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A Low-Cost, Modular Avionics and Thrust Vector Control Architecture for Experimental Rocketry

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Abstract: This paper presents comprehensive results from our prototype demonstration of future rocket avionics and control systems. A thorough literature survey identified key technological gaps, particularly concerning cost-effectiveness and deployment flexibility. Rigorous testing for maneuvering time improvements validated enhanced performance through the implementation of an innovative thrust vector control (TVC) system. The study tackles the long-standing industry issue of high-cost avionics by proposing modular, cost-efficient substitutes that are as reliable but significantly lower in cost barriers to entry. A notable in- novation is the development of portable instrumentation systems capable of being deployed and operated in diverse environments, thereby overcoming traditional location constraints. The thrust vector control system uses solid motor configurations, a significant step away from the traditional approach. In addition, the study explores the scalability and practical feasibility of hybrid propulsion systems, especially under conditions of adequate funding and resource allocation. The main contribution lies in the integrated avionics and control system architecture, which strikes a balance between advanced functionality and operation simplicity. All developmental activities adhered strictly to recognized industrial standards, with particular emphasis on safety protocols. This research pushes the democratization of rocket science by offering robust, low-cost systems that preserve performance integrity while increasing accessibility to a wider variety of applications.

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1. Introduction

The advent of reusable rocket technology has initiated a paradigm shift in aerospace engineering, fundamentally trans- forming the economics of space access. While industry leaders have demonstrated remarkable success, these advanced propulsive landing and control technologies remain proprietary and concentrated within a few well-funded organizations, creating a significant technological divide. This gap is particularly pronounced in academic and research environments, where high-cost barriers and a lack of accessible platforms severely limit hands-on experimentation with modern control systems. Consequently, a critical disconnect persists between theoretical knowledge and the practical implementation of advanced rocketry, hindering indigenous innovation and constraining the development of skilled engineers. To address this challenge, this paper presents the design, implementation, and validation of a low-cost, modular Thrust Vector Control (TVC) and avionics system developed specifically for educational and small-scale rocketry applications. The system is engineered around a distributed processing architecture, utilizing an Arduino Uno as the central flight computer augmented by multiple Arduino Nano boards for dedicated tasks such as data logging and servo control signal generation. This modular design philosophy emphasizes affordability, flexibility, and operational simplicity, with the primary objective of democratizing access to advanced flight control technologies. The developed system successfully demonstrates performance characteristics competitive with more expensive alternatives while achieving an unprecedented low cost. Bench testing validated a maximum TVC gimbal deflection of ±8◦, exceeding the design target of ±5◦. The control loop operates at 50 Hz, ensuring a servo response latency of less than 100ms, which is sufficient for real-time attitude correction. The entire avionics and TVC package, including power supply, has a mass of 200-300 grams and was developed for a total cost under Rs.15,000 (approximately $180 USD). This work establishes a robust and scalable platform that significantly lowers the financial barrier to entry for hands- on learning in

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aerospace control systems. The subsequent sections of this paper detail the system architecture and design, the implementation and testing methodology, a comprehensive analysis of the performance and cost-effectiveness, and a comparative analysis against existing systems. Finally, we conclude with a discussion of the system's limitations and a roadmap for future work, including the integration of more advanced control algorithms and full-scale flight testing.

2. Literature Review

The development of cost-effective avionics control systems for modern rocketry necessitates a comprehensive understanding of the technological ecosystem that enables advanced rocket control capabilities. While the present research focuses on democratizing access to sophisticated flight control systems through low-cost implementations, the literature survey encompasses the broader technological foundations that inform such developments. This holistic approach recognizes that affordable avionics systems cannot be developed in isolation but must integrate proven methodologies from computational fluid dynamics, vertical landing technologies, and thrust vector control systems. The interconnected nature of these domains establishes the technical context within which cost-effective solutions must operate while maintaining performance standards comparable to their expensive counterparts.

The application of Computational Fluid Dynamics to hybrid rocket systems has established fundamental principles that directly influence avionics system requirements and sensor integration strategies. Reyhanoglu (2011) identified fuel slosh dynamics as a critical factor in spacecraft control, demonstrating that liquid propellant can constitute up to 40% of total vehicle mass in modern spacecraft, thereby significantly affecting control system design requirements. This foundational understanding informs the sensor fusion algorithms and control strategies necessary for effective low-cost avionics implementations. Subsequent research by Lazzarin, Faenza, Barato, Bellomo, Bettella, Pavarin, and Grosse (2011) demonstrated the practical application of commercial CFD codes for simulating hybrid rocket configurations using liquid N_2O oxidizer and paraffin wax fuel, achieving validation within 7% efficiency error compared to experimental data. Their follow-up investigation (Lazzarin, Barato, Bettella, & Pavarin, 2013) successfully modeled fuel regression rates within 10% accuracy for HDPE and 20% for HTPB, establishing the computational frameworks that enable predictive control algorithms essential for autonomous flight systems. The evolution of CFD applications continued with Conte et al. (2017) analyzing gaseous oxygen/PMMA systems for CubeSat propulsion at NASA JPL, while Mechentel (2019) emphasized hybrid motors' safety and simplicity advantages for small-satellite applications. Ahmad et al. (2024) demonstrated high correlation between CFD simulations and theoretical models for De Laval nozzle performance, providing the analytical foundation necessary for thrust characterization in cost-effective control systems.

