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Adaptive Robust Tracking Control of Robotic Manipulator based on SMC and Fuzzy Control Strategy

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Abstract

In recent years, robotic systems have been widely used in different applications, and this has motivated researchers to develop different control methods. A model-free, intelligent, robust control method for a nonlinear robotic manipulator system is proposed in this work. This paper presents a novel solution for the major drawbacks of the sliding mode control scheme, which are chattering. Prior knowledge is needed about the dynamic model of the controlled system and the upper bound of uncertainty. In this paper, a fuzzy-like PD controller with SMC (FLPDSM) is proposed. The fuzzy-like PD controller was designed according to fuzzy rules and membership functions based on the nominal model of the robot manipulator. A robust control term was added to the control signal to compensate for the system uncertainty, and external disturbances are compensated by adding an auxiliary robust term to the SMC control law. Two methods for designing robust control terms are proposed. The first proposed method assumes that the upper bound of system uncertainty is known although it cannot be exactly determined due to external disturbances and uncertainty. Hence, a second method was proposed that assumes this bound to be unknown, and an adaptive gain based on Lyapunov theory was used to derive the adaptation law. The Lyapunov second method was used to ensure the stability of the closed loop system. Performance tests on the proposed methods were implemented through simulation studies for the two-link robotic manipulator, and the test results were compared with the standard SMC to verify the effectiveness of the proposed method. A good trajectory tracking with a high robustness against parameter variations and external disturbances was observed under the presented control scheme.

***Keywords**: SMC, Robotic Systems, Fuzzy Control, Trajectory Tracking.*

1. Introduction

Robotic manipulators are used successfully in many particular applications, and especially in industrial factories. Accuracy and precision are important features that encourage the use of robotic manipulators in plants that aim to enhance their products and manufacturing processes [1]. There are many challenges that make tracking accuracy in robotic manipulators difficult, including high nonlinearity, system uncertainties, and strong coupling between adjacent joints, hence, several control schemes have been proposed to solve these problems by designing a stable and robust controller. Because of its simplicity in structure and the relatively easy tuning of parameters, the Proportional Integral Derivative (PID) controller is applied in different control system [2]. Fuzzy logic was used to schedul of the PID controller to control the hybrid robot manipulator [3]. Fuzzy type 2 had been proposed for the control of the 2dof robotic manipulator with Grey wolf optimization used for tuning the parameters [4]. The particle swarm optimization method was combined with the PID controller to stabilize the humanoid robot [5] . An adaptive backstepping control with a simple adaptive estimated Lyapunov theorem has been used for the control of the robotic manipulator [6]. Many advanced control schemes, including adaptive and artificial intelligence methods, have been used to tune the parameters of the PID. The number of degrees of freedom and system uncertainties of the robotic manipulator have significant effects on control performance. The sliding mode control (SMC) represents an efficient control scheme for nonlinear systems, that is applied successfully in many mechanical systems and robotic manipulators. Chattering is the major disadvantage of SMC and different control schemes have been proposed to eliminate the chattering. Among the solutions to the chattering problem in the SMC is the use of saturation approximation functions instead of the discontinues function, and low-pass filtering [7-12]. Recently, the fuzzy logic technique has been widely applied to approximate the signum discontinues term [13-18]. Implementing the SMC control law requires the upper bound of the uncertainties, and the external disturbance must be known [19]. The values of these bounds are very important in the selection of the switching gain. To ensure stability, the switching gain must be greater than the upper bound of uncertainty, which is unknown, and assuming large values for the upper bound may be the reason for chattering. This paper presents two robust control schemes based on fuzzy control and SMC. The important features of the proposed controller in this paper can be summarized as follows: i) the upper bound of uncertainty is not required, ii) the proposed controller is model-free, iii) Lyapunov theory is used to avoid the overestimation of the switching gain, construct an adaptation law for the switching gain, and also guarantee the stability of the controlled system.

2. Robotic Manipulator Dynamic

The dynamic equations of n rigid-link robotic manipulator system based on the Lagrange-Euler equations of motion are:

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

$$M(q) = M_o(q) + \Delta M(q) \quad \ldots(2)$$

$$C(q,\dot{q}) = C_o(q,\dot{q}) + \Delta C(q,\dot{q}) \quad \ldots(3)$$

$$F(\dot{q}) = F_o(\dot{q}) + \Delta F(\dot{q}) \quad \ldots(4)$$

Where $q = [q_1, q_2, \cdots, q_n]^T \in R^n$ is the joint angular position vector, $\dot{q} = [\dot{q}_1, \dot{q}_2, \cdots, \dot{q}_n]^T \in R^n$ is the joint angular velocity vector, $M(q) \in R^{n x n}$ denotes the inertia matrix, $C(q, \dot{q}) \in R^{n x n}$ represents the centrifugal-Coriolis matrix, $F(\dot{q}) \in R^n$ is the friction torque vector, $G(q) \in R^n$ denotes the gravity term, $\tau_d \in R^n$ is the external disturbance vector, and $\tau = [\tau_1, \tau_2, \cdots, \tau_n]^T$ is the torque vector. $M_o(q), C_o(q, \dot{q})$ and $F_o(\dot{q})$ refer to the nominal model of the robotic manipulator, and $\Delta M(q), \Delta C(q, \dot{q})$ and $\Delta F(\dot{q})$ refer to the uncertainty in the dynamic model of the robotic manipulator. The proposed control method assumes the following [20]:

Assumption 1: Boundedness of the inertia matrix

$$\|M(q)\| \leq k_1 \quad \ldots(5)$$

where k_1 is a positive scalar.

Assumption 2: Boundedness of the centrifugal matrix

$$\|C(q,\dot{q})\| \leq k_2 \quad \ldots(6)$$

where k_2 is a positive scalar.

Assumption 3: Boundedness of the friction vector

$$\|F(\dot{q})\| \leq k_3\|\dot{q}\| + F_0 \quad \ldots(7)$$

where k_3 and F_0 are positive scalars.

Assumption 4: Boundedness of the gravity vector

$$\|G(q)\| \leq k_4 \quad \ldots(8)$$

where k_4 is a positive scalar.

Assumption 5: The model in (1) is linearly parameterized, so it can be represented by the following expression:

$$Y\emptyset = M(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + F(\dot{q}) \quad \ldots(9)$$

$$\dot{q}_r = \dot{q}_d + \gamma(q_d - q) \quad \ldots(10)$$

where $Y = Y(q, \dot{q}, \dot{q}_r, \ddot{q}_r) \in R^{n \times p}$ is a matrix that contains a known nonlinear function, $\emptyset \in R^p$ is a vector that contains unknown parameters, and $\boldsymbol{\gamma}$ is a positive diagonal matrix.

