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Adaptive fuzzy sliding-mode control for robot manipulator with uncertain model and external disturbance

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ABSTRACT

In practice, robots operate as nonlinear systems and often encounter factors like nonlinear friction, load variations, and external disturbances during tasks. To address these challenges, a smart control approach has been developed that combines the strengths of fuzzy logic and sliding mode control (SMC) for precise robot manipulator positioning. The key benefit of SMC lies in its robustness, maintaining stability despite noise or parameter changes in the system. However, designing an SMC system often faces difficulties due to practical limitations, making deployment not always feasible in real-world applications. Additionally, a large control law amplitude can lead to chattering around the sliding surface. To overcome these issues, the study introduces a fuzzy logic-based method to adaptively estimate the control law's magnitude, guided by Lyapunov stability principles. This control scheme is tested on a four-degree-of-freedom robot manipulator, with simulation results confirming its effectiveness in MATLAB.

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1. INTRODUCTION

Robotic manipulators are an automation device that is quite commonly used in industrial factories today. Not only does it serve the product assembly process, but it also contributes to handling complex tasks in production. In particular, in toxic, dangerous, and risky working environments for humans, robotic hands are the perfect replacement. However, a robot manipulator with many different kinematic uncertainties is an uncertain nonlinear system with many variables. For example, load variations, nonlinear friction, and external disturbances reduce system stability and performance. These frequent influences will reduce the controller's trajectory tracking accuracy. The stability of the robot manipulator system is changed due to repetitive movements, which will accumulate errors. Therefore, key indicators for industrial development depend on maintaining the performance and improving the trajectory tracking accuracy of robotic manipulators.

There are several classical and modern control methods for robotic manipulators, including proportional integral derivative (PID) controllers [1]-[4], adaptive control [5]-[7], sliding mode control (SMC) [8]-[12], and backstepping [13]-[16]. With the advantage of stability and sustainability even when the system has disturbances or when the object's parameters change, the SMC is a typical choice in robot control. However, when the amplitude of the control law changes greatly and with the impact of the sign function, the control signal can become chattering, less stable and have a negative impact on the actuators. To overcome the disadvantages of sliding controllers, many scientists have researched and proposed combining sliding control techniques with neural networks [17]-[21], especially combined with fuzzy controllers [22]-[25]. Among them, fuzzy control is used by many research scientists because of its simplicity in design. For example, fuzzy controllers are applied in controlling robots to perform complex tasks that are difficult to perform with conventional control analysis models or controlling mobile robots.

From the above analysis, it can be seen that for the problem of motion control for robot systems, there are many control methods. However, current controllers are designed based on a combination of many control methods, using a single control method is difficult to meet the complex working conditions of robots. With this combination, we can simultaneously exploit the advantages of many different methods and overcome the disadvantages of each method. Therefore, this study introduces a adaptive fuzzy sliding mode adaptive control (AFSMC) method aimed at improving the trajectory tracking accuracy of robot manipulators.

2. DYNAMIC MODEL OF ROBOT MANIPULATOR

There are many methods of studying robot dynamics, but the most common is the Lagrange mechanics method, specifically using the Lagrange-Euler equation. For robot joints, with separate dynamic sources and control channels, gravity effects, inertia, Coriolis, and centripetal effects cannot be ignored. However, these aspects have not been fully considered in classical mechanics. Lagrangian mechanics studies the above problems as a closed system, so this is a suitable mechanical principle for robot dynamics problems. In general, the n-link robot system [26] has a dynamic equation described as (1):

$$\mathcal{B}(q)\ddot{q} + \mathcal{C}(q,\dot{q})\dot{q} + \mathcal{G}(q) = \tau - \tau_d(q,\dot{q}) - \mathcal{F}_d\dot{q} - \mathcal{F}(\dot{q}) \tag{1}$$

where, $q \in \mathbb{R}^n$ represents the vector of joint angles of the robot; $\mathcal{B}(q) \in R^{n\times n}$ denotes the inertia matrix; $\mathcal{C}(q,\dot{q}) \in \mathbb{R}^n$ accounts for the centripetal and Coriolis forces; $\mathcal{G}(q) \in R^n$ is the gravity vector; $\mathcal{F}_d \in \mathbb{R}^{n\times n}$ and $\mathcal{F}(\dot{q}) \in \mathbb{R}^n$ describe the friction forces; $\tau_d(q,\dot{q}) \in \mathbb{R}^n$ captures external disturbances and unmodeled dynamics; and $\tau \in \mathbb{R}^n$ represents the joint torques.

