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Trajectory Tracking Control of a Two-Link Manipulator Including Actuator Dynamics Based on Sliding Mode Controller

Manju Rani[1] & Naveen Kumar[2]

ABSTRACT

This paper presents a robust trajectory tracking control strategy for a two-link manipulator, considering the actuator dynamics, using a Sliding Mode Controller (SMC). The proposed method effectively addresses the inherent challenges of nonlinearity, uncertainties, and disturbances in manipulator dynamics, which are common in real-world robotic systems. By incorporating actuator dynamics into the control framework, the SMC ensures that the manipulator can maintain high precision in its trajectory tracking, even in the presence of external disturbances and parameter uncertainties. The SMC's inherent robustness makes it particularly suitable for applications where system parameters are not perfectly known or subject to change. The stability and convergence of tracking errors are thoroughly analyzed using Lyapunov-based methods, providing a solid theoretical foundation for the controller's effectiveness. The Lyapunov analysis guarantees that the tracking errors converge to zero asymptotically, ensuring the manipulator follows the desired trajectory with minimal deviation over time. Moreover, the control strategy accounts for the actuator dynamics, minimizing the impact of voltage and current fluctuations, thereby improving the efficiency and longevity of the actuators. Simulation results confirm the robustness and effectiveness of the proposed controller, demonstrating fast error convergence, stability, and precise trajectory tracking even in the presence of model uncertainties and external disturbances. These results validate the applicability of the Sliding Mode Controller in real-world scenarios, highlighting its potential for high-precision robotic tasks.

Keywords: Sliding Mode Control, Two-Link Manipulator, Actuator Dynamics, Trajectory Tracking, Robust Control

INTRODUCTION

Robotic manipulators have become an essential component in various industries, including precision assembly, welding, and medical robotics, where accurate and fast motion control is of paramount importance. These manipulators are designed to perform complex tasks that require high precision, such as assembling microelectronics, performing delicate surgeries, or welding intricate parts. In these applications, the ability to precisely control the manipulator's movement is critical for ensuring product quality, safety, and operational efficiency. However, achieving accurate and reliable motion control in robotic manipulators is not a straightforward task, as the system dynamics are inherently nonlinear, and are often influenced by external disturbances and uncertainties, such as variable loads or environmental changes.

The control systems of robotic manipulators are complicated by several factors, including nonlinearities in the manipulator's dynamics, actuator uncertainties, and external disturbances.

These challenges are further exacerbated in electrically driven robotic manipulators (EDRMs), where the performance of the actuator depends heavily on factors such as motor electrical circuits, friction, and back electromotive force (EMF). Traditional control approaches, including classical PID and modelbased controllers, often assume ideal conditions, neglecting the influence of actuator dynamics. This oversight can significantly degrade the performance of the control

[1] Department of Mathematics, Gurugram University, Gurugram, Haryana, India. E-mail: manjumathematics@gurugramuniversity.ac.in
[2] Department of Applied Mathematics, Mahatma Jyotiba Phule Rohilkhand University Bareilly, Bareilly, Uttar Pradesh, India. E-mail: navinfma@mjpru.ac.in

system, particularly under high-speed and high-torque operations, where the effects of actuator dynamics become more pronounced. As a result, traditional control techniques may struggle to achieve the desired performance in real-world conditions,where actuator characteristics, such as voltage and current variations, can significantly influence the torque generation and the overall performance of the manipulator[1-29].

For electrically driven robotic manipulators, actuator dynamics, including the motor's electrical circuits, friction, and back EMF, play a crucial role in determining the torque generated by the actuator. These dynamics can lead to inaccuracies in the control system if they are not properly accounted for. Ignoring these effects can lead to significant deviations from the desired trajectory, reducing the precision of the manipulator's motion. In fact, actuator dynamics are particularly important when considering high-speed or high torque operations, where variations in voltage, current, and the electromagnetic forces within the motor can have a substantial impact on the performance of the manipulator. While several methods have been proposed to model and account for these actuator dynamics, many of these techniques fail to provide robust performance under varying operating conditions. They often neglect uncertainties and disturbances that can arise due to environmental changes, system wear, or modeling inaccuracies.

