flight has become increasingly apparent. Traditionally, model rockets have relied on passive stabilization methods, such as fins and stable airframe design, to maintain their orientation and ensure a safe trajectory. However, as rocket designs become more complex and ambitious, these conventional methods have shown limitations in providing the level of stability required for optimal performance and safety.

This research paper delves into the design and development of a model rocket equipped with an active stabilization system. The active stabilization system represents a paradigm shift in model rocketry, where modern sensor technology, actuators, and microcontrollers work in synergy to actively adjust the rocket's orientation during flight [9]. By continuously counteracting external disturbances, the active stabilization system aims to enhance the rocket's stability, improve trajectory accuracy, and increase overall flight safety.

Model Rockets are a class of small rockets designed to be of low weight (1500 grams maximum) and can reach altitudes of 200 to 2,000 feet. Model Rocketry is done for the purpose of research and experimentation, and majorly enjoyed as a hobby. Most of the small model rocket motors are single use engines, with lightweight molded clay nozzles and cardboard bodies, ranging in impulse class from A to G. Model rockets generally use commercially manufactured black-powder motors [3]. A model motor's class is determined by its impulse. Motors are divided into classes from A to G. Black powder rocket motors are only commonly produced up to Class F. Each class's upper limit is double the upper limit of the previous class

There are two types of static stability, longitudinal stability and directional stability. Longitudinal stability is the stability of rocket in the pitching plane []. Rockets or indeed any structure travelling in free fall are inherently unstable in flight, in that any external disturbance or internal misalignment of the thrust vector with the center of mass will cause the vehicle to deviate from its intended path, and a restoring force must be provided by the vehicle itself. To overcome this problem, conventional rockets and missiles have used active stabilization, where electromechanical control systems to detect such deviations from the predetermined path and correct for them. A wide range of these systems has been developed. One such method is the gimbaled thrust system [2]. In a gimbaled thrust system, the nozzle of the rocket can be swivel from side to side. As the nozzle is moved, the direction of the thrust is changed relative to the center of gravity of the rocket. Using this method, the stability condition is achieved. The center of gravity (Cg) is ahead of the center of pressure (Cp). Rocket will be more stable if the distance between Cg and Cp is larger.

Further MATLAB® Simulink was used to simulate Thrust Vector Control (TVC) mechanism and to obtain Proportional Integral Derivative (PID) gains for the flight computer code for the actual launch. The control algorithm for the actuators is based out of PID. The pitch and yaw data from one of the sensors of the flight computer was used to control TVC mechanism. The mechanism consists of a gimbal, which was 3D printed using Polylactic Acid (PLA) and two actuators or servos. The TVC mechanism is discussed in detail in Section 3.

In order to recover the rocket after the launch piston base parachute deployment mechanism has been adapted. A ground test of parachute deployment was done in the process. The deployment mechanism is discussed in Section3. Using Autodesk® Fusion 360 CAD models were created. For the flight computer Autodesk® Eagle was used to create a 2-layer PCB. In Section 3, the experimental setup and methodology used to evaluate the model rocket's performance are explained. This section also discusses the safety protocols adopted to mitigate potential risks associated with active stabilization. The results and analysis of the conducted tests are presented in Section 6, comparing the performance of the active stabilization system against traditional passive stabilization methods.

The research concludes with a discussion of the implications of the findings, the limitations of the study, and future directions for further research and development in the field of model rocketry with active stabilization. Ultimately, this research aims to contribute valuable insights into the application of advanced stabilization techniques, driving the hobby of model rocketry towards safer, more reliable, and high-performance rockets.

2. LITERATURE REVIEW AND OBJECTIVE

A crucial component of rocket design and operation is rocket's stability. It speaks to a rocket's capacity to keep the appropriate orientation and trajectory while in flight. Without adequate stability, a rocket may move unevenly or even swerve off track, which might endanger the safety of the crew or cause mission failure. Rocket stability is governed by a number of principles. Such as, Center of Gravity, Center of Pressure, Static Margin and Thrust Vectoring.

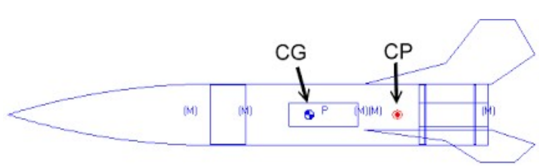

Figure 1: Placement of Centre of Pressure (Cp) and Centre of Gravity (Cg).

