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Design of 2-DOF Thrust Vector Control System for Rockets and Missiles

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Abstract: This paper outlines the development and implementation of a Thrust Vector Control (TVC) system specifically designed for solid propellant rocket engines, aiming to enhance the portability of hybrid and liquid propellant rocket systems. The proposed system ensures trajectory stability and rapid response to flight emergencies by effectively counteracting external perturbations such as wind. Key components include gyroscopic (GYRO) sensors, a high-performance microcontroller, and servo motors, collectively referred to as thrust vectoring components, which dynamically adjust thrust direction opposite to the rocket's trajectory to maintain stability. Drawing from an extensive literature review of existing TVC system designs, with a focus on thrust characteristics and engine combustion timing, the design integrates geometric properties, kinematics, forces, energy requirements, safety, cost, and control methods, aligning with both mechanical and avionic design principles. The anticipated outcome is an advancement in rocket propulsion technology, characterized by improved angular speed control, trajectory linearity, and rapid response capabilities.

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1. Introduction

Thrust Vector Control (TVC), also known as thrust vectoring, is a pivotal technology used in vehicles such as rockets and airplanes to modify the direction of exhaust thrust. This technology enables precise control over vehicle orientation and maneuverability. Unlike conventional guidance systems that rely on fins, TVC provides a viable alternative, particularly in environments without atmospheric conditions, where fins lose their effectiveness. By adjusting the direction of the rocket's exhaust plume, TVC dynamically alters engine thrust, influencing the vehicle's trajectory and attitude. This paper provides an overview of the principles and applications of TVC technology, highlighting its significance in enhancing vehicle maneuverability beyond the constraints of traditional guidance mechanisms. A major challenge for academic institutions and organizations worldwide involved in small satellite development has been securing a launch. Only a limited number of nanosatellites launches (formally defined as 1 to 10 kg) have taken place, with even fewer at the picosatellite (0.1 to 1 kg) or femtosatellite (<100 g) scales. The lack of dedicated launch vehicles and high costs impose significant limitations on these launches. Additionally, integration and regulatory challenges mean that launching small satellites as secondary payloads often requires substantial lead time between hardware completion and actual flight. Developing a dedicated launch vehicle specifically designed for nanosatellites would enhance launch responsiveness and facilitate the deployment of numerous small payloads [1].

Integrating gyroscope technology has the potential to revolutionize rocket propulsion systems through the development of a gyroscope sensor-enabled thrust vector control (TVC) system. The proposed TVC system aims to enhance rocket mobility and stability during flight by leveraging gyroscope sensors, renowned for their accuracy in monitoring angular velocity. This innovative approach addresses the limitations of conventional TVC systems, which often rely on complex or less precise orientation control methods. Gyroscope sensors enable precise, real-time thrust direction adjustments, improving trajectory accuracy and response to external factors such as wind disturbances. This project aspires to advance propulsion technology and pave the way for more reliable and efficient space exploration missions.

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2. Literature Review

This study explores the design of two separate controllers for attitude control in a spinning rocket equipped with thrust vectoring capabilities. The first controller employs a single-input/single-output (SISO) architecture and does not account for gyroscopic coupling between control channels. In contrast, the second controller utilizes a multi-input/multi-output (MIMO) architecture specifically designed to address the effects of gyroscopic coupling. A comparative analysis is conducted to evaluate the effectiveness of these two approaches at varying roll rates. The controllers are assessed based on their susceptibility to coupling-induced inaccuracies and their ability to track step commands. Both controllers are developed using a linear-quadratic regulator (LQR) synthesis methodology, inspired by the MIMO characteristics of the second controller. Performance evaluations incorporate time response and singular value analyses to assess controller efficiency **[2]**.

The initial development of an inexpensive thrust vector control (TVC) system that can be adapted for small launch vehicles capable of carrying nanosatellite-class payloads to the lower atmosphere is presented in this study. A closed-loop control system is being flight-tested on a small prototype liquid-propelled rocket as part of a series of demonstrations. All components of a guidance, navigation, and control (GNC) system are integrated, along with telemetry. The inertial measurement unit (IMU) consists of a GPS sensor, accelerometers, and rate gyros. The main engine is gimballed to control pitch and yaw. This study evaluates the system's stability and its ability to execute commands effectively **[1]**.

Rapid advancements in Model Predictive Control (MPC) algorithms and techniques, combined with the increasing computational capabilities of embedded platforms, enable real-time optimization for fast mechanical systems. This study presents the implementation of an optimized GNC system for controlling the movement of a small-scale, electrically thrust-vectored rocket prototype. The purpose of this prototype is to provide a low-cost platform for testing GNC algorithms for automated sounding rocket landings. Using the PolyMPC library, guidance and trajectory tracking are addressed in real time on embedded hardware as continuous-time optimal control problems. An Extended Kalman Filter (EKF) is employed to estimate actuator offsets and external disturbances **[3]**.

