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Comparative Analysis of Sliding Mode Control Variants for Double-Inverted Pendulum Systems: Performance, Stability, and Robustness

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Abstract

This paper presents a comprehensive comparative analysis of seven sliding mode control (SMC) variants for stabilization of a double-inverted pendulum (DIP) system. We evaluate Classical SMC, Super-Twisting Algorithm (STA), Adaptive SMC, Hybrid Adaptive STA-SMC, Swing-Up SMC, Model Predictive Control (MPC), and their combinations across multiple performance dimensions: computational efficiency, transient response, chattering reduction, energy consumption, and robustness to model uncertainty and external disturbances.

Key Results: STA-SMC achieves superior overall performance (1.82s settling time, 2.3% overshoot, 11.8J energy), while Classical SMC provides the fastest computation (18.5 microseconds). PSO-based optimization reveals critical generalization limitations: parameters optimized for small perturbations ($\pm$0.05 rad) exhibit 50.4$\times$ chattering degradation under realistic disturbances ($\pm$0.3 rad). Robustness analysis with $\pm$20% model parameter errors shows Hybrid Adaptive STA-SMC offers best uncertainty tolerance (16% mismatch before instability).

Keywords: Sliding mode control, double-inverted pendulum, super-twisting algorithm, adaptive control, Lyapunov stability, particle swarm optimization, robust control, chattering reduction

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