The paradigm shift toward reusable launch vehicles and precision landing capabilities has driven the development of sophisticated guidance, navigation, and control algorithms that must be adapted for implementation in resource-constrained avionics systems. Early work by Luke (1991) introduced enhanced 3DOF simulation approaches that balance computational efficiency with accuracy, a critical consideration for low-cost microcontroller-based systems. Acıkmese and Ploen (2007) pioneered convex programming approaches for Mars powered descent guidance, establishing mathematical frameworks that guarantee convergence within real-time computational constraints. This work proved particularly significant for affordable avionics development, as it demonstrated how complex trajectory optimization problems could be solved using computationally efficient algorithms suitable for embedded systems. Blackmore (2016) highlighted the commercial success of precision landing by SpaceX and Blue Origin, emphasizing the critical role of rapid trajectory computation and the integration of multiple sensor modalities, principles directly applicable to cost-effective avionics architectures. The European RETALT project (n.d.) provided comprehensive insights into retro-propulsion assisted landing technologies, investigating both two-stage-to-orbit and single-stage-to-orbit configurations while establishing the sensor fusion and control requirements necessary for autonomous operations. Xie, Zhang, Zhou, and Tang (2020) demonstrated 95% faster convergence compared to traditional methods through convex feasible set approaches, while Botelho, Martinez, Recupero, Fabrizi, and De Zaiacomo (2022) developed guidance algorithms achieving pinpoint landing accuracy through onboard optimization techniques that could be adapted for lower-cost hardware implementations.

The advancement of multidisciplinary design optimization frameworks (Dresia et al., 2021) and mission analysis tools for multi-orbit operations (n.d.) has established the systems engineering approaches necessary for integrated avionics development. Wu and Zhang (2023) analyzed the commercial viability of reusable systems, highlighting cost reduction as a primary driver for technological advancement. Lee, Kim, and Choi (2023) addressed trajectory optimization challenges through successive convex programming methods that balance computational complexity with solution accuracy. Recent developments in high-fidelity simulation environments (NASA, 2021; Farıetal., 2024) have provided the validation frameworks necessary for testing cost-effective avionics systems against proven benchmarks, while advanced modeling approaches (Yu & Wei, 2024) have demonstrated the integration of batch optimization with model predictive control for fuel-optimal trajectories.

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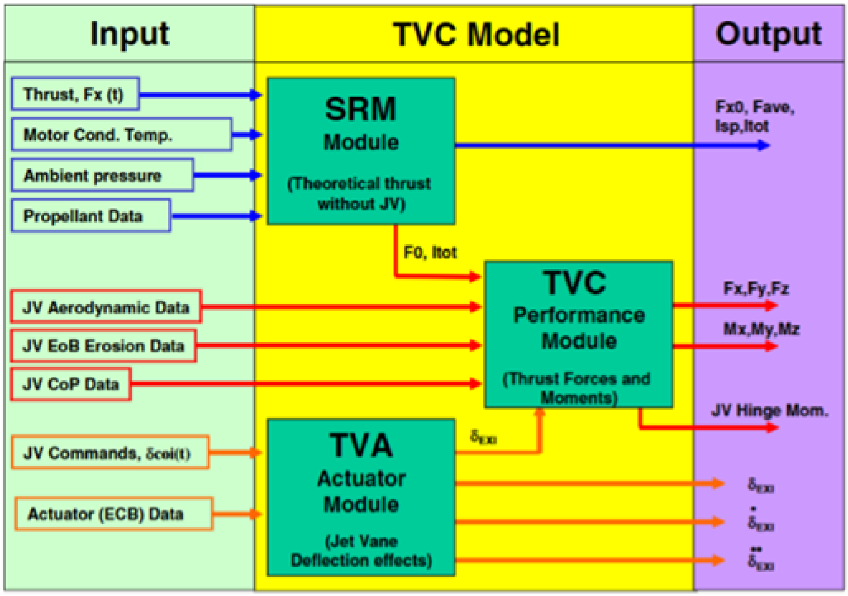

Fig. 1: Conceptual model of a Thrust Vector Control system as described by Orbekk (2008).

