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Eliminating chattering phenomenon in sliding mode control of robot manipulators in the joint space using fuzzy logic

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Abstract

In industrial robotic manipulator, due to the presence of quite nonlinear dynamic and structural and nonstructural uncertainties, a precise model is not easily obtained. As a result, designing a model-based controller with a suitable function is a challenging issue. Sliding mode control is a robust control with numerous applications which can overcome the aforementioned uncertainties. However, this control method has several defects such as chattering in input control in implementing stage. In this article, Fuzzy sliding mode control based on TSK method for controlling manipulator position tracking is suggested. This control method not only has advantages of sliding mode but also it has no chattering control effect in implementation process. To justify the performance of proposed Fuzzy based SMC in control signal chattering, a robot manipulator with two revolute joint has been used. The simulation results reveal the desirable efficiency of Fuzzy sliding mode control.

Keywords: Robot manipulator; Joint space; Uncertainty; Fuzzy sliding mode control; TSK method; Chattering.

1. Introduction

In classical control theory, most problems are solved based on mathematical tools and system model. Industrial manipulators are the systems which have totally non-linear dynamic equations with uncertainties. Selecting an appropriate control technique with an ability to eliminate uncertainties and warrant the necessary precision and accuracy in controlling the robot manipulator is of crucial importance. The technique for sliding mode control has been presented by researchers between 1950 and 1959. Their first achievements were related to a second-degree linear system [1]. In 1978, Utkin worked on sliding mode control and its application in systems with variable structures [2]. In 1985, sliding mode control was first utilized in robust control tracking of submarines [3]. In the same year, robust tracking of non-linear systems and their application in robotics went under scrutiny [4].

Due to sliding mode control's capability in facing model uncertainties and system disturbances, it has attracted considerable attention in controlling industrial manipulators [5, 6] Although this control method proves to be effective in facing extant uncertainties, its input has discontinuity in operational stage, so called control chattering. This chattering leads to activation of robot manipulator's dynamic modes which in turn reduces the performance of control input.[5, 6, 7] Various methods for eliminating control chattering in sliding mode control have been proposed thus far. However, in most of these techniques, the reduction in control chattering has led to an increase in tracking error. A number of these methods include: higher degree sliding control mode [8], dynamic sliding mode control [9], terminal sliding mode control [10], integral sliding mode control [11], designing sliding surfaces based on linear matrices for systems with time delay and uncertainty [12, 13, 14], designing linear-static sliding surface [15], and sliding mode control by utilizing shifted and rotational sliding surfaces [16, 17]. Although the aforementioned methods for eliminating control chattering enjoy several advantages, they have disadvantages which cause a number of problems in the operations of the controller. Some of these drawbacks are as follows:

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- Lacking required ability to control tracking error poses several problems in precise tracking of the desired trajectory; as a result, it reduces the performance of the controller.
- Complex calculations cause time delay in operation of controllers and actuators and eliminate real time control and occasionally challenges control system stability.
- The presence of integral term in the design of sliding surface will cause a phenomenon named “integrator wind-up” and, as a result, it leads to the saturation of controllers and actuators as well as system instability. Resolutions to this phenomenon significantly increase the calculations volume.
- Complexity of controller design stages reduces the engineers’ and designers’ interest in utilizing these controllers.

In the second section of this article, dynamic equations of robot manipulator in joint space and their specifications will be presented. In section 3, a sliding mode controller for tracking robot manipulator will be designed. The mathematical proof indicates that closed-loop system with proposed control will possess global asymptotic stability. Next, a method will be proposed to eliminate chattering in control law. In the method presented, though control law is free of chattering, the precision in the tracking of robot manipulator position has decreased and the controller is encountered with tracking error. Nevertheless, in most industrial applications, precise tracking of the desired trajectory by means of a robot is crucially important. In section 4, a fuzzy sliding mode control based on TSK method is proposed to eliminate chattering phenomena and guarantees tracking the desired trajectory by means of robot manipulator and, finally, in section 5, a case study on a revolute two-link manipulator has been simulated and implemented in order to demonstrate and compare the performance of the proposed controllers.

2. Dynamic equations of a robot manipulator in joint space

Dynamic equation of a robot manipulator in joint space is a nonlinear, multi-input, multi-output and second order differential equation which is expressed as follows [18–26]:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) + T_d = u \tag{1}$$

$$\mathrm{H}(q,\dot{q}) = \mathrm{G}(q) + \mathrm{T_d} \tag{2}$$

In which $M(q) \in R^{n\times n}$ is the inertia matrix, $V(q,\dot{q}) \in R^{n\times n}$ is a matrix including sections related to Coriolis and centrifugal forces, $G(q) \in R^n$ is the gravitation vector, $T_d \in R^n$ is a vector including disturbances or un-modeled dynamics, $q(t) \in R^n$ is the vector of joint positions, $\dot{q}(t) \in R^n$ is the vector of joint velocities, $\ddot{q}(t) \in R^n$ is the vector of joint accelerations, and $u \in R^n$ is the vector of robot manipulator input torque.

To simplify equation (1), the following equation is defined.