The conditions for a stable rocket are that the center of pressure must be located below the center of gravity. There is a simple test that can be done on a model rocket to determine the stability. Tie a string around the body tube at the location of the center of gravity. The Cg and Cp for a rocket is illustrated in Figure 1.

2.1 Passive Stabilization Methods

The simplest of all passive controls is a stick. Fire arrows were simple rockets mounted on the ends of sticks that kept the center of pressure behind the center of mass. Fire arrows were inaccurate in spite of this. Air had to be flowing past the rocket before the center of pressure could take effect. While still on the ground and immobile, the arrow might lurch and fire the wrong way. The accuracy of fire arrows was improved considerably years later by mounting them in a trough aimed in the proper direction. The trough guided the arrow until it was moving fast enough to become stable on its own.

2.2 Active Stabilization Methods

Canards and tilting fins seem very similar to one another; the only major distinction is where they are located on the rocket. At the front are canards, while at the back are tilting fins. The fins and canards tilt like rudders while in flight to deflect airflow and steer the rocket in a different direction. Unintentional directional changes are detected by motion sensors on the rocket, and they can be corrected by slightly tilting the fins and canards. These two gadgets have an advantage due to their size and weight. Compared to big fins, they are lighter and smaller and create less drag.

Fins and canards can be completely eliminated by other active control techniques. By adjusting the angle at which the exhaust gas leaves the rocket engine, course corrections can be done while the rocket is in flight. Exhaust direction can be changed using a variety of methods. Vanes are tiny fin-like components installed inside the rocket engine's exhaust. The exhaust is deflected by tilting the vanes, and the rocket responds by pointing the other way as a result of action-reaction.

Gimbaling the nozzle is a further technique for altering the direction of the exhaust. An exhaust gas-passing nozzle that can wobble is known as a gimbaled nozzle. The rocket adjusts by altering course in response to tilting the engine nozzle in the right direction. The thrust vectoring mechanism is shown in Figure 2.

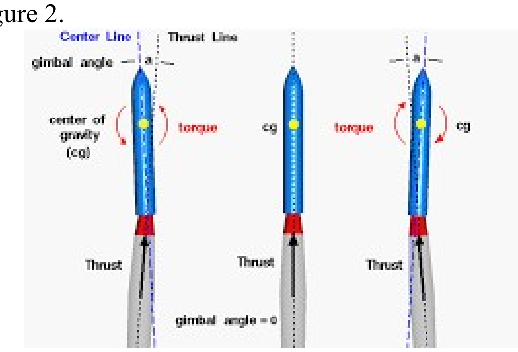

Figure 2: Thrust Vectoring

3. MATERIALS AND METHODS

The knowledge gained from the literature review to custom design and manufacture the rocket airframe (body) and the parachute recovery system. The rocket body was designed in such a way that the mounting of the flight computer and also the gimbal system are easily accommodated inside of the rocket.

3.1 Rocket Motor

For a rocket weighing 1.28 kg and having a defined apogee at 200 ft, an F type solid rocket motor was required. Since commercial-off-the-shelf F type solid rocket motors are not available in India and are significantly expensive to ship, a homemade motor was the only option. The fuel that we chose was a sugar-based rocket propellant. Model rocket propellants include sugar-based propellants, also known as rocket candy. Its main fuel is sugar, and its main oxidizer is low energy nitrate. In some circumstances, the fuel, the oxidizer, and the additives could be the propellant's constituents. Using sugar as fuel in a rocket propellant is considered as an excellent active component; however, it is limited with its inconsistent characteristics between batches of propellant due to its persistent caramelization and excessively high-pressure index. In our case, the fuel formulation was 35% sugar and 65% potassium nitrate (KNO_3), with no added additives/catalysts. This mixture is popularly known as KNSU. This formulation was chosen for its optimum propellant performance. The rocket motor is shown in the Figure 3.

Figure 3: KNSU rocket motor.