Let $d(t)$ be the function containing the friction force $\mathcal{F}(\dot{q})$, disturbance $\tau_d(q,\dot{q})$ and other uncertain components, then (1) can be shortened to (2):

$$\ddot{q} = -\mathcal{B}^{-1}(q)\mathcal{C}(q,\dot{q})\dot{q} - \mathcal{B}^{-1}(q)\mathcal{G}(q) - d(t) + \mathcal{B}^{-1}(q)\tau \tag{2}$$

where $d(t) = \mathcal{B}^{-1}(q)[\mathcal{F}(\dot{q}) + \tau_d(q,\dot{q})]$.
Suppose $\mathcal{D} = \mathcal{B}^{-1}(q)\mathcal{C}(q,\dot{q})$, $\mathcal{E} = \mathcal{H} = \mathcal{B}^{-1}(q)$, then (2) is rewritten as (3):

$$\ddot{q} = -\mathcal{D}\dot{q} - \mathcal{E}\mathcal{G}(q) - d(t) + \mathcal{H}\tau \tag{3}$$

if the matrices $\mathcal{B}(q)$ and $\mathcal{C}(q,\dot{q})$ are uncertain, then (3) is rewritten as (4):

$$\ddot{q} = -(\mathcal{D} + \Delta\mathcal{D})\dot{q} - (\mathcal{E} + \Delta\mathcal{E})\mathcal{G}(q) - d(t) + (\mathcal{F} + \Delta\mathcal{F})\tau \tag{4}$$

The properties of the manipulator's dynamic model [26] are as follows:
- $\mathcal{B}(q)$ is a symmetric, positive-definite matrix with bounded values, satisfying b_1 and b_2 such that $b_1 \le \mathcal{B}(q) \le b_2$ for some positive constants;
- $\mathcal{C}(q,\dot{q})$ remains limited, with a known function $c(q)$ such that $\mathcal{C}(q,\dot{q}) \le c(q)\|\dot{q}\|$; and the matrix $\dot{\mathcal{B}} - 2\mathcal{C}$ exhibits skew-symmetry, which means that for any vector x, $x^T(\dot{\mathcal{B}} - 2\mathcal{C})x = 0$ the relation holds.

3. ADAPTIVE FUZZY SLIDING MODE CONTROLLER FOR ROBOT MANIPULATOR

3.1. Sliding mode controller design

The sliding control technique has been proven by many studies to be stable and sustainable [8], [9]. In this section, sliding controllers are briefly summarized, without going into proving those properties again. Let $q_d(t)$ be the desired trajectory and $q(t)$ be the actual trajectory of the manipulator, then the position tracking error $e(t) = q_d(t) - q(t)$ is used as the basis to determine the sliding surface, calculated as (5) [27], [28]:

$$s(t) = \mathcal{K}_3\frac{de(t)}{dt} + \mathcal{K}_1 e(t) + \mathcal{K}_2\int e(t)dt \tag{5}$$

the matrices $\mathcal{K}_1 \in \mathbb{R}^{n\times n}$, $\mathcal{K}_2 \in \mathbb{R}^{n\times n}$, and $\mathcal{K}_3 \in \mathbb{R}^{n\times n}$ represent the proportional, integral, and derivative gain matrices, respectively.
Derivative of (5):

$$\dot{s}(t) = \left(\mathcal{K}_1 e(t) + \mathcal{K}_2 \int e(t)dt + \mathcal{K}_3 \frac{de(t)}{dt}\right)' \quad (6)$$

$$\dot{s}(t) = \mathcal{K}_3[\ddot{q}_d(t) + (\mathcal{D} + \Delta\mathcal{D})\dot{q} + d(t) - (\mathcal{F} + \Delta\mathcal{F})\tau + (\mathcal{E} + \Delta\mathcal{E})\mathcal{G}(q)] + \left(\mathcal{K}_1 \frac{de(t)}{dt} + \mathcal{K}_2 e(t)\right) \quad (7)$$

for the tracking error $e(t)$ to approach the slip surface and move along the slip surface towards the origin, the slip surface must be stable, i.e., $\lim_{t\to\infty} e(t) = 0$ [27], [28].