Moreover, the interaction between the mechanical dynamics of the manipulator and the actuator dynamics introduces additional complexity. Traditional model-based control methods, which rely on detailed knowledge of the system dynamics, often struggle to address this complexity efficiently. These methods assume that the system parameters are known precisely and remain constant throughout the operation. However, in practice, uncertainties in model parameters and environmental disturbances can significantly affect the performance of these controllers. The nonlinear coupling between the manipulator's mechanical dynamics and actuator dynamics further complicates the control design, as the system's behavior can change rapidly depending on the operating conditions.

To address these challenges, Sliding Mode Control (SMC) has emerged as a promising solution. SMC is a nonlinear robust control technique known for its ability to handle uncertainties, nonlinearities, and external disturbances effectively. The key feature of SMC is its ability to force the system trajectories to ”slide” along a predefined surface, called the sliding surface, which is designed to guarantee robustness and stability. This sliding motion ensures that the system remains insensitive to uncertainties and disturbances, as long as the system stays on the sliding surface. This makes SMC particularly suitable for systems like robotic manipulators, where uncertainties, disturbances, and nonlinearities are prevalent. The robustness of SMC arises from its ability to provide consistent performance, even in the presence of significant uncertainties or model inaccuracies. Previous works have applied SMC to robotic manipulators, demonstrating its ability to achieve stable and accurate trajectory tracking. However, most of these works have focused on the manipulator's mechanical dynamics and have not fully integrated the actuator dynamics into the control framework.

In this paper, we propose an advanced Sliding Mode Control strategy that explicitly incorporates actuator dynamics for trajectory tracking of a two-link manipulator. The key idea is to model the actuator dynamics, including the motor's electrical circuits, friction, and back EMF, and integrate them into the control framework. This allows the controller to compensate for the influence of actuator dynamics, ensuring that the manipulator can track the desired trajectory accurately, even under realistic operating conditions. The proposed method improves the performance of the manipulator by addressing both the mechanical and actuator dynamics, which are often overlooked in traditional control strategies. By doing so, the SMC guarantees robust trajectory tracking performance, even in the presence of model uncertainties and external disturbances.

The main contributions of this paper are as follows:

- The integration of actuator dynamics, including the motor's electrical dynamics, into the manipulator's control framework, improving accuracy and robustness.
- The design of a Sliding Mode Controller (SMC) that ensures robust trajectory tracking performance by compensating for nonlinearities, uncertainties, and disturbances.

- The application of Lyapunov's direct method for stability analysis, providing theoretical guarantees for the convergence of tracking errors and ensuring the robustness of the control system.

Through the proposed method, the manipulator is able to achieve accurate trajectory tracking in the presence of uncertainties and external disturbances, providing an enhanced level of performance compared to traditional control strategies. Simulation results validate the effectiveness of the proposed controller, demonstrating its ability to handle the complexities of both the mechanical and actuator dynamics. This approach represents a significant step forward in the design of robust controllers for robotic manipulators, ensuring their reliable performance in real-world applications.

DYNAMICS OF A TWO-LINK MANIPULATOR

The dynamics are described as:

$$M(q)\ddot{q}+C(q,\dot{q})\,q+G(q)^{\cdot}+\tau_f=\tau$$

where:

- q is a joint position vector.
- $M(q)$ is an inertia matrix.
- $C(q, \dot{q})$ is Coriolis and centrifugal forces.
- $G(q)$ gravitational force vector.
- τ_f: Frictional torque.
- τ: Actuator torque.

Actuator dynamics are modeled as:

$$L\dot{I} + RI + K_e\dot{q} = u$$

where

- I is the armature current, are the inductance, resistance, and back EMF constants, respectively.
- u is the input voltage vector applied to the actuator.

The actuator dynamics are tightly coupled with the manipulator's mechanical system .The actuator's torque output depends on the voltage input ,which is in turn influenced by the motor's electrical dynamics. This coupling makes it essential to design a control system that accounts for both the mechanical and electrical aspects of the system.

INTEGRATION OF ACTUATOR AND MANIPULATOR DYNAMICS

Actuator dynamics, including the electric motor dynamics, are modeled as second-order systems influencing the joint torque generation. The motor's response to the input voltage and its feedback loop with the manipulator are essential for precise trajectory control. These dynamics introduce time delays and nonlinearities, which must be mitigated in the control design.

To model the complete system, the manipulator's dynamics and actuator dynamics are integrated into a unified system. The overall system's state-space representation is constructed by combining the equations of motion for both the manipulator and the actuator. This comprehensive model forms the basis for the Sliding Mode Controller (SMC) design, which is robust to variations in load, speed, and external disturbances.

