

IMPLEMENTATION OF DYNAMIC THRUST VECTOR CONTROL FOR HIGH-PRECISION ORIENTATION, AND ALTITUDE STABILIZATION IN ADVANCED DEFENCE AND SPACECRAFT APPLICATIONS

Project Reference No.: 48S_BE_4838

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Keywords:

Sensor Fusion, Kalman Filtering, Gimbal Mechanism, Real-Time Control Systems, Embedded Flight Controller

Introduction:

Thrust Vector Control (TVC) is a fundamental technology that significantly enhances the orientation, navigation, and maneuverability of aerospace vehicles, particularly in space or high-altitude environments where traditional control surfaces lose effectiveness. This project introduces a Dynamic Thrust Vector Control System (DTVC) that integrates advanced actuator mechanisms, sensor fusion, and real-time control algorithms. The system is intended for precision flight in applications like launch vehicles, guided missiles, and spacecraft. The Gimballed Thrust Vectoring is shown in Figure 1. Conventional systems such as aerodynamic fins or RCS thrusters present constraints in terms of weight, fuel consumption, and response time. The proposed solution addresses these limitations through embedded microcontroller systems, IMU-based orientation feedback, and adaptive control techniques that ensure precision and responsiveness. Real-time telemetry and adaptive filtering methods like Kalman and Complementary filters are employed for noise reduction and optimal thrust adjustments. By implementing both simulation and a physical working prototype, the project validates the performance and robustness of the developed DTVC system, ensuring practical applicability in modern aerospace and defence industries.

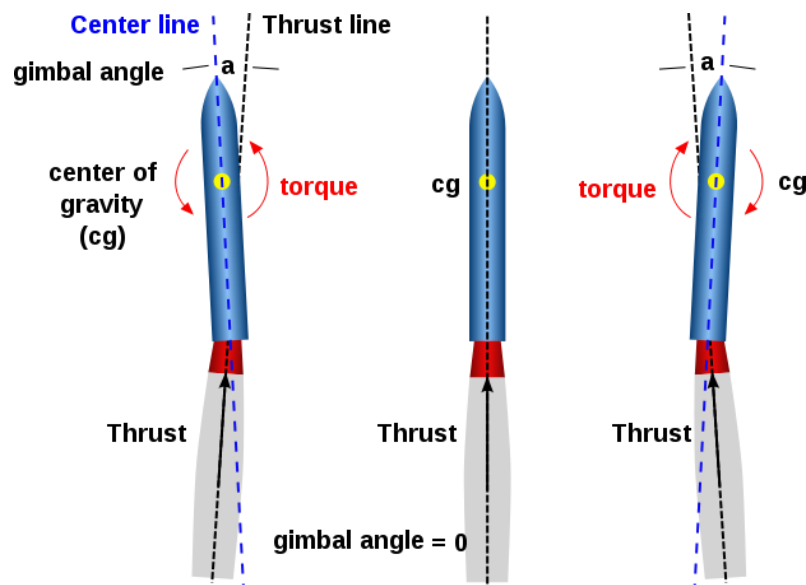


Figure 1: Gimbaled Thrust Vectoring

Objectives:

- To design a thrust vector mechanism that allows for controlled redirection of thrust.
- To develop a control algorithm that dynamically adjusts thrust vectoring to maintain stability and enable rapid maneuverability.
- To evaluate the performance of the TVC system across different flight regimes, including atmospheric and non-atmospheric conditions.
- To assess the fuel efficiency of the TVC system and its impact on overall mission sustainability.
- To analyze the feasibility of integrating the TVC system into existing aerospace platforms and its adaptability for future applications.

Methodology:

The implementation of the Thrust Vector Control System (TVCS) follows a structured approach combining embedded hardware, sensor integration, wireless telemetry, and real-time control algorithms. The core control is built around an STM32F411CEU6 microcontroller, interfaced with MPU6050 (IMU) and HMC5883L magnetometer to gather orientation data. This information is processed through SMC-based and

adaptive control algorithms to generate PWM signals for actuating servo motors along the X and Y axes.

