

Design of Sliding Mode Control for Robot Arm Trajectory Tracking Based on Chattering Suppression

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Abstract: With the rapid development of industrial automation, robotic arms, as important automation equipment, are playing an increasingly important role in various fields such as manufacturing, logistics, and healthcare. In the practical application of robotic arms, ensuring their precise and stable movement according to the predetermined trajectory is crucial. However, a major drawback of sliding mode control is the presence of chattering, which can adversely affect the trajectory tracking performance of the robotic arm. Chattering not only causes instability in the movement of the robotic arm but also poses a potential threat to its lifespan and safety. This paper addresses the chattering issue in sliding mode control by proposing a novel control strategy that combines a disturbance observer with a composite reaching law. The main contributions of this work include the construction of a dynamic model for a dual-link robotic arm using the Lagrange function method, designing a disturbance observer to estimate and compensate for external disturbances, and developing a composite reaching law to reduce chattering. The proposed method is validated through simulation experiments, demonstrating its effectiveness in improving trajectory tracking accuracy and stability.

Keywords: Robotic arm, Chattering suppression, Disturbance observer, Composite reaching law, Sliding mode control

1. Introduction

The widespread application of robotic arms in industries demands precise trajectory tracking control due to increasingly complex tasks [1] and the shift from repetitive to customized production [2]. High precision and efficiency are essential for applications in industrial automation [3], aerospace [4], medical [5] surgery [6], and precision guidance. Sliding mode control (SMC) is favored for its robustness and low dependency on system modeling [7], but its inherent chattering issue compromises tracking accuracy and stability. To address this, a novel control strategy combining a disturbance observer with a composite reaching law is proposed, effectively suppressing chattering and improving robotic arm trajectory tracking performance.

2. Literature Review

Trajectory tracking control is crucial for robotic arms to ensure precise path adherence. Various methods, including PID, iterative learning, robust, adaptive, neural network, and sliding mode control (SMC) [8], have been developed, with SMC notable for its robustness and adaptability [9].

The disturbance observer is vital for mitigating external disturbances and model uncertainties by estimating discrepancies and providing feedback compensation. Recent advancements focus on improving estimation accuracy, real-time performance, and robustness. SMC, a nonlinear control strategy, dynamically adjusts system behavior based on its state, relying on the sliding surface and reaching law [10]. Innovations in sliding surface design, such as linear matrix inequalities and adaptive techniques, and reaching laws like exponential and power-based variants, have reduced chattering and enhanced performance, leading to more precise and stable robotic arm control.

3. Methods

3.1. Dynamic Model of the Robotic Arm

The simplified dynamic model of the robotic arm is shown as follows:

$$\tau = M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) \quad (1)$$

In the actual operation of the robotic arm, there exist internal frictions within the system, such as Coulomb friction and viscous friction. The disturbance is defined as τ_d :

$$\begin{cases} \tau + \tau_d = M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) \\ y = q \end{cases} \quad (2)$$

3.2. Disturbance Observer Design

The observer estimates the disturbances based on the difference between the actual output and the nominal model output. The estimated disturbances are then fed back into the control system to compensate for the disturbances, thereby improving the system's robustness and stability. The common form of interference observer is as follows:

$$\begin{aligned} \dot{\hat{\tau}}_d &= L(q, \dot{q})(\tau_d - \hat{\tau}_d) \\ &= -L(q, \dot{q})\hat{\tau}_d + L(q, \dot{q})\tau_d \\ &= -L(q, \dot{q})\tau_d + L(q, \dot{q})(M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) - T) \end{aligned} \quad (3)$$

The interference observer suppresses the interference from, which not only effectively reduces the impact of external interference but also significantly improves the stability of the system. The system model equation after observation can be represented by equation (4).

$$\ddot{q} = M^{-1}(q)(\tau + \varepsilon - C(q, \dot{q})\dot{q} - G(q)) \quad (4)$$

$$\begin{aligned} \dot{v}_{1i} &= \varepsilon_i^T \dot{\varepsilon}_i \\ &= -\varepsilon_i^T L_i(q_i, \dot{q}_i)\varepsilon_i \\ &\leq 0 \end{aligned} \quad (5)$$

The stability analysis shows that the disturbance observer is stable.

3.3. Composite Reaching Law Design

A composite reaching law is proposed to reduce chattering in sliding mode control. The reaching law combines a power term and a variable speed term to achieve fast convergence and reduce chattering.

