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Original Article

Study on Effective Control Strategies of a Multi-DoF Robot Arm Model: A Sliding Mode Control Method

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Abstract *- Robots have played a crucial role in industrial automation and control. However, they are inherently multivariable, nonlinear, and subject to uncertainties, making their control a complex challenge. Consequently, advancing control algorithms for industrial robots is a critical research imperative. This paper presents a novel sliding mode control (SMC) algorithm for a multi-degree-of-freedom robotic system, specifically a four-degree-of-freedom robotic arm. The proposed approach ensures rapid convergence, robust stability, and strong disturbance rejection, even in the presence of parameter variations and external disturbances. A key advantage of SMC lies in its ability to enforce system trajectory adherence to the desired sliding surface, thereby enhancing position and velocity control accuracy. However, a well-known limitation of traditional SMC is the chattering phenomenon, which can degrade system stability and operational efficiency. To address this issue, this study introduces an optimized controller design that effectively balances stability, disturbance rejection, and smooth dynamic response. The findings of this research contribute to the broader application of SMC in industrial robotics, offering improved performance and reliability in practical implementations.*

Keywords *- 4-DoF robot arm, SMC, FLC, PSO, Optimization.*

1. Introduction

A four-degree-of-freedom (DoF) robotic arm, consisting of four articulated joints, is designed to perform various tasks such as pick-and-place, operations, welding, and assembly. Typically anchored at its base, the articulated structure of a robotic arm facilitates versatile and precise manipulation. Robotic arms are widely employed in various industrial sectors [1], including automotive manufacturing and food processing, offering significant advantages.

Key benefits such as high precision, the capacity for continuous operation, and the ability to handle heavy payloads make them well-suited for complex, high-accuracy tasks. Consequently, industrial robots are increasingly replacing manual labor in modern manufacturing environments. Continued advancements and integration in robotics are expected to play a pivotal role in further enhancing operational efficiency and accuracy. Often designed to functionally mimic the human arm, robotic arms utilize articulated joints to execute pre-programmed movements with precision [1, 2].

Effective control of multi-degree-of-freedom (DoF) robotic arms, essential in modern automation, necessitates a robust control architecture. This architecture must process input commands and sensor feedback signals to enable task execution, scaling complexity from basic position tracking to advanced trajectory optimization and dynamic compensation.

Servomotors are commonly chosen as actuators for typical industrial four-DoF robotic arms due to their high precision in controlling position, velocity, and torque, ensuring smooth, stable motion. However, controlling these manipulators effectively presents challenges due to inherent nonlinearities and uncertainties, which can limit the performance of traditional linear controllers like Proportional-Integral-Derivative (PID) and Proportional-Integral (PI).

Consequently, advanced strategies such as Fuzzy Logic Control (FLC) and Sliding Mode Control (SMC) are increasingly investigated [3, 4]. The FLC adeptly handles nonlinear dynamics without requiring precise system models, while SMC offers superior robustness against disturbances and parameter variations. Despite its robustness, the practical application of SMC can be complicated by implementation issues like chattering. This study, therefore, focuses on comparing the performance of PID, PI, FLC, and SMC controllers via simulation on a 4-DoF robotic arm to identify a reliable and efficient control solution suitable for industrial use.

The PID controller is a well-established feedback control technique that uses proportional, integral, and derivative actions to achieve fast response, reduce steady-state error, and suppress oscillations. However, its performance deteriorates under nonlinear conditions or when model uncertainties arise. The PI controller, a simplified version that omits the derivative term, is easier to implement and can maintain system stability, though often at the expense of slower transient performance.

The FLC, an intelligent control methodology, does not require an exact mathematical model. Instead, it leverages heuristic rules and fuzzy logic principles to manage nonlinear systems effectively [5, 6]. While FLC provides flexibility and robustness, the design of an optimal fuzzy rule base and membership functions remains a challenging task.

Although numerous studies have applied PID, PI, and FLC techniques to robotic control, these methods often assume idealized conditions and are limited in robustness against external disturbances and system nonlinearities. Furthermore, many existing applications focus on robotic arms with fewer degrees of freedom or only analyze control under nominal system parameters.