Assumption 6: The desired trajectories and their derivatives$q_d(t), \dot{q}_d(t)$, and $\ddot{q}_d(t)$are bounded as follows:

$$|q_d(t)| \leq M_{d1} \quad , \quad |\dot{q}_d(t)| \leq M_{d2} \quad , \quad |\ddot{q}_d(t)| \leq M_{d3}, \quad \ldots(11)$$

with M_{d1}, M_{d2}, and M_{d3}being positive constants.

3. Sliding Mode Control

The objective of SMC is to make trajectory states $\mathbf{q}$ track the desired trajectory $\mathbf{q_d}$. The first step in the SMC is designing the sliding surface. For a second-order system, the sliding surface is given by:

$$s(t) = \gamma\, e(t) + \dot{e}(t) \quad \text{...(12)}$$

$$e(t) = q - q_d \quad \text{...(13)}$$

$$e(t) = [e_1(t)\; e_2(t)\; \cdots\; e_n(t)]^T \quad \text{...(14)}$$

where $\mathbf{e}(t)$ is the error signal that represents the difference between the desired trajectory and the actual trajectory. An equivalent control term in the conventional SMC is calculated by setting $\dot{\mathbf{s}}(t) = 0$, and this will determine the control effort required to achieve a good performance without considering the external disturbance and system uncertainties.

$$\dot{s}(t) = \gamma\dot{e}(t) + \ddot{e}(t) \quad \text{...(15)}$$

$$= \gamma\dot{e}(t) + \ddot{q} - \ddot{q}_d \quad \text{...(16)}$$

$$\ddot{q} = M^{-1}(q)[\tau - C(q,\dot{q})\dot{q} - F(\dot{q}) - G(q) - \tau_d] \quad \text{...(17)}$$

where $\boldsymbol{\gamma}$ is a diagonal matrix.

In the equivalent control term, only the known part of the dynamic model of the controlled system is taken into account, which yields:

$$\dot{s}(t) = \gamma\, \dot{e}(t) + M_o^{-1}(q)[\tau - C_o(q,\dot{q})\dot{q} - F_o(\dot{q}) - G_o(q)] \quad \text{...(18)}$$

$$\dot{s}(t) = 0 \quad \text{...(19)}$$

$$\gamma\, \dot{e}(t) + M_o^{-1}(q)\big[\tau_{eq} - C_o(q,\dot{q})\dot{q} - F_o(\dot{q}) - G_o(q)\big] = 0 \quad \text{...(20)}$$

$$\tau_{eq} = C_o(q,\dot{q})\dot{q} - F_o(\dot{q}) - G_o(q) + M_o(q)\gamma\, \dot{e}(t) \quad \text{...(21)}$$

However, the equivalent control term is not sufficient to achieve good performance in practical applications due to many challenges like parameter variations and external disturbances. A control law is presented to compensate for these uncertainties. The overall SMC control signal is:

$$\tau = \tau_{eq} + \tau_r \quad \text{...(22)}$$

$$\tau_r = k\, sgn(s) = [k_1 sgn(s_1)\; \cdots\; k_n sgn(s_n)]^T \quad \text{...(23)}$$

$$sgn(s_i) = \begin{cases} 1 & if\ s_i > 0 \\ -1 & if\ s_i < 0 \end{cases} \quad \text{...(24)}$$

where $\boldsymbol{\tau_r}$ is the robust term and the value of $\boldsymbol{k}$ is large and must be greater than the upper bound of uncertainty.

There are many challenges to implementing the control law of the conventional SMC. As shown in (21), the exact dynamic mode of the robotic system and the upper bound of uncertainty must be known to select the gain of the robust term. Moreover, the sign function causes the chattering phenomena that may cause damage to the actuators.

4. Proposed FLPDSM Design

This section discusses in detail the two terms of the proposed control method. Figure 1 displays the block diagram for the proposed control scheme. The proposed control law is:

$$\tau = \tau_F + \tau_r \quad \text{...(25)}$$

where $\boldsymbol{\tau_F}$ is the output of the fuzzy-like PD controller that was designed based on the nominal model of the robotic system, and $\boldsymbol{\tau_r}$ refers to the robust control signal that overcomes the uncertainties and external disturbances that were not included in the fuzzy-like PD controller's design. Two methods are proposed for the robust control term $\boldsymbol{\tau_r}$: In the first method, the upper bound of the dynamic model of the robotic system is assumed to be known, while in the second method, this bound is assumed to be unknown.

4.1 Fuzzy-Like PD Controller

A fuzzy-like PD controller is proposed to achieve good performance with fuzzy rules, and was designed without considering parameter variations, and external disturbances. Only the nominal model of the robot manipulator is considered. The inputs to the fuzzy controller are the normalized error and the derivative of the error. The output of the fuzzy controller is τ_F.

$$\tau_F = k_f u_f \quad \text{...(26)}$$

$$u_f(t) = FPD\big(e(t), \dot{e}(t)\big) \quad \text{...(27)}$$

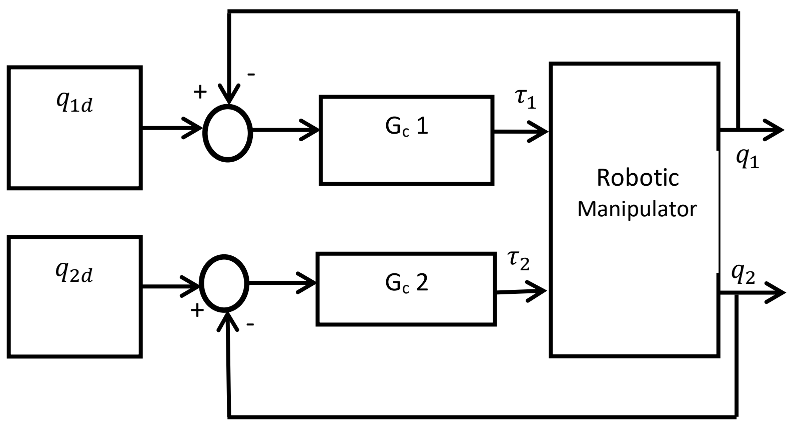

Fig. 1. Basic decentralized control scheme for two link robotic manipulator.

where $\boldsymbol{k_f}$ is a positive diagonal matrix that refers to the output scaling factor, and $FPD(\boldsymbol{e}(t), \dot{\boldsymbol{e}}(t))$denotes the fuzzy logic decision system. The membership functions for the input variables $\boldsymbol{e}(t)$ and $\dot{\boldsymbol{e}}(t)$ and the output variable$\boldsymbol{u_f}(t)$ are shown in figure 2. Five fuzzy functions, defined as Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB), are used as membership functions. Table 1 lists the rules used in this controller. The intersection minimum has been used for the fuzzification process, while the center average operations were used for defuzzification.