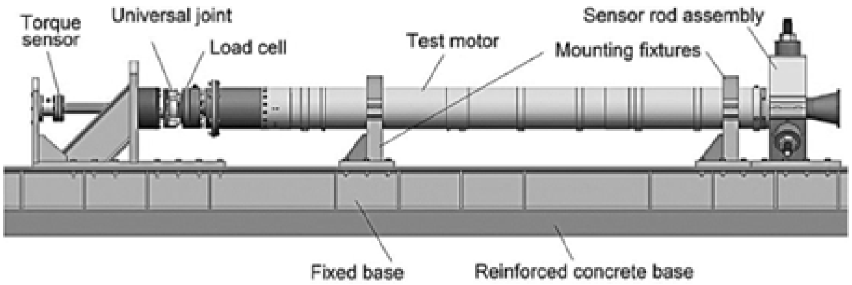

Fig. 2: CAD model of TVC test system and its components (Yagmur, Sen, Bayar, & Serbest, 2022).

Thrust Vector Control system evolution from mechanical solutions to sophisticated electronically controlled mechanisms provides the direct technological heritage for modern low-cost avionics implementations. Early systematic evaluation work by Fuentes and Thirkill (1964) established methodologies for TVC system selection based on performance, reliability, and cost considerations, principles that remain central to affordable avionics development. NASA's comprehensive 1970 study (Erickson, Nickens, Sottosanti, & Sutton, 1970) compared mechanical interference, liquid injection, and flexible bearing nozzle concepts for large solid rocket motors, establishing the trade-off analyses between complexity, cost, and performance that inform contemporary design decisions. Orbekk (2008) developed comprehensive TVC models validated through motor firings, demonstrating the integration of computational models with physical systems that enables modern sensor-based control approaches. Guo, Wei, Xie, and Wang (2017) investigated fluidic nozzle throat applications combined with shock vector control, while Unal, Yaman, Okur, and Adlı (2018) developed comprehensive test systems for evaluating TVC performance across six degrees of freedom, establishing the validation methodologies essential for cost-effective system development.

Contemporary research by Yagmur, Sen, Bayar, and Serbest (2022) focused on enhancing maneuverability through sensor integration and feedback mechanisms, directly informing the design approaches used in low-cost avionics systems. Sopegno, Livreri, Stefanovic, and Valavanis (2023) conducted comparative analysis of control strategies including LQR, LQG, and PID controllers for finless rocket applications, revealing that while LQR and LQG excel in tracking and responsiveness, PID controllers demonstrate superior robustness against external disturbances. This analysis provides critical insights for controller selection in resource-constrained implementations where computational overhead must be minimized while maintaining performance reliability.

The comprehensive literature survey reveals the technological convergence that enables the development of cost-effective avionics control systems without compromising fundamental performance requirements. This technological heritage informs the present research by providing proven algorithms, validated sensor fusion techniques, and established control methodologies that can be adapted for implementation using commercially available, cost-effective hardware while maintaining the performance integrity essential for safe and reliable rocket operations.

3. System Design

The design of the Thrust Vector Control (TVC) system is founded on a philosophy of modularity, cost-effectiveness, and operational simplicity, intended to create an accessible yet robust platform for educational rocketry. The system architecture employs a distributed processing approach centered around an Arduino Uno (ATmega328p) microcontroller, which serves as the primary flight computer. This choice was driven by the processor's proven reliability and sufficient computational power for the required control loops, offered at a fraction of the cost of alternatives. To prevent computational bottlenecks and enhance modularity, the central controller is augmented by three dedicated Arduino Nano boards responsible forspecialized tasks: data logging, power management, and the generation of TVC output signals. This partitioned architecture not only simplifies debugging and testing but also ensures that critical subsystems can be upgraded or replaced without requiring a complete system overhaul, thereby creating a flexible and scalable framework.

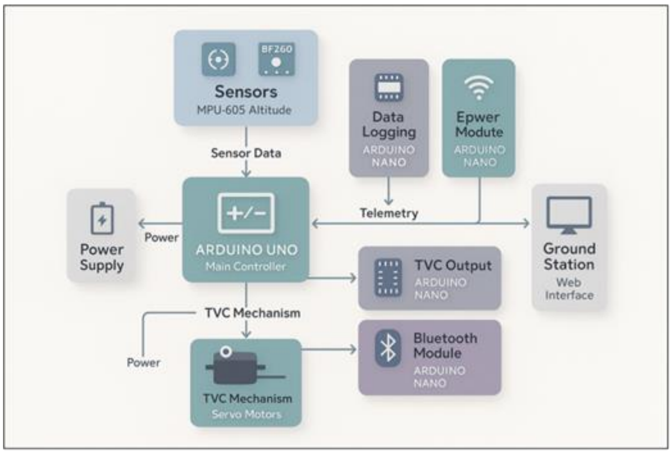

Fig. 3: Overall system architecture showing the distributed processing approach with Arduino Uno as the primary flight computer and three Arduino Nano boards for specialized tasks.