This paper details a novel application of the SMC for a 4-DoF robotic arm, specifically engineered to mitigate the challenges posed by nonlinear system dynamics, parametric uncertainties, and external disturbances inherent in such manipulators. While the theoretical principles of SMC are well-documented in control literature, comprehensive studies focusing on its practical implementation nuances and rigorous performance validation for multi-joint robotic arms, particularly via simulation platforms like MATLAB / SIMULINK, remain relatively scarce.

Consequently, this study aims to contribute to the field through the following specific objectives:

- To conduct a comparative performance analysis evaluating SMC against both classical control strategies (PID) and another advanced technique (Fuzzy Logic Control - FLC) applied to multi-DoF robotic arm control.
- To present a systematic design methodology and implementation framework for SMC tailored specifically for multi-joint robotic applications.
- To rigorously evaluate the effectiveness and robustness of the proposed SMC algorithm using MATLAB / SIMULINK simulations that incorporate representative system uncertainties and external disturbance models.

The findings derived from the simulation results demonstrate that the implemented SMC strategy affords enhanced robustness, superior trajectory tracking precision, and more effective vibration suppression compared to the benchmarked conventional and FLC methodologies. These results strongly suggest that SMC represents a viable and potentially advantageous control solution for deployment in demanding real-world industrial robotic systems.

The remainder of this paper is structured as follows: Section 2 outlines the control methodology for the multi-DoF robotics arm, detailing a step-by-step procedure for designing the SMC strategy. Section 3 presents the simulation results conducted in MATLAB/SIMULINK to evaluate the effectiveness of the proposed approach. Finally, Section 4 concludes the paper with a summary of key findings and suggestions for future works.

2. Control Methodology for a Robot Arm

One of the most important characteristics of the SMC is its ability to impart robustness to nonlinear systems by applying a discontinuous control signal. This signal, typically a set-valued function, drives the system states towards a predefined sliding surface, effectively forcing the system to operate along a desired trajectory. The discontinuous nature of the state feedback control law is fundamental to SMC's operation.

Consider a nonlinear system with the following typical representation:

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

Where:

- $q, \dot{q}, and\ \ddot{q}$ are the 4×1 vectors representing the position, velocity, and acceleration of the four robot joints, respectively.
- τ is a 4×1 torque vector acting on the joints;
- $M(q)$: Inertia matrix;
- $C(q,\dot{q})$: Coriolis matrix;
- $G(q)$: Gravity vector;
- $F(\dot{q})$: Friction vector from the robot's dynamics;
- τ_d : External torque acting on the system.

For convenience in control design, define the state variables as expressed in Equation (2). Let the control input signal be $u = \tau$. Then, derive a more compact state-space representation of the system:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dots\dots\dots. \\ \dot{x}_{n-1} = x_n \\ \dot{x}_n = f(x) + g.x(u) + d \\ y = x_1 \end{cases} \quad (2)$$

Where u is the control input signal, *y* is the output signal, *x* is the state vector, and *d* is the disturbance signal. Assuming that $1/g(x)$, $f(x)$ and d are bounded functions, the control problem is formulated as follows:

"Determine the control input such that the output y tracks the reference signal r".

To design the SMC to be applied to a multi-DoF robot model, let us consider the schematic diagram of a typical SMC controller, as shown in Figure 1.

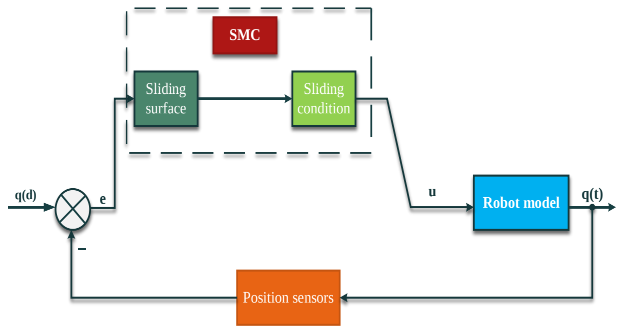

Fig. 1 A schematic diagram of a typical SMC controller

This work proposes a procedure to design the SMC controller through the four steps below.

