IJRAME
ISSN (ONLINE): 2321-3051
INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING

Design of Sliding Mode Controller Enhanced by Fuzzy Logic Algorithm for Industrial Robot

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Abstract

In this paper a sliding mode control enhanced by fuzzy logic algorithm method is proposed for the robust tracking control of industrial robot manipulator. The proposed controller ensures the advantage of fuzzy logic algorithm and sliding mode control. There are two parts of the proposed method: first the design of sliding mode control for robust stability and second the development of fuzzy logic algorithms to reduce chattering effectively. The stability of control is proven by Lyapunov stability method and the performance of tracking error is shown in a table by using RMS value.

Keywords: Puma robot; sliding mode control; fuzzy logic based sliding mode control design.

1. INTRODUCTION

The sliding mode control (SMC) approach is recognized as one of the efficient tools to design robust controller for complex high order nonlinear dynamic industrial robot manipulator operating under uncertainty conditions. The research in this area were initiated in the former soviet union(Russia) about 40 years ago and then the sliding mode control methodology has been receiving much more attention from the international control community within the last two decades [1].

In control theory, SMC is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behavior. The ultimate trajectory will not exist entirely within one control structure. Instead, it will slide along the boundaries of the control structures. The motion of the system as it slides along these boundaries is called a sliding mode and the geometrical locus consisting of the boundaries is called the sliding (hyper) surface. The sliding mode control is adopted for dealing with higher order ,nonlinear system for racking automobile air conditioning of temperature regulation to control evaporator out-temperature tracking performance with acceptable compressor action [2].Chen et al.[3] have discussed adaptive sliding mode dynamic controller for wheeled mobile robot trajectory tracking. They developed kinematics controller as well as adaptive sliding mode dynamic controller to make the real velocity for mobile robot to reach its desired velocity and check its stability by using Lyapunov stability theorem [3].Bessa et al.[4] have presented sliding mode control technique enhanced by fuzzy algorithm for reducing chattering problem using Lyapunov theorem with Barbalat's lemma. Chen et al. [5] derived a sliding mode trajectory tracking control algorithm for robot arm without using inverse inertia matrix. Lin and Chen developed a robust fuzzy sliding mode controller to achieve trajectory tracking for two link robot manipulator using MIMO nonlinear system [6].A variable structure model following control is designed to achieve performance of robot system[7].Here the robust trajectory tracking problem a robot manipulator for uncertainties and disturbance based on neural network-based sliding mode adaptive controller is designed which ensures trajectory tracking of robot manipulator using Lyapunov theory [8].

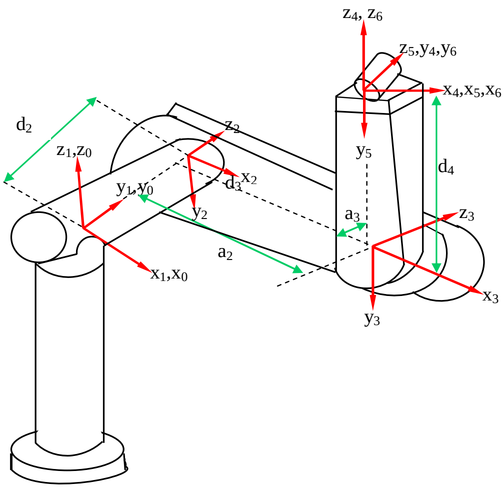

Figure 1.1 Six degree of puma robot

The boundary layer design is used to control the chattering in SMC but for high level noise measurement it because ineffective so they developed a new design non-trival for reducing chattering by low pass filter control signal. It gives provides similar result as boundary layer in coping high level noise measurement [9, 10, 11, 12]. Slotine and Sastry [13] have presented a methodology of feedback control to achieve accurate trajectory tracking for a class of nonlinear time varying system for disturbance and parameter variation. They developed piecewise feedback control using SMC for trajectory tracking of manipulator to reduce chatter along sliding surface.

This paper has been organized into four sections. Following the introduction, Sliding mode controller for joint position control has been described in section 2. The simulation results are discussed in section 3. Finally the conclusions are given in section 4.