3.2 Airframe

The airframe of the rocket is made out of cardboard. Because it is lightweight and simple to deal with, cardboard was an appropriate option. The avionics bay and recovery bay were separated from the rest of the airframe based on calculation. Each segment has a different function and stores various components, but when joined together by a coupler tube (also made of cardboard), they form the entire airframe. The model rocket has a base airframe that houses the motor and the avionics and an upper airframe that contains the nose cone and recovery mechanism.

The Recovery Bay is 0.3m in length, the Avionics & Propulsion Bay is 0.5 m long, and both have an outer diameter and thickness of 78 mm and 3 mm respectively. The coupler tube has the same thickness and has an outside diameter of 75 mm. In order to balance the needs of attaining flight to the specified height and providing the room needed within the rocket for the other subsystems, i.e., the motor and electronics bay, a diameter size of 75 mm was found to be adequate. The lower airframe may accommodate a larger motor tube with a 75 mm diameter, boosting GodSpeed's to maximum altitude. The CAD model of the rocket was created using Autodesk® Fusion 360 and is shown in the Figure 4.

Figure 4: CAD model of GodSpeed rocket.

Figure 5: CAD model of GodSpeed rocket.

3.3 Recovery System

The recovery system of a model rocket is an essential component that ensures a safe descent and landing after the rocket's flight. It is designed to slow down the rocket's descent and minimize the impact forces upon landing. The recovery system's design considers the rocket's weight, size, and desired descent rate. The size and type of parachute is chosen to provide a controlled descent that avoids excessive drifting or high-speed descents. Proper stability during descent is crucial to ensure the recovery system functions effectively, avoiding tumbling or instability. The type of recovery device used in our rocket was an ejection charge. An ejection charge is a small pyrotechnic device that produces gas or smoke when ignited. It is typically placed inside the rocket's body and is activated by an electronic or mechanical timer. The ejection charge creates pressure that deploys the recovery system, pushing it out of the rocket's body. We used an electric match containing red phosphorous for the purpose. The recovery system is shown in the Figure 6.

Figure 6: Parachute Ejection System.

3.4 Gimbal Mechanism

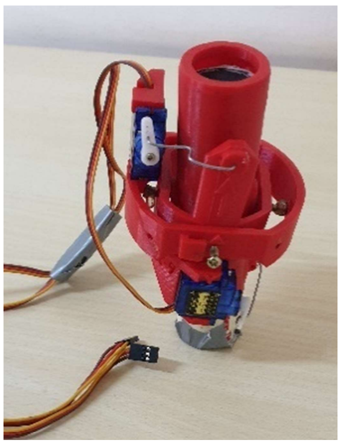

Figure 7: Thrust Vectoring gimbal.

The gimbal mechanism shown in the Figure 7 aides the rocket to stabilize along X and Y-axis, which represents pitch and yaw axis of a rocket, respectively. 3D printing technology helped to develop light weight mechanism. The gimbal is driven by 2 SG90 servos, which can control each axis individually. The mechanism can move ±15 degree in X and Y-axis. The inner part of the gimbal will hold the solid rocket motor.

3.5 Flight Computer Algorithm

The control algorithm involves various stages such as:

1. Launch Detection: The flight computer will detect the launch by looking at the acceleration data in Y-axis. If Acceleration along Z-axis > 2 the flight computer will turn on the data logging and stabilization system.
2. Apogee Detection: The flight computer will look at the barometric sensor and finds the altitude. If the current altitude keeps on decreasing flight computer will deploy parachutes from the recovery bay.
3. Launch abort: Launch abort is a sequence where the flight computer will detect the change in angle from the sensors right after the launch. If change in angle is greater than 45deg, flight computer will deploy the parachutes and aborts the launch.
4. Motor Burn Out: Motor burn out is the sequence where the flight computer will detect the acceleration in Z-axis. If acceleration is less than 0. The GSFTI will turn off the servos or stability controller.

The flowchart for the algorithm is shown in the Figure 8.

