Adaptive Fuzzy Sliding Mode Control Using Supervisory Fuzzy Control for 3 DOF Planar Robot Manipulators

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***Abstract*—Controlling industrial robots involves addressing complexities like nonlinearities, uncertainties, and external disturbances when devising control laws. This paper introduces a control strategy for robot manipulators, combining fuzzy logic control with the sliding mode control (SMC) approach. The use of SMC in robotics is driven by its advantageous features, such as design simplicity and robustness. However, the conventional SMC may suffer from a chattering effect, which can be problematic. To tackle this, we employ an adaptive fuzzy sliding mode control (AFSMC) with a proportional-integral-derivative (PID) sliding surface. In this method, a fuzzy logic control is employed to generate the control signal for impact. Furthermore, the output gain of the fuzzy sliding mode control (FSMC) is dynamically adjusted online using a supervisory fuzzy system to prevent chattering. The stability of the system is ensured based on the Lyapunov stability theorem. Numerical simulations using the dynamic model of a 3-degree-of-freedom planar rigid robot manipulator with uncertainties illustrate the effectiveness of the approach in addressing trajectory tracking issues. Comparative simulations with conventional SMC incorporating a PID sliding surface highlight the satisfactory control performance of the robot system. The proposed AFSMC demonstrates favorable tracking performance and robustness against uncertainties and disturbances.**

***Index Terms*— Fuzzy control, Robots, Sliding mode control (SMC), Uncertainties.**

I. INTRODUCTION

Controlling rigid robot manipulators' motion is a formidable task, primarily due to the nonlinearities and coupling effects inherent in robotic systems [1]. A myriad of strategies has been explored to tackle this challenge, including feedback linearization [2, 3], model predictive control [1, 4], and sliding mode control [5, 6]. In the context of robotics, feedback linearization is achieved through inverse dynamics control [7], while computed torque control, as developed in [8, 9], relies on feedback linearization. However, these designs hinge on a comprehensive understanding of the dynamics of the robotic system. To address unknown robotic dynamics, adaptive control schemes have been proposed [10]. These approaches assume linear parameterizations, where unknown parameters exhibit a linear structure and are considered constant or slowly varying. However, the nonlinear, highly coupled, and time-varying nature of robotic dynamic systems may render the linear parameterization property inapplicable [10]. Moreover, practical robotic systems often feature uncertainties such as changing payload, nonlinear friction, unknown disturbance, and high-frequency dynamics, which may not be precisely known. Thus, there is a need to consider both structured uncertainties (parametric) and unstructured uncertainties (un-modeled dynamics). Sliding mode control (SMC) stands out as an effective nonlinear robust control approach, providing system dynamics with an invariance property to uncertainties when the system dynamics are controlled in the sliding mode [11-16]. The initial step in SMC design involves selecting a sliding surface that models the desired closed-loop performance in state variable space. Subsequently, a hitting control law is designed to force the system state trajectories towards the sliding surface and maintain them on it. The period before reaching the sliding surface is termed the reaching phase, and once the system trajectory reaches the sliding surface, it adheres to it, sliding along it towards the origin. Under specific conditions, SMC exhibits robustness to system perturbation and external disturbance [11, 17]. However, this control strategy is not without drawbacks, notably the occurrence of large control chattering, which can wear coupled mechanisms and induce undesirable high-frequency dynamics. Various methods to reduce chattering have been proposed. One approach introduces a boundary layer around the switching surface, replacing relay control with a saturation function. Another method [18] substitutes max–min-type control with a unit vector function. However, these approaches offer no assurance of convergence to the sliding mode and involve a tradeoff between chattering and robustness. Continuous SMC can exponentially guide the system state to a chattering-free sliding mode but tends to result in conservative designs. The integration of fuzzy control with SMC provides a solution, combining the strengths of fuzzy control with SMC to achieve reduced chattering without compromising robust performance [19-21]. Recently, Fuzzy SMC (FSMC) has proven effective for this purpose. Fuzzy logic, initially proposed by Zadeh [22], is a powerful tool for controlling ill-defined or parameter-variant plants. By

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encapsulating heuristic engineering rules, a fuzzy logic controller can handle severe uncertainties, although some implementations may incur a heavy computational burden. Fuzzy schemes with explicit expressions for tuning can alleviate this issue [23]. The control methodology proposed in this paper adopts a computational-intelligence approach to address engineering challenges associated with sliding-mode controllers. The paper outlines the design of an adaptive fuzzy sliding mode controller with a PID sliding surface, incorporating fuzzy tuning techniques to achieve reduced chatter and system robustness against parameter uncertainty, load disturbance, and nonlinearities. The novel control algorithm combines fuzzy logic with the PID sliding mode control method, utilizing adaptive fuzzy algorithms and robust control techniques to ensure robust tracking performance for uncertain robotic systems. The closed-loop system's global stability in the Lyapunov sense is proven, given bounded signals and the system's ability to asymptotically track the desired reference output in the presence of modeling uncertainties and disturbances. To validate the proposed control algorithm, simulations are conducted on a 3 DOF planar manipulator arm, yielding satisfactory control performance. The chattering phenomenon is effectively addressed by replacing a pure sign function in the control law with fuzzy control. Comparative analysis with existing conventional sliding mode controllers for robot manipulators demonstrates the advantages and superior control performance of the developed variable structure PID controller. The subsequent sections of this paper present the dynamical model of the robot (Section 2), the characteristics of SMC with PID sliding surface (Section 3), FSMC (Section 4), AFSMC (Section 5), simulation results (Section 6), and finally, the conclusions and contributions of the work (Section 7).