Assume that the uncertainty component is not considered. For good control performance, the control signal represented by $\tau_{eq}(t)$ is expressed as (8) [29]:

$$\tau_{eq}(t) = (\mathcal{K}_3\mathcal{F})^{-1}\left[\mathcal{K}_3\ddot{q}_d(t) + \mathcal{K}_3\mathcal{E}\mathcal{G}(q) + \mathcal{K}_1\frac{de(t)}{dt} + \mathcal{K}_2 e(t) + \mathcal{K}_3\mathcal{D}\dot{q}(t)\right] \quad (8)$$

however, when there is an external disturbance or uncertain parameters appear in the model. To eliminate the influence of such adverse components, the SMC control signal is determined according to (9):

$$\tau(t) = \tau_{eq}(t) + \tau_r(t) \quad (9)$$

where $\tau_r(t) = \mathcal{K}_r \mathrm{sign}(s)$ is the output signal of the SMC; $\mathrm{sign}(s)$ is the sign function and $\mathcal{K}_r$ denotes the SMC control gain which is the upper limit of the model disturbance and uncertainty.
The structure of SMC with PID slide surface is built as shown in Figure 1.

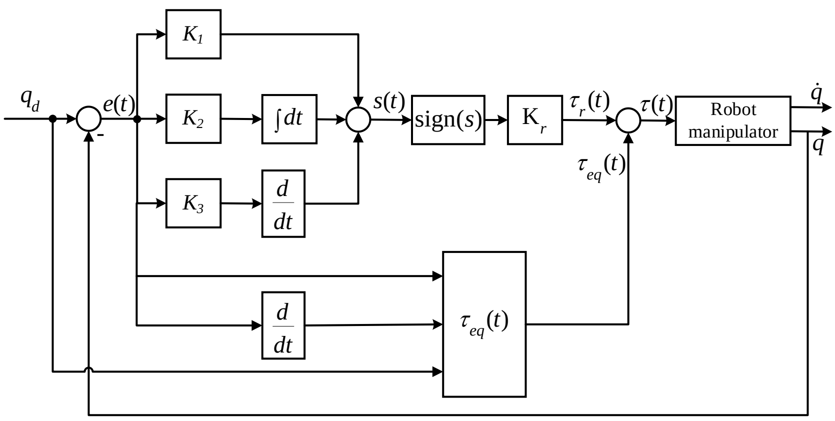

Figure 1. SMC controller structure

The Lyapunov function is chosen as (10):

$$\mathcal{V}(t) = \frac{1}{2}s^T(t)s(t) \quad (10)$$

derivative both sides of (10):

$$\dot{\mathcal{V}}(t) = s^T(t)\dot{s}(t) \quad (11)$$

substitute (7) into (11):

$$\dot{\mathcal{V}}(t) = s^T(t)\left\{\mathcal{K}_1\frac{de(t)}{dt} + \mathcal{K}_3[(\mathcal{D} + \Delta\mathcal{D})\dot{q} + d(t) - (\mathcal{F} + \Delta\mathcal{F})\tau(t) + \ddot{q}_d(t) + (\mathcal{E} + \Delta\mathcal{E})\mathcal{G}(q)] + \mathcal{K}_2 e(t)\right\} \quad (12)$$

substitute (9) into (12):

$$\dot{\mathcal{V}}(t) = s^T(t)\left\{\mathcal{K}_1\frac{de(t)}{dt} + \mathcal{K}_3\left[\ddot{q}_d(t) + \mathcal{D}\dot{q} + \mathcal{E}\mathcal{G}(q) - \mathcal{F}\left(\tau_{eq}(t) + \tau_r(t)\right) + \mathcal{L}(t)\right] + \mathcal{K}_2 e(t)\right\} \quad (13)$$

where: $\mathcal{L}(t) = d(t) - \Delta\mathcal{F}\tau(t) + \Delta\mathcal{D}\dot{q} + \Delta\mathcal{E}\mathcal{G}(q)$
Substitute (8) into (13):