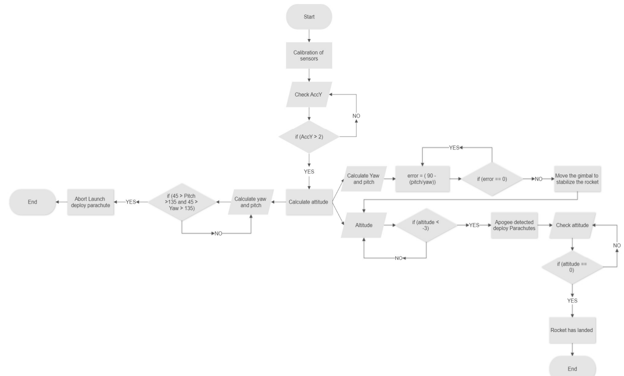

Figure 8: Flowchart for flight computer algorithm.

3.6 Avionics

The Avionics system of the rocket will control its position and record all the data from onboard sensors to SD card. Arduino Nano is used as a processor in GodSpeed Telecommunication Interpreter (GSFTI) flight computer. GSFTI uses a MPU6050 an inertial measurement unit (IMU) sensor for position control and BMP-180 a barometric pressure sensor for altitude, pressure and temperature data. The IMU is 3-axis accelerometer and 3-axis gyroscope. The pitch and yaw data from the sensor is then used to control the position of the rocket. PCB design for the flight computer was done using Autodesk® Eagle. The Flight computer houses couple of power Mosfet outputs for igniting electric matches for deploying parachute and also uses a Light Emitting Diode (LED) and a buzzer to know the state of the rocket. GSFTI can be powered by 12V battery. GSFTI is shown in the Figure 9.

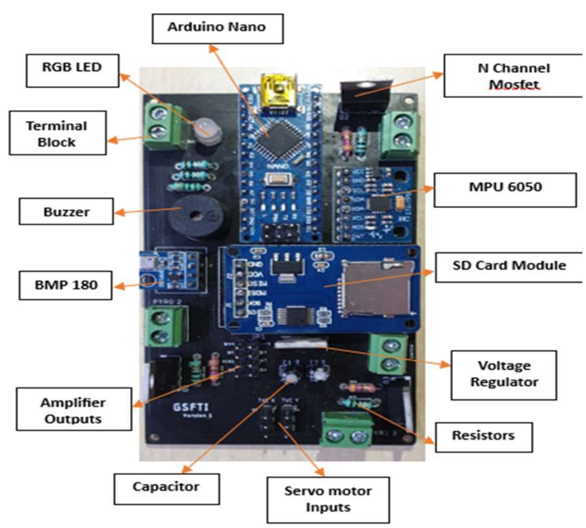

Figure 9: Avionics- GodSpeed Flight Telecommunication Interpreter.

3.7 Control System Design

Matlab Simulink was used to the design the control model to obtain flight trajectories and to tune the PID values. The Simulink model is shown below. 3DOF block is used, which uses thrust data from the plot and returns orientation or position of the rocket. The control system uses PID controller to stabilize the rocket. The PID values are tuned for the given rocket mass and are shown in the Table 1, Moment of Inertia (MOI), Moment Arm and thrust curve of the motor. Mass moment of inertia can be calculated using equation 1. Simulink inputs are shown in the Table 1. Pre Flight tuning of the rocket was done to obtain the PID values from the Simulink model Figure 10. The Figure 11 represents the experiment carried out to get the cycle time (C_t). The C_t is value is obtained by swivel rocket around its Cg and recording the time of peak to peak. The PID values obtained from Simulink are used in control algorithm of flight computer, which will rotate the servos without any overshoot.

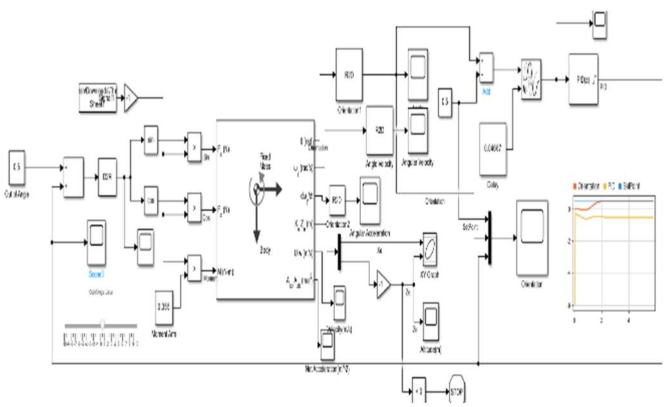

Figure 10: Simulink model for TVC simulation.