In conclusion, this paper delves into the intricate realm of robot manipulator control, navigating the challenges posed by nonlinearities and coupling effects. The proposed adaptive fuzzy sliding mode controller with PID sliding surface emerges as a promising solution, addressing uncertainties, disturbances, and chattering. The incorporation of fuzzy logic enhances the robustness of the system, offering a viable approach for real-world robotic applications. Simulations on a 3 DOF planar manipulator arm substantiate the efficacy of the proposed methodology, paving the way for advancements in the field of robotic control. This comprehensive exploration contributes valuable insights for researchers and practitioners alike, fostering further developments in adaptive control strategies for robotic systems.

II. DESCRIPTION OF ROBOT MANIPULATOR MODEL

The basics of robot dynamics and control are sufficiently well known by now that we will be brief in our derivation of the control algorithm. Thus, given the Euler-Lagrange dynamic equations for an n-link robot [9]:

$$B(q)\ddot{q} + C(q,\dot{q})\dot{q} + F_d\dot{q} + F_s(\dot{q}) + \tau_d(q,\dot{q}) + g(q) = \tau \qquad (1)$$

where $q,\dot{q},\ddot{q} \in R^n$ are the joint position, velocity, and acceleration vectors, respectively; $B(q)$ denotes the bounded positive definite inertia matrix; $C(q,\dot{q})$ expresses the coriolis, centripetal matrix; $g(q)$ is the gravity vector; $F_d \in R^{n\times n}$ and $F_s(\dot{q}) \in R^n$ represent the dynamic friction coefficient matrix and static friction vector, respectively; $\tau_d(q,\dot{q})$ is the vector of disturbances and un-modeled dynamics; τ is the control vector representing the torque exerting on joints. Eq. (1) can be written as:

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

where $d(t) = B(q)^{-1}(F_d\dot{q} + F_s\dot{q}) + \tau_d(q,\dot{q})$ d(t) represents ternal load disturbance, nonlinear friction, and un-modeled dynamics. From (2), the dynamic equations for an n-link robot are written as:

$$\ddot{q} = -D\dot{q} - Eg(q) - d(t) + Fu(t) \qquad (3)$$

where $D = B^{-1}(q)C(q,\dot{q})$, $E = F = B^{-1}(q)$, and $u(t) = \tau$ is the control vector. If some uncertainties representing parameter variations, ΔD, ΔF and ΔE are assumed to be present on the system, Eq. (3) can be rearranged as:

$$\ddot{q} = -(D+\Delta D)\dot{q} - (E+\Delta E)g(q) - d(t) + (F+\Delta F)u(t) \qquad (4)$$

where the uncertainties are bounded such that $\Delta D_l \le |\Delta D| \le |\Delta D_h|$, $\Delta E_l\, |\Delta E| \le \Delta E_h$ and $\Delta F_l \le |\Delta F| \le \Delta F_h$, and the subscripts l and h denote lower and upper uncertainty values.

III. SLIDING MODE CONTROLLER WITH PID SLIDING SURFACE

It is known that the crucial and the most important step of sliding mode control (SMC) design is the construction of the sliding surface $s(t)$ which is expected to response desired control specifications and performance [24]. The trajectories are enforced to lie on the sliding surfaces. The sliding proportional-integral-derivative PID surface in the space of tracking error can be defined as [24]:

$$s(t) = K_p e(t) + K_i \int e(\xi)d\xi + K_d \frac{d}{dt}e(t) \qquad (5)$$

where K_p is $n\times n$ positive proportional gain matrix, K_i is $n\times n$ positive integral gain matrix, and K_d is $n\times n$ positive derivative gain matrix parameters to be selected. For 3-DOF robot manipulator, $n = 3$ and $K_p = \mathrm{diag}\{k_{p1}, k_{p2}, k_{p3}\}$, $K_d = \mathrm{diag}\{k_{d1}, k_{d2}, k_{d3}\}$ and $K_i = \mathrm{diag}\{k_{i1}, k_{i2}, k_{i3}\}$, and $e(t) = q_d(t)-q(t)$ is the tracking position error, in which $q_d(t)$ is the desired trajectory. The purpose of sliding mode control law is to force tracking error $e(t)$ to approach the sliding surface and then move along the sliding surface to the origin. Therefore, it is required that the sliding surface is stable, which means lim$e(t) = 0$; then the error will die out asymptotically. This implies that the system dynamics will track the desired trajectory asymptotically [24]. Take the derivative of sliding surface with respect to time and use (4), then

$$\begin{aligned}\dot{s}(t) &= K_p\dot{e}(t) + K_i e(t) + K_d\ddot{e}(t)\\ &= K_p\dot{e} + K_i e + K_d[\ddot{q}_d + (D+\Delta D)\dot{q}\\ &+(E+\Delta E)q(q) - (F+\Delta F)u(t) + d(t)]\end{aligned} \qquad (6)$$