$$\dot{\mathcal{V}}(t) = s^T(t)\left\{\mathcal{K}_1\frac{de(t)}{dt} + \mathcal{K}_3\left[\ddot{q}_d(t) + \mathcal{D}\dot{q} + \mathcal{E}\mathcal{G}(q) - \mathcal{F}\left(\left((\mathcal{K}_3\mathcal{F})^{-1}\left[\mathcal{K}_1\frac{de(t)}{dt} + \ddot{q}_d + \mathcal{K}_3\mathcal{D}\dot{q} + \mathcal{K}_3\mathcal{G}(q) + \mathcal{K}_2 e(t)\right]\right) + \tau_r(t)\right) + \mathcal{L}(t)\right] + \mathcal{K}_2 e(t)\right\} \quad (14)$$

$$\Rightarrow \dot{\mathcal{V}}(t) = s^T(t)\left\{\mathcal{K}_1\frac{de(t)}{dt} + \mathcal{K}_3[\ddot{q}_d(t) + \mathcal{D}\dot{q} + \mathcal{E}\mathcal{G}(q)] - \mathcal{K}_3\mathcal{F}\left(\left(\left[\mathcal{K}_1\frac{de(t)}{dt} + \mathcal{K}_3\ddot{q}_d + \mathcal{K}_3\mathcal{D}\dot{q} + \mathcal{K}_2 e(t) + \mathcal{K}_3\mathcal{E}\mathcal{G}(q)\right](\mathcal{K}_3\mathcal{F})^{-1}\right) + \tau_r(t)\right) + \mathcal{K}_3\mathcal{L}(t) + \mathcal{K}_2 e(t)\right\} \quad (15)$$

$$\Rightarrow \dot{\mathcal{V}}(t) = s^T(t)\left\{\mathcal{K}_3[\ddot{q}_d(t) + \mathcal{D}\dot{q} + \mathcal{E}\mathcal{G}(q)] - \left(\left[\mathcal{K}_1\frac{de(t)}{dt} + K_2 e(t) + K_3\ddot{q}_d + \mathcal{K}_3\mathcal{D}\dot{q} + \mathcal{K}_3\mathcal{E}\mathcal{G}(q)\right] + \tau_r(t)\right) + \mathcal{K}_3\mathcal{L}(t) + \mathcal{K}_1\frac{de(t)}{dt} + \mathcal{K}_2 e(t)\right\} \quad (16)$$

Simplifying (16):

$$\dot{\mathcal{V}}(t) = s^T(t)[-\tau_r(t) + \mathcal{K}_3\mathcal{L}(t)] \quad (17)$$

Substituting $\tau_r(t) = \mathcal{K}_r \operatorname{sign}(s)$ into (17):

$$\dot{\mathcal{V}}(t) = s^T(t)[-\mathcal{K}_r \operatorname{sign}(s) + \mathcal{K}_3\mathcal{L}(t)] \quad (18)$$

by selecting $\mathcal{K}_r$ such that $\mathcal{K}_r > \mathcal{K}_3|\mathcal{L}(t)|$, we guarantee that $\dot{\mathcal{V}}(t)$ remains negative for all $t \neq 0$. Therefore the system is stable.

3.2. Adaptive fuzzy sliding mode adaptive control design

The structure of the AFSMC is shown in Figure 2 [29]. The fuzzy controller's output:

$$y = \frac{\sum_{l=1}^{N} \max\mu_{W^l}(y)\prod_{i=1}^{n}\mu_{A_i^l}(x_i)}{\sum_{l=1}^{N}\left(\prod_{i=1}^{n}\mu_{A_i^l}(x_i)\right)} \quad (19)$$