The challenge of thrust vector control (TVC) during orbit insertion when launching multiple satellites with a single vehicle is also examined. This includes the issue of aligning the thrust vector of a two-axis gimballed thruster (GT) with the center of mass of the upper stage and the commanded direction, which can introduce velocity errors and disturbance torques. To address this, a system is proposed that combines separate attitude control for the upper stage with gimbal rotation for the GT. The goal is to align the thrust vector with the command direction through coordinated behavior of the upper platform and gimbal rotation. Numerical simulations demonstrate the effectiveness of the proposed method **[4]**.

3. TVC Model

The limited availability of information and the potential hazards associated with operating such flying vehicles have constrained scholarly research in this field. To advance research and explore various thrust vector control (TVC) technologies, we developed a small-scale prototype as an experimental platform for TVC algorithm deployment and in-flight validation. Our vehicle is designed for ease of construction and modification at a relatively low cost, utilizing readily available components and affordable materials. Unlike conventional test vehicles that rely on mechanical TVC for propulsion, our prototype employs an electric-powered microcontroller and gyroscope as the source of thrust. This significantly reduces the cost and logistical challenges associated with rocket engine operations while maintaining a high degree of similarity to actual rocket dynamics.

The proposed design optimizes thrust vector control by integrating advanced technologies, such as a gyroscope sensor and an Arduino microcontroller. This integration minimizes reliance on traditional feedback mechanisms while enabling the development of sophisticated control systems capable of responding quickly and accurately to changes in spacecraft attitude and trajectory. Effective handling behavior is particularly critical in aerospace applications, as it enhances maneuverability and overall flight performance.

A key feature of this design is the gimbal mechanism, which serves as the primary component for unrestricted flight control in response to spacecraft attitude variations. The gimbal mechanism is optimized for movement along both the longitudinal (x) and vertical (y) axes, allowing for wider deflection angles. These adjustments in thrust vectoring are essential for maintaining spacecraft orientation and trajectory precision.

Unlike traditional methods that utilize external vanes or additional nozzles for thrust deflection, this system integrates the TVC mechanism directly within the engine assembly, creating a simple yet effective thrust vectoring solution. At the core of the TVC system is the gimbal ring—a specialized component featuring concentric rings that facilitate multi-axis rotation. This system consists of three concentric rings: the innermost ring is directly attached to the engine, while the outermost ring is securely fixed to the spacecraft chassis, providing two degrees of freedom for precise thrust direction control.

Additionally, the incorporation of advanced sensors, such as gyroscopes and Arduino-based microcontrollers, enhances system responsiveness and accuracy by continuously monitoring spacecraft behavior. This real-time data processing capability enables rapid adjustments in thrust magnitude and direction, thereby improving spacecraft performance and ensuring stability during various mission phases.

The extensive integration of advanced technologies, coupled with a sophisticated gimbal-based TVC system, presents a promising advancement in aerospace engineering. By achieving highly efficient and precise thrust vector control at an advanced scale, this system has the potential to revolutionize spacecraft maneuverability, expand operational capabilities, and pave the way for new advancements in space exploration and satellite applications.

4. Mechanism

The gimbal system is a highly specialized joint optimized for the specific purpose at hand. Due to its unique geometry design and integration with the engine, custom joints were required. The design process was guided by several key criteria:

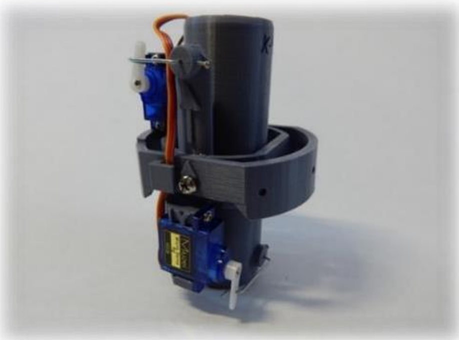

Figure-1 Mechanism

Key Design Considerations for the Thrust Vector Control (TVC) System

- **Minimum Weight:** The primary design goal was to minimize weight to reduce unnecessary loading on the spacecraft. Maintaining a low mass-to-thrust ratio is crucial for optimizing fuel efficiency and overall performance.
- **Simplicity:** The design prioritizes simplicity to facilitate easy assembly, maintenance, and operation. A straightforward structure minimizes failure points, thereby increasing reliability and reducing the risk of malfunctions.
- **Material Strength:** Given the high pressures exerted by the engine, the selected materials must possess high strength and durability to withstand these forces without excessive wear or structural failure. Ensuring the integrity of the gimbal system is critical for long-term operational reliability.
- **Suitability for 3D Printing:** To expedite prototyping and testing, materials compatible with 3D printing were preferred. However, materials like PLA (Polylactic Acid) were avoided for actual testing, as they cannot endure the extreme temperatures and pressures experienced during engine operation.