The control effort being derived as the solution of $\dot{s}(t) = 0$ without considering uncertainty ($d(t) = 0$) is to achieve the desired performance under nominal model, and it is referred to as equivalent control effort [5, 23], represented by $u_{eq}(t)$

$$u_{eq}(t) = (K_d F)^{-1}[K_P \dot{e} + K_i e + K_d \ddot{q}_d + K_d D\dot{q} + K_d Eg(q)] \tag{7}$$

However, if unpredictable perturbations from the parameter variations or external load disturbance occur, the equivalent control effort cannot ensure the favorable control performance. Thus, auxiliary control effort should be designed to eliminate the effect of the unpredictable perturbations [25]. The auxiliary control effort is referred to as reaching control effort represented by $u_r(t)$. For this purpose, the Lyapunov function can be chosen as:

$$V(t) = \frac{1}{2} s^T(t)s(t) \tag{8}$$

with $V(0) = 0$ and $V(t) > 0$ for $s(t) \neq 0$. A sufficient condition to guarantee that the trajectory of the tracking position error will translate from reaching phase to sliding phase is to select the control strategy, also known as the reaching condition [24]:

$$\dot{V}(t) = s^T(t)\dot{s}(t) < 0, \quad s(t) \neq 0 \tag{9}$$

To satisfy the reaching condition, the equivalent control $u_{eq}(t)$ given in Eq. (7) is augmented by a hitting control term $u_r(t)$. Totally, the SMC law can be represented as:

$$u(t) = u_{eq}(t) + u_r(t) \tag{10}$$

The block diagram of the sliding mode control with PID sliding surface is shown in Fig. 1. If the bound is selected too large, the sign function of the reaching control law will result in serious chattering phenomena in the control efforts. The undesired chattering control efforts will wear the bearing mechanism and might excite unstable system dynamics. On the other hand, if the bound is selected too small, the stability conditions may not be satisfied. It will cause the controlled system to be unstable [25]. The finite time delays for the control computation and limitations of practical control systems render the implementation of such control signals. In other words, the sign function in overall control will cause the control input to produce the chattering phenomenon. In the current study, this problem is resolved through the application of a fuzzy control scheme to determine an appropriate reaching law.

IV. FUZZY SLIDING MODE CONTROL

Fuzzy control (FC) has supplanted conventional technologies in many applications [26]. One major feature of fuzzy logic is its ability to express the amount of ambiguity in human thinking. Thus, when the mathematical model of the process does not exist, or exists but with uncertainties, FC is an alternative way to deal with the unknown process. However, the huge number of fuzzy rules for high-order systems makes the analysis complex. Therefore, much attention has been focused on the fuzzy sliding mode control FSMC [25, 26].

As reported in [25, 26], in this paper, in order to eliminate the chattering problem, a fuzzy inference engine is used for reaching phase and fuzzy sliding mode control methodology is proposed. The main advantage of this method is that the robust behavior of the system is guaranteed. The second advantage of the proposed scheme is that the performance of the system in the sense of removing chattering is improved in comparison with the same SMC technique without using FC [26]. The configuration of our fuzzy sliding mode control (FSMC) scheme is shown in Fig. 2; it contains an equivalent control part and a two- input single-output FSMC in which Mamdani's fuzzy inference method is used.

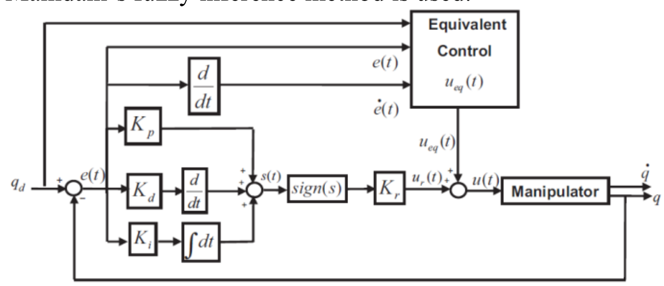


Fig. 1. Block diagram of the sliding mode control with PID sliding surface.

The reaching law is selected as:

$$u_r(t) = K_f u_f(t) \tag{11}$$

where K_f is the normalization factor of the output variable, and $u_f(t)$ is the output of the FSMC, which is determined by the normalized $s(t)$ and $\dot{s}(t)$. The fuzzy control rules can be represented as the mapping of the input linguistic variables $s(t)$ and $\dot{s}(t)$ to the output linguistic variable $u_f(t)$ as follows [26]:

$$u_f(t) = FSMC(s(t), \dot{s}(t)) \tag{12}$$

where it denotes the functional characteristics of the fuzzy linguistic decision schemes. The membership function of input linguistic variables $s(t)$ and $\dot{s}(t)$ and the membership functions of output linguistic variable $u_f(t)$ are shown in Figs. 3 and 4, respectively.