By substituting (2) in (1) we obtain:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + H(q,\dot{q}) = u \tag{3}$$

Relation (1) has the following specifications:

Specifications 1: inertia matrix $M(q)$ is symmetric and positive-definite.

Specifications 2: $\dot{M}(q) - 2V(q,\dot{q})$ is a skew-symmetric matrix, that is:

$$x^T\dot{M}(q)x = 2x^TV(q,\dot{q})x \quad , \quad \forall x,q,\dot{q} \in R^n \tag{4}$$

3. Design of sliding mode controller for robot manipulator

To design sliding mode control, sliding surface vector is defined as [27–31]:

$$S = ({}^{d}/_{dt} + \lambda)^{n-1}e \tag{5}$$

In equation (5), $e = q - q_d$ is the tracking error vector in which $q = [q_1\ q_2 \ldots q_n]^T$ is the vector of joint positions and $q_d = [q_{1d}\ q_{2d} \ldots q_{nd}]^T$ is the vector of desired trajectory and $\lambda = \mathrm{diag}[\lambda_1, \lambda_2, \ldots, \lambda_n]$ is a diagonal matrix in which $\lambda_1, \lambda_2, \ldots, \lambda_n$ are constant and positive coefficients.

Generally, to design sliding mode controller, the variable $q_r^{(n-1)}$ is defined as:

$$q_r^{(n-1)} = q^{(n-1)} - s \tag{6}$$

Since the robot manipulator is expressed by the second order differential equation, therefore equation (6) with $n = 2$ is determined as:

$$\dot{q}_r = \dot{q} - s \tag{7}$$

Differentiating equation (7) we obtain:

$$\ddot{q}_r = \ddot{q} - \dot{s} \tag{8}$$

Point 1: Since q, $\dot{q}$, $\ddot{q}$ and S are $n \times 1$ vectors, thus $\dot{q}_r$ and $\ddot{q}_r$ are $n \times 1$ vectors.

To design sliding mode controller, with respect to equations (7) and (8), equation (3) is changed to:

$$M(q)\ddot{q}_r + M(q)\dot{s} + V(q,\dot{q})\dot{q}_r + V(q,\dot{q})s + H(q,\dot{q}) = u \tag{9}$$

Now, the control law is proposed as:

$$u = \hat{u} - Ksgn(s) \tag{10}$$

In which $\mathrm{sgn}(s)$ is the sign function and $\hat{u}$ is selected as:

$$\hat{u} = \hat{M}(q)\ddot{q}_r + \hat{V}(q,\dot{q})\dot{q}_r + \hat{H}(q,\dot{q}) \tag{11}$$

In relations (10) and (11), $\hat{M}(q)$, $\hat{V}(q,\dot{q})$ and $\hat{H}(q,\dot{q})$ are estimations of $M(q)$, $V(q,\dot{q})$ and $H(q,\dot{q})$, respectively and $K = \mathrm{diag}[k_1, k_2, \ldots, k_n]$ is a positive-definite diagonal matrix. Substituting equations (10) and (11) in (9) we obtain:

$$M(q)\ddot{q}_r + M(q)\dot{s} + V(q,\dot{q})\dot{q}_r + V(q,\dot{q})s + H(q,\dot{q}) = \widehat{M}(q)\ddot{q}_r + \widehat{V}(q,\dot{q})\dot{q}_r + \widehat{H}(q,\dot{q}) - Ksgn(s) \quad (12)$$

Equation (12) is simplified as:

$$M(q)\dot{s} + V(q,\dot{q})s = \left(\widehat{M}(q) - M(q)\right)\ddot{q}_r + \left(\widehat{V}(q,\dot{q}) - V(q,\dot{q})\right)\dot{q}_r + \left(\widehat{H}(q,\dot{q}) - H(q,\dot{q})\right) - Ksgn(s) \quad (13)$$

For the sake of simplicity of the aforementioned equations, $\Delta M(q) = \widehat{M}(q) - M(q)$, $\Delta V(q,\dot{q}) = \widehat{V}(q,\dot{q}) - V(q,\dot{q})$, $\Delta H(q,\dot{q}) = \widehat{H}(q,\dot{q}) - H(q,\dot{q})$ and $\Delta f = \Delta M(q)\ddot{q}_r + \Delta V(q,\dot{q})\dot{q}_r + \Delta H(q,\dot{q})$ are defined and equation (13) is simplified as:

$$M(q)\dot{s} + V(q,\dot{q})s = \Delta M(q)\ddot{q}_r + \Delta V(q,\dot{q})\dot{q}_r + \Delta H(q,\dot{q}) - Ksgn(s) = \Delta f - Ksgn(s) \quad (14)$$

Point 2: $\Delta f \in R^n$ is a vector including all parametric, non-structural uncertainties as well as un-modeled dynamics.