Material Selection and Structural Design

The chosen design employs different materials for various components of the gimbal system:

- **Engine Thrust and Load-Bearing Pins:** These components are constructed from stainless steel, featuring a threaded shaft with strategically mounted bars along the length of the shaft. This arrangement facilitates smooth rotation and effective distribution of load.

- **Spacer Elements:** Used to maintain proper separation between the concentric rings, these spacers ensure precise alignment while preventing unwanted contact or mechanical interference.
- **Component Integration:** The final design incorporates features that enhance compatibility between structural elements. Specifically, the geometry of the spacecraft's lower chassis influences the joint design, enabling both flexibility and precision in the assembly process.
- **Actuator Anchoring:** The inner ring of the gimbal system includes two vertical plates extending along the engine's length. These plates serve as anchor points for the actuators, which play a crucial role in adjusting the gimbal mechanism to control the spacecraft's trajectory with high accuracy.

By integrating these considerations, the design ensures a lightweight, robust, and easily manufacturable thrust vector control system, enhancing the spacecraft's maneuverability and reliability in various mission scenarios.

A) CAD Design

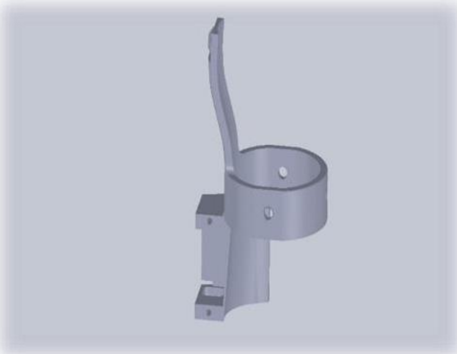

Figure-2 Inner Gimbal

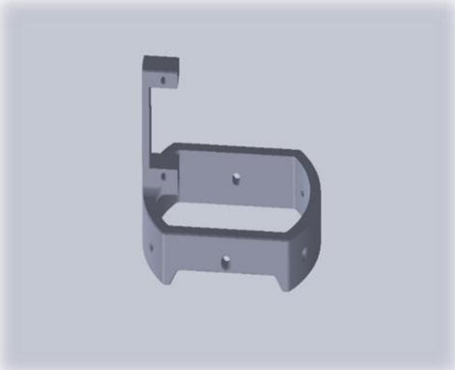

Figure-3 Outer Gimbal

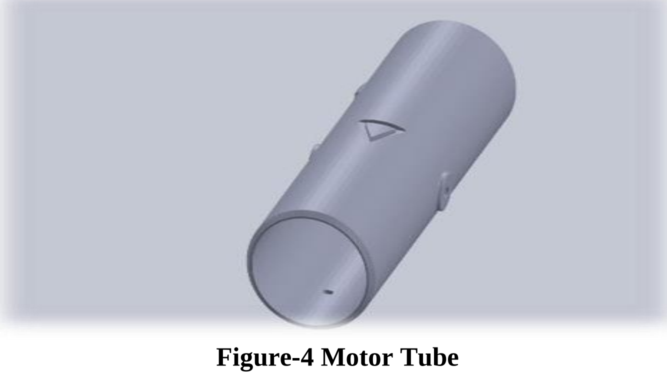

Figure-4 Motor Tube

5. Sensor and Programming

A) Microcontroller

A microcontroller, like an Arduino, is a highly integrated circuit consisting of a processor core, memory, and programmable input/output peripherals. Its purpose is to perform specific tasks in electronic systems, ranging from simple applications to complex industrial processes. Microcontrollers are typically programmed in high-level languages such as C or C++, using integrated development environments (IDEs) and software tools provided by microcontroller manufacturers. Once programmed, the microcontrollers execute embedded software designed for specific tasks. Known for its open-source nature and user-friendly interface, Arduino has become a key tool in the field of electronics prototyping. Its IDE simplifies the programming process and delivers code to the Arduino board, facilitating rapid development. This seamless integration empowers users to improve productivity, speed up iteration, and conduct efficient testing.

Figure-5 Arduino Microcontroller

The advantages of the Arduino platform, combined with gyroscopic sensors, present compelling opportunities in aerospace engineering, especially in thrust vector control. Thrust vector control allows dynamic directional adjustments to guide spacecraft. Researchers are harnessing Arduino's power to develop sophisticated control algorithms designed for spaceflight requirements. Gyroscopes detect changes in orientation, allowing the system to dynamically adjust thrust vectoring devices. This combination of Arduino and gyroscopic sensors holds great promise for improving spacecraft maneuverability, stability, and efficiency in space exploration. By using innovative technological solutions, researchers can optimize spacecraft systems to enhance spacecraft operations.

