Design Synthesis, Dynamic Modeling, and Machine Learning–Enhanced Control of a Dual-Axis Thrust Vectoring Gimbal for Active Stabilization in Small-Scale Rocket Systems

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Thrust vector control (TVC) enables rockets to adjust their trajectory by redirecting engine thrust, providing active stabilization during powered flight when aerodynamic fins are less effective, usually at lower altitudes. Small-scale rockets often rely on manually tuned proportional-integral-derivative (PID) controllers, which may underperform under nonlinear dynamics and changing actuator conditions. This project investigated whether integrating machine learning-based adaptive control with a dual-axis TVC gimbal could improve flight stability and response accuracy. A lightweight, nested-ring gimbal capable of ±5 degrees of deflection was implemented. It was optimized for aerodynamic efficiency, and structural integrity was evaluated through benchtop testing. A hybrid control architecture combined baseline PID feedback with a regression-based machine learning model (TensorFlow Lite) trained on synthetic data to predict optimal gain parameters. An Arduino Nano microprocessor conducted the internal calculations and processed inertial measurement unit feedback, and executed real-time control adjustments. Bench and supervised static testing demonstrated full dual directional deflection with response times under 200 milliseconds. Compared to static PID tuning, the machine learning-enhanced controller reduced steady-state attitude error and decreased overshoot across repeated thrust profiles. These findings indicate that data-driven adaptive tuning can significantly enhance thrust vector control performance in small-scale rockets, demonstrating a potentially scalable framework that integrates mechanical design, dynamic modeling, and artificial intelligence for aerospace stabilization systems.

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