Step 1: Choose the sliding surface

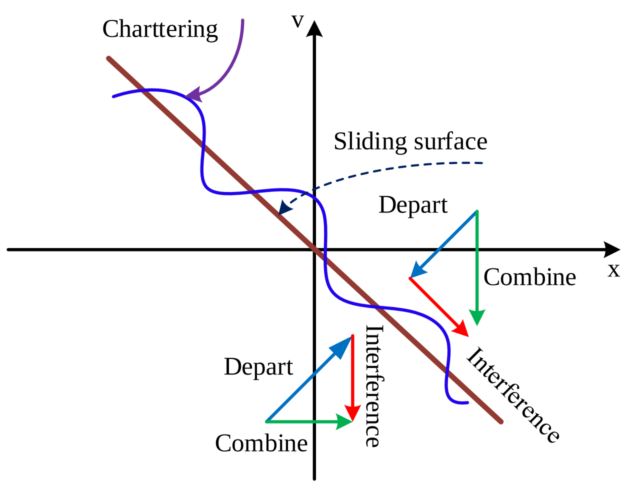

Fig. 2 An illustration of the SMC plane

The sliding surface [7] is defined as a linear equation of the form $s = bx_1 + x_2 = 0$, $x_2 = \dot{x}_1 \Leftrightarrow x_2 = -bx_1 \Leftrightarrow \dot{x}_1 = -bx_1$ where x_1 it represents the position x_2 and represents the velocity. If the sliding surface is not equal to 0 it implies that the system state does not lie on the sliding surface; instead, it could be located anywhere else in the phase plane. The control objective is to design a controller that ensures the system state always converges towards the sliding surface ($s \to 0$) (see Figure 2).

Step 2: Sliding mode control law

The sliding mode control law ensures that the system state converges to the sliding surface [8, 9] and then remains on it. A commonly used sliding mode control law is expressed in Equation (3):

$$u = u_{eq} + u_{sw} \tag{3}$$

Where u_{eq} is determined by solving the sliding surface equation $S(x) = 0$; u_{sw} is the switching control component, which is typically implemented as a sign function: $\dot{s} = -\eta.sign(s)$.

If we want to fine-tune the rate of s^{g} that, the speed at which the states converge to 0, by adding a coefficient: $\dot{s} = -\eta.sign(s)$ where η is the amplification factor that modifies the magnitude of the deviation and is responsible for the balance discussed earlier.

The condition to ensure convergence is to employ the Lyapunov criterion to guarantee the system's stability:

$$V = \frac{1}{2} S^2(x) \tag{4}$$

and the convergence condition is:

$$\dot{V} = S.\dot{S} \tag{5}$$

This is equivalent to two following cases:

(a) If S > 0 then $\dot{S} < 0$

(b) If S < 0 then $\dot{S} > 0$.

If the above two control conditions are satisfied, then regardless of the state, the trajectories will always move toward the sliding surface. This means we can define a convergence condition, or in other words, S is always directed opposite to $\dot{S}$. This is precisely the controller that we need to implement.

Step 3: Addressing the noise issue

Chattering may occur due to the u_{sw} component. Instead of using the sign function, which results in continuous switching, we can replace it with a new theta function:

$$\theta = \begin{cases} 1 : S > \phi \\ \dfrac{S}{\phi} : |S| \le \phi \\ -1 : S > \phi \end{cases} \tag{6}$$

Step 4: Simulation and experimental verification

It is necessary to perform simulations to assess the control performance, conduct experiments, and fine-tune the controller parameters.

3. Simulation Results and Evaluation

Following the development of the SMC, MATLAB/SIMULINK simulations are essential for validating its performance before practical application. Obviously, MATLAB's capabilities allow for detailed analysis of the SMC's stability, robustness, and overall effectiveness within a nonlinear dynamic system.

Figure 3 shows the simulation model built in the MATLAB/SIMULINK environment. Remember that the dynamic model of a 4-DoF arm robot is designed based on Equations (1) and (2). Meanwhile, the sliding block representing the SMC is built based on the four steps proposed earlier.