2. Sliding Mode Controller (SMC) For Joint Position Control

SMC is one of the very attractive and effective nonlinear robust control methodologies that provide system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode. There are two way to design SMC for industrial robot nonlinear invariance uncertainty, the first step of SMC design is to select a sliding surface that models the desired closed-loop performance in state variable space. In the second step, design a hitting control law such that the system state trajectories are forced toward the sliding surface and stay on it. The period of time before reaching the sliding surface is called the reaching phase in trajectory tracking of manipulator if the system trajectory achieve this surface then it stays on it and slides along it up to the origin. But under some conditions, the SMC is robust with respect to system perturbation and external disturbance [14].

2.1. Dynamic Model

The dynamic model of an n-link robotic manipulator can be expressed as [15].

$$M(q)\ddot{Q} + c(q,\dot{q})\dot{Q} + g(q) + f(q,\dot{q}) = u(t) \quad (1)$$

Where
$Q \in r^n$ is the joint position ,$\ddot{q} \in R^n$ is the joint velocity vector ,$\ddot{q} \in R^n$ is the joint acceleration vector, $c(q,\dot{q})\dot{Q} \in R^{n\times n}$ represents for the croilis and centrifugal torques, $m(q) \in r^{n\times n}$ is the inertia matrix,$g(q) \in r^n$ is the gravity vector;$f(q,\dot{q}) \in R^{n\times n}$ is the unstructured uncertainty of dynamics disturbance and $u(t) \in r^{n\times n}$ is the control input vector. In short form we can write equation (1) as:

$$M(\theta)\ddot{\theta} + h(\theta,\dot{\theta}) = u(t) + w(t) \tag{2}$$

Where $\theta \epsilon R^n$ and $\dot{\theta}$ are the angle and angular velocity, respectively, $M(\theta)$ is the symmetric inertia matrix, $h(\theta,\dot{\theta})$ implies the Coriolis force, centrifugal force, gravity force, and dynamic friction, w(t) is a disturbance such as static friction, and u(t) is the input control torque vector. Since parameters of the industrial robot are not determined correctly,
Where $M(\theta), h(\theta,\dot{\theta})$ denoted as

$$M(\theta) = M^0(\theta) + \Delta M(\theta) \tag{3}$$

$$h(\theta,\dot{\theta}) = h^0(\theta,\dot{\theta}) + \Delta h(\theta,\dot{\theta}) \tag{4}$$

Where "0" denotes the nominal value and "Δ" denotes the estimating error

2.2. Sliding mode control

Consider the sliding mode control system shown as in fig. The objective is to drive the joint position vector $\dot{q}$ to track the desired joint position vector $\dot{q}_d$.
Let the tracking error vector be

$$e = q_d - q \tag{5}$$

$$\dot{e} = \dot{q}_d - \dot{q} \tag{6}$$

$$\ddot{e} = \ddot{q}_d - \ddot{q} \tag{7}$$

Where $e = [e_1, e_2 \dots \dots .. e_n]^T$.define the sliding surface function as

$$s = \dot{e} + \lambda e \tag{8}$$

Where $\lambda = diag[\lambda_1, \lambda_2, \dots \dots \dots, \lambda_m], \Lambda_i = 1,2, \dots \dots .., m$ are positive constant. Differentiating above equation with respect to time, one can obtain

$$\dot{s} = \ddot{e} + \lambda\dot{e} \tag{9}$$

$$\dot{s} = \ddot{q}_d - \ddot{q} + \lambda(\ddot{q}_d - \dot{q}) \tag{10}$$

Let the control input be

$$u(t) = -M(q)[\Lambda\dot{e}(t) - \ddot{q}_d] + \dot{h}(q,\dot{q}) - P(t)s(t) - Q(t)sgn(s) \tag{11}$$

$$u_s = -Ksgn(s)$$

Define a Lyapunov function candidate

$$V = \left(\frac{1}{2}\right)s^T(t)M(\theta)s(t) \tag{12}$$

Differentiating it w.r.t. time

$$\dot{V} = \left(\frac{1}{2}\right)s^T\dot{M}s + s^T M\dot{s} \tag{13}$$

The position error can be denoted as

$$s(t) = \Lambda e(t) + \dot{e}(t) \tag{14}$$

$$\dot{s}(t) = \Lambda\dot{e}(t) + \ddot{e}(t) \tag{15}$$

$$e(t) = q_d(t) - q(t) \tag{16}$$

$$\dot{e}(t) = \dot{q}_d(t) - \dot{q}(t) \tag{17}$$

$$\ddot{e}(t) = \ddot{q}_d(t) - \ddot{q}(t) \tag{18}$$

From equation (4)