3.1. Proof of closed-loop system stability

To prove closed-loop system stability of equation (14), with respect to the dynamic features of robot manipulator as mentioned in section 2, Lyapunov function candidate is proposed as:

$$V(s) = \frac{1}{2}s^T M(q)s \quad (15)$$

Differentiating with respect to time in equation (15) we obtain:

$$\dot{V}(s) = s^T M(q)\dot{s} + \frac{1}{2}s^T \dot{M}(q)s \quad (16)$$

With respect to equation (4), equation (16) is rewritten as:

$$\dot{V}(s) = s^T(M(q)\dot{s} + V(q,\dot{q})s) \quad (17)$$

From equations (14) and (17), the following equation is concluded:

$$\dot{V}(s) = s^T[\Delta f - Ksgn(s)] = \sum_{i=1}^{n}(s_i[\Delta f_i - K_i sgn(s_i)]) \quad (18)$$

From equation (18), s_i is the ith entry of sliding surface vectors, Δf_i is the ith entry of the vector Δf and K_i is the ith entry of the main diagonal of matrix k. To prove closed-loop system stability, equation (18) must be less than zero, that is:

$$\dot{V}(s) = \sum_{i=1}^{n}(s_i[\Delta f_i - K_i sgn(s_i)]) < 0 \quad (19)$$

The aforementioned equation is satisfied if:

$$K_i > \|\Delta f_i\| \quad (20)$$

Thus by selecting appropriate K which satisfies equation (20), closed-loop system will possess the global asymptotic stability.

3.2. Modification of proposed control

Although robot manipulator with the proposed controller will have global asymptotic stability, control input will have chattering which can activate the dynamic modes of robot manipulator. Thus to avoid such an adverse phenomenon, control law is modified as [19]:

$$u = \hat{u} - Ksat(S/\phi) \quad (21)$$

In the aforementioned equation, by choosing the proper ϕ (boundary layer thickness), we can eliminate chattering at control input; however, we will have no control on the tracking error of robot manipulator position. As a matter of fact, by selecting various ϕ , one of the following conditions will occur in the controller:

1. By choosing large ϕ, chattering in control input would be eliminated and the error in robot manipulator tracking position will increase.
2. By choosing small ϕ, the accuracy in tracking position robot manipulator will improve, but unfortunately, the chattering phenomenon will occur.

Nevertheless, in most applications of robot manipulator such as assembling, eliminating control input chattering as well as accuracy in tracking robot manipulator position is of significant importance. Therefore, to improve the capabilities of this controller, in controlling position tracking error and encountering unfavorable phenomenon of chattering in control input, we will utilize the first-order fuzzy TSK system.

4. Design of fuzzy sliding mode controller for a robot manipulator

A first-order fuzzy TSK system is delineated by fuzzy if-then rules which show the relations between inputs and outputs. Generally, first-order fuzzy TSK control system rules are defined as:

$$if\ x_1\ is\ A_1^i\ and \dots and\ \ x_n\ is\ \ A_n^i\ then \quad y^i = a_0^i + a_1^i x_1 + \cdots + a_n^i x_n \quad (22)$$

in which $i = 1,2,\dots,M$ and M is the number of fuzzy rules. y^i's are the output of these M fuzzy rules and $a_0^i, a_1^i, \dots, a_n^i$ are constant coefficients.

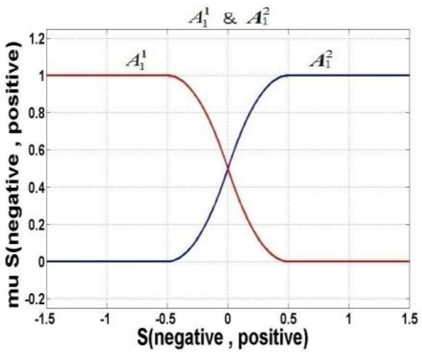
To design sliding mode controller, equation (10) could be stated as:

$$\begin{cases} u_p = \hat{u} + K & , \ s < 0 \\ u_n = \hat{u} - K & , \ s > 0 \end{cases} \quad (23)$$

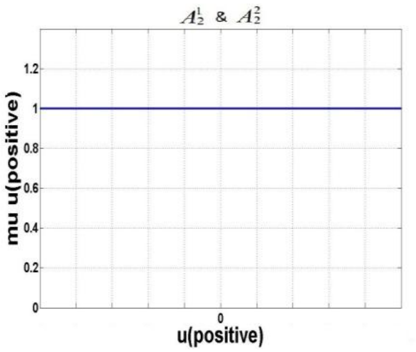
With respect to equation (23), controller fuzzy rules could be stated as:

$$if\ s\ is\ A_1^1\ and\ u_p\ is\ A_2^1\ and\ u_n\ is\ A_3^1$$
$$then\ \ y^1 = a_0^1 + a_1^1 s + a_2^1 u_p + a_3^1 u_n \tag{24}$$
$$if\ s\ is\ A_1^2\ and\ u_p\ is\ A_2^2\ and\ u_n\ is\ A_3^2$$
$$then\ \ y^2 = a_0^2 + a_1^2 s + a_2^2 u_p + a_3^2 u_n$$

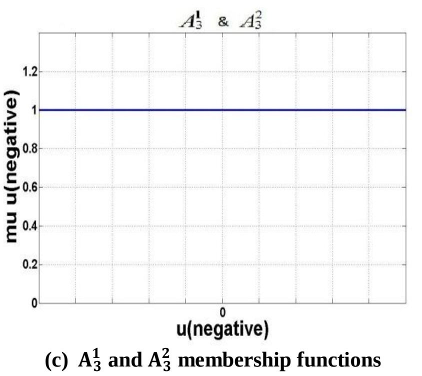
In the aforementioned relation, $a_0^1 = a_0^2 = a_1^1 = a_2^2 = a_1^2 = a_3^1 = 0$ and $a_2^1 = a_3^2 = 1$ and membership functions will be defined as that in figure1.