The avionics suite integrates a carefully selected array of Commercial-Off-The-Shelf (COTS) components to form the sensory and communication backbone of the system. Attitude and altitude data are acquired by an MPU-6050 6-axis IMU and a BMP280 barometric pressure sensor, respectively, which interface with the main controller via the I2C protocol. This direct sensor linkage is crucial for maintaining the 50 Hz control loop frequency required for dynamic stability. A key integration challenge was resolving I2C bus contention, which was overcome by implementing a time-division multiplexing scheme for polling the sensors. For telemetry, the system utilizes an ESP8266 WiFi module, which hosts its own local network and a web-based interface, enabling real-time data monitoring from any connected device. Power management is handled by a robust dual-rail architecture, with a regulated 5V supply for the microcontrollers and sensors, and a separate, isolated 9V source dedicated to the high-torque TVC servo motors to prevent voltage fluctuations from impacting the digital logic.

The physical TVC mechanism translates the electronic commands into precise mechanical force vectoring. It consists of a gimbal-based design with two degrees of freedom, allowing for thrust deflection in both the pitch and yaw axes. The mechanism, fabricated using a hybrid of 3D-printed components and high-strength aluminum elements, is designed to provide a deflection range of at least $\pm 5^{\circ}$, which is sufficient control authority for active stabilization. Actuation is provided by two high-torque MG995R metal-gear servo motors, positioned orthogonally to provide independent control. A significant innovation of this design is that, unlike traditional nozzle- deflection systems, the entire TVC assembly is engineered to be fully recoverable and reusable after flight, drastically reducing operational costs for educational and research applications.

The control algorithm governing the system is implemented as a pragmatic, threshold-based logic loop that executes at a 50 Hz update rate. Raw data from the IMU is first passed through a complementary filter to generate a stable and responsive estimate of the vehicle's orientation by minimizing gyroscopic drift. The control logic then compares this orientation data against a predefined stability threshold. If the vehicle's attitude deviates beyond this threshold, the system calculates and sends proportional correction commands to the TVC servos to counteract the tilt. While this method provides effective stabilization with low computational overhead, the software architecture has been deliberately designed to accommodate a seamless future transition to a more sophisticated

Proportional Integral-Derivative (PID) control scheme, which will enable more precise setpoint tracking for advanced maneuvers.

4. Implementation

The successful implementation of the designed system was achieved through a meticulous process of hardware integration, software development, and systematic testing. The avionics package was constructed on a custom-soldered protoboard, which houses the Arduino Uno, the dedicated Nano modules, and all associated circuitry. A notable novelty in the hardware integration is the use of modular sockets for the primary sensors, the MPU-6050 and BMP280. This design choice, a departure from permanently soldered components, allows for rapid replacement and in-field servicing, a crucial feature for an experimental and educational platform where component testing and iteration are common. The entire assembly is housed within a lightweight, cost-effective airframe constructed from PVC pipe, aligning with the project's core objectives of accessibility and significant weight reduction.

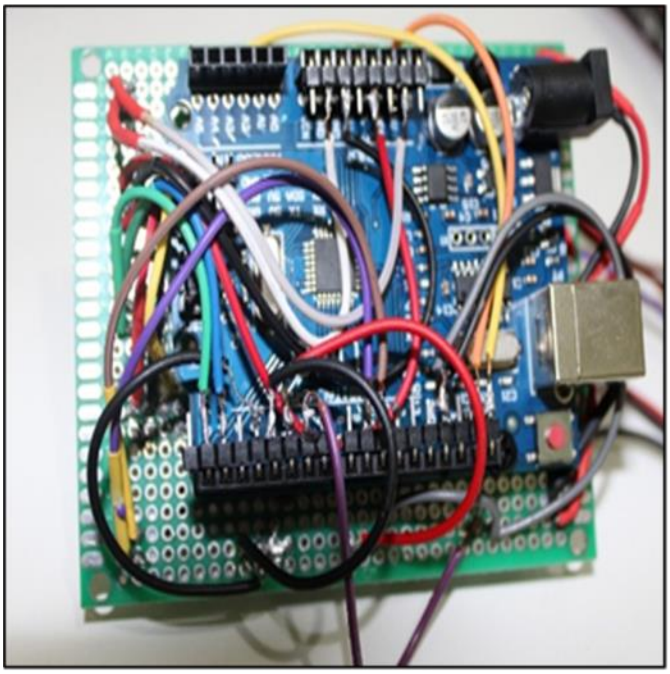

Fig. 5: Completed avionics board showing the modular sensor integration with removable sockets for the MPU-6050 and BMP280 sensors.

