Adaptive Preset-Time Tracking Control for State-Constrained Nonlinear Switching Systems Under Replay Attacks

Yancheng Yan
School of Automation Engineering
University of Electronic Science and Technology of China
Chengdu 611731, China
yanchyan@126.com

***Abstract*—This paper addresses the preset-time tracking issue for a type of state-constrained nonlinear switching systems under exogenous disturbances, subjected to replay attacks occurring in the controller-actuator (C-A) channel. Initially, a nonlinear performance function is constructed that relies exclusively on the restricted states to manage the time-varying state constraints. Moreover, by introducing a coordinate transformation and integrating it into every phase of the backstepping approach, the feasibility condition imposed on the virtual control signals is fully avoided. As a result, an innovative adaptive tracking control strategy is proposed, capable of simultaneously addressing exogenous disturbances and replay attacks. Specifically, the proposed control structure ensures that all tracking errors converge into a predefined small region around the equilibrium point within a preset time while ensuring that all signals in the closed-loop system comply with the corresponding state restrictions. Finally, the efficacy and superiority of the proposed control framework are theoretically confirmed and practically illustrated through a representative case study.**

***Index Terms*—Nonlinear system, Reply attacks, Switching system, Constraint control.**

I. Introduction

The control of nonlinear switching systems has become a prominent research area due to its broad applicability in various engineering disciplines, such as robotics, aerospace, and networked control systems. One of the critical challenges in this domain is ensuring preset-time tracking, particularly when the system is subject to both exogenous disturbances and cyber-attacks like replay attacks. These attacks, which typically occur in the controller-actuator (C-A) communication channel, can significantly degrade the performance and stability of the system.

Traditional control approaches often assume ideal operational conditions, neglecting the impact of time-varying state constraints and cyber threats. Such assumptions may lead to inadequate performance in practical applications, especially in scenarios where state constraints are critical for system safety and reliability. Addressing these issues requires innovative control strategies that can accommodate time-varying state constraints while simultaneously counteracting the adverse effects of exogenous disturbances and replay attacks.

In this paper, we propose a novel adaptive tracking control framework designed to ensure preset-time tracking for state-constrained nonlinear switching systems. The proposed approach introduces a nonlinear performance function dependent solely on the restricted states, effectively managing the time-varying state constraints. Furthermore, by integrating a coordinate transformation into each step of the backstepping method, the conventional feasibility conditions imposed on virtual control signals are eliminated, enhancing the control scheme's robustness and applicability.

II. Contributions

The primary contributions of this paper are summarized as follows:

1) **Nonlinear Performance Function:** We develop a novel nonlinear performance function tailored to handle time-varying state constraints in nonlinear switching systems. This function is constructed based exclusively on the restricted states, ensuring compliance with the system's state constraints throughout the control process.
2) **Coordinate Transformation and Backstepping Integration:** By incorporating a coordinate transformation into each phase of the backstepping technique, we effectively bypass the traditional feasibility conditions on virtual control signals. This innovation significantly enhances the flexibility and applicability of the proposed control strategy in complex systems.
3) **Adaptive Tracking Control Strategy:** We propose an adaptive tracking control strategy capable of addressing both exogenous disturbances and replay attacks. The control scheme guarantees that tracking errors converge to a predefined small region around the equilibrium point within a preset time, while ensuring that all signals within the closed-loop system adhere to the required state constraints.
4) **Theoretical and Practical Validation:** The effectiveness and superiority of the proposed control framework are rigorously validated through theoretical analysis and

a representative case study, demonstrating its practical applicability and advantages over existing methods.

III. Conclusion

In this paper, we have presented an innovative adaptive tracking control framework designed for state-constrained nonlinear switching systems under the influence of exogenous disturbances and replay attacks. The proposed approach addresses the challenges associated with time-varying state constraints by introducing a novel nonlinear performance function and leveraging coordinate transformation within the backstepping methodology. The resulting control strategy not only ensures that all tracking errors converge to a small neighborhood around the equilibrium point within a preset time but also guarantees that all signals in the closed-loop system respect the imposed state constraints. Theoretical analysis and a practical case study confirm the efficacy and superiority of the proposed framework, making it a significant contribution to the field of nonlinear switching systems control. Future work may explore extending this approach to more complex scenarios, including systems with stochastic disturbances and other forms of cyber-physical attacks.

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