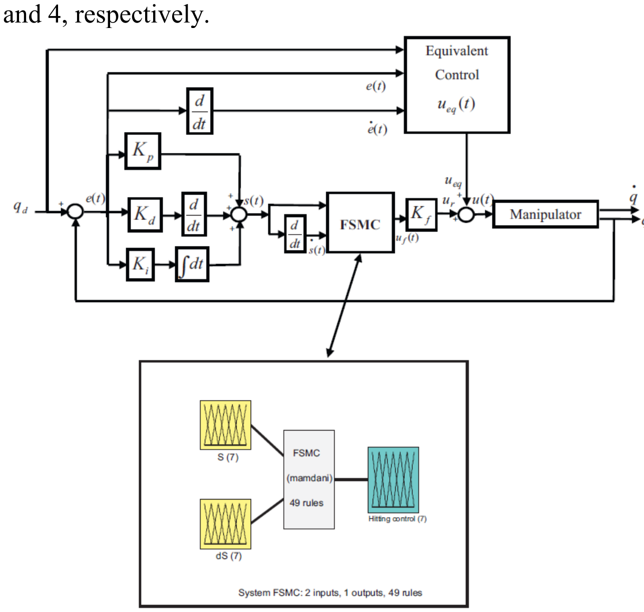


Fig. 2. Block diagram of the fuzzy sliding mode control with PID sliding surface.

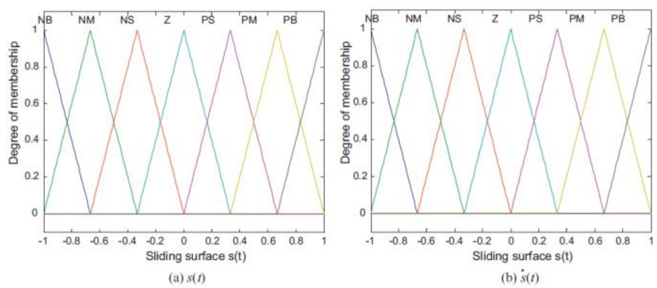


Fig. 3. Fuzzy sets of sliding surface $s(t)$ and derivative of sliding surface $\dot{s}(t)$.

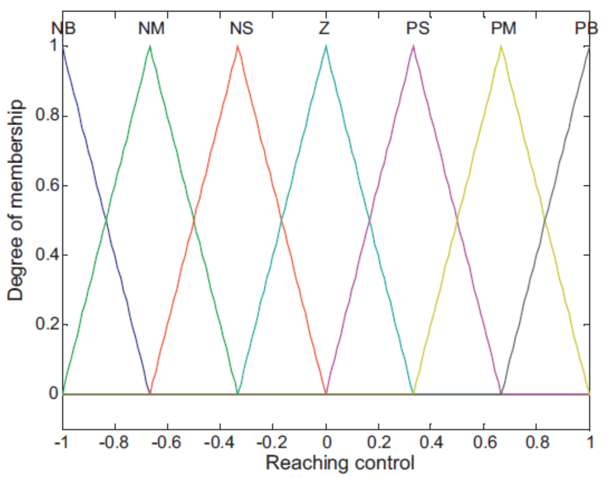


Fig. 4. Fuzzy sets of reaching control $u_f(t)$.

They are decomposed into seven fuzzy partitions expressed as NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). The fuzzy control surface of the output $u_f(t)$ is shown in Fig. 5. The fuzzy rules are extracted in such a way that the stability of the system would be satisfied and these rules contain the input–output relationships that define the control strategy. These linguistic fuzzy rules are defined heuristically in the following form [22]:

$R^{(1)}$ :: IF $s(t)$ is A_1^l and $\dot{s}(t)$ is A_2^l THEN $u_f(t)$ is B^l

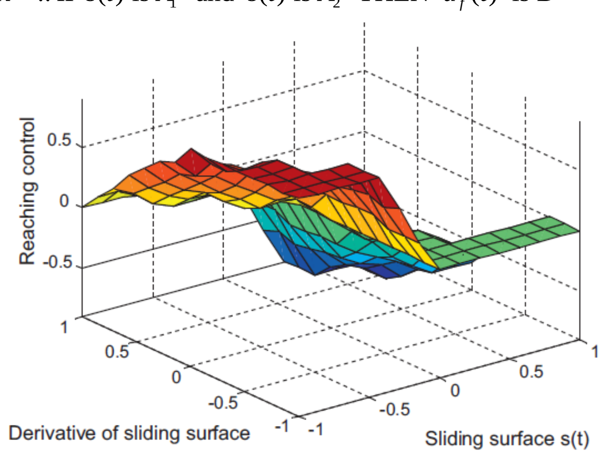


Fig. 5. Control surface of $u_f(t)$.

where A^l_1 and A^l_2 are the labels of the input fuzzy sets. B^l is the labels of the output fuzzy sets. $l = 1, 2, \ldots\ldots, m$ denotes the number of the fuzzy IF-THEN rules. For the fuzzy implication, the intersection minimum operation has been used, the center average defuzzification process has been selected. The fuzzy rule table is designed as in Table 1 [27]. Totally, the FSMC law can be represented as:

$$\begin{aligned} u(t) &= u_{eq}(t) + u_r(t) = u_{eq}(t) + K_f u_f(t) \\ &= u_{eq}(t) + K_f \,\mathrm{FSMC}(s(t), \dot{s}(t)) \end{aligned} \tag{13}$$

The stability of the robotic system, represented by Eq. (4), controlled by $u(t)$ in (13), where the equivalent control part $u_{eq}(t)$ is in (7), is proved by using the Lyapunov function can be chosen as:

$$V(t) = \frac{1}{2} s^T(t) s(t) \tag{14}$$

$$\dot{V}(t) = s^T(t) \dot{s}(t) \tag{15}$$

Table 1. Rule matrix of FSMC.

