Title

Controller Design for Trajectory Tracking of UAV

Abstract

Researchers are increasingly focusing on the development of advanced control strategies capable of addressing the inherent complexities of quadcopter dynamics to enhance trajectory-tracking performance. Despite significant progress, achieving accurate trajectory tracking remains a major challenge due to the underactuated structure, nonlinear coupling, and highly dynamic behavior of quadcopters. In this context, the present study introduces the design, optimization, and validation of advanced sliding-mode control (SMC) schemes tailored for precise and robust quadcopter trajectory tracking. The nonlinear dynamics of the quadcopter are modeled using the Euler–Lagrange approach within the MATLAB ODE45 environment, considering a cross-configuration structure that incorporates both aerodynamic and gyroscopic effects to ensure a realistic representation of the system.

Using this model as a foundation, three robust controllers are developed based on advanced Sliding Mode Control (SMC) methodologies: the PID-Based Super-Twisting SMC (PID ST-SMC), the PID-Based Integral Super-Twisting SMC (PID IST-SMC), and the Third-Order Conditioned Adaptive Barrier-Based Integral Terminal Super-Twisting SMC (3-CABIT-STSMC). To ensure the stability of each proposed controller, a comprehensive Lyapunov stability analysis is performed. Furthermore, to enhance overall controller performance and achieve optimal dynamic response, Particle Swarm Optimization (PSO) is employed to systematically tune the gain parameters, thereby improving tracking accuracy and effectively mitigating chattering effects commonly observed in conventional SMC approaches. The proposed controllers are first validated through extensive numerical simulations, with results demonstrating notable improvements in trajectory-tracking accuracy and robustness. Among the designed control strategies, the 3-CABIT-STSMC exhibits superior performance, attributed to its adaptive barrier function and super-twisting reaching law, which collectively ensure precise tracking while preventing control signal saturation. A saturation function is also integrated within the control structure to suppress residual chattering and enhance smoothness in the control action. To further assess its practical feasibility and validate the control algorithms under realistic operational conditions, a controller-in-the-loop (CIL) implementation is conducted, confirming the real-time effectiveness of the proposed approach and effectively bridging the gap between simulation and practical application. The results demonstrate that the proposed method significantly improves trajectory-tracking accuracy, highlighting its potential for reliable real-world quadcopter applications.

Keywords: Quadcopter UAV, Cross Configuration, Trajectory Tracking, Sliding Mode Control, Particle Swarm Optimization.

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