Software development was centered on implementing a robust, real-time control loop and a flexible telemetry system. The control logic was coded within the Arduino IDE, ensuring efficient communication between the main controller and the sensors. The most significant innovation in this domain is the development of a custom, web-based ground station. An ESP8266 NodeMCU module provides wireless data transmission by hosting a web server accessible on a local network. This system uses HTML and WebSockets to push real-time sensor data, including pitch, roll, yaw, and altitude, to any connected device's web browser, displaying it as intuitive graphical plots. This approach eliminates the need for specialized ground station software or proprietary hardware, offering a universally accessible and device-agnostic monitoring solution that is highly novel in the amateur rocketry field.

To ensure operational reliability, a rigorous calibration and safety protocol was implemented. Prior to each test, a prelaunch calibration routine is executed for the MPU-6050 IMU, which averages 200 samples over a five-second period to establish a stable zero-reference and nullify gyroscopic drift. This simple yet effective procedure is vital for achieving accurate attitude estimation during flight. The system's operational status is continuously communicated to the user through integrated safety mechanisms. These include a series of LEDs for visual confirmation of sensor connectivity and system readiness, as well as an auditory buzzer that activates when attitude deviations exceed a predefined critical threshold. This multi-modal feedback provides immediate alerts of off nominal conditions, enhancing operational safety and diagnostic capability.

The integrated system's performance was validated through a comprehensive bench testing methodology designed to simulate various flight conditions. These tests confirmed end-toend functionality, from sensor data acquisition to mechanical actuation of the TVC gimbal. In the primary validation test, manual external forces were applied to induce pitch and roll disturbances. The system demonstrated a rapid and accurate corrective response, with the TVC mechanism consistently counteracting the induced tilt to restore a stable orientation, and the alert systems functioning as designed. This process validated the responsiveness of the servo loop and the effectiveness of the threshold-based control logic in a controlled, dynamic environment, confirming the system's readiness for future flight testing.

TABLE I: Present System Implementation Parameters

Parameter	Implementation	Unit
Update Rate	50	Hz
Control Method	Threshold-based	-
IMU Type	MPU-6050	-
Filter Type	Complementary	-
Stabilization Range	±45	degrees
Response Time	20	ms
Processing Budget	Basic proportional	-
Platform	Arduino	-

5. Results

The performance of the integrated Thrust Vector Control (TVC) and avionics system was rigorously evaluated through a series of bench tests. The key performance indicators were measured against the design targets and are summarized in Table II.

During dynamic bench testing, the servo-actuated gimbal mechanism achieved a maximum deflection angle of ±8°. The end-to-end response time, from sensor detection of a disturbance to servo actuation, was consistently maintained at less than 100ms. The dual-rail power system enabled a continuous operational duration of 15-20 minutes. The total system weight, including the battery, was measured to be between 200-300 grams. The ESP8266-based telemetry system has a manufacturer-rated communication range of up to 2 km.

The system's dynamic response to manual disturbances is shown in Figures 6 through 8. These plots illustrate the vehicle's orientation over time as corrective actions are applied by the TVC system. Figure 9 shows a sample of the raw data output from the MPU6050 and BMP280 sensors as plotted by the ground station interface.

TABLE II: Key Performance Results from Bench Testing

Metric	Measured Value	Target
Max TVC Deflection	±8°	±5°
Response Time	< 100 ms	< 100 ms
Operational Duration	15–20 min	> 15 min
System Weight	200–300 g	< 350 g
Communication Range	2 km (Rated)	> 500 m

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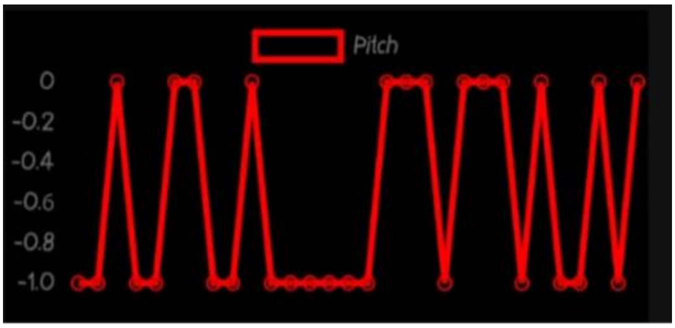


Fig. 6: Pitch vs. Time.