$U_f(t)$	s(t)						
s(t)	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	Nb	NM	NS	Z	PS	PM
Z	Nb	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PN	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

V. ADAPTIVE FUZZY SLIDING MODE CONTROLLER

FC usually embeds the intuition and experience of a human operator. Recently it has been used in the form of supervisor for a number of applications. In this section, the fuzzy sliding mode controller (FSMC) with varying control gain is presented. The general structure of the proposed controller is given in Fig. 6. Specifically, a supervisory fuzzy inference system is used to adaptively tune the reaching control gain K_f in order to improve the performance of the controller.

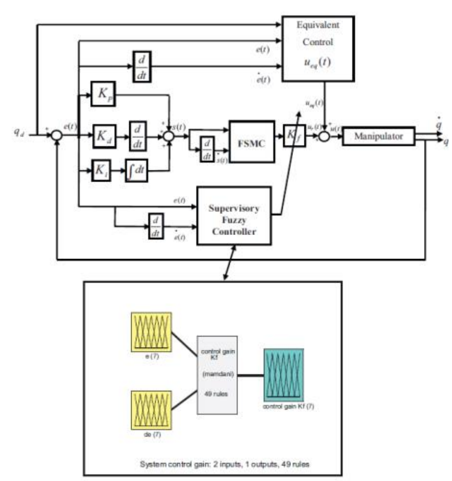


Fig. 6. Block diagram of the adaptive fuzzy sliding mode control with PID sliding surface.

The supervisory fuzzy system of the proposed tuning method contains operator knowledge in the form of IF-THEN rules to decide the control gain K_f according to the current operating conditions of the controlled system. Here, the control rules of the supervisory fuzzy system are developed with the error e and derivative of error e˙ as a premise, and K_f = diag{k_{f1}, k_{f2}, ... k_{fn}} as a consequent of each rules. The triangle shape membership functions with 50% of overlapping for the inputs and outputs fuzzy variables are considering as shown in Figs. 7–10 shows the fuzzy control surface of K_f. This surface has been used to adaptively tune K_f = diag{k_{f1}, k_{f2}, ... k_{fn}} on line. The physical domain of the inputs $(e, \dot{e})$ is in the range {−0.01, 0.01} and that of the output (K_f= diag{k_{f1}, k_{f2}, k_{f3}}, for 3 DOF, n = 3) is in the range {4000, 7500}, respectively, selected based on trial and error approach. The fuzzy variables are defined for the rule base as, $(e, \dot{e})$ ={NB(Negative Big), NM(Negative Medium), NS(Negative Small), Z(Zero), PS(Positive Small), PN(Positive Medium), PB(Positive Big)}; (K_f) = {VVS (Very Very Small), VS (Very Small), S (Small), M (Medium), B (Big), VB (Very Big) and VVB (Very Very Big). A typical fuzzy control rule of the proposed supervisory fuzzy control is expressed as:

$$R^{(i)} :: \text{IF } e(t) \text{ is } E_1^i \text{ and } \dot{e}(t) \text{ is } E_2^i \text{ THEN } K_f(t) \text{ is } G^i$$

where E^i_1 and E^i_2 are the labels of the input fuzzy sets. G_i is the labels of the output fuzzy sets. i = 1, 2, ... , p denotes the number of the fuzzy IF-THEN rules. The linguistic fuzzy rules of the supervisory fuzzy system are given in Table 2. Intersection minimum operation has been used for the fuzzy implication, and center average defuzzification method is used to compute the crisp value of the outputs.

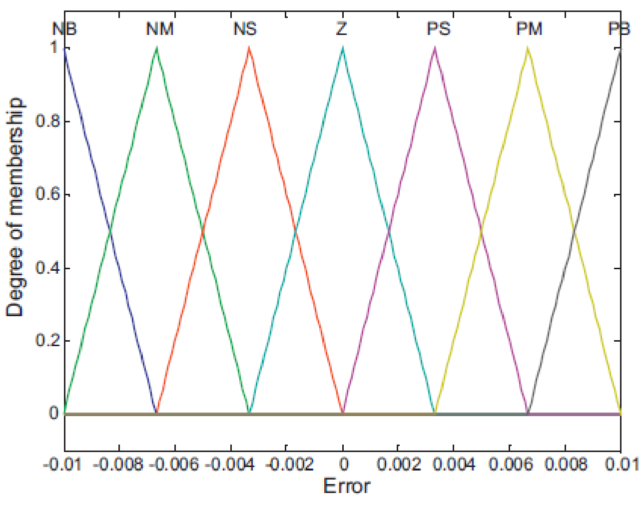


Fig. 7. Membership function of error.

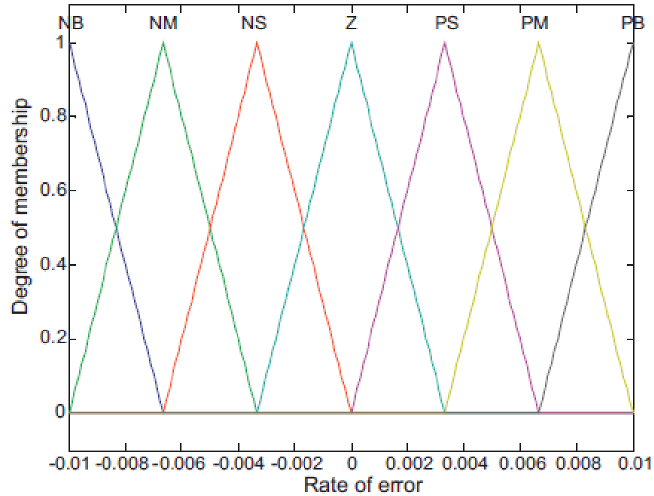


Fig. 8. Membership function of change of error.