(a) A_1^1 and A_1^2 membership functions



(b) A_2^1 and A_2^2 membership functions



(c) A_3^1 and A_3^2 membership functions

Fig. 1. Utilized membership functions for fuzzy system

Point 3: The bound of the abscissa in figures 1.a. and 1.b. are defined based on the input bound of the designed sliding mode control, which differs for each joint as defined in section 3.

Assuming $x = [s, u_p, u_n]^T$ to be input vector of fuzzy TSK system, its output will be calculated based on the combination of fuzzy rules (24) and is expressed as follows:

$$y = \frac{\sum_{i=1}^{2} f^i(x) y^i(x)}{\sum_{i=1}^{2} f^i(x)} \tag{25}$$

$f^i(x)$ is the firing strength of the ith rule, which is obtained from the following equation:

$$f^i(x) = \mu_{A_1^i}(x_1) * \mu_{A_2^i}(x_2) * \mu_{A_3^i}(x_3) \tag{26}$$

" $*$ " is the indicator of a t-norm and $\mu_{A_j^i}(x_j)$ indicates the membership degree of the input x_j in the membership function A_j^i from the ith rule.

5. A case study on revolute double-joint robot manipulator

The controllers which have been designed and scrutinized in this article are conducted on the revolute double-joint robot manipulator of figure 2.

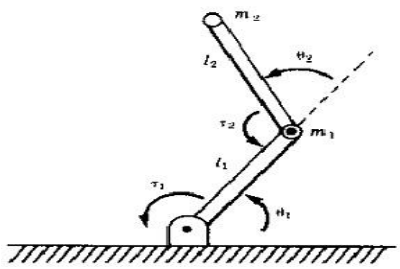


Fig. 2. Robot manipulator with two revolute joints

Dynamic equations of this robot are as follows [18]:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) + T_d = u \tag{27}$$

In which:

$$M(q) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{28}$$

$$M_{11} = L_2^2 m_2 + 2L_1 L_2 m_2 (cosq_2) + L_1^2(m_1 + m_2) \tag{29}$$

$$M_{12} = M_{21} = L_2^2 m_2 + L_1 L_2 m_2 (cosq_2) \tag{30}$$

$$M_{22} = L_2^2 m_2 \tag{31}$$

$$V(q,\dot{q}) = \begin{bmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{bmatrix} \tag{32}$$

$$V_{11} = -L_1 L_2 m_2 (sinq_2)\dot{q}_2 \tag{33}$$

$$V_{12} = -L_1 L_2 m_2 (sinq_2)\dot{q}_1 - L_1 L_2 m_2 (sinq_2)\dot{q}_2 \tag{34}$$

$$V_{21} = L_1 L_2 m_2 (sinq_2)\dot{q}_1 \quad (35)$$

$$V_{22} = 0 \quad (36)$$

$$G(q) = \begin{bmatrix} G_{11} \\ G_{21} \end{bmatrix} \quad (37)$$

$$G_{11} = L_2 m_2 g(cosq_1)(cosq_2) + L_1 g(m_1 + m_2)(cosq_1) \quad (38)$$

$$G_{21} = L_2 m_2 g(cosq_1)(cosq_2) \quad (39)$$

$$T_d = \begin{bmatrix} T_{d_1} \\ T_{d_2} \end{bmatrix} \quad (40)$$

In each link, mass distribution is considered as point particle and center of mass of each link is considered to be determined at the end. L_1 is the length of first link, L_2 is the length of the second link, m_1 is the mass of the first link, m_2 is the mass of the second link, g is the gravity, T_d is the disturbance or un-modeled dynamic and u is the input torque of the joints.

The quantities for the robot which are utilized in this testing have been presented in table 1.

Point 4: $\hat{L}_1$, $\hat{m}_1$, $\hat{L}_2$, and $\hat{m}_2$ are the estimations from the actual quantities of L_1, m_1, L_2, and m_2 which have been utilized in calculation of $\hat{u}$.

Table 1. Parameters of revolute double-joint robot

L_1=1.5m	$\hat{L}_1$=1.6m
m_1=15kg	$\hat{m}_1$=14.5kg
L_2=1m	$\hat{L}_2$=1.1m
m_2=10kg	$\hat{m}_2$=9.5kg
T_{d_1}=T_{d_2}=5	g=9.8 $^{m}/_{s^2}$

The quantities of controlling parameters in controller (13) which have been utilized in this simulation are presented in Table 2.

Point 5: quantities k_1 and k_2 are calculated based on Eq. (19).