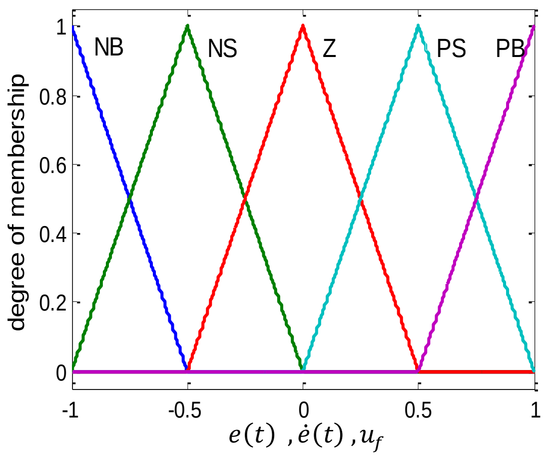

Fig. 2. Membership functions for the fuzzy controller

Table 1,
Fuzzy controller rules

$\dot{e}(t)$ \ $e(t)$	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

4.2 Robust Auxiliary Controller

Any robust control scheme must take into account parameter variations and external disturbances in order to provide a controller that is robust to unpredictable variations. In this section, two methods are presented to select a suitable auxiliary controller. In the first proposed method, the upper bound of uncertainty is assumed to be known, while in the second proposed method, it assumed to be unknown.

4.2.1 Proposed I: Constant Switching Gain

In this method, the switching gain, whose value is determined based on Lyapunov theory, is kept constant, as shown in figure 3.

$$\boldsymbol{\tau_r} = \boldsymbol{k}\, sgn\,(\mathbf{s}) = [k_1 sgn(s_1) \cdots k_n sgn(s_n)]^T \quad \ldots(28)$$

The proposed control law can be written as:

$$\tau = k_f u_f + k\, sgn(\mathrm{s}) \quad \ldots(29)$$

Theorem 1

Considering the nonlinear robotic system in (1), and the proposed robust fuzzy control method in (29), the closed loop system will be asymptotically stable with approximately zero error signals if the controller parameters are selected as follows:

$$\|\mathrm{k}\| > \|\mathrm{Y}\emptyset + k_f\| \quad \ldots(30)$$

$$k_f > 0 \quad \ldots(31)$$

Proof.

Let V be the candidate Lyapunov function used to verify the stability.

$$V = \frac{1}{2}\mathrm{s}^T \mathrm{Ms} \quad \ldots(32)$$

$$\dot{V} = \mathrm{s}^T\mathrm{M}\dot{\mathrm{s}} + \frac{1}{2}\mathrm{s}^T\dot{\mathrm{M}}\mathrm{s} = \mathrm{s}^T\mathrm{M}\dot{\mathrm{s}} + \mathrm{s}^T\mathrm{Cs} \quad \ldots(33)$$

$$\dot{V} = \mathrm{s}^T[\mathrm{M(q)}\ddot{\mathrm{q}}_\mathrm{r} + \mathrm{C(q,\dot{q})}\dot{\mathrm{q}}_\mathrm{r} + \mathrm{G(q)} + \mathrm{F}(\dot{\mathrm{q}}) - \tau] \quad \ldots(34)$$

$$\dot{V} = \mathrm{s}^T[\mathrm{Y}\emptyset - \tau] \quad \ldots(35)$$

$\dot{V} = s^T[Y\emptyset - \tau_F - \tau_r]$ ...(36)

$\dot{V} = s^T[Y\emptyset - k_f u_f - \tau_r]$ ...(37)

The outputs of the fuzzy controller are normalized between [-1, 1], then

$\|u_f\| \le 1$ ...(38)

$s^T k_f u_f \le \|s\|\|k_f\|$ ...(39)

$\dot{V} \le \|s\|[\|Y\emptyset\| - \|k\| + \|k_f\|]$ ...(40)

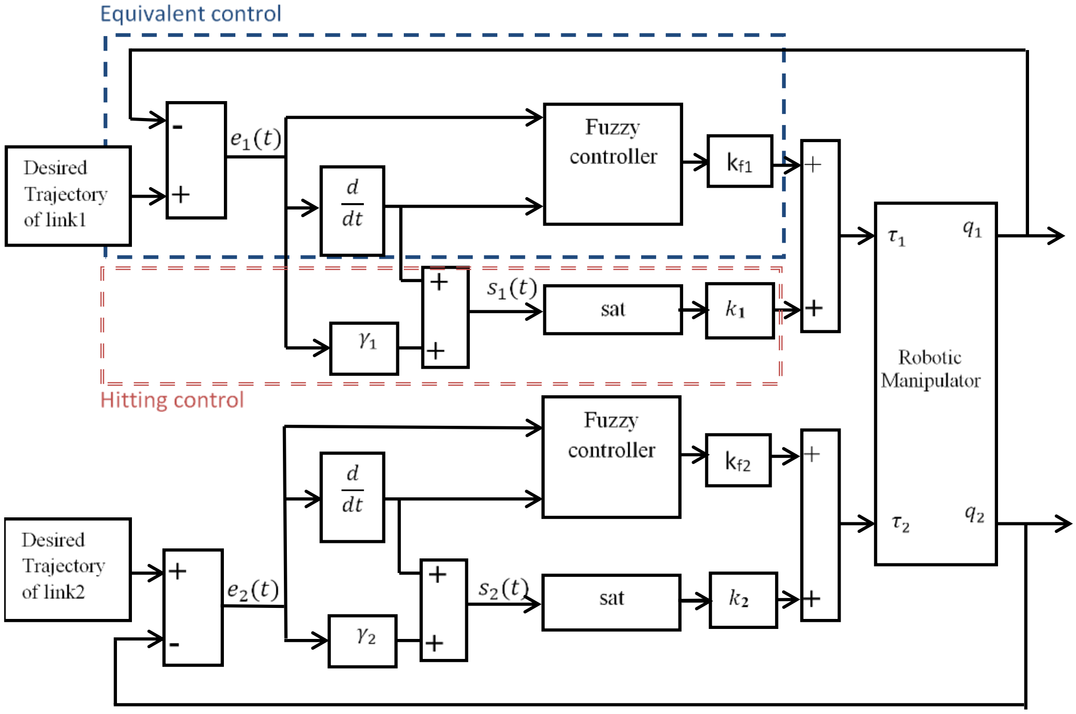

Fig. 3. Block diagram for the proposed scheme I (constant robust gain).

$\dot{V} \le \|s\|[\|Y\emptyset\| + \|k_f\| - \|k\|]$ ...(41)

If k is selected based on the following condition:

$\|k\| > \|Y\emptyset\| + \|k_f\|$ ...(42)

Then

$\dot{V} \le 0$ ...(43)

thus, the closed loop system is asymptotically stable.