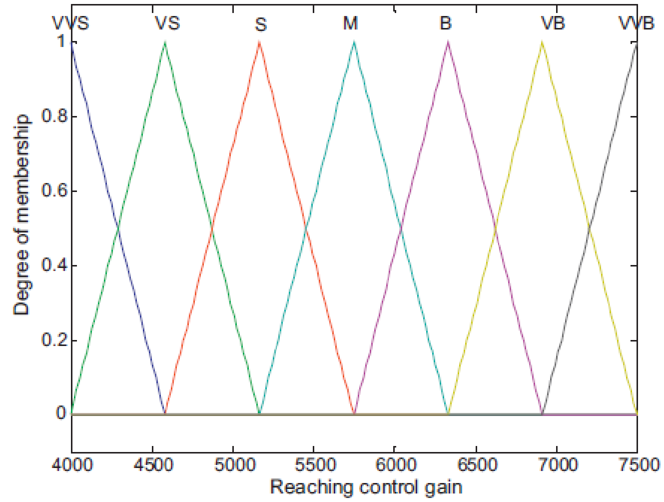


Fig. 9. Membership functions of K_f.

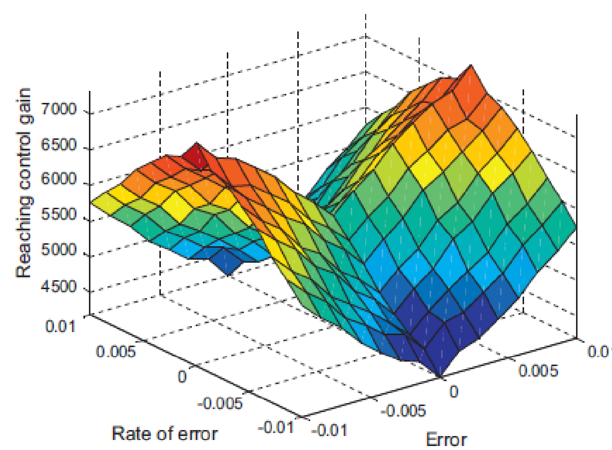


Fig. 10. Fuzzy control surfaces of K_f.

Table 2. Rule matrix of supervisory fuzzy control.

K_f	e(t)						
e(t)	NB	NM	NS	Z	PS	PM	PB
NB	M	S	VS	VVS	VS	S	M
NM	B	M	S	VS	S	M	B
NS	VB	B	M	S	M	B	VB
Z	VVB	VB	B	M	B	VB	VVB
PS	VB	B	M	S	M	B	VB
PN	B	M	S	VS	S	M	B
PB	M	S	VS	VVS	VS	S	M

VI. Simulation Results

The proposed AFSMC was tested for the control of 3 DOF rigid three-link manipulator shown in Fig. 11. All simulations are carried out using MATLAB 7.01. Uncertainties representing the dynamic effects as nonlinear viscous and static frictions, small joint and link elasticity, backlash and bounded torque disturbances by the terms in Eq. (1) are given by:

$$F_d\dot{q} = \begin{bmatrix} f_d\dot{q}_1 \\ f_d\dot{q}_2 \\ f_d\dot{q}_3 \end{bmatrix} = \begin{bmatrix} 5\dot{q}_1 \\ 5\dot{q}_2 \\ 5\dot{q}_3 \end{bmatrix} \qquad F_s(\dot{q}) = \begin{bmatrix} f_s\mathrm{sign}\dot{q}_1 \\ f_s\mathrm{sign}\dot{q}_2 \\ f_s\mathrm{sign}\dot{q}_3 \end{bmatrix} = \begin{bmatrix} 5\mathrm{sign}(\dot{q}_1) \\ 5\mathrm{sign}(\dot{q}_2) \\ 5\mathrm{sign}(\dot{q}_3) \end{bmatrix}$$

$$\tau_d = \begin{bmatrix} 20+02\sin(20(t-1))+30\sin(10(t-0.5))+20u(t-0.5)+20u(t-1) \\ 20+02\sin(20(t-1))+30\sin(10(t-0.5))+20u(t-0.5)+20u(t-1) \\ 20+02\sin(20(t-1))+30\sin(10(t-0.5))+20u(t-0.5)+20u(t-1) \end{bmatrix}$$

In order to show the effectiveness of the proposed approach, two simulations are performed:

a. Tracking control of high-speed trajectory

The desired trajectory used here is given as: $q_d(t)$=1-cos(pi*t), $0 \le t \le 4$. The parameters of the PID sliding surface are K_p = diag{300, 300, 300} , K_i = diag{250, 250, 250}, and K_d = diag{20, 20, 20}. For the conventional SMC, the hitting control gain K_r is set as: K_r =diag{15000, 15000, 15000}. For the FSMC, the hitting control gain K_f is set as: s K_f = diag{5000, 5000, 5000}. For the AFSMC, the range of the output gain K_f = diag{k_{f1}, k_{f2}, k_{f3}} is (4000, 7500).