The stability of the proposed reaching law is analyzed using the Lyapunov function, and its effectiveness is validated through simulation experiments.

$$\dot{x} = f(x, u, t) \quad (6)$$

$$s(x, t) = s(x_1, x_2, \dots, x_n, t) = 0 \quad (7)$$

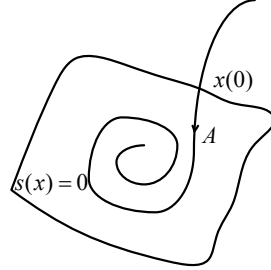


Figure 1: Process of System State Approaching Sliding Mode Surface

By innovatively combining the power term and the variable speed term, this paper designs a novel combination approach law that can provide a faster approach speed when the system is far away from the sliding surface while significantly reducing the chattering phenomenon when the system approaches the sliding surface. In addition, by adjusting relevant parameters, the most suitable parameter values for the current system state can be selected to achieve optimal system performance. This approach law also has adaptability, which can automatically adjust according to changes in the system state to adapt to different control requirements and environmental conditions. It is proven that the initial position of the system state can reach the sliding surface at any position within a finite time.

4. Results and Discussion

To evaluate the effectiveness of a disturbance observer in suppressing interference for robotic arm trajectory tracking, a series of comparative experiments will be conducted. The experiments compare two scenarios: trajectory tracking performance without the disturbance observer and performance after its integration. This comparison will demonstrate the observer's role in reducing system interference and enhancing tracking accuracy.