Note: The time axis is presented without units in the original data.

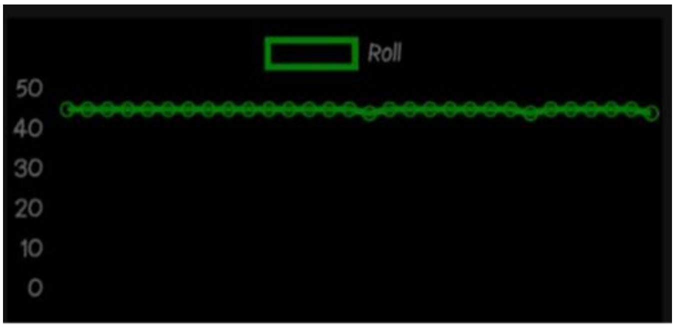


Fig. 7: Roll vs. Time. Note: The time axis is presented without units in the original data.

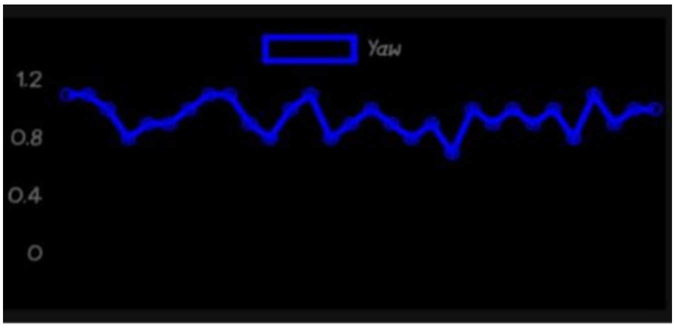
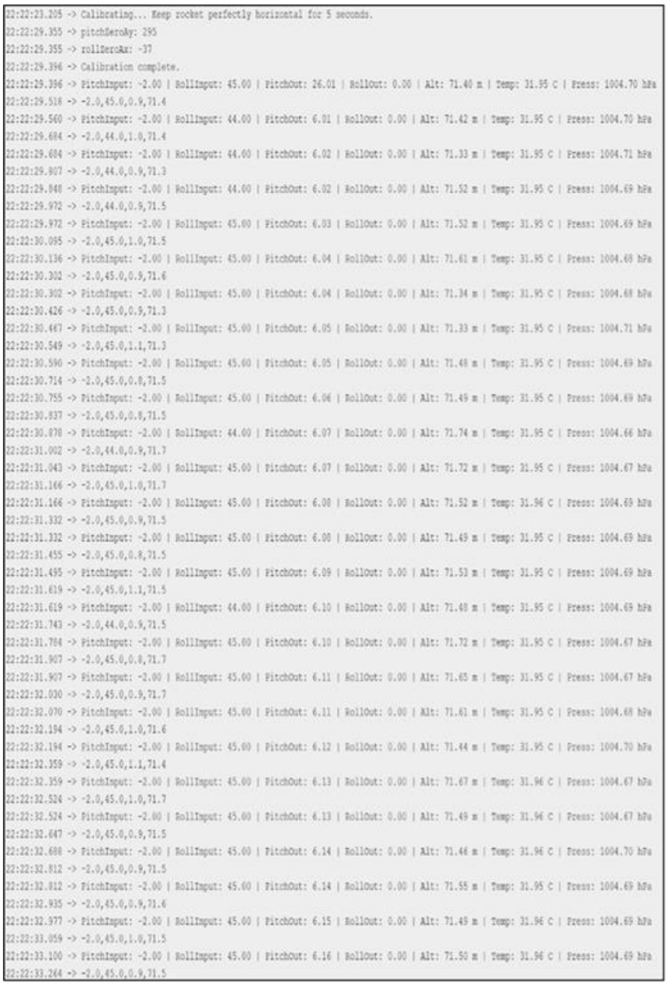


Fig. 8: Yaw vs. Time. Note: The time axis is presented without units in the original data.