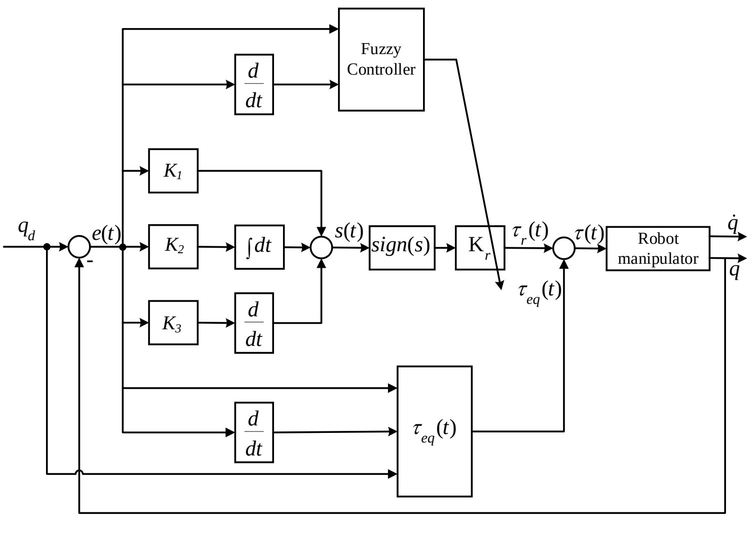

Figure 2. AFSMC structure

The fuzzy controller designed in this study takes two inputs: the error $e(t)$ and its derivative $\dot{e}(t)$, and produces an output signal $\mathcal{K}_r$. The configuration of this fuzzy controller implemented in MATLAB is depicted in Figure 3. The membership functions of input and output are illustrated in Figures 4-6.

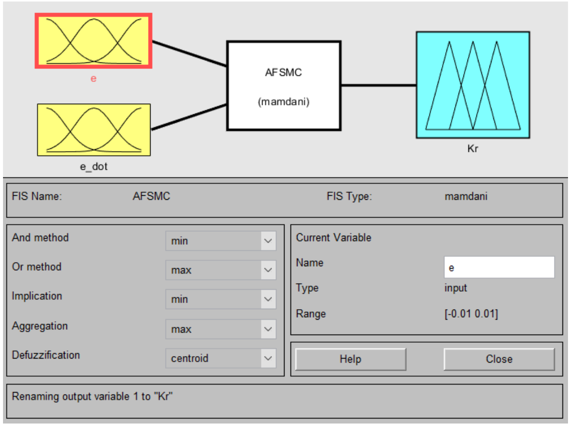

Figure 3. Block diagram of fuzzy controller on MATLAB software

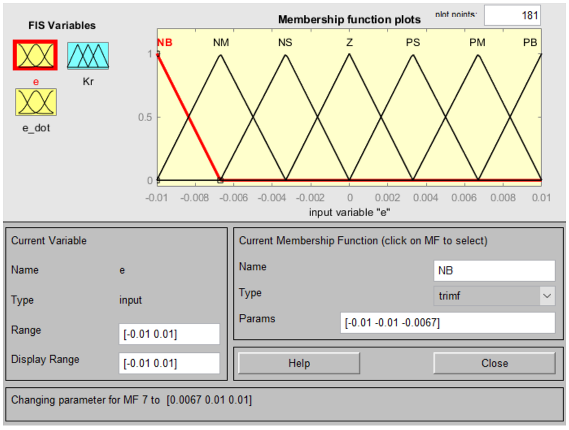

Figure 4. Input e(t)

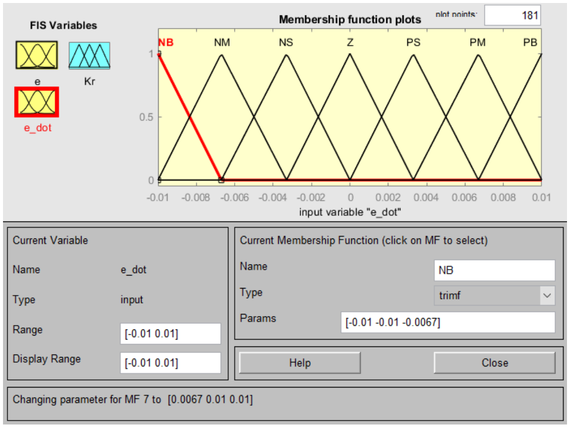

Figure 5. Input $\dot{e}(t)$

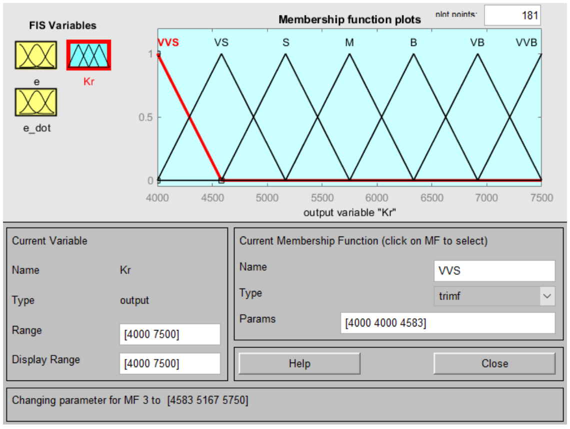

Figure 6. Output $\mathcal{K}_r$

Select the composition device as MAX-MIN and defuzzify by the center point method. The control rule is illustrated as in Table 1. The fuzzy control surface of $\mathcal{K}_r$ is used to adaptively adjust $\mathcal{K}_r$ online as shown in Figure 7.