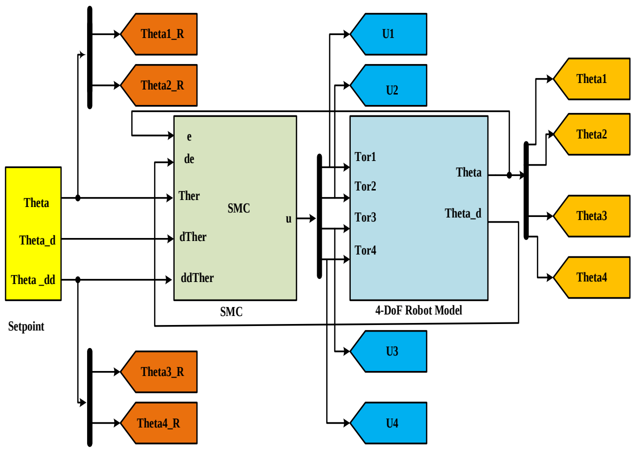

Fig. 3 MATLAB/SIMULINK simulation block diagram

Simulation parameters for the SMC's sliding surface coefficient: $s = bx_1 + x_2$ with the slope parameter $b = 150$. Constant-Speed Reaching Law: $\dot{s} = -\eta.sign(s) - k.s$ where the amplification factor is $\eta = 0.5$, and $k = 170$. These parameters will be applied to the SMC to run the strategy and obtain good control performance.

To make a comparative platform to validate the applicability of the proposed SMC, two other controllers, PID and FLC, are also applied to the robot control. One of the major challenges with PID [13] and FLC controllers lies in selecting the optimal parameters to ensure the system achieves the highest efficiency. If these parameters are not properly tuned, the system may experience excessive overshoot or slow response times.

To address these issues, the authors have employed the PSO algorithm to automatically search for the best parameter settings for the PID [10, 11, 14] and FLC controllers. For the PID controller, the convergence of the index ITAE is illustrated in Figure 4.

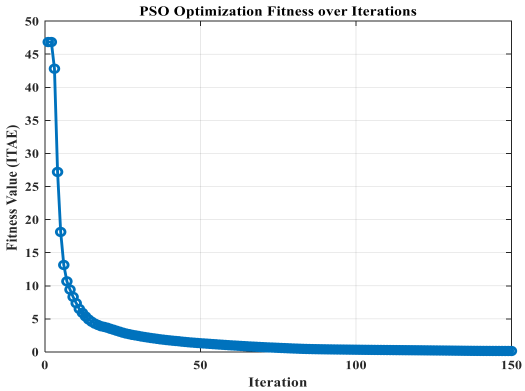

Fig. 4 PID controller optimization process using the PSO mechanism

Observing Figure 4 illustrating the convergence of the PSO algorithm, it is obvious that the objective function value ITAE gradually decreases over 150 iterations. Initially, the error is quite large, but after several iterations, the PSO algorithm gradually converges to an optimal value, demonstrating a significant improvement in the performance of the PID controller [15-17].

This indicates that PSO has found the optimal set of parameters for the PID controller, enabling the system to achieve faster response, greater stability, and reduced error. The PSO algorithm helps the PID controller adapt better to the system, avoiding local minima and optimizing control more effectively.

The convergence process of PSO also reflects the algorithm's adaptability to each stage of optimization. The explanations are as follows:

- Initial stage: The system has a large error, and the PSO algorithm makes strong adjustments to rapidly reduce the error.
- Middle stage: PSO continues to fine-tune the parameters for gradual optimization, helping the system reach the desired state.
- Final stage: The convergence process slows down as PSO approaches the optimal solution, ensuring the PID controller achieves its best performance.

Table 1. PID controller tuning parameters

Parameters	Values
KP1	1.454693163485600e+03
KI1	4.878968242086086e+04
KD1	3.120375484166062
KP2	1.130165992340450e+04
KI2	2.641575219735312e+03
KD2	6.828071031124016
KP3	1.930427308964681e+03
KI3	6.990125188134642e+05
KD3	1.470788820460272
KP4	35.265113672236176
KI4	5.704892723267358e+02
KD4	3.580665056567202

The convergence of tuning factors for the FLC controller is illustrated in Figure 5.

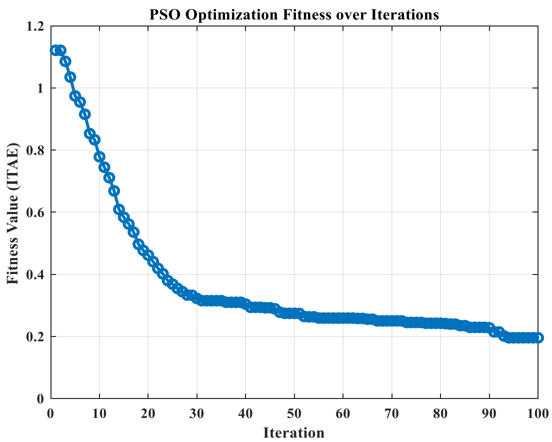

Fig. 5 Optimization process of scaling factors for the FLC

Using PSO to optimize the FLC controller helps determine the appropriate parameters to improve control performance. PSO operates based on a global search principle, preventing it from getting stuck in local minima, thereby optimizing the controller more effectively.