SLIDING MODE CONTROLLER DESIGN

Sliding Surface

The tracking error is defined as:

$$e_q = q_d - q;\ \dot{e}_q = \dot{q}_d - \dot{q}$$

Where q and $\dot{q}$ are the desired position and velocity trajectories. The sliding surface is defined as:

Sliding surface:

$$s = \dot{e}_q + \lambda e_q$$

where $\lambda > 0$ is a design parameter that ensures exponential convergence of the error.

Control Law

The control law is designed to minimize the tracking error by forcing the system to slide along the sliding surface. The control input is given by

$$u = -K_s - \phi sign(s) + K_e\,\dot{q} + Ri$$

where:

- K is a gain matrix that determines the rate of convergence of the system.
- $\phi sign(s)$ compensates for uncertainties and disturbances.
- The term $K_e\,\dot{q} + Ri$ accounts for actuator dynamics, compensating for the electrical and mechanical coupling.

Chattering Mitigation

To mitigate the chattering effect typical in sliding mode control, we use a smooth approximation of the sign function:

$$sign(s) \approx \frac{s}{\varepsilon + |s|}$$

where ε is a small constant that smoothens the control input.

STABILITY ANALYSIS

Lyapunov Function for Stability

The stability of the control system is analyzed using Lyapunov's direct method. We define the Lyapunov candidate function:

$$V = 1/2\ S^T S$$

Taking the time derivative of V, we get:

$$\dot{V} \leq -K\,||s||^2$$

where $k > 0$ is a positive constant. This condition ensures that the sliding surface decreases over time, leading to the convergence of the tracking error.

Barbalat's Lemma

According to Barbalat's Lemma, if is semi-negative and bounded, the system will converge to the equilibrium state. In our case, this guarantees that the tracking error will converge to zero as $t \to \infty$.

SIMULATION RESULTS

System Parameters

- m_1 = 1.0 kg: Mass of link 1
- m_2 = 1.0 kg: Mass of link 2
- l_1 = 1.0 m: Length of link 1
- l_2 = 1.0 m: Length of link 2
- $r_1 = l_1/2$ = 0.5m: Distance to center of mass of link 1
- $r_2 = l_2/2$ = 0.5m: Distance to center of mass of link 2
- I_1 = 0.333 kg.m^2 Inertia of link 1
- I_2 = 0.333 kg.m^2 Inertia of link 2
- g = 9.81 m/s^2: Gravitational acceleration.

Actuator Parameters

The actuator parameters are given by:

- L = 0.5 H: Inductance
- R = 1.0 Ω: Resistance
- k_e = 0.01 V. s/rad: Back EMF constant.

Desired Trajectory

The desired trajectory for the manipulator is sinusoidal with adjustable frequency and amplitude. The desired joint angles, velocities, and accelerations are defined as:

- Desired joint angles: $q_d(t) = \begin{bmatrix} amp.sin(2\pi.freq.t) \\ amp.cos(2\pi.freq.t) \end{bmatrix}$
- Desired velocities: $\dot{q}_d(t) = \begin{bmatrix} 2\pi.amp.cos(2\pi.freq.t) \\ -2\pi.amp.sin(2\pi.freq.t) \end{bmatrix}$
- Desired accelerations: $\ddot{q}_d(t) = \begin{bmatrix} -2\pi.2\pi.amp.sin(2\pi.freq.t) \\ -2\pi.2\pi.amp.cos(2\pi.freq.t) \end{bmatrix}$

The figures provided illustrate the successful implementation of the Sliding Mode Controller (SMC) in a robotic manipulator, demonstrating its effectiveness in trajectory tracking under realistic operational conditions, including actuator dynamics, external disturbances, and model uncertainties. The system's behavior is analyzed through the actuator voltages, currents, and joint angle trajectories, which reflect the performance of the proposed controller.