$\dot{V} = \left(\frac{1}{2}\right) s^T \dot{M} s + s^T M(\Lambda \dot{e}(t) + \ddot{q}_d(t) - \dot{q}(t))$

(19)

$= \left(\frac{1}{2}\right) s^T \dot{M} s + s^T(\Lambda M \dot{e} + M\ddot{q}_d(t) - M\dot{q}(t))$

(20)

Using the euler-langragian equation

$M(q)\ddot{q} + h(q, \dot{q}) = u(t) + w(t)$

(21)

$\dot{V} = \left(\frac{1}{2}\right) s^T \dot{M} s + s^T[M\,\Lambda \dot{e} - h + u + w + \ddot{q}_d]$

(22)

Where $u(t) = -M(q)[\Lambda \dot{e}(t) - \ddot{q}_d] + \dot{h}(q, \dot{q}) - P(t)s(t) - Q(t)sgn(s)$

$\dot{V} = \left(\frac{1}{2}\right) s^T \dot{M} s + s^T[M\Lambda \dot{e} - h + w + M\ddot{q}_d] + s^T[-M^0\{\Lambda \dot{e} - \ddot{q}_d\} + h^0 - Ps - Qsgn(s)]$

(23)

$\dot{V} = s^T\left[-P + \frac{\dot{M}}{2}\right] s - s^T[Qsgn(s) - \Lambda M \dot{e} + \dot{h} - w - M\ddot{q}_d]$

(24)

$< -s^T\left[P - \frac{\dot{M}}{2}\right] s + s^T[-Qsgn(s) + \Lambda M \dot{e} - \dot{h} + w + M\ddot{q}_d]$

(25)

Because $\left[-P + \frac{\dot{M}}{2}\right]$ is a positive definite matrix and $-s^T\left[P - \frac{\dot{M}}{2}\right]<0$, thus above equation becomes the decay of the energy of s as long as $s \neq 0$.Thus, the tracking control is guaranteed.

2.3. Fuzzy sliding mode control

It is not easy way to calculate the value of K because k depends on the bound of uncertainties. Although s large value of k overcomes the effect of uncertainties, it cause in chattering.in order to solve this problem sliding mode control enhanced by fuzzy logic algorithm is proposed in this paper. A fuzzy control gain is to replace the switching control input gain; the fuzzy controller consists of fuzzifier, fuzzy rule base, fuzzy inference engine and defuzzifier.

The output of fuzzy system can be

$COA(A) = y = \frac{\sum_{i=1}^{3} \mu_{A(y)} * y}{\sum_{i=1}^{3} \mu_{A(y)}}$

(26)

Where

Y=output value after defuzzified

$y = \text{defuzzified value} = \frac{A_1 y_1 + A_2 y_2 + A_3 y_3}{A_1 + A_2 A + _3}$

(27) $\mu_{A(y)=}$Weighting of the membership function

y_i = distance from centroid to x axis

Let $\psi(x) = \frac{\prod_{i=1}^{n} \mu_{A(y)}}{\sum_{i=1}^{n} \mu_{A(y)}}$

(28)

N is number of fuzzy rules. The input chattering is induced from the discontinuous function sgn(s) and the constant value of K. now fuzzy gain function k_f .The fuzzy gain function k_f is defined as $K_f = [k_{f1}, k_{f2}, \dots \dots, k_{fn}]^T$ where K_{fi} is output of fuzzy logic controller.

A triangular membership function is used to eliminate the chattering, i.e.