During the optimization process, particles in the population update their positions based on the ITAE value, aiming to minimize the time-integrated error. Over multiple iterations, the algorithm gradually adjusts the FLC parameters, optimizing membership functions and inference rules to enhance the system's adaptability.

The final results show that PSO has successfully found the optimal set of parameters, enabling FLC to operate more efficiently, minimize errors, and improve system stability. The optimized parameters obtained are detailed in the following table:

Table 2. FLC controller tunning parameters

Parameters	Values
K1	0.814325934051675
K2	11.847819021618697
K3	1.003350190924505e+02
K4	0.178830608040163
K5	86.964006641008520
K6	26.706535794167530
K7	0.255990318168811
K8	0.866140423390653
K9	72.078494958708790
K10	0.344864058658097
K11	1.868563040523576
K12	85.837369049146080

Numerical simulation results implemented in MATLAB/SIMULINK are provided in Figures 6-9.

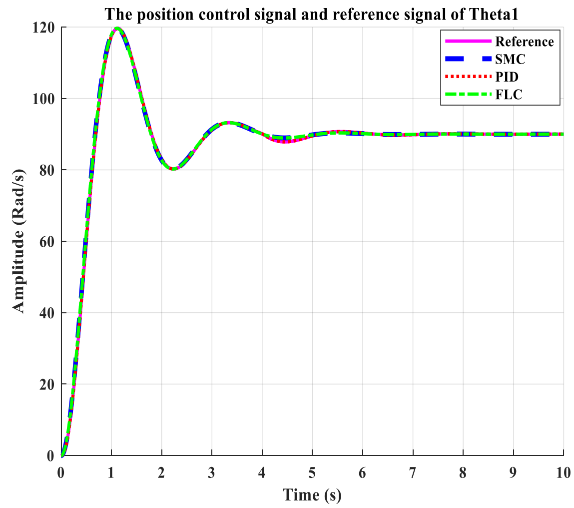

Fig. 6 Position response for Theta1

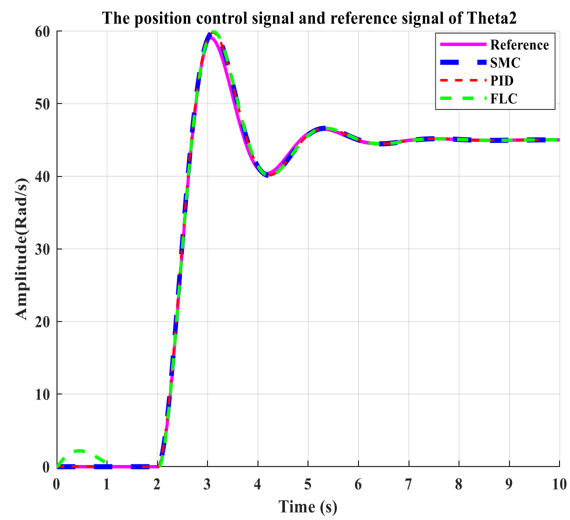

Fig. 7 Position response for Theta2

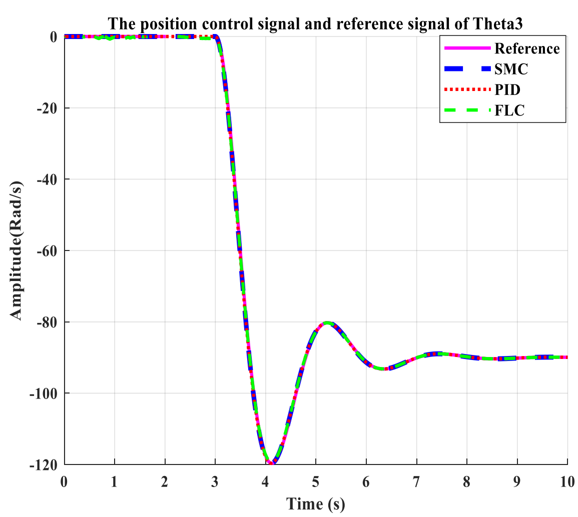

Fig. 8 Position response for Theta3

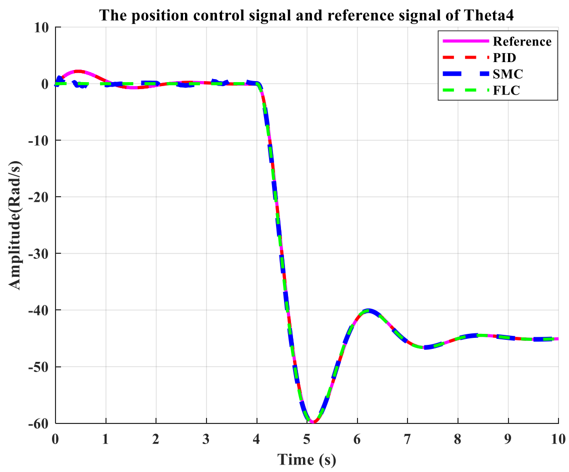

Fig. 9 Position response for Theta4

Consider control criteria such as rise time, overshoot, and ITAE (Integral Time Absolute Error) index to set comparative results. Tables 3-6 represent these comparative criteria.

Table 3. Controller evaluation criteria for Theta1

Controller	Evaluation Criteria
PID-PSO	- Rise Time: 0.4568 (s) -Overshoot: 32.91% - ITAE: 0.042977877623335
FLC-PSO	- Rise Time: 0.5071 (s) - Overshoot: 32.3962% - ITAE:0.071374563216500
SMC	- Rise Time: 0.4559 (s) - Overshoot: 32.89% - ITAE: 0.002504

3.1. Comments (Theta1)

From Table 3, it is clear that a comparative analysis of the control methodologies reveals distinct performance characteristics. The SMC exhibits the fastest rise time, measured at 0.4559 seconds, coupled with a relatively low overshoot of 32.296%.