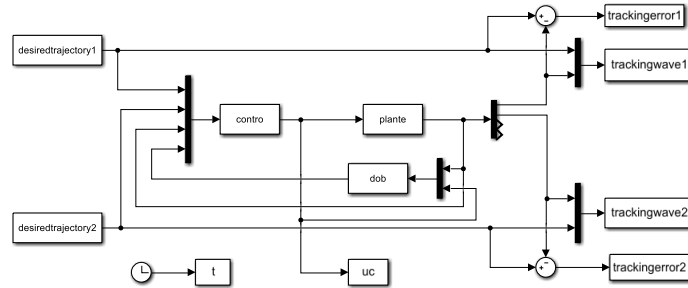


Figure 2: Schematic diagram of trajectory-tracking simulation

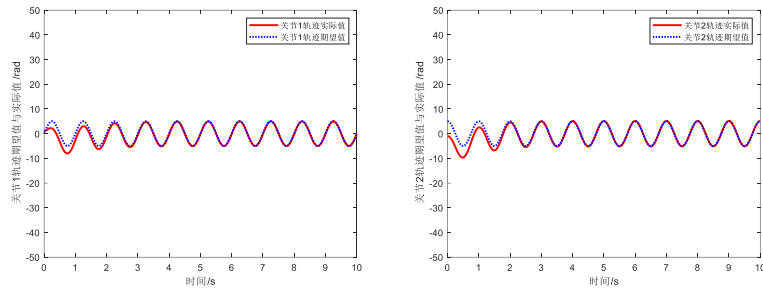


Figure 3: Trajectory tracking effect without adding disturbance observer

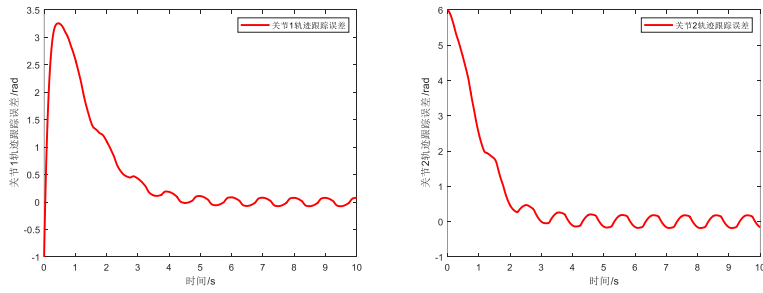


Figure 4: Trajectory tracking error without adding disturbance observer

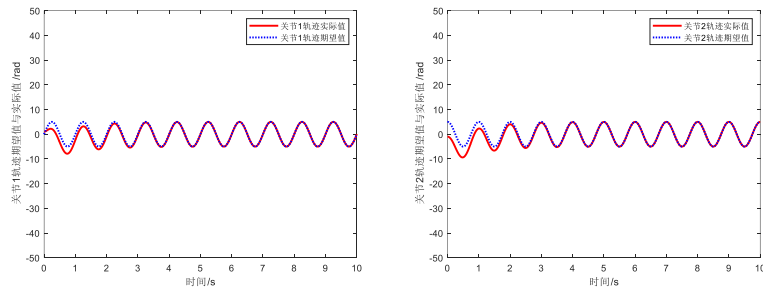


Figure 5: Trajectory tracking effect with added disturbance observer

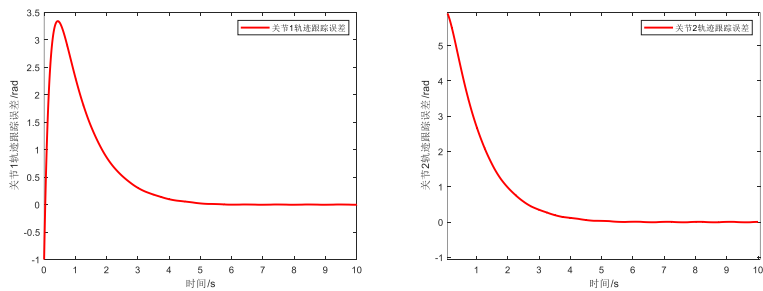


Figure 6: Trajectory tracking error with added disturbance observer

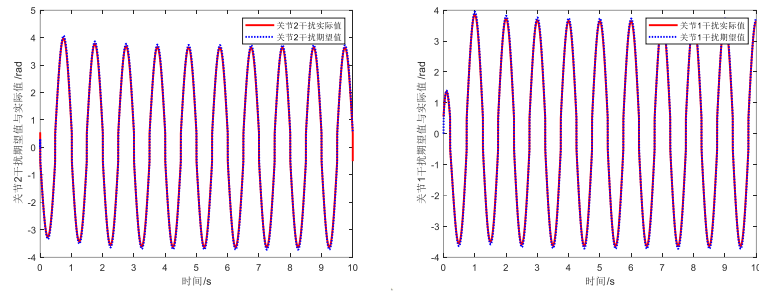


Figure 7: Tracking effect of interference observer on interference

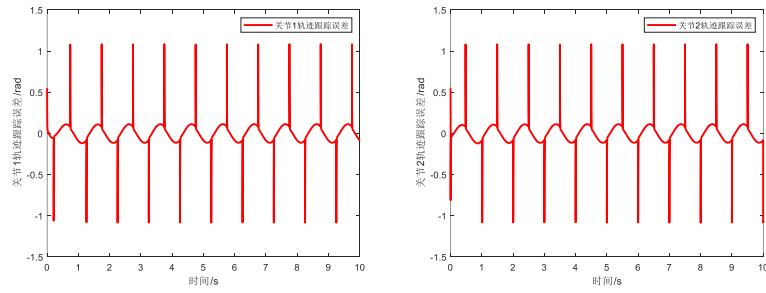


Figure 8: Error in Interference Observations

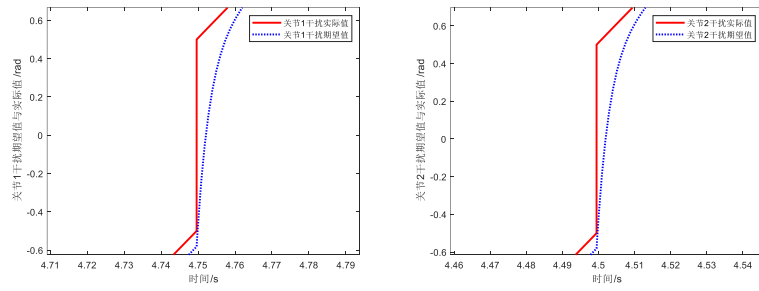


Figure 9: Local Enlarged View of Interference Observation

We used the Simulink module of MATLAB software to build a simulation platform and establish a second-order robotic arm model for simulation.

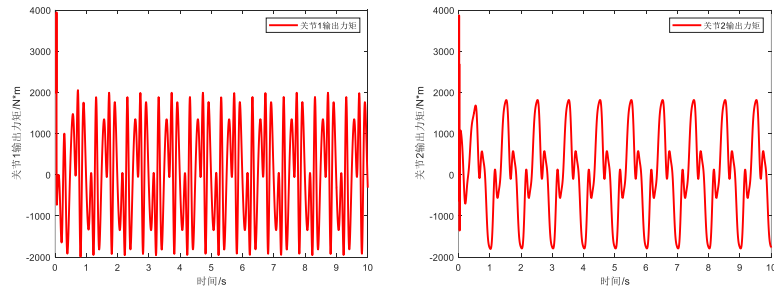


Figure 10: Output torque of sliding mode controller using combined approaching law

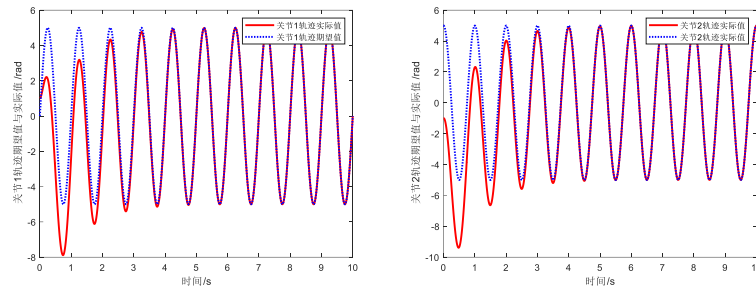


Figure 11: Trajectory tracking performance of sliding mode controller using exponential convergence law