Figure 11: Pre-flight Rocket Tuning.

$$mMOI = \frac{(M \times g \times Ct^2 \times COM^2)}{(4 \times \pi^2 \times RL)} \quad 1$$

Table 1: Simulink Inputs

Parameter	Value
Mass of the Rocket (kg) - M	1.235 kg
Cycle time - (C_t)	1.4 s
Cg (center of gravity)	45.5 cm
Length from Cg to rope - COM	35.5 cm
Length of rope from table to Vehicle (m)- RL	63 cm
Mass Moment of Inertia - mMOI	0.12032 kg-m^2

Table 2: PID gains for control algorithm

PID gains	Values
Proportional (P)	0.65
Integral (I)	0.7
Derivative (D)	0.2

4. RESULTS AND DISCUSSION

The GodSpeed total weight was 1.235 kg. The Figure 13 shows Blow-Up view of GodSpeed which shows all the systems. It has two sections Recovery-bay which holds recovery part of the rocket and Avionics-bay which carried rockets flight. Figure 12 represents steady state time response. The Blue line represents change in angle and orange line shows time taken by the rocket to reach that angle.

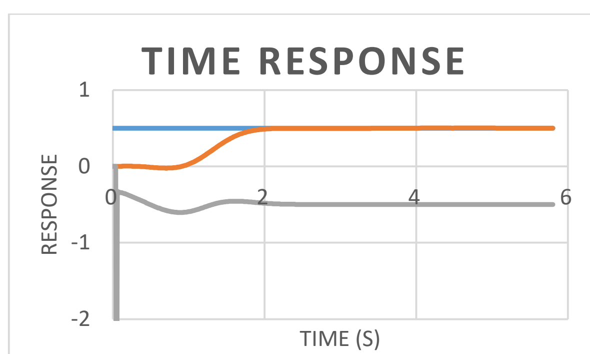

Figure 12: Steady state time response for actuators.

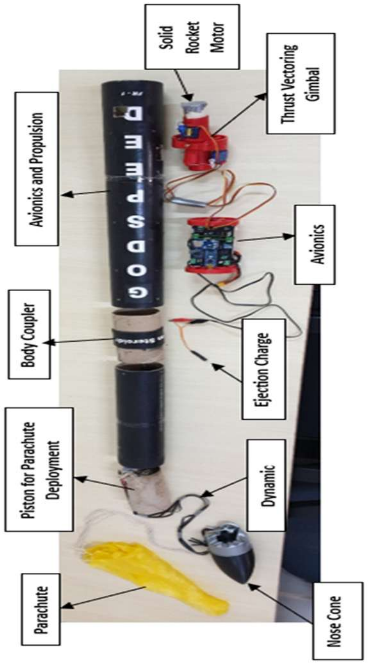

Figure 13: Blow-up view of GodSpeed rocket.

Figure 14: GodSpeed Launch.

5. CONCLUSIONS

The project aimed to improve the stability and control of the model rocket during flight, ultimately enhancing its performance and safety. The gimbal system offers a practical and efficient solution to the inherent instability of rockets, providing a stable and controlled flight experience. Throughout the project, extensive research was conducted on the design and development of model rocketry, stability principles, and active stabilization methods. The team paid close attention to detail, ensuring proper alignment, balance, and secure attachment of the components to guarantee optimal performance and safety. Various tests were performed, measuring the rocket motor's static thrust production, the unfurling of the parachute recovery system, among other tests. The data collected during these tests provided valuable insights into the performance of the rocket and the gimbal system and allowed for iterative improvements and adjustments. We also acquired hands-on experience in fabrication, testing, and project management, honing our technical and collaborative skills. In conclusion, the project has successfully achieved its objectives of creating a model rocket system that incorporates an active stabilization mechanism using a gimbal system. In conclusion, the project has successfully achieved its objectives of creating a model rocket system that incorporates an active stabilization mechanism using a gimbal system. We are grateful for the opportunity to have worked on this project and we are excited to see what the future holds.

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NOMENCLATURE

Cp	Centre of Pressure	--
Cg	Centre of Mass	--
DOF	Degrees of Freedom	--
GSFTI	GodSpeed Flight Telecommunication Interpreter	--
mMOI	Mass Moment of Inertia	kg-m^2

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