Table 1. Fuzzy control rule

K_r		$e(t)$						
		PB	PM	PS	Z	NS	NM	NB
$\dot{e}(t)$	PB	M	S	VS	VVS	VS	S	M
	PM	B	M	S	VS	S	M	B
	PS	VB	B	M	S	M	B	VB
	Z	VVB	VB	B	M	B	VB	VVB
	NS	VB	B	M	S	M	B	VB
	NM	B	M	S	VS	S	M	B
	NB	M	S	VS	VVS	VS	S	M

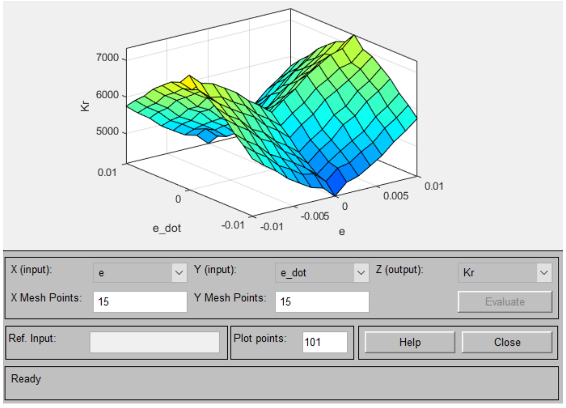

Figure 7. Fuzzy control surfaces of $\mathcal{K}_r$

3.3. Simulation results

Simulation is performed on MATLAB software with the proposed AFSMC algorithm to control the four-degree-of-freedom manipulator system as shown in Figure 8. The matrix $\mathcal{B}$ and the vectors $\mathcal{C}$, $\mathcal{G}$ in the dynamic (1) of the controlled robot are represented as in [30]. The parameters related to the robot manipulator used to conduct the experimental simulation are clearly and detailedly presented in Table 2.

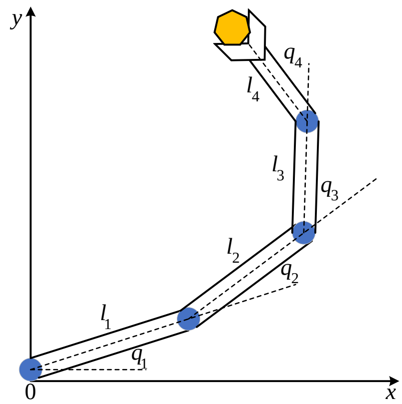

Figure 8. Four-degree-of-freedom manipulator

Table 2. Parameters of the four-degree-of-freedom manipulator

Symbol	Meaning	Unit	Value
l_1	Length of link 1	0.12	m
l_2	Length of link 2	0.12	m
l_3	Length of link 3	0.09	m
l_4	Length of link 4	0.09	m
m_1	Mass of link 1	0.6	kg
m_2	Mass of link 2	0.6	kg
m_3	Mass of link 3	0.45	kg
m_4	Mass of link 4	0.45	kg

where: $\mathcal{F}_d\dot{q} = \begin{bmatrix} 10\dot{q}_1 \\ 10\dot{q}_2 \\ 10\dot{q}_3 \\ 10\dot{q}_3 \end{bmatrix}$; $\mathcal{F}(\dot{q}) = \begin{bmatrix} 10\text{sign}(\dot{q}_1) \\ 10\text{sign}(\dot{q}_2) \\ 10\text{sign}(\dot{q}_3) \\ 10\text{sign}(\dot{q}_4) \end{bmatrix}$.

Select the controller parameters as follows: $\mathcal{K}_1 = \text{diag}([200\ 200\ 200\ 200])$; $\mathcal{K}_2 = \text{diag}([600\ 600\ 600\ 600])$; and $\mathcal{K}_3 = \text{diag}([100\ 100\ 100\ 100])$;

Figures 9-16 shows that the AFSMC controller achieves excellent tracking, low error, and fast response. It overcomes SMC's chattering issue, keeping the robot's trajectory stable even with model uncertainties. The system remains stable and tracks well under external disturbances. It is highly adaptable: when parameters change, the response stays correct. Overall, the AFSMC controller ensures stability, high tracking accuracy, and improved efficiency, demonstrating strong technical performance.