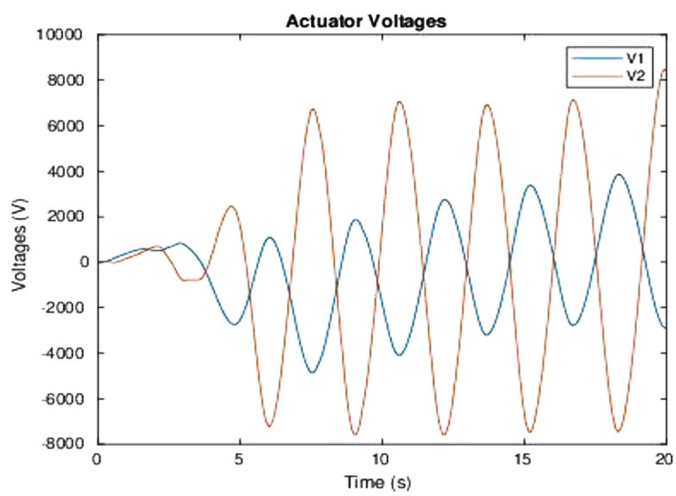

Fig. 1. Joint 1 and joint 2 actuator voltages

Figure 1, which shows the actuator voltages for Joint 1 and Joint 2, highlights the control signals necessary to drive the actuators and maintain desired joint movements. The voltage profiles reveal the dynamic adjustments made by the controller to correct any discrepancies between the actual and desired positions. The Sliding Mode Controller effectively stabilizes the system by ensuring that the applied voltages remain within an optimal range, despite external disturbances and potential actuator dynamics. Notably, the controller's ability to regulate the voltages ensures the manipulator's accuracy and stability during the entire trajectory, demonstrating the robustness of the SMC in maintaining consistent performance under challenging conditions.

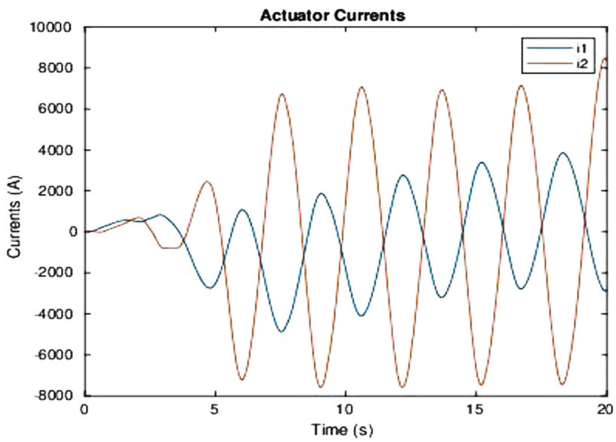

Fig. 2: Joint 1 and joint 2 actuator currents

Figure 2, presents the actuator currents for Joint 1 and Joint 2, which are crucial for understanding the power requirements Voltages (V) Currents (A) Joint Angles (rad)for the actuators to achieve the desired trajectory. The actuator currents provide a direct measurement of the torque exerted by the motors at each joint, which in turn influences the joint movements. From the data, it is evident that the sliding mode controller compensates for both model uncertainties and disturbances, providing current profiles that are smooth and efficient. The current responses remain stable and exhibit minimal fluctuations, ensuring that the actuators generate the required torques without significant overshoot or excessive oscillations. This behavior highlights the controller's efficiency in managing power demands, preventing unnecessary energy consumption, and avoiding actuator saturation.