Remark:

The problem is that the upper bound of the robotic system dynamic (**Y**$\emptyset$) is not exactly known and is related to the upper bound of uncertainty. Selecting a larger value for **k** will cause chattering, and a smaller value may make the system unstable. A second method was proposed to overcome this problem.

4.2.2 Proposed II: Adaptive gain

To avoid the problem of the unknown upper bound of the dynamic model of the robotic system, Lyapunov's theorem is applied to design an adaptation law for the gain of the robust term to estimate the upper bound of the robot dynamic. As a result, there is no need to know the upper bound of the dynamic model, which is related to the upper bound of system uncertainty and external disturbance, which cannot be easily determined in practical applications. Figure 4 shows the second proposed method.

Let

$\rho = Y\emptyset - k_f u_f$ ...(44)

$\boldsymbol{\rho}$cannot be determined exactly because it's based on dynamic of the robot manipulator.

The proposed robust control is:

$\tau_r = \hat{\rho}$ ...(45)

Where $\hat{\boldsymbol{\rho}}$ represents estimation of $\boldsymbol{\rho}$. Then the estimation error can be defined as:

$\tilde{\rho} = \rho - \hat{\rho}$ ... (46)

The proposed control law is:

$\tau = k_f u_f + \hat{\rho}$ ...(47)

Theorem 2 If the control law in (46) is used for the nonlinear robotic manipulator in (1), then the controlled system will be asymptotically stable with zero error signals if the parameters $\hat{\mathbf{E}}$ are adjusted by the following adaptation law:

$\dot{\tilde{\rho}} = -L^{T^{-1}} s$ ...(48)

$\hat{\rho}(t) = \int_{t-1}^{t} \dot{\hat{\rho}}(t)\, dt + \hat{\rho}(t-1)$ ...(49)

where $\mathbf{L} \in R^{n \times n}$ is the adaptation rate.

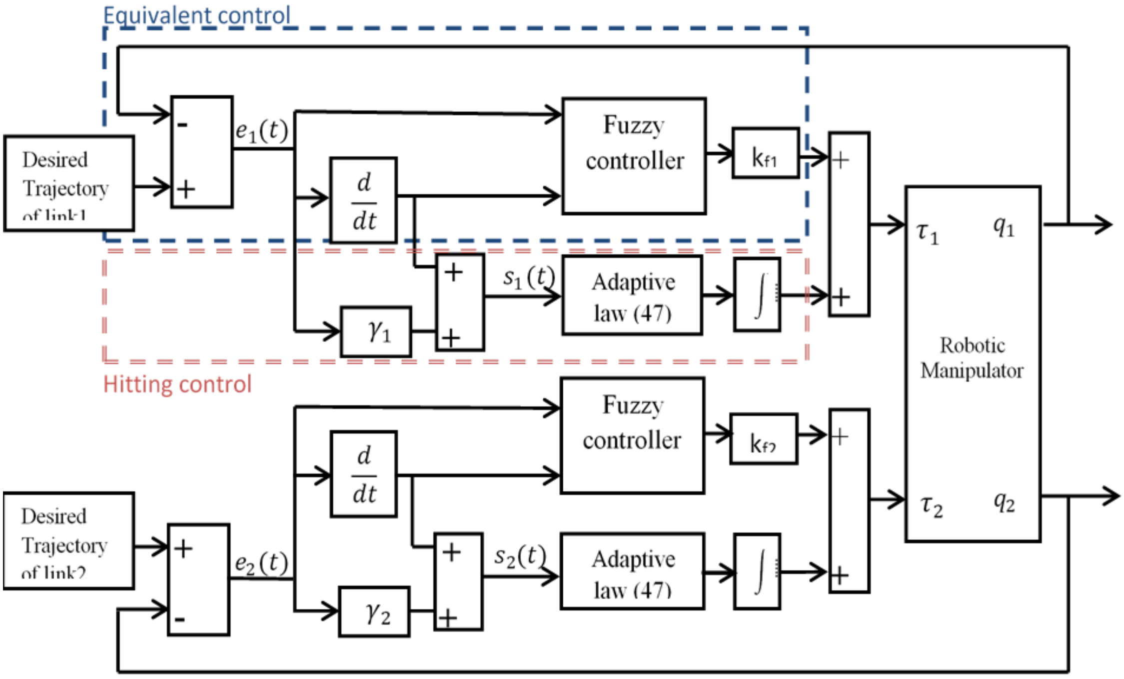

Fig. 4. Block diagram for the proposed scheme II (adaptive robust gain).

Proof.

Let

Let V be the candidate Lyapunov function.

$$V = \frac{1}{2}s^T Ms + \frac{1}{2}\tilde{\rho}^T L\tilde{\rho} \quad \ldots(50)$$

$$\dot{V} = s^T M\dot{s} + \frac{1}{2}s^T \dot{M}s + \dot{\tilde{\rho}}^T L\tilde{\rho} \quad \ldots(51)$$

$$= s^T M\dot{s} + s^T Cs + \dot{\tilde{\rho}} L\tilde{\rho} \quad \ldots(52)$$

$$s^T[M(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + F(\dot{q}) - \tau] + \dot{\tilde{\rho}}^T L\tilde{\rho} \quad \ldots(53)$$

$$\dot{V} = s^T\left[Y\emptyset - k_f u_f - \tau_r\right] + \dot{\tilde{\rho}}^T L\tilde{\rho} \quad \ldots(54)$$

$$\dot{V} = s^T[\rho - \hat{\rho}] + \dot{\tilde{\rho}}^T L\tilde{\rho} \quad \ldots(55)$$

$$\dot{V} = s^T[\tilde{\rho}] + \dot{\tilde{\rho}}^T L\tilde{\rho} \quad \ldots(56)$$

$$\dot{V} = \left[s^T + \dot{\tilde{\rho}}^T L\right]\tilde{\rho} \quad \ldots(57)$$

If $\dot{\tilde{\rho}} = -L^{T^{-1}} s$ ...(58)

Then

$$\dot{V} = 0 \quad \ldots(59)$$

As a result, the adaptation law for the control parameter $\hat{\rho}(t)$ will be as follows:

$$\hat{\rho}(t) = \int_{t-1}^{t} \dot{\hat{\rho}}(t)\, dt + \hat{\rho}(t-1) \quad \ldots(60)$$

Thus, the controlled system with the proposed method is asymptotically stable with zero tracking error.