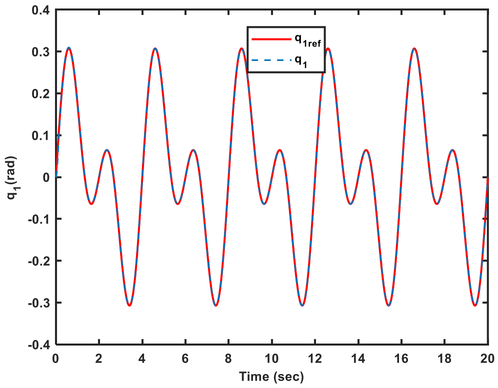

Figure 9. Tracking the position of link 1

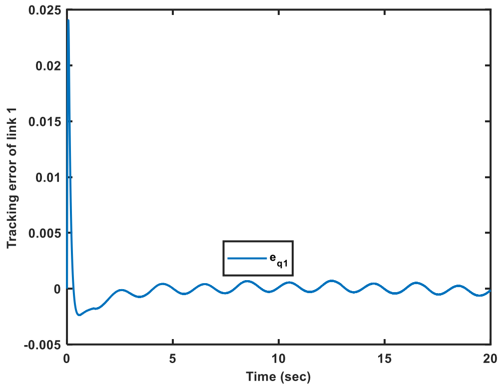

Figure 10. Position error of link 1

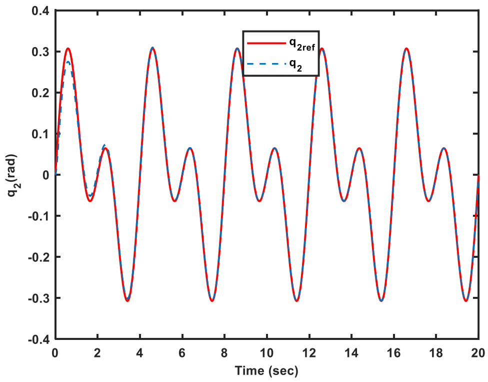

Figure 11. Tracking the position of link 2

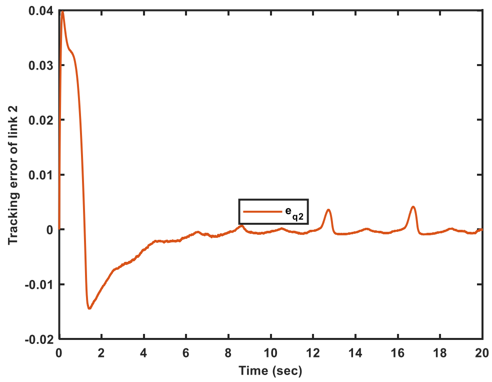

Figure 12. Position error of link 2

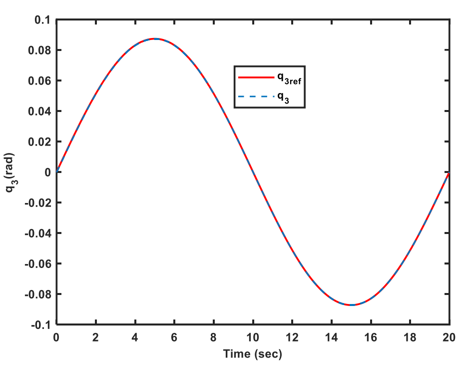

Figure 13. Tracking the position of link 3

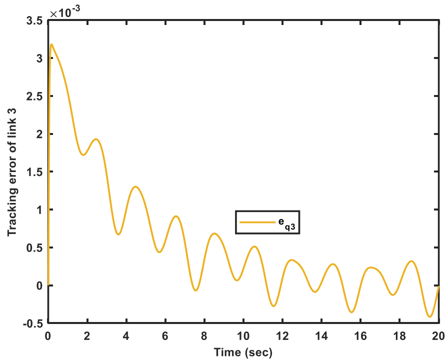

Figure 14. Position error of link 3

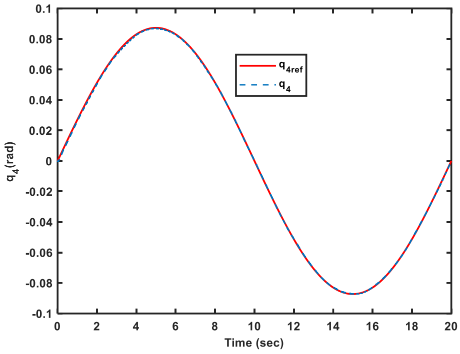

Figure 15. Tracking the position of link 4

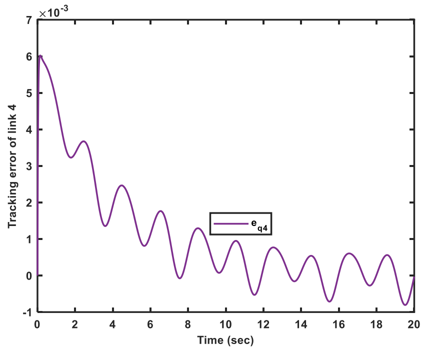

Figure 16. Position error of link 4

Figure 17 compares the tracking performance of the AFSMC with that of a controller based on the radial basis function (RBF) neural network [31]. The black line (q_{ref}) represents the reference trajectory, the target the system aims to follow over time. The blue line (q_{AFSMC}) shows the system response with the AFSMC, while the red dashed line (q_{RBF}) depicts the response with the RBF neural network controller.

Figure 18 illustrates the tracking error of both controllers over time. The blue line indicates that the AFSMC maintains an almost zero error, demonstrating excellent tracking accuracy and stability. Conversely, the error for the RBF controller (red line) fluctuates more significantly, implying less precise tracking and greater sensitivity to input changes or external disturbances. This highlights the superior stability and accuracy of the AFSMC in trajectory tracking.

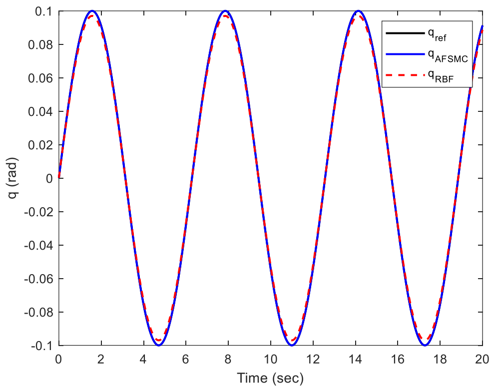

Figure 17. Trajectory of the robot manipulator