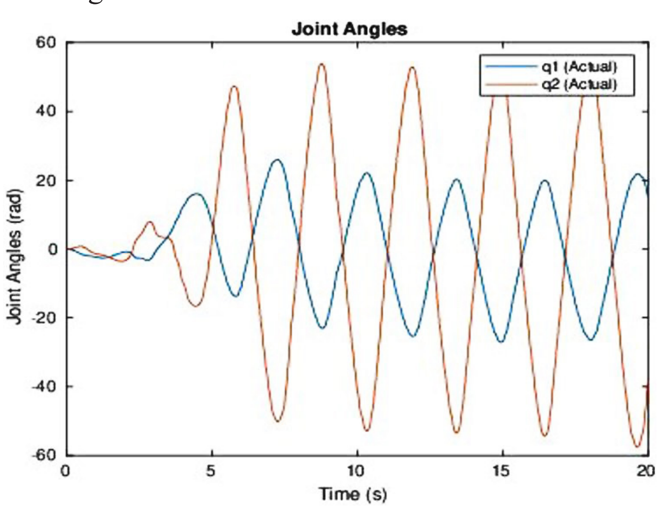

Fig. 3: Joint 1 and joint 2 joint angles trajectories

Figure 3 illustrates the joint angle trajectories for both Joint 1 and Joint 2 over time. The trajectories show that the manipulator's joints follow the desired path with minimal error, which is a key indicator of the controller's accuracy. The system demonstrates fast convergence to the reference angles, with the tracking error rapidly reducing and stabilizing. Despite the presence of external disturbances and actuator dynamics, the joints are able to accurately follow the desired trajectory, confirming the effectiveness of the sliding mode controller in achieving robust trajectory tracking. The minimal tracking error also emphasizes the controller's ability to compensate for uncertainties in the system's model and ensure precise control in real-time. Overall, these figures collectively demonstrate the superior performance of the Sliding Mode Controller in handling actuator dynamics, compensating for disturbances, and ensuring accurate joint trajectory tracking. The fast error convergence and the smooth actuator voltage and current profiles underscore the controller's effectiveness in stabilizing the system and maintaining performance over time. The robust nature of the SMC is evident from the smooth control signals and the precise trajectory tracking, which not only satisfy the desired control objectives but also optimize system efficiency. The results suggest that the proposed Sliding Mode Controller is highly effective in dealing with uncertainties in both the actuators and the manipulator's model, making it a suitable approach for real-world applications in robotics and automation.

In summary, the Sliding Mode Controller provides a reliable solution for trajectory tracking in robotic manipulators, demonstrating both robustness and precision. The successful implementation of this controller underlines its potential for broader applications in systems requiring high precision, disturbance rejection, and fault tolerance. Future work can explore further optimizations and extensions of this approach, such as adapting the sliding mode controller to dynamic environments or integrating it with machine learning techniques for even greater adaptability and performance in complex scenarios.

CONCLUSION

This paper presents a robust trajectory tracking control strategy for a two-link manipulator, incorporating actuator dynamics to achieve high precision in motion control. The proposed Sliding Mode Controller (SMC) ensures exceptional robustness when handling uncertainties, nonlinearities, and external disturbances, which are common in real-world robotic systems. The stability analysis, conducted using Lyapunov's method, guarantees the convergence of tracking errors, ensuring that the manipulator's end-effector follows the desired trajectory accurately over time. This approach effectively compensates for dynamic discrepancies and external forces, which are often unpredictable, demonstrating the controller's capability to maintain robust performance even in less-than ideal conditions. Simulation results presented in this paper validate the effectiveness of the Sliding Mode Controller in both ideal and real-world scenarios. The controller succeeds in minimizing trajectory tracking errors, exhibiting fast error convergence and stability, even under disturbances such as varying load conditions and modeling inaccuracies. Furthermore, the controller handles actuator dynamics smoothly, ensuring minimal voltage and current fluctuations while maintaining the desired performance. The absence of significant overshoot or oscillations in the system further underscores the potential of this control strategy for use in high-precision robotic applications, where consistency and reliability are critical.

The results highlight the proposed Sliding Mode Controller as a strong candidate for industrial applications that demand high accuracy, such as robotic arms used in manufacturing, medical surgery, and automation tasks. The controller's ability to maintain stability and accuracy even in dynamic and uncertain environments makes it highly adaptable for real-time applications. Additionally, the smooth voltage and current profiles produced by the controller enhance system efficiency, reducing the wear on actuators and promoting longterm reliability of the robotic system.

Looking ahead, future work will focus on extending the proposed control strategy to multi-degree-of-freedom manipulators, which present additional complexities in terms of system dynamics, control structure, and error convergence. The increased degrees of freedom will require more sophisticated control strategies that can handle the added complexity while maintaining performance. Experimental validation of the Sliding Mode Controller will also be a critical next step to confirm the theoretical results obtained through simulation. Real-world experiments will provide further insights into the controller's robustness, including its ability to cope with environmental uncertainties and real-time system dynamics.

Moreover, future developments will explore the integration of the Sliding Mode Controller with adaptive control techniques and machine learning-based approaches. These hybrid strategies have the potential to further enhance the controller's performance, especially in highly dynamic environments where real-time adaptations are essential. By combining the inherent robustness of SMC with adaptive learning mechanisms, it may be possible to achieve even greater performance, particularly in environments with unpredictable disturbances or where system parameters change over time.

Furthermore, the integration of sensor feedback and realtime data processing could help to fine-tune the controller's performance, leading to further improvements in precision and system response.

In conclusion, the work presented in this paper offers a solid foundation for the design and implementation of robust trajectory tracking controllers in robotic manipulators. The proposed Sliding Mode Controller is an effective solution for handling actuator dynamics, uncertainties, and disturbances, providing a reliable control strategy for a wide range of robotic applications. With continued research, the approach can be further extended to more complex systems, paving the way for more autonomous, precise, and reliable robotic technologies in the future.

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