5. Simulation Results

In this section, a two-link rigid planar robotic manipulator system is used to illustrate the robustness and effectiveness of the presented method. Figure 5 shows the schematic diagram of the two-link planar robotic manipulator, with the dynamic model expressed as follows:

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = \begin{bmatrix}M_{11} & M_{12}\\ M_{12} & M_{22}\end{bmatrix}\begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix} + \begin{bmatrix}-b\dot{q}_2 & -b\dot{q}_1 - b\dot{q}_2\\ -b\dot{q}_1 & 0\end{bmatrix}\begin{bmatrix}\dot{q}_1\\ \dot{q}_2\end{bmatrix} + \begin{bmatrix}v_1\dot{q}_1\\ v_2\dot{q}_2\end{bmatrix} + \begin{bmatrix}p_1 sgn(\dot{q}_1)\\ p_2 sgn(\dot{q}_2)\end{bmatrix} + \begin{bmatrix}g_1\\ g_2\end{bmatrix} \quad \ldots(61)$$

with

$$M_{11} = I_1 + I_2 + m_1{L_{c1}}^2 + m_2\left({L_{c2}}^2 + {L_1}^2 + 2L_1L_{c2}cos(q_2)\right)M_{12} = I_2 + m_2\left({L_{c2}}^2 + L_1L_{c2}\cos(q_2)\right)$$

$M_{22} = I_2 + m_2{L_{c2}}^2$,

$b = m_2L_1L_{c2}\sin(q_2)$,

$g_1 = m_1L_{c1}g cos(q_1) + m_2 g(L_{c2}cos(q_1+q_2) + L_1 cos(q_1))$,

$g_2 = m_2 g L_{c2} cos(q_1+q_2)$.

where q_1 and q_2 are angular positions, τ_1 and τ_2 are torques, L_1 and L_2 are lengths, m_1 and m_2 are masses, I_1 and I_2 are lengthwise centroid inertia, L_{c1} and L_{c2} are distances from the joint to the center of gravity, v_1 and v_2 are coefficients of viscous friction, and p_1 and p_2 are coefficients of dynamic friction of Link1 and Link2, respectively. The parameters of the two-link robotic manipulator used in the current simulation study are listed in table 2. In order to prove its effectiveness, the proposed control scheme is compared with the standard SMC. Table 3 lists the values of the parameters of the proposed controllers and the SMC that are used in the simulation. The integral time absolute error ($ITAE$) performance index is used for the comparison, which was used to numerically evaluate the performance of the tracking error.

$$ITAE = \int_0^{tf} t|e(t)|dt \quad \ldots(62)$$

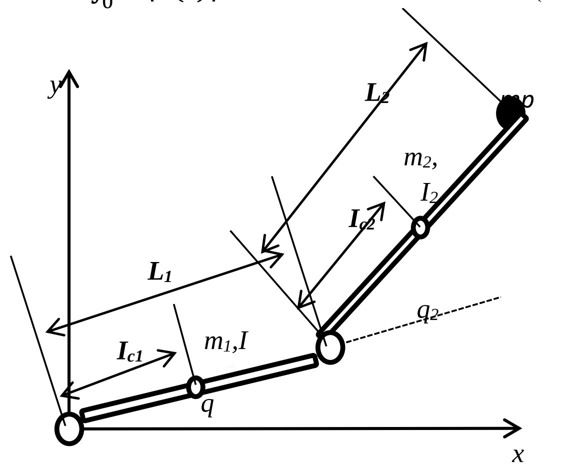

Fig. 5. Schematic diagram of two linkobotic system.

Table 2,
Robotic Manipulator parameters

Parameter	Link1	Link2
Mass (kg)	1.0	1.0
Length (m)	1.0	1.0
Viscous friction coefficient	0.1	0.1
Ddynamic friction coefficient	0.1	0.1
Lengthwise centroid inertia (kg m^2)	0.5	0.5
Distance from joint to center of gravity (m)	0.2	0.2

5.1 Robustness test: Model Uncertainties

The robustness and effectiveness of the presented control methods are examined in the presence of the model of uncertainties and compared with the SMC. The system uncertainty includes variations in the mass, static, and dynamic coefficients of friction of Link1 as well as Link2. These parameters are increased by 15% of their nominal values. The desired trajectory used in this simulation is given as:

$$q_{1d}(t) = -0.1 + \cos(2\pi t) \quad \ldots(63)$$

$$q_{2d}(t) = 0.5 + sin(2\pi t) \quad \ldots(64)$$

The ITAE values for the proposed method I, proposed method II, and SMC are listed in table 4. To illustrate the comparison, variations in the ITAE for Link1 and Link2 are shown in figure 6. This comparison indicates that the ITAE for the proposed method II is less than for the other methods, whereas the ITAE for the proposed method I and SMC are approximately equal which means that the proposed method II is more robust than the SMC and the proposed method I. Figures 7 and 8 show the tracking position, tracking error, and input torque for Link1 and Link2, respectively. These figures clearly indicate that the proposed control methods have very good tracking performance and smaller position tracking errors in Link1 and Link2. However, with respect to the chattering problem, figures 7 (c) and 8 (c) show that the control signals of proposed methods I and II are significantly smoother than that of the SMC.

Table 3,
The parameters of proposed and SMC controllers

Control Method	Law	Parameter	Link1	link2
Proposed II	$\tau = k_f u_f + \hat{E}$	k_f	250	250
	$\dot{\hat{E}} = L^{-1} s^T$	L	1	1
	$s(t) = \gamma\, e(t) + \dot{e}(t)$	γ	5	5
Proposed I	$\tau = k_f u_f + k\, sat(s, \emptyset)$	k_f	250	250
		k	300	300
		$\emptyset$	0.05	0.05
SMC	$u = M_0(q)\ddot{q}_r + N_0(q)\dot{q}_r + G_0(q) + H_0(q) + k_1 sat(s, \emptyset)$	k_1	400	400
	$\dot{q}_r(q) = \dot{q}_d - \gamma(q - q_d)$	$\emptyset$	0.05	0.05
	$s(t) = \gamma e(t) + \dot{e}(t)$	γ	5	5

