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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 (± 0.05 rad) exhibit $50.4\times$ chattering degradation under realistic disturbances (± 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

Contents

section0	1. Introduction
section0	2. System Model and Problem Formulation
section0	3. Controller Design
section0	4. Lyapunov Stability Analysis
section0	5. PSO Optimization Methodology
section0	6. Experimental Setup and Benchmarking Protocol
section0	7. Performance Comparison Results
section0	8. Robustness Analysis
section0	9. Discussion
section0	10. Conclusion and Future Work