B) MPU6050

The MPU6050 is a versatile sensor module that is widely used in electronics due to its high accuracy and range of measurement speeds. It combines a three-dimensional accelerometer and gyroscope, providing readings along the X, Y, and Z axes for both sensors. The accelerometer measurement is in gravity (g), while the gyroscope reading is in degrees per second (dps). In addition, it has a temperature sensor that provides a temperature reading in degrees Celsius. Communication with microcontrollers is facilitated by standard protocols such as Inter-Integrated Circuit (I2C) or Serial Peripheral Interface (SPI), making it compatible with Arduino and other platforms. The compact size and low power consumption of the MPU6050 make it suitable for a variety of applications requiring motion detection and tracking. Its integration into a robot allows for accurate movement detection, aiding in tasks such as balance control and navigation. Drones benefit from the accurate measurement of direction and heading, enabling them to fly safely even in challenging conditions.

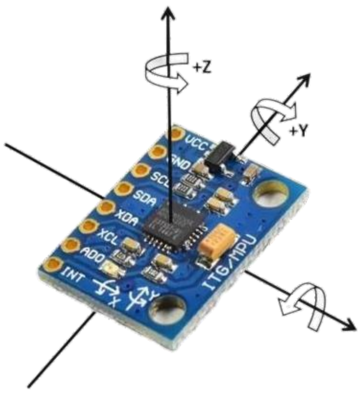

Figure-6 MPU6050

Known for its accuracy in motion and precise measurement, the MPU6050 also plays an important role in Thrust Vector Control (TVC) applications. TVC involves dynamically changing the direction of travel to control a spacecraft or vehicle. The MPU6050's integrated accelerometer and gyroscope data enable engineers to accurately monitor the spacecraft's trajectory and forward speed, which is critical for implementing sophisticated control algorithms.

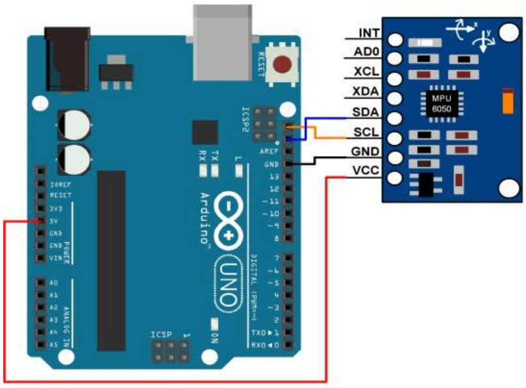

Figure-7 Arduino with MPU6050

Overall, the role of the MPU6050 in TVC applications highlights its versatility and significance in aerospace engineering. By harnessing its motion, orientation, and precise sensing capabilities, engineers can enhance the maneuverability and controllability of spacecraft, advancing the frontiers of space exploration.

C) Coding

The Arduino IDE (Integrated Development Environment) is a software tool used for writing, compiling, and uploading code to the Arduino microcontroller board. It provides a user-friendly interface that simplifies the process, making it accessible to both beginners and experts. The IDE supports several C and C++ programming languages, along with a rich set of libraries. The customization rule designed for our system uses the MPU6050 sensor and servo motor control to enable direction changes. When sensor gyroscope data is combined with servo motor manipulation, the algorithm maps gyroscope values to servo positions, thereby adjusting the mechanism’s orientation to achieve the desired thrust direction. This integration allows our system to dynamically adjust spacecraft behavior, providing more accurate and precise thrust vector control.

6. Conclusion

In conclusion, the advent of propulsion systems incorporating gyro-enabled thrust-vector control (TVC) has greatly advanced rocket technology. While traditional propulsion systems have formed the backbone of rocket propulsion, gyro-powered TVC represents a paradigm shift, impacting various fields including space exploration, tourism, and security management. The proposed model not only offers valuable insight into the complexity of gyro-powered TVC devices but also serves as a foundation for future innovations in the aerospace industry. This technology holds the potential to revolutionize space vehicle design and operation by providing precise control over thrust. It promises enhanced safety measures, improved productivity, and more reliable space missions. Moreover, gyro-powered TVCs pave the way for continuous improvements in aerospace technology, driven by ongoing research and development efforts. As scientists and engineers work to optimize and refine these systems, the potential for innovation in space becomes increasingly apparent. From opening new possibilities for space exploration to strengthening defense capabilities and advancing commercial aviation, gyro-powered TVCs are poised to drive significant growth in various sectors. Ultimately, gyro-powered TVCs are a testament to human ingenuity and innovation, offering a glimpse into the future of navigation systems. With continued research and development, these technologies have the potential to propel the space industry to unprecedented success, ushering in a new era of exploration, safety, and efficiency in space and beyond.

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8. Conflict of Interest

The authors declare no conflicts of interest.

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