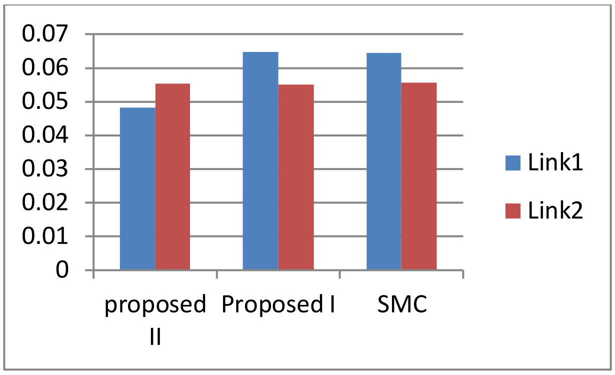

Fig. 6. ITAE variations for model uncertainties

Table 4,
Performance index ITAE values for model uncertainties

	Proposed II	Proposed I	SMC
Link1	0.0483	0.0648	0.0645
Link2	0.0552	0.0551	0.0556

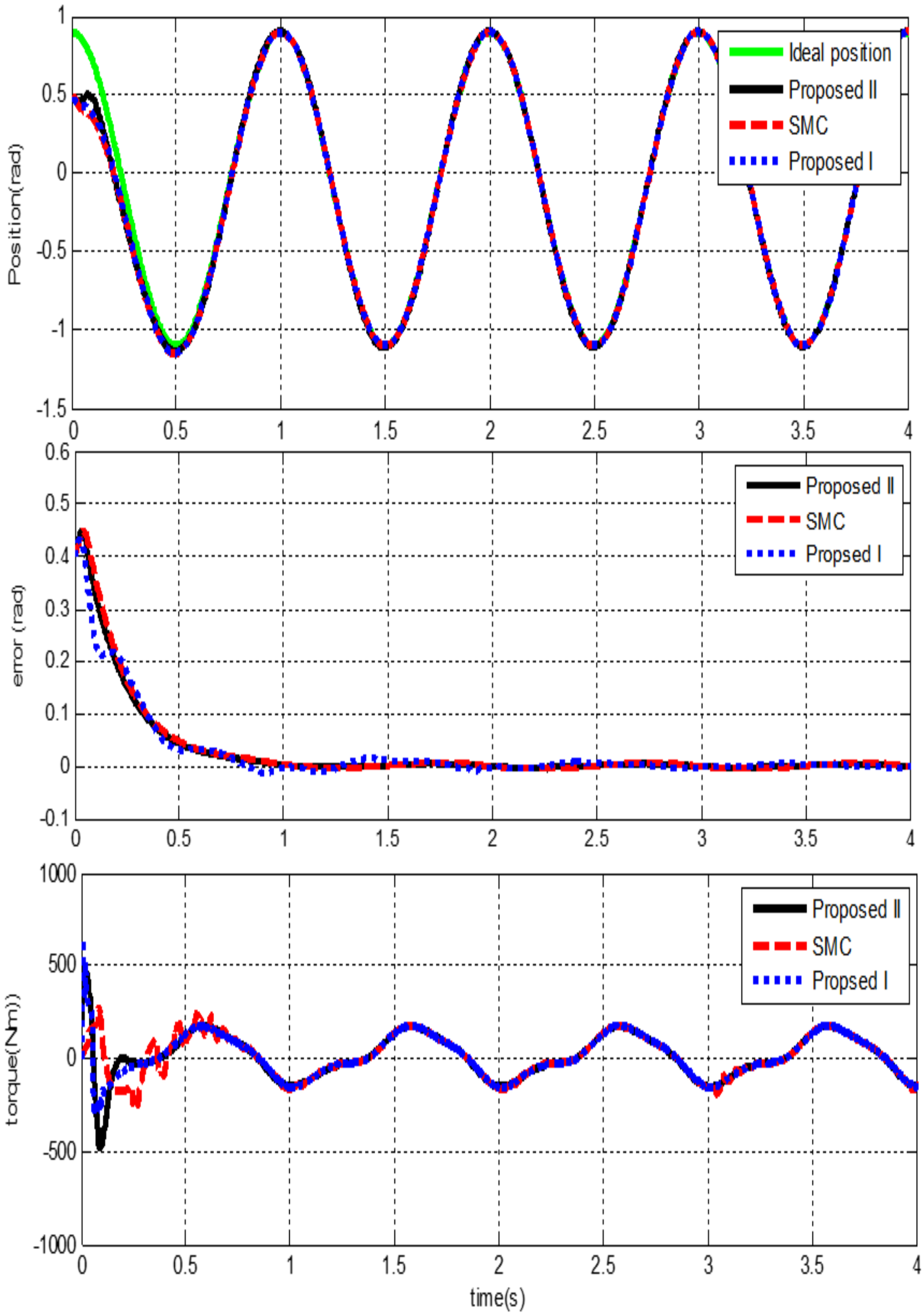

Fig. 7. Angular position (a), tracking error (b), and input torque (c) of Link1 under model uncertainties

5.2 Robustness Test: Disturbance Rejection

This section discusses the robustness of the proposed controller in the case of an external disturbance when applied to the controller output for Link1 and Link2. The disturbance signals $d_1(t)$ and $d_2(t)$ that were applied respectively, on Link1 and Link2 are:

$$d_1(t) = 9sin(5t),\ d_2(t) = 9\sin(7t) \qquad \dots(65)$$

The desired trajectory used in this simulation is given as:

$$q_{1d}(t) = q_{2d}(t) = \sin(2\pi t) \qquad \dots(66)$$

The ITAE values are listed in table 5. The ITAE variations for all methods are also shown in figure 9, which indicates the clear superiority of proposed method II. The simulation results for this case are shown in figures 10 and 11. The results obtained show a fast response of the proposed and SMC methods with good tracking performance. The results also clearly indicate the superiority of the proposed method II in comparison with the SMC and the proposed method I. Moreover, the adaptation technique that was used to estimate the upper bound of the dynamic model eliminates the chattering. Therefore, the control signal of the proposed method II is very smooth.