Table 2. Controlling parameters in revolute double-joint robot manipulator

k_1=150	k_2=75
λ_1=50	λ_2=30

By the parameters mentioned in tables 1 and 2, relation (13) is applicable. Matrix $\dot{M}(q) - 2V(q,\dot{q})$ is calculated as:

$$\dot{M}(q) - 2V(q,\dot{q}) = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \quad (41)$$

$$A_{11} = 0 \quad (42)$$

$$A_{12} = 2L_1 L_2 m_2 (sinq_2)\dot{q}_1 + L_1 L_2 m_2 (sinq_2)\dot{q}_2 \quad (43)$$

$$A_{21} = -2L_1 L_2 m_2 (sinq_2)\dot{q}_1 - L_1 L_2 m_2 (sinq_2)\dot{q}_2 \quad (44)$$

$$A_{22} = 0 \quad (45)$$

It is evident that with respect to Eq. (4), matrix (41) is a skew-symmetric matrix for this double-link robot. Thus, considering Lyapunov function candidate as equation (15), we can conclude Eq. (19) for the double-link robot as:

$$\dot{V}(s) = \sum_{i=1}^{2}(s_i[\Delta f_i - K_i sgn(s_i)]) < 0 \quad (46)$$

Therefore, we can conclude global asymptotic stability for closed-loop system. To investigate the weaknesses of sliding mode controllers (14) and (21) and indicating the favorable operation of the proposed fuzzy sliding mode control, simulations are performed in three steps:

Step 1 of simulation: control input of equation (14) is simulated for the revolute double-joint robot. Schematic of this simulation is shown in Fig. 3.

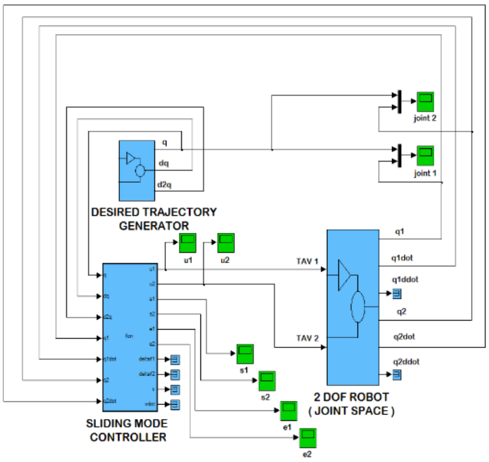
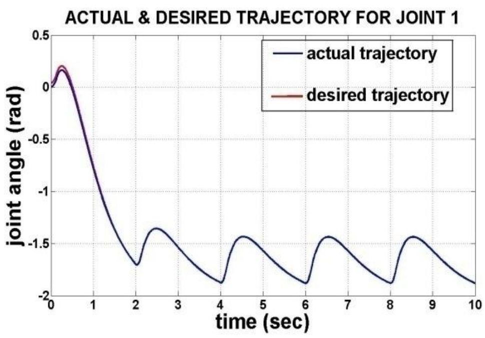
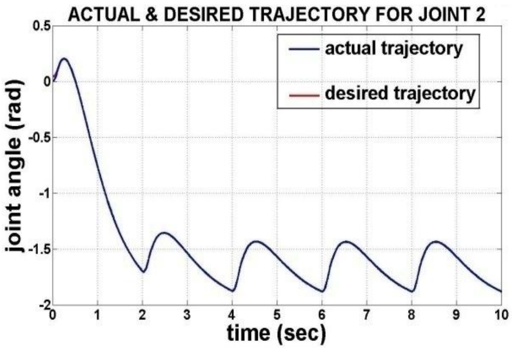


Fig. 3. Schematic of control input diagram of equation (14) for revolute double-joint robot

After performing the simulation, the desired and actual trajectories in joints 1 and 2 have been shown in Fig. 4.



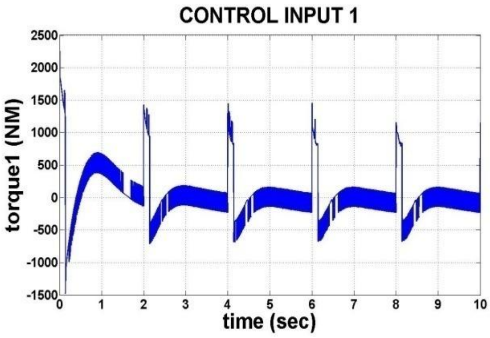
(a) The desired and actual trajectory for joint 1



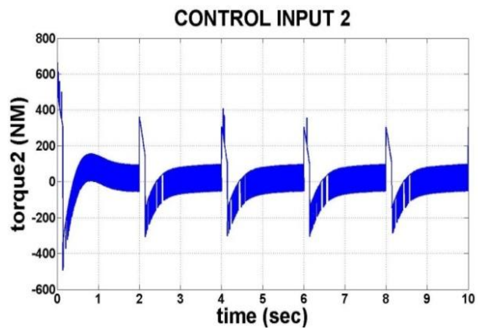
(b) The desired and actual trajectories for joint 2

Fig. 4. The desired and actual trajectories for joints 1 & 2

It is evident that the maximum tracking error is 0.0371 radians for joint 1 and 0.0201 radians for joint 2. Actual trajectory in joints 1 and 2 matches the desired trajectories after 1.397 seconds and 0.681 seconds, respectively. Figure 5 shows the exerted control input to the joints 1 and 2.