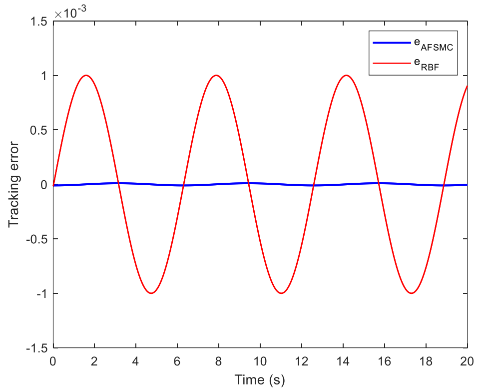

Figure 18. Position tracking error of robot manipulator

4. CONCLUSION

The paper presents the design method of AFSMC controller for robot manipulator, adaptive SMC combined with the advantages of fuzzy logic to improve quality, reduce trajectory tracking error for robot manipulator. The 4-degree-of-freedom manipulator model is used to illustrate the design method. The stable and efficient operation of the AFSMC controller has been proven by using Lyapunov stability theory and verified by simulation results on MATLAB software. From the results achieved, it contributes to adding new control methods for robot manipulators; is a useful document in the research of the field of robots with high precision, speed and flexibility. Implementing automation with robot manipulators, businesses increase their competitiveness in the market. Robot manipulators are the premise for implementing automation solutions in production and smart factories. To confirm the accuracy and reliability of the system, we propose to carry out practical experiments in the future. Specifically, this work could include using existing robotic manipulator platforms to test and calibrate the parameters of AFSMC, thereby optimizing the performance in practical applications. This would not only confirm the feasibility of the method but also contribute to improving its application in the field of automatic control.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Nguyen Cao Cuong	✓	✓			✓	✓		✓	✓	✓	✓	✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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