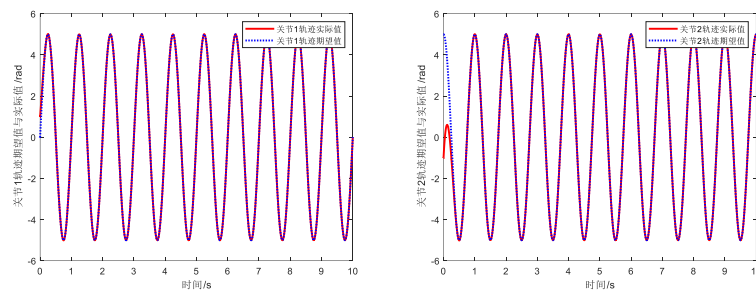


Figure 12: Trajectory tracking performance of sliding mode controller using combination approach law

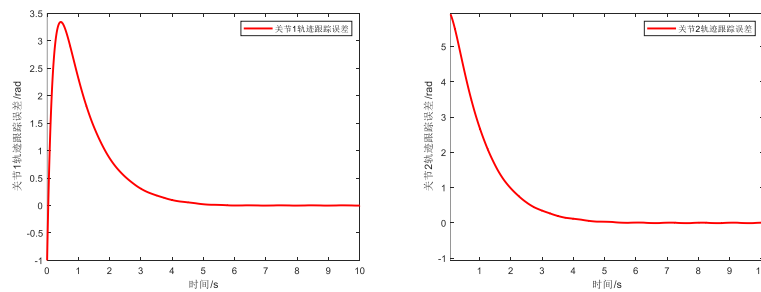


Figure 13: Trajectory tracking error of sliding mode controller using exponential convergence law

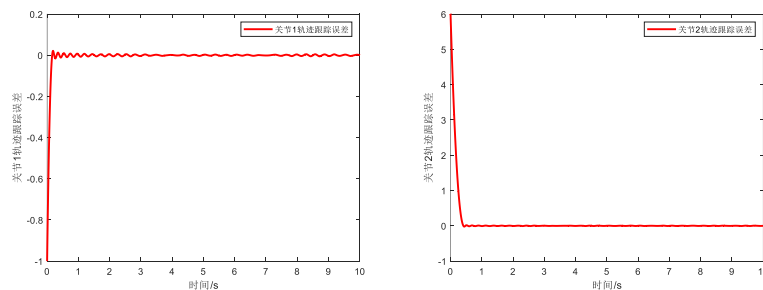


Figure 14: Tracking Error of Sliding Mode Controller Using Combination Approach Law

A robotic arm system with a disturbance observer demonstrates superior trajectory tracking performance compared to one without. Analysis of tracking and error curves reveals that both systems stabilize within ~ 5 seconds, but the observer-equipped system exhibits reduced trajectory fluctuations during convergence and significantly lower steady-state error. This highlights the observer's

effectiveness in suppressing disturbances and enhancing accuracy, stability, and anti-interference capability, optimizing both dynamic and steady-state performance.

A notable error mutation in the disturbance tracking error data (Figure 9) arises from the defined disturbance signal, which combines rectangular waves and sine functions, causing abrupt changes. The observer exhibits a lag in responding to such sudden disturbances, leading to error peaks. This issue stems from suboptimal parameter tuning, which also impacts adjustment time and overshoot. Future parameter adjustments must account for the robotic arm's load, component capacity, and performance requirements to balance torque reduction with acceptable response characteristics.

Experimental results demonstrate that the sliding mode controller with the combined reaching law outperforms the exponential reaching law in terms of adjustment time, overshoot, stabilization time, and error reduction, confirming its superior performance.

5. Conclusion

This paper introduces a novel control strategy for robotic arm trajectory tracking, integrating a disturbance observer with a composite reaching law. The method effectively mitigates chattering in sliding mode control, enhancing tracking accuracy and stability. Simulation results confirm its efficacy in reducing disturbances and chattering, highlighting its potential for industrial automation and other applications. To further improve the system's response to sudden disturbances, the disturbance observer model can be enhanced, such as by employing a super-twisting sliding mode observer. This observer excels in fast tracking and precise disturbance estimation, significantly boosting the system's disturbance suppression capabilities and optimizing both stability and dynamic performance.

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