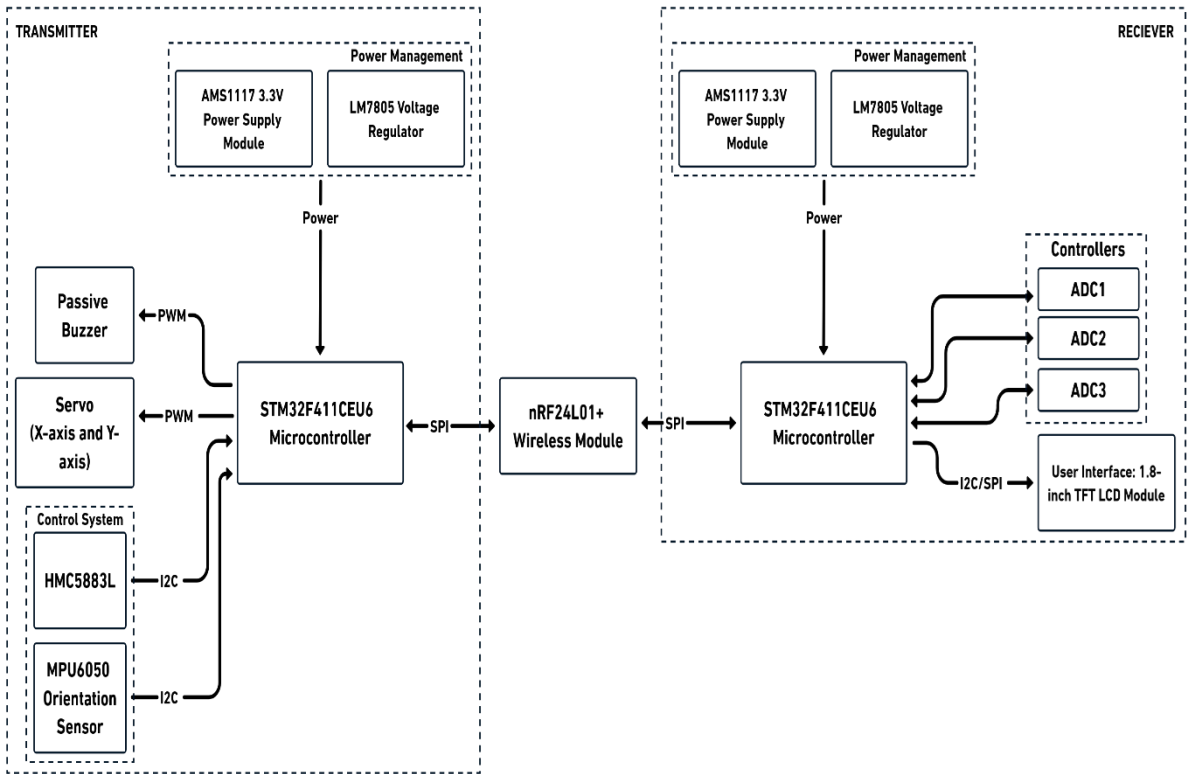


Figure 2: General block diagram of Hardware implementation of TVCS

The servo-actuated gimbal mechanism serves as the foundation for directional thrust control, enabling real-time pitch and yaw adjustments by dynamically altering the orientation of the propulsion system. This is achieved through precision-controlled high-torque servo motors, which respond to feedback signals for accurate alignment. Figure 2 represents how the power system utilizes a buck converter to efficiently regulate a 7.4V Li-ion battery down to 3.3V, supplying clean and consistent power to the microcontroller, sensors, and communication modules. For telemetry, the NRF24L01+ wireless transceiver transmits real-time sensor data to a ground station, where thrust levels, orientation angles, and system diagnostics are visualized on a 1.8" ST7735 TFT LCD display. To ensure robust orientation tracking, sensor fusion is employed using both complementary and Kalman filters, which process gyroscope and accelerometer data to reduce sensor drift and high-frequency noise.

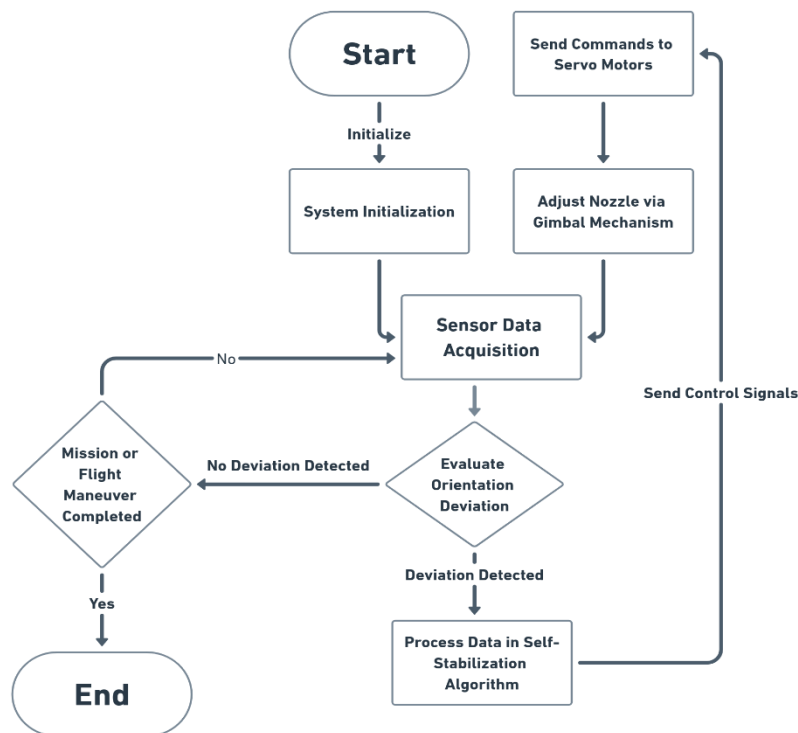


Figure 3: Flowchart of a Thrust Vector Control System (TVCS)