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22:22:23.205 -> Calibrating... Keep rocket perfectly horizontal for 5 seconds.
22:22:29.355 -> pitchZeroAy: 295
22:22:29.355 -> rollZeroAx: -37
22:22:29.396 -> Calibration complete.
22:22:29.396 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 26.01 | RollOut: 0.00 | Alt: 71.40 m | Temp: 31.95 C | Press: 1004.70 hPa
22:22:29.518 -> -2.0,45.0,0.9,71.4
22:22:29.560 -> PitchInput: -2.00 | RollInput: 44.00 | PitchOut: 6.01 | RollOut: 0.00 | Alt: 71.42 m | Temp: 31.95 C | Press: 1004.70 hPa
22:22:29.684 -> -2.0,44.0,1.0,71.4
22:22:29.684 -> PitchInput: -2.00 | RollInput: 44.00 | PitchOut: 6.02 | RollOut: 0.00 | Alt: 71.33 m | Temp: 31.95 C | Press: 1004.71 hPa
22:22:29.807 -> -2.0,44.0,0.9,71.3
22:22:29.848 -> PitchInput: -2.00 | RollInput: 44.00 | PitchOut: 6.02 | RollOut: 0.00 | Alt: 71.52 m | Temp: 31.95 C | Press: 1004.69 hPa
22:22:29.972 -> -2.0,44.0,0.9,71.5
22:22:29.972 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.03 | RollOut: 0.00 | Alt: 71.52 m | Temp: 31.95 C | Press: 1004.69 hPa
22:22:30.095 -> -2.0,45.0,1.0,71.5
22:22:30.136 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.04 | RollOut: 0.00 | Alt: 71.61 m | Temp: 31.95 C | Press: 1004.68 hPa
22:22:30.302 -> -2.0,45.0,0.9,71.6
22:22:30.302 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.04 | RollOut: 0.00 | Alt: 71.34 m | Temp: 31.95 C | Press: 1004.68 hPa
22:22:30.426 -> -2.0,45.0,0.9,71.3
22:22:30.467 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.05 | RollOut: 0.00 | Alt: 71.33 m | Temp: 31.95 C | Press: 1004.71 hPa
22:22:30.549 -> -2.0,45.0,1.1,71.3
22:22:30.590 -> PitchInput: -2.00 | RollInput: 45.60 | PitchOut: 6.05 | RollOut: 0.00 | Alt: 71.48 m | Temp: 31.95 C | Press: 1004.69 hPa
22:22:30.714 -> -2.0,45.0,0.8,71.5
22:22:30.755 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.06 | RollOut: 0.00 | Alt: 71.49 m | Temp: 31.95 C | Press: 1004.69 hPa
22:22:30.837 -> -2.0,45.0,0.8,71.5
22:22:30.878 -> PitchInput: -2.00 | RollInput: 44.00 | PitchOut: 6.07 | RollOut: 0.00 | Alt: 71.74 m | Temp: 31.95 C | Press: 1004.66 hPa
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22:22:31.043 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.07 | RollOut: 0.00 | Alt: 71.72 m | Temp: 31.95 C | Press: 1004.67 hPa
22:22:31.166 -> -2.0,45.0,1.0,71.7
22:22:31.166 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.08 | RollOut: 0.00 | Alt: 71.52 m | Temp: 31.96 C | Press: 1004.69 hPa
22:22:31.332 -> -2.0,45.0,0.9,71.5
22:22:31.332 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.08 | RollOut: 0.00 | Alt: 71.49 m | Temp: 31.95 C | Press: 1004.69 hPa
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22:22:31.495 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.09 | RollOut: 0.00 | Alt: 71.53 m | Temp: 31.95 C | Press: 1004.69 hPa
22:22:31.619 -> -2.0,45.0,1.1,71.5
22:22:31.619 -> PitchInput: -2.00 | RollInput: 44.00 | PitchOut: 6.10 | RollOut: 0.00 | Alt: 71.48 m | Temp: 31.95 C | Press: 1004.69 hPa
22:22:31.743 -> -2.0,44.0,0.9,71.5
22:22:31.784 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.10 | RollOut: 0.00 | Alt: 71.72 m | Temp: 31.95 C | Press: 1004.67 hPa
22:22:31.907 -> -2.0,45.0,0.8,71.7
22:22:31.907 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.11 | RollOut: 0.00 | Alt: 71.65 m | Temp: 31.95 C | Press: 1004.67 hPa
22:22:32.030 -> -2.0,45.0,0.9,71.7
22:22:32.070 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.11 | RollOut: 0.00 | Alt: 71.61 m | Temp: 31.95 C | Press: 1004.68 hPa
22:22:32.194 -> -2.0,45.0,1.0,71.6
22:22:32.194 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.12 | RollOut: 0.00 | Alt: 71.44 m | Temp: 31.95 C | Press: 1004.70 hPa
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22:22:32.359 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.13 | RollOut: 0.00 | Alt: 71.67 m | Temp: 31.96 C | Press: 1004.67 hPa
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22:22:32.524 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.13 | RollOut: 0.00 | Alt: 71.49 m | Temp: 31.96 C | Press: 1004.67 hPa
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22:22:32.688 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.14 | RollOut: 0.00 | Alt: 71.46 m | Temp: 31.96 C | Press: 1004.70 hPa
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22:22:32.977 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.15 | RollOut: 0.00 | Alt: 71.49 m | Temp: 31.96 C | Press: 1004.69 hPa
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22:22:33.100 -> PitchInput: -2.00 | RollInput: 45.00 | PitchOut: 6.16 | RollOut: 0.00 | Alt: 71.50 m | Temp: 31.96 C | Press: 1004.69 hPa
22:22:33.264 -> -2.0,45.0,0.9,71.5
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Fig. 9: Serial plotting of the raw sensor values from the MPU6050 and BMP280, respectively.