(a) The exerted control input to joint 1



(b) The exerted control input to joint 2

Fig. 5. Exerted control inputs to joints 1 and 2

It is evident that the exerted control input has a chattering domain of 290 Newton meters for joint 1 in most time intervals. This domain is 150 Newton meters for joint 2. This chattering can lead to the activation of dynamic modes of robot manipulator.

Step 2 of simulation: To overcome the adverse chattering phenomenon in control inputs, equation (21) is simulated for revolute double-joint robot. Schematic of simulation diagram has been shown in figure 6.

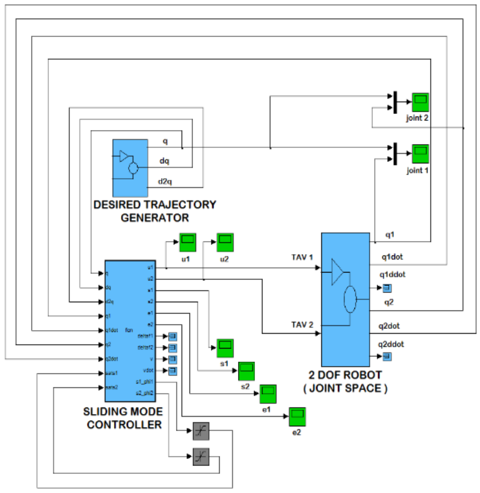


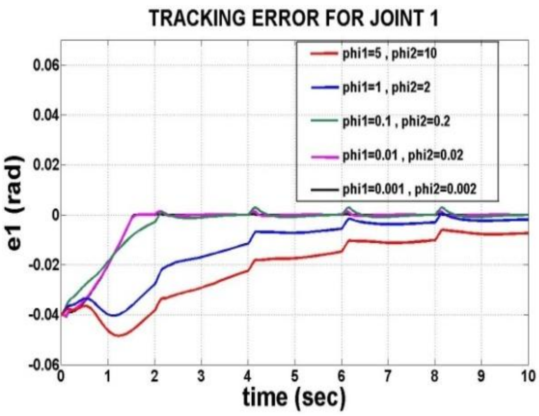
Fig. 6. Schematic of input control diagram of equation (21) for revolute double-joint robot

In this simulation, we have used various quantities for ϕ_1 and ϕ_2, which have been demonstrated in table 3.

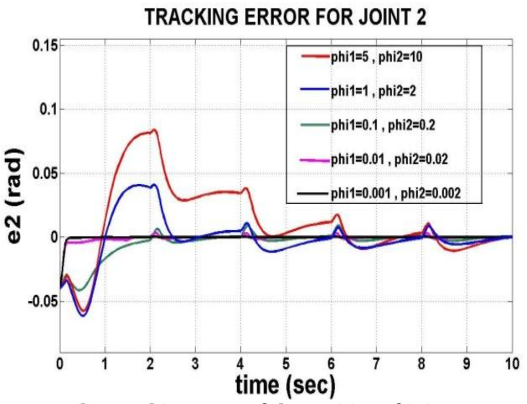
Table 3. Quantities ϕ_1 and ϕ_2 utilized in equation (21)

1	ϕ_1=5	ϕ_2=10
2	ϕ_1=1	ϕ_2=2
3	ϕ_1=0.1	ϕ_2=0.2
4	ϕ_1=0.01	ϕ_2=0.02
5	ϕ_1=0.001	ϕ_2=0.002

After the simulation execution, tracking errors of joints 1 and 2 for various quantities of ϕ_1 and ϕ_2 are shown in figure 7.



(a) Tracking error of the position of joint 1

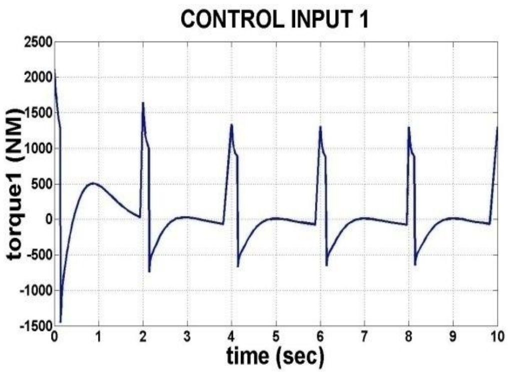


(b) Tracking error of the position of joint 2

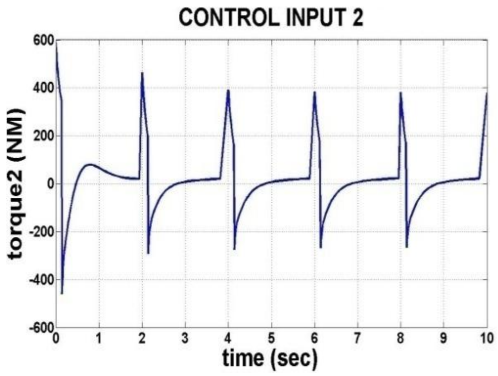
Fig. 7. Tracking error of the position of joints 1 and 2 for various quantities of $\phi_1$and $\phi_2$stated in table 3

As it is shown in Fig. 7, the maximum tracking error occurs for larger quantities of $\phi_1$and ϕ_2,and vice versa, the minimum tracking error occurs for smaller quantities of $\phi_1$and ϕ_2, such that for $\phi_1 = 5$ and $\phi_2 = 10$, the maximum tracking error in joint 1 will be 0.048 radians and this quantity never equals zero. In addition, the maximum tracking error in joint 2 will be 0.085 radians and although it reaches zero after 4.74 seconds, it never remains zero. For $\phi_1 = 0.01$ and $\phi_2 = 0.02$, in joint 1, the tracking error will be zero after 1.58 seconds and some periodic oscillations will occur further. Similarly, in joint 2, tracking error will become zero after 1.6 seconds and some periodic oscillations will occur later. For $\phi_1 = 0.001$ and $\phi_2 = 0.002$, in joint 1, the tracking error will become zero after 1.56 seconds and, in joint 2, this will happen after 0.18 seconds and the tracking error will remain zero in both joints.