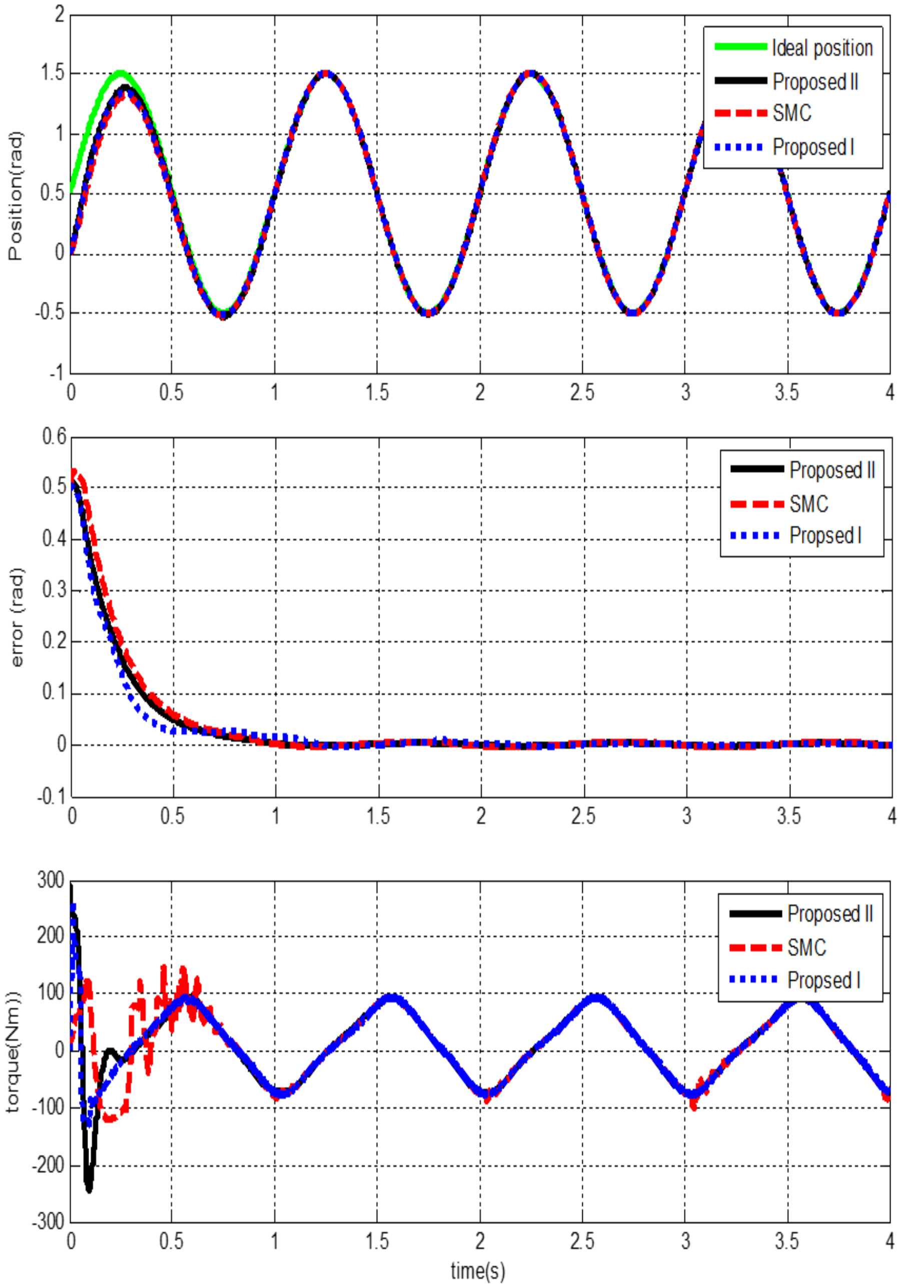

Fig. 8. Angular position (a), tracking error (b), and input torque (c) of Link2 under model uncertainties

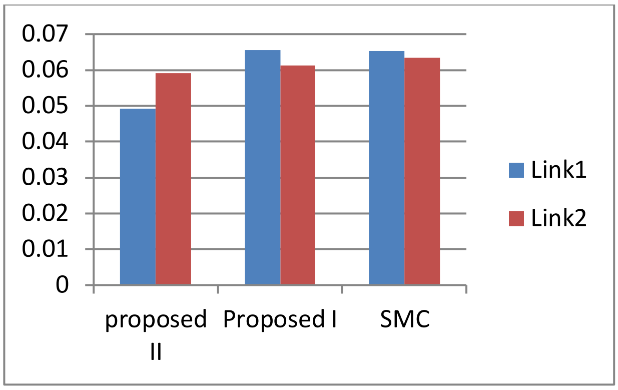

Fig. 9. ITAE variations for adding external disturbance

Table 5,
Performance index ITAE values for disturbance rejection.

	Proposed II	Proposed I	SMC
Link1	0.0493	0.0655	0.0653
Link2	0.0590	0.0613	0.0633

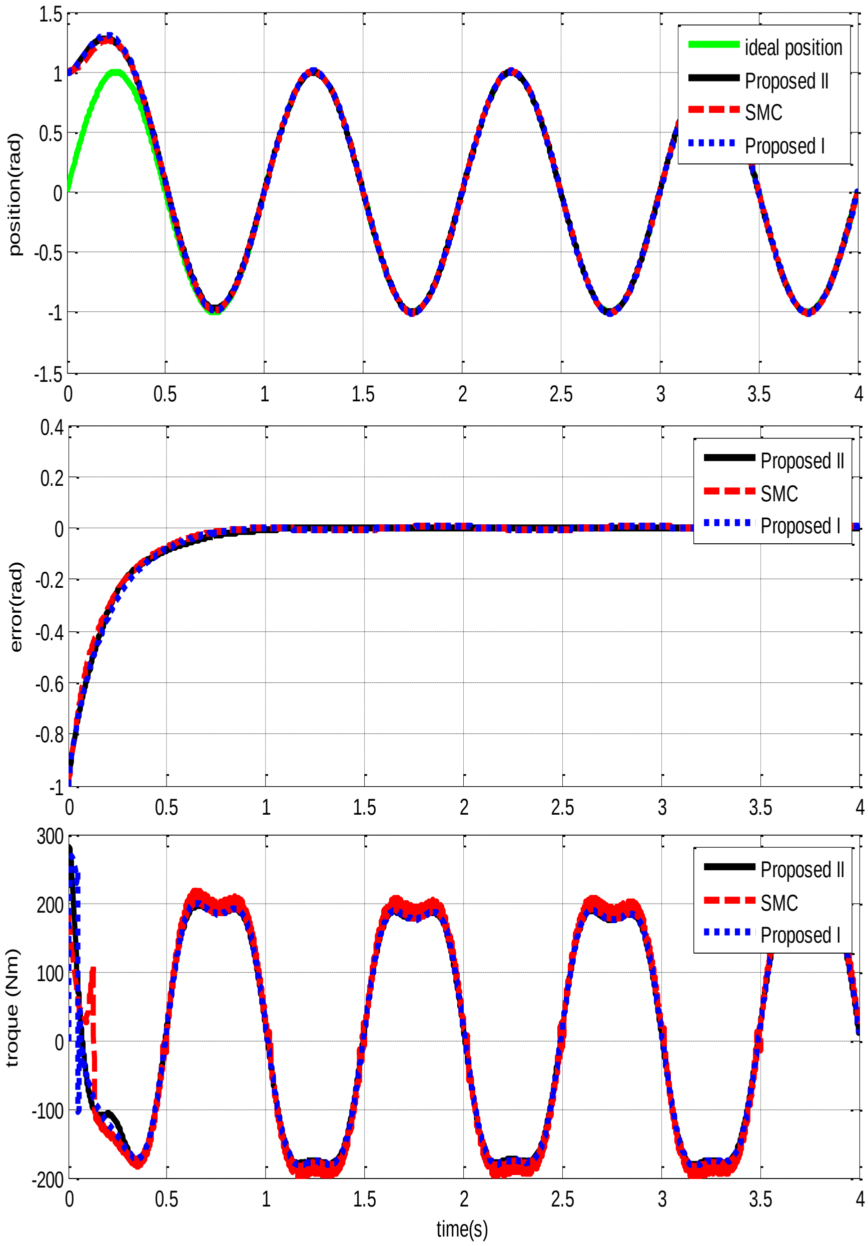

Fig. 10. Angular position (a), tracking error (b), and input torque (c) of link1 subjected to external disturbance