Notably, the SMC achieved the lowest Integral Time-weighted Absolute Error (ITAE) value of 0.002504. This combination of metrics signifies that SMC delivers the most rapid response, superior stability, and the highest long-term accuracy among the three control strategies evaluated.

The FLC-PSO demonstrated the lowest overshoot, registering at 32.3962%, effectively minimizing system oscillations. However, this method exhibited the slowest rise time, measured at 0.5071 seconds, indicating a comparatively sluggish response compared to SMC and the PID-PSO.

While FLC-PSO presented the highest ITAE value of 0.0713, suggesting a larger accumulated error, it maintained a favorable balance between response speed and overall system stability.

The PID-PSO demonstrated a rapid rise time of 0.4568 seconds, closely approximating that of SMC, and a low ITAE value of 0.0429, highlighting its capability for long-term control accuracy. However, the PID-PSO exhibited the highest overshoot of 32.91% among the three methods, potentially leading to increased oscillatory behavior compared to the SMC and the FLC-PSO.

Table 4. Controller evaluation criteria for Theta2

Controller	Evaluation Criteria
PID-PSO	- Rise Time: 0.4557 (s) - Overshoot: 32.79% -ITAE: 0.007309360045362
FLC-PSO	- Rise Time: 0.0683 (s) - Overshoot: 39.33 % -ITAE: 1.417255692160156
Proposed SMC	- Rise Time: 0.4560 (s) - Overshoot: 31.22 % -ITAE: 0.0001382

3.2. Comments (Theta2)

Based on the data from Table 4, the controllers' performance can be evaluated as follows:

-SMC has a fast rise time (0.4560 s) and the lowest overshoot (31.22%), along with the smallest ITAE (0.0001382). This indicates that SMC provides the fastest response, high stability, and the best long-term accuracy among the three methods

-FLC-PSO has the fastest rise time (0.0683 s) but the highest overshoot (39.3398%) and the largest ITAE (1.4172). This indicates that although FLC-PSO responds quickly, the system exhibits significant oscillations and high accumulated error, making it less effective compared to SMC and PID-PSO.