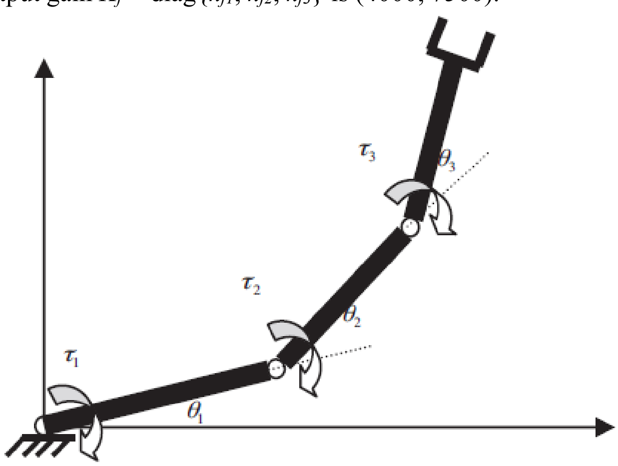


Fig. 11. Rigid three link robot manipulator.

Figs. 12–14 show the trajectory tracking for joints 1, 2, and 3, respectively. Fig. 15 shows the joint tracking position error profile for joints 1, 2, and 3, respectively. Performance indices of integral absolute error (IAE) and integral time multiplied absolute error (ITAE) are used for comparison. The values of different errors for various control strategies and various joints are tabulated in Table 3.

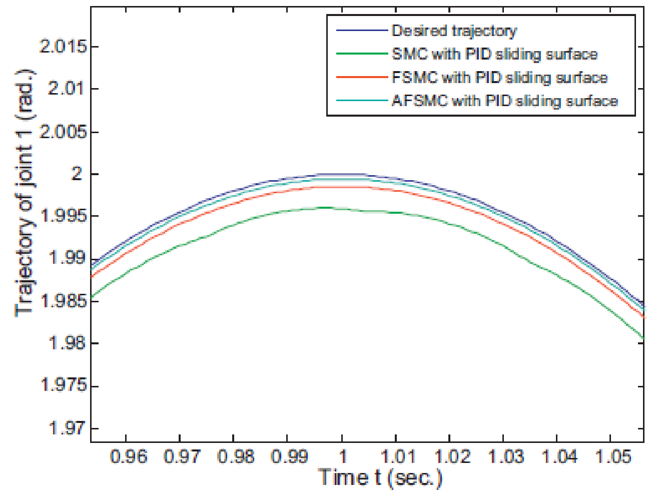


Fig. 12. Trajectory of joint 1.

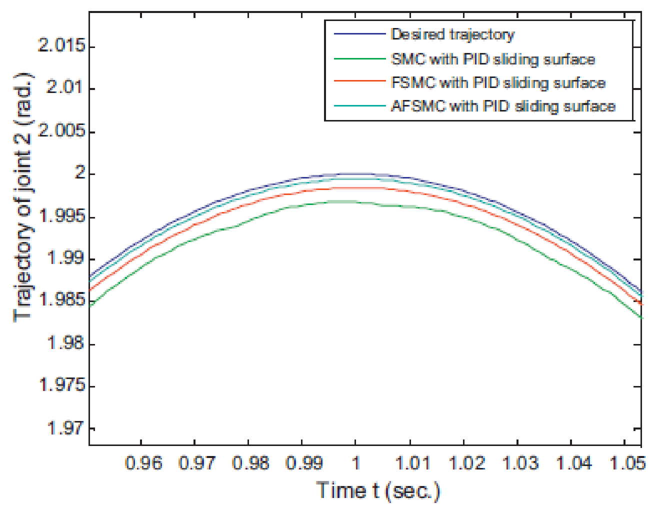


Fig. 13. Trajectory of joint 2.

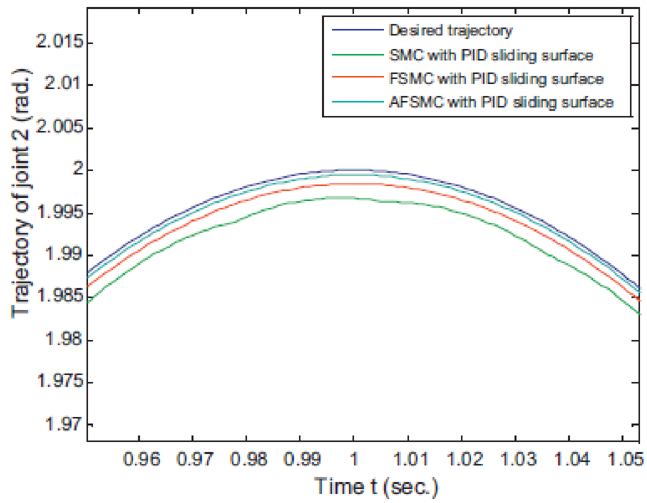
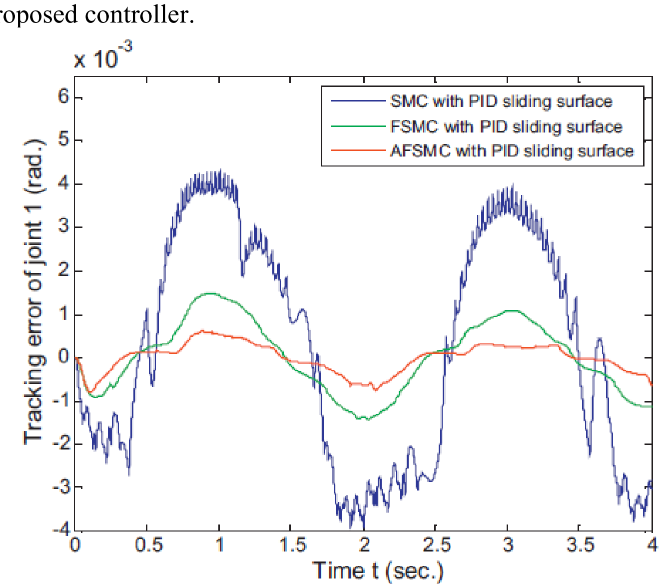