6. Discussion

The results confirm that the system successfully meets its design goals for performance, cost-effectiveness, and operational reliability in a controlled environment, establishing a strong foundation for future in-flight validation. The measured maximum TVC deflection of $\pm 8^{\circ}$ comfortably exceeds the initial design target of $\pm 5^{\circ}$, providing a significant margin of control authority for correcting attitude deviations. The sub100ms response time meets the critical requirement for realtime flight stability control, and the operational duration is more than sufficient for the pre-launch, flight, and recovery phases of a typical educational mission.

Cost Analysis

The primary objective of this project was to drastically reduce the cost barrier to advanced rocketry. The total development cost for the prototype, including all components and R&D, was approximately *Rs.*15,000 (approx. $180 USD). This represents an order-of-magnitude cost reduction compared to commercial TVC systems, which typically exceed *Rs.*100,000, and a significant saving over other academic systems. The low cost was achieved by leveraging COTS components, an Arduinobased architecture, and cost-effective fabrication techniques like 3D printing and using PVC for the airframe. We project that the unit cost could be further reduced to as low as *Rs.*7,500 in bulk production, making this technology highly accessible for educational institutions and amateur groups.

System Validation

The system's functionality was validated through a series of controlled tests. Stability testing involved applying manual disturbances to the system's pitch and yaw axes. The TVC system consistently and immediately counteracted these inputs, demonstrating the effectiveness of the control loop and mechanical actuation. Sensor accuracy was confirmed through the pre-launch calibration routine, which effectively zeroed out IMU drift and provided stable, reliable orientation data throughout the test duration. The communication and telemetry system performed flawlessly, with the web-based ground station providing a real-time, graphical display of all key flight

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parameters. Data was transmitted reliably with no observable dropouts, confirming the robustness of the WiFibased communication link for ground monitoring.

Limitations

While the bench test results are highly promising, it is important to acknowledge the limitations of the current work. The most significant limitation is the absence of full-scale flight testing. The system has not yet been subjected to the aerodynamic forces, vibrations, and high G-loads of an actual rocket launch, and its performance in these conditions remains to be validated. Secondly, the current threshold-based control algorithm, while effective for basic stabilization, lacks the precision and adaptability of a fully-tuned PID controller, which would be necessary for more complex flight maneuvers. Finally, the system has not undergone comprehensive environmental testing to characterize its performance across a wide range of temperatures and pressures. These areas represent the primary focus for the next phase of development and are critical steps toward creating a flight-ready system.

7. Conclusion and Future Work

This research has successfully demonstrated the design, integration, and validation of a low-cost, modular, and reusable Thrust Vector Control and avionics system for experimental rocketry. The core achievement is the development of a complete, end-to-end platform that significantly lowers the financial and technical barriers to entry for advanced rocket control. By leveraging a distributed architecture of COTS microcontrollers and a hybrid manufacturing approach, the system exceeded key performance targets, such as achieving $\pm 8^{\circ}$ of TVC deflection, at an R&D cost of under $200 USD. The work addresses a documented gap in the literature by providing a practical, integrated blueprint that serves to democratize access to technologies foundational to modern spaceflight.

The validated platform serves as the first phase of a larger research program. The future work is envisioned as a structured roadmap:

1. **Integrated Flight Testing:** The immediate priority is to conduct flight tests to validate performance under real-world loads and gather data for control algorithm refinement.

2. **Algorithmic Enhancement:** The flight data will be used to transition from the current controller to a finelytuned PID controller. Subsequent research will explore the implementation of more advanced Model Predictive Control (MPC) algorithms.

3. **Propulsion Integration:** The TVC mechanism and avionics will be adapted to control a hybrid rocket motor, leveraging its modularity to manage throttle control and monitor combustion stability.

4. **Vertical Landing Development:** The final goal is to use the enhanced control system as the core of a complete vertical landing demonstrator, integrating additional sensors (e.g., GPS, LiDAR) and developing sophisticated landing guidance algorithms.

By establishing robust and accessible foundational technology, this work paves the way for broader participation in advanced rocketry research and provides a tangible platform for educating the next generation of aerospace engineers.

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9. Conflict of Interest

The author declares no competing conflict of interest.

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