

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. Through rigorous Lyapunov stability analysis, we establish theoretical convergence guarantees for each controller variant. Performance benchmarking with 400+ Monte Carlo simulations reveals that STA-SMC achieves superior overall performance (1.82s settling time, 2.3

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

1 1. Introduction

1.1 1.1 Motivation and Background

In December 2023, Boston Dynamics' Atlas humanoid robot demonstrated unprecedented balance recovery during a push test, stabilizing a double-inverted-pendulum-like configuration (torso + articulated legs) within 0.8 seconds using advanced model-based control. This real-world demonstration highlights the critical need for fast, robust control of inherently unstable multi-link systems—a challenge that has motivated decades of research on the double-inverted pendulum (DIP) as a canonical testbed for control algorithm development.

The DIP control problem has direct applications across multiple domains:

1. **Humanoid Robotics:** Torso-leg balance for Atlas, ASIMO, and bipedal walkers requiring multi-link stabilization
2. **Aerospace:** Rocket landing stabilization (SpaceX Falcon 9 gimbal control resembles inverted pendulum dynamics)

3. **Rehabilitation Robotics:** Exoskeleton balance assistance for mobility-impaired patients with real-time stability requirements
4. **Industrial Automation:** Overhead crane anti-sway control with double-pendulum payload dynamics

These applications share critical characteristics with DIP: **inherent instability, underactuation** (fewer actuators than degrees of freedom), **nonlinear dynamics**, and **stringent real-time performance requirements** (sub-second response). The DIP system exhibits these same properties, making it an ideal testbed for evaluating sliding mode control (SMC) techniques, which promise robust performance despite model uncertainties and external disturbances.

Sliding mode control (SMC) has evolved over nearly five decades from Utkin's pioneering work on variable structure systems in 1977 [?] through three distinct eras: (1) **Classical SMC (1977-1995)**: Discontinuous switching with boundary layers for chattering reduction [?, ?, ?, ?, ?, ?], (2) **Higher-Order SMC (1996-2010)**: Super-twisting and second-order algorithms achieving continuous control action [?, ?, ?, ?, ?, ?, ?, ?], and (3) **Adaptive/Hybrid SMC (2011-present)**: Parameter adaptation and mode-switching architectures combining benefits of multiple approaches [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Despite these advances, comprehensive comparative evaluations across multiple SMC variants remain scarce in the literature, with most studies evaluating 1-2 controllers in isolation rather than providing systematic multi-controller comparisons enabling evidence-based selection.

1.2 Literature Review and Research Gap