The architecture represented in Figure 3 includes system initialization, sensor acquisition, error calculation, self-stabilization correction, and real-time feedback for thrust control. A MATLAB/Simulink simulation and Hardware-in-the-Loop (HIL) testing environment validate the responsiveness and accuracy of the system. Additional ADC interfaces allow manual input for dynamic control tuning. All subsystems are integrated on a compact PCB, and 3D CAD models ensure structural stability of the gimbal frame.

Result and Conclusion:

The Dynamic Thrust Vector Control System (DTVC) showed excellent precision, responsiveness, and adaptability across various test stages. MATLAB/Simulink simulations confirmed system (as represented in the graphs in Figure 4 and Figure 5) stability with minimal overshoot and quick convergence. Hardware-in-the-loop (HIL) testing validated real-time responsiveness and robustness under simulated flight conditions.

The servo-driven gimbal accurately adjusted orientation using real-time feedback from MPU6050 sensor. The SMC controller effectively maintained target orientation, while

complementary and Kalman filters enhanced measurement accuracy by reducing drift and noise.

The NRF24L01+ telemetry module provided reliable data transmission with minimal packet loss and low latency. Real-time on-screen displays aided in monitoring and tuning orientation metrics. A buck converter ensured consistent voltage output during high-power operations.

The system achieved stable closed-loop control, fast actuation, and efficient communication. Orientation corrections were performed in under one second, with angular errors within ± 2 degrees. The gimbal's mechanical design enabled necessary motion while preserving structural integrity.