Figure 8 shows exerted control inputs to the joints 1 and 2 for $\phi_1 = 5$ and $\phi_2 = 10$.



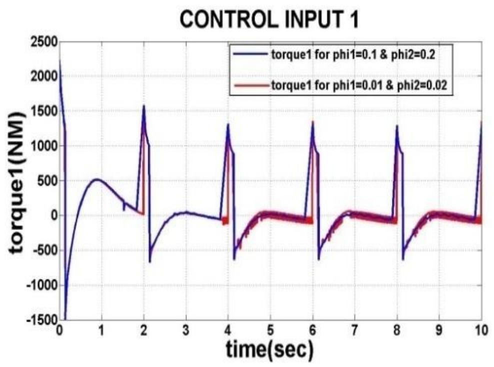
(a) Exerted control input to joint 1



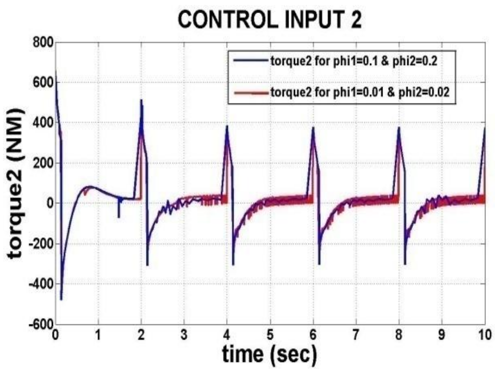
(b) Exerted control input to joint 2

Fig. 8. Exerted control inputs to joints 1 and 2 for $\phi_1 = 5$ and $\phi_2 = 10$

According to figure 8, it is evident that control inputs have no chatterings. Figure 9 shows control inputs for $\phi_1 = 0.1$ and $\phi_2 = 0.2$ and $\phi_1 = 0.01$ and $\phi_2 = 0.02$.



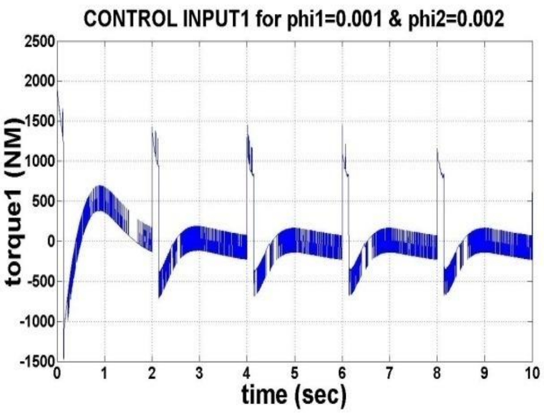
(a) Exerted control input to joint 1



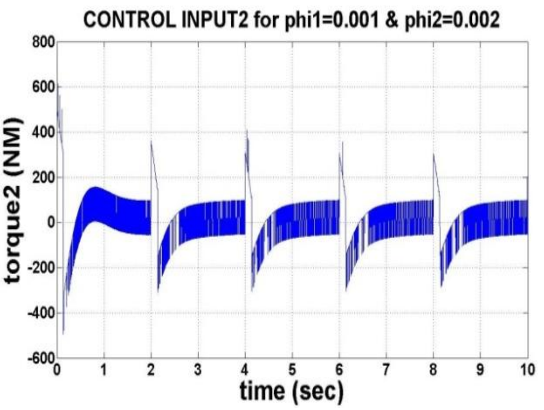
(b) Exerted control input to joint 2

Fig. 9. Exerted control inputs to joints 1 and 2 for $\phi_1 = 0.1$, $\phi_2 = 0.2$ and $\phi_2 = 0.01$, $\phi_2 = 0.02$

The increase in chattering with the reduction in quantities of ϕ_1 and ϕ_2 is clear from figure 9, such that for $\phi_1 = 0.1$ and $\phi_2 = 0.2$ control inputs have minimized chattering, while for $\phi_1 = 0.01$ and $\phi_2 = 0.02$, control input of joint 1 has a chattering domain of 98 Newton meters and that of joint 2 has a chattering domain of 40 Newton meters.
Figure 10 shows control inputs for $\phi_1 = 0.001$ and $\phi_2 = 0.002$.



(a) Exerted control input to joint 1



(b) Exerted control input to joint 2

Fig. 10. Exerted control inputs to joints 1 and 2 for $\phi_1 = 0.001$ and $\phi_2 = 0.002$

According to this figure, the chattering domain of exerted control inputs to joints 1 and 2 are 280 Newton meters and 140 Newton meters, respectively. The increase in control input chattering is clear in figure 10 compared to figures 8 and 9.