Fig. 14. Trajectory of joint 3.

b. Pick and place task

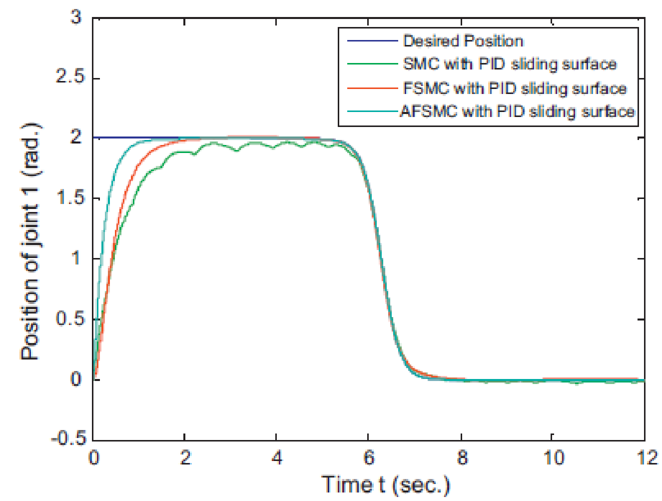
The desired joint angle function is chosen as: $q_d(t) = 2 + (-1 + \tanh(10\cos(0.25t)))$, $0 \leq t \leq 12sec$. This function is a pick-and-place type task that is widely used in industrial applications. The parameters of the PID sliding surface are set as: K_p = diag{20, 20, 20}, K_i = diag{15, 15, 15}, and K_d = diag{5, 5, 5}. For the conventional SMC, the hitting control gain K_r is set as: K_r = diag{20000, 20000, 20000}. For the FSMC, the hitting control gain K_f is set as: K_f = diag{5500, 5500, 5500}. For the AFSMC, the range of the output gain K_f = diag{k_{f1}, k_{f2}, k_{f3}} is (4000, 7500). Fig. 16 shows the position for joints 1, 2, and 3, respectively.

Simulation results show that the proposed AFSMC has faster tracking with smaller error values than both conventional SMC and FSMC. It is observed that the proposed AFSMC has the smallest IAE and ITAE performance indices among the other controllers, which proves the efficiency of the proposed controller.



(a) Joint 1

Fig. 15. Trajectory tracking error of joint 1.



(a) Joint 1

Fig. 16. Position of joint 1.

Table 3. Performance comparison of the controllers for the trajectory tracking control.

Algorithm	IAE			ITAE		
	Joint 1	Joint 2	Joint 3	Joint 1	Joint 2	Joint 3
Conventional SMC	3.92	3.62	5.01	16.81	11.41	17.4
FSMC	0.54	0.54	0.54	2.51	2.52	2.52
AFSMC	0.17	0.16	0.17	0.76	0.74	0.75

Table 4. Performance comparison of the controllers for the pick-place task.

Algorithm	IAE			ITAE		
	Joint 1	Joint 2	Joint 3	Joint 1	Joint 2	Joint 3
Conventional SMC	1395.7	1194	1336.7	3235.9	1829.9	2293
FSMC	723.8	725.8	728.6	508.8	531.9	552.2
AFSMC	446.6	452.3	461.4	298.7	360.3	420.8

VII. CONCLUSION

This paper outlines the development of an adaptive fuzzy sliding mode control (AFSMC) successfully employed in the motion control of robot manipulators. The robust non-chattering AFSMC, based on a fuzzy control (FC) scheme, offers significant advantages in practical applications by combining the robustness of sliding mode control (SMC) and the chattering elimination of fuzzy control. To enhance the performance of fuzzy sliding mode control (FSMC), online tuning of the hitting control gain is implemented according to the error states of the system using a supervisory fuzzy controller. Notably, this method operates without requiring knowledge of the system's uncertainty and disturbance bounds. Additionally, it eliminates the chattering phenomenon commonly observed in traditional SMC without compromising system robustness. This approach demonstrates success in challenging scenarios involving robot manipulators with complex, nonlinear, time-varying, and coupled differential equations for each link's dynamics. In situations demanding precise tracking of fast trajectories with high nonlinearities and uncertainties, conventional sliding mode control (SMC) schemes prove inadequate, resulting in suboptimal performance. The Adaptive Fuzzy Inference System-based controller outperforms conventional methods in the control of robot manipulators. Simulation results confirm the effectiveness of the proposed control methodology, indicating superior tracking performance and robust characteristics compared to a simple sliding mode controller.

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