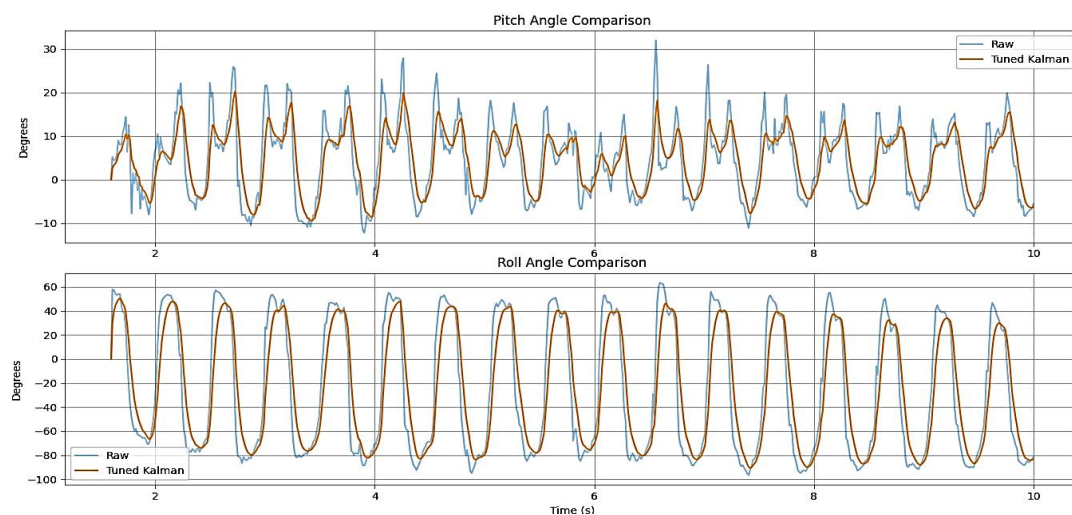


Figure 4: Kalman Filter Response for Pitch and Roll Angles

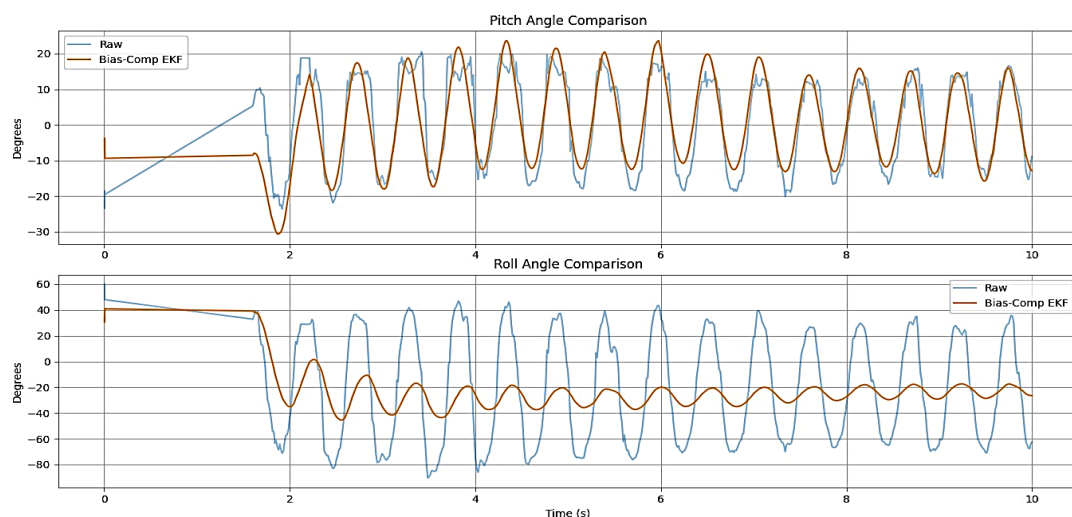


Figure 5: Bias-Compensated Extended Kalman Filter (EKF) Response for Pitch and Roll Angles

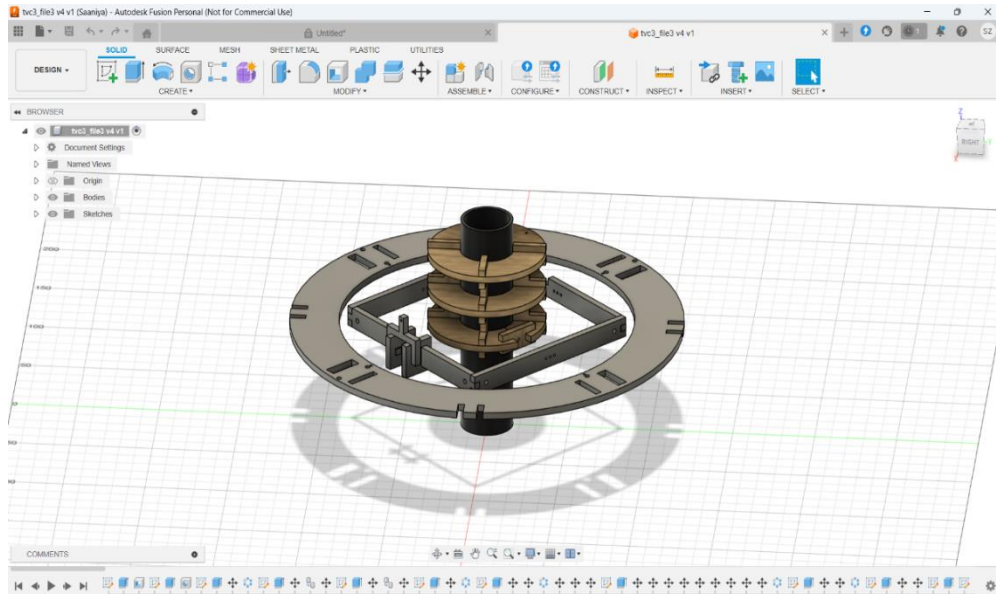


Figure 6: *Thrust Vector Control Device designed using AutoDesk Fusion 360*

Overall, DTVC met its objectives through a well-integrated hardware-software approach, proving scalable, modular, and suitable for aerospace and defence applications.

Project Outcome & Industry Relevance:

This project resulted in a modular and fully functional DTVC prototype, including both hardware and simulation environments. The outcomes include a compact embedded flight controller system with integrated feedback loops, a 3D-modeled gimbal structure, and validated performance for aerospace thrust vectoring applications. Its industry relevance lies in its potential for deployment in next-gen defence missiles, UAVs, and space launch vehicles, offering enhanced maneuverability, reduced fuel consumption, and improved trajectory accuracy. The use of readily available components makes the design cost-effective and accessible for further research and commercial adaptation.

Working Model vs. Simulation/Study:

This project comprises both a working physical model and simulation studies. The hardware model includes a servo-controlled gimbal mechanism, embedded control unit, and sensor suite. Simulations in MATLAB/Simulink and real-time HIL testing validated control performance.

Project Outcomes and Learnings:

The team successfully implemented a DTVC system and gained hands-on experience in embedded systems, sensor fusion, control algorithms, and aerospace design. Key learnings include real-time orientation correction, PID tuning, filter design for noisy sensor data, and integration of hardware-software systems for aerospace applications. The project also taught important lessons in iterative testing, modular design, and communication protocol implementation.

Future Scope:

1. Integration of machine learning for adaptive control and predictive correction of trajectory deviations.
2. Miniaturization of the controller and sensor modules for deployment in nano/micro-satellites.
3. Use of AI-assisted flight prediction systems and actuator fault detection mechanisms.
4. Long-duration flight testing in varied environmental conditions to validate reliability.