Step 3 of simulation: Fuzzy sliding mode control input is simulated for revolute double joint robot. Schematic diagram of this simulation is presented in Figure 11.

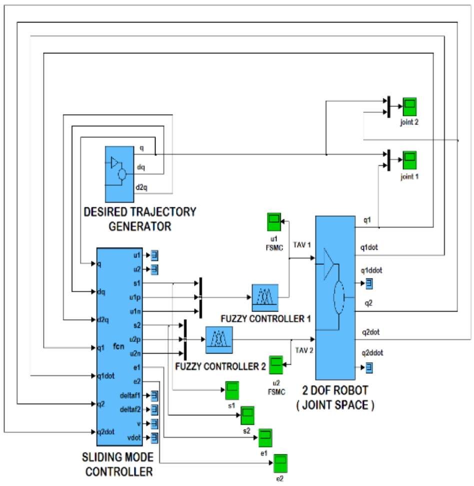


Fig. 11. Schematic of fuzzy sliding mode control diagram for revolute double-joint robot

After execution of simulation, position tracking errors of joints 1 and 2 have been indicated in figure 12.

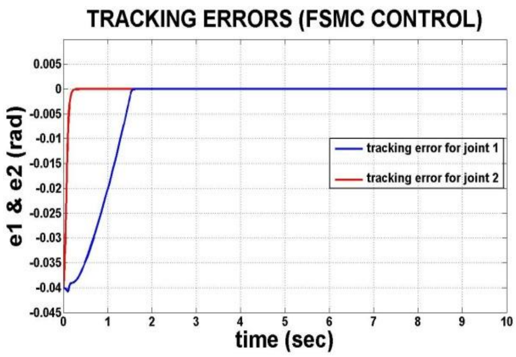
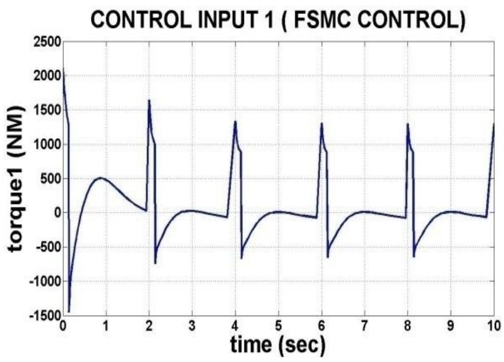
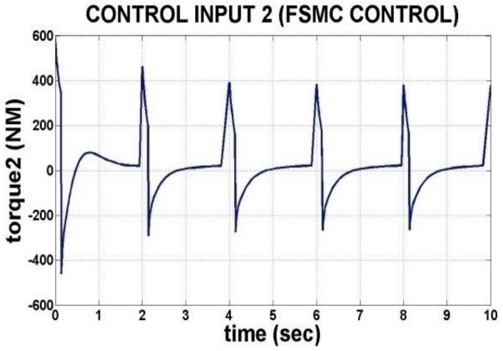


Fig. 12. Tracking error of positions of joints 1 and 2

According to this figure, position tracking error for joints 1 and 2 will reach zero after 1.545 and 0.229 seconds, respectively and, thereafter, tracking will continue with no errors and oscillations. Figure 13 shows control inputs for joints 1 and 2.



(a) Exerted control input to joint 1



(b) Exerted control input to joint 2

Fig. 13. Exerted control inputs to joints 1 and 2

As it is understood from Fig 13, control inputs for joints 1 and 2 have no chattering. Given figures 12 and 13 and comparing them with the results of previous simulations, we understand that by exerting fuzzy sliding mode control input to revolute double-joint robot, we have achieved our control objectives which were having zero position tracking error and free-of-chattering control inputs.

6. Advantages of proposed control

As it was observed in the previous section, fuzzy sliding mode control had a more favorable operation compared to the modified classic sliding mode control. Since all the merits of proposed control cannot be demonstrated through simulation, they are tersely stated:

1. Most robot manipulator control methods have arduous calculations in execution step. Thus utilizing these control methods in controlling industrial manipulators is difficult and inefficient. Still, the proposed principle control rules are based on two rules. Therefore, fuzzy sliding mode control has low calculations volume and it has the capability to be utilized in industrial manipulators.
2. In the proposed method, by utilizing feedback linearization, first the known dynamics are eliminated. As a result, the bound of the uncertainties will be extremely limited.
3. In the proposed control, due to decrease in uncertainty bounds, control input domain reduces. Consequently, we can use actuator with less power in the execution of the proposed method.

7. Conclusions

In this study, a controller for tracking the position of the robot manipulator in joint space was primarily designed by combination of sliding mode control and feedback linearization. Next, a solution was provided to minimize control input chattering. Finally, for complete elimination of control chattering, fuzzy sliding mode control was designed based on fuzzy logic. For comparing the operation of the proposed controllers, simulations in three steps were conducted on a revolute double-joint robot manipulator. The results of the simulations clearly demonstrates that fuzzy sliding mode control input is free of control chattering and tracking error converges to zero after a short time and remains zero in the tracking period.

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