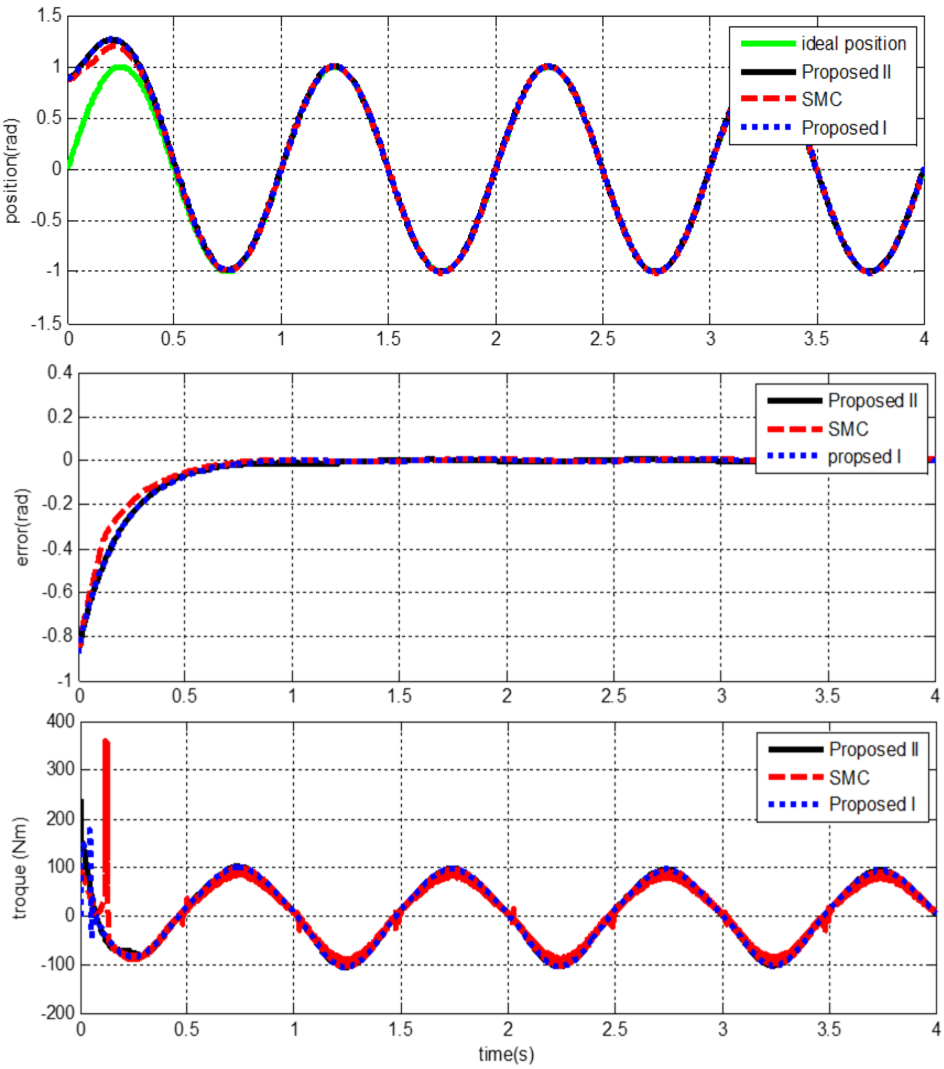

Fig. 11. Angular position (a), tracking error (b), and input torque (c) of link2 subjected to external disturbance.

6. Conclusion

This paper proposes an adaptive fuzzy robust control system for robotic manipulators. Two robust controllers are proposed for the two cases in which the upper bound of the dynamic model is known, and the upper bound is unkown. The proposed intelligent, robust, and model-free control scheme based on FLC can be applied successfully in practical applications due to its simplicity in structure. It combines the robustness of the SMC and an intelligent adaptation of the FLC. The Lyapunov theorem is used to approve the stability of the controlled system with the proposed control method and estimate the upper bound of the dynamic model. The simulation results show the effectiveness of the proposed control methods and indicate the superiority of the proposed method in the response to model uncertainty and external disturbance.

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التحكم المتين لذراع الانسان الالي بناء على طريقة الوضع المنزلق واستراتيجية التحكم الغامض

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الخلاصة

في السنوات الأخيرة، تم استخدام الأنظمة الروبوتية على نطاق واسع في تطبيقات مختلفة، وهذا ما حفز الباحثون على تطوير أساليب التحكم المختلفة. يُقترح في هذا العمل طريقة تحكم ذكية وقوية وخالية من النماذج لنظام مناور آلي غير خطي. تقدم هذه الورقة حلاً جديدًا للعيوب الرئيسة لنظام التحكم في الوضع المنزلق، هنالك حاجة إلى معرفة مسبقة حول النموذج الديناميكي للنظام المتحكم فيه والحد الأعلى من عدم اليقين. في هذا البحث، تم اقتراح وحدة تحكم PD مع SMC (FLPDSM). وتم تصميم وحدة التحكم PD اعتمادا على المعلومات المتوافرة عن النظام . وتمت إضافة مصطلح تحكم متين إلى إشارة التحكم للتعويض عن عدم اليقين في النظام، ويتم تعويض الاضطرابات الخارجية عن طريق إضافة مصطلح قوي مساعد إلى قانون التحكم SMC. وتم اقتراح طريقتين لتصميم شروط التحكم القوية. تفترض الطريقة الأولى المقترحة أن الحد الأعلى لعدم اليقين في النظام معروف على الرغم من أنه لا يمكن تحديده بدقة بسبب الاضطراب الخارجي وعدم اليقين. ومن ثم تم اقتراح طريقة ثانية تفترض أن هذا الحد غير معروف، وتم استخدام الكسب التكيفي القائم على نظرية ليابونوف لاشتقاق قانون التكيف. تم استخدام طريقة لابونوف الثانية لضمان استقرار نظام الحلقة المغلقة. تم تنفيذ اختبارات الأداء على الطرق المقترحة من خلال دراسات المحاكاة للمناول الآلي ثنائي الوصلة، وتمت مقارنة نتائج الاختبار مع SMC القياسي للتحقق من فعالية الطريقة المقترحة. وقد لوحظ تتبع مسار جيد بمتانة عالية ضد اختلافات المعلمات والاضطرابات الخارجية في إطار مخطط التحكم المقدم.