-PID-PSO has a fast rise time (0.4557 s), close to SMC, with an overshoot of 32.79%, higher than SMC but lower than FLC-PSO. The small ITAE value (0.0073) indicates a low accumulated error, contributing to a more stable system compared to FLC-PSO.

Table 5. Controller evaluation criteria for Theta3

Controller	Evaluation criteria
PID-PSO	- Rise Time: 0.4549 (s) - Overshoot: 33.03% - ITAE: 0.0001379
FLC-PSO	- Rise Time: 0.4626 (s) - Overshoot: 32.52% - ITAE: 0.088090029781113
Proposed SMC	- Rise Time: 0.4539 (s) - Overshoot: 33.08% - ITAE: 0.0001342

3.3. Comments (Theta3)

Similarly, the data in Table 5 can reveal the following conclusions:

-SMC has a fast rise time (0.4539 s) and an overshoot of 33.08%, which is higher than FLC-PSO but lower than PID-PSO. The very small ITAE value (0.0001342) indicates that SMC enhances system stability and minimizes accumulated error, making it suitable for high-precision applications.

-PID-PSO has a rise time of 0.4549 s, which is close to SMC, and the lowest overshoot (33.03%), reducing system oscillations. The very small ITAE value (0.0001379) indicates high control accuracy in the long term, slightly less effective than SMC.

-FLC-PSO has the slowest rise time (0.4626 s) and the lowest overshoot (32.5226%), which helps reduce system oscillations. However, the highest ITAE value (0.08809) indicates a significantly higher accumulated error compared to the other two methods, affecting long-term accuracy.

Table 6. Controller evaluation criterion for Theta4

Controller	Evaluation Criteria
PID-PSO	- Rise Time: 0.4506 (s) - Overshoot: 32.72% -ITAE: 0.040689722421967
FLC-PSO	- Rise Time: 0.4555 (s) - Overshoot: 32.79% -ITAE: 0.040689722421967
SMC	- Rise Time: 0.4576 (s) - Overshoot: 32.63% -ITAE: 0.135186419475668

3.4. Comments (Theta4)

Several comments on the data shown in Table 6 are:

The PID-PSO controller demonstrates a rapid rise time of 0.4506 seconds and excellent long-term regulation, as evidenced by its low ITAE of 0.0407. However, it exhibits a significant overshoot of 32.72%, potentially causing minor system oscillations.

Regarding the FLC-PSO, while achieving a comparable ITAE of 0.0407, indicating good long-term stability, the FLC-PSO has the highest overshoot at 32.79% and a slightly slower rise time of 0.4555 seconds compared to PID-PSO. This suggests it requires further optimization for faster response.

The SMC provides the best overall control performance, with the lowest overshoot of 32.63% and the smallest ITAE of 0.0249, signifying superior accuracy and stability. However, it has the slowest rise time at 0.4576 seconds, resulting in a marginally slower response.

4. Conclusions and Future Work

This study has presented the design and application of the SMC strategy for a 4-DoF robotic manipulator, with the objective of achieving robust stability and rapid disturbance rejection in the presence of system uncertainties and external disturbances. The efficacy of the proposed SMC scheme is evaluated through comprehensive numerical simulation validation, leading to the following key findings:

(i) The implemented SMC controller effectively maintains system stability, even when subjected to external disturbances and parameter variations. Notably, the manipulator exhibits precise trajectory tracking, accurately following the desired reference trajectories with minimal positional errors.

(ii) The controller demonstrates robust performance across various operating conditions, highlighting its suitability for dynamic environments.

(iii) However, the inherent discontinuity of the control law results in chattering, a phenomenon that can introduce undesirable high-frequency oscillations.

To further improve performance and address the limitations of the conventional SMC implementation in the 4-DoF robot, several potential enhancements are explored. These include applying control signal smoothing techniques, such as boundary layer methods or higher-order sliding mode control, to mitigate chattering while preserving robustness. Optimizing the adaptive sliding mode control algorithm, enabling dynamic adjustment of control parameters based on real-time system conditions, can further enhance performance and adaptability. Furthermore, the utilization of the PSO algorithm for parameter tuning of the PID and FLC controllers is proposed as a means to optimize the performance of these control strategies, either in conjunction with or as a hybrid approach to SMC, to achieve superior control performance for the 4-DoF robotic manipulator.

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