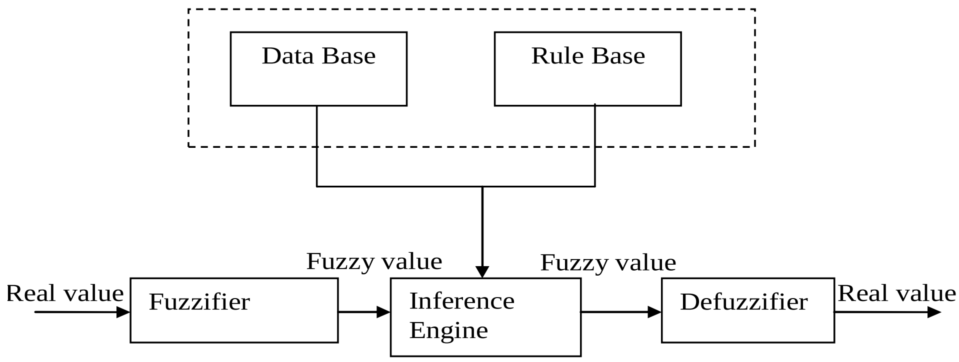

Figure 2.1 Structure of fuzzy logic controller

$$h(s_i) = \frac{2}{\frac{s_i-2}{s_i-4}} - 1 \qquad (29)$$

Hence the control input

$$u(t) = -M(q)[\Lambda\dot{e}(t) - \ddot{q}_d] + \dot{h}(q,\dot{q}) - P(t)s(t) - Q(t)sgn(s) - K_f h(s) \qquad (30)$$

The fuzzy rules are in such format:

IF s_i is A_i^n , THEN K_{fi} is $B_i{}^n$

Where A_i^n and $B_i{}^n$ are fuzzy sets. Define the membership function as LN,SN,Z,SP,LP ,where N represent negative, L represent positive, Z represent zero, L represent large and S represent small.

TABLE 2.1 FUZZY RULE BASE

s_i	LN	SN	Z	SP	LP
K_{fi}	LN	SN	Z	SP	LP

The membership functions are chosen to be triangular function, i.e.

$$\mu_{A_l{}^i}(s_i) = \left(\frac{s_i-\alpha_i}{s_i-\beta_i}\right)^2 \qquad (31)$$

Where α_i and β_i is the side of triangle .The parameter of the membership function of s_i is pre-defined .the value of K_{fi} is updated the defuzzification K_{fi} can be described as

$$K_{fi} = \frac{\sum_{i=1}^{n}\theta^n{}_{ki}\mu_{A^i}s_i}{\sum_{i=1}^{n}\mu_{A^i}(s_i)} = \varphi_{ki}^T\psi_{ki}(s_i) \qquad (32)$$

Where $\chi_{ki}(s_i) = [\chi_{ki}^1, \chi_{ki}^2, \dots\dots\dots.., \chi_{ki}^n]^T$ (33)

$$\chi_{ki}^i(s_i) = \frac{\mu_{A^i}(s_i)}{\sum_{i=1}^{n}\mu_{A^i}(s_i)}, \text{ and } \theta_{ki} = [\theta_{ki}^1, \theta_{ki}^2, \dots\dots\dots\dots.., \theta_{ki}^n]^T \qquad (34)$$

Where $k_{fi} = \tilde{\sigma}_{K_{id}}^T\chi_{k_i}(s_i)$ is the optimal compensation forΔ_{f_i} . According to the Wang's theorem, there exists $\eta_i > 0.\left|\Delta_{f_i} - \sigma_{K_{id}}^T\chi_{k_i}(s_i)\right| \le \eta_i$

(35)

Where η_i may be small as possible as. Now define the estimation error as

$$\tilde{\sigma}_{k_i} = \sigma_{k_i} - \sigma_{k_d} \qquad (36)$$

Now $k_{f_i} = \tilde{\sigma}_{k_i}{}^T\chi_{k_i}(s_i) + \sigma_{K_{id}}^T\chi_{k_i}(s_i)$

(37)

Let the control law

Vol.1 Issue.7,
November 2013.
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$$\dot{\sigma}_{k_i} = s_i \chi_{k_i}(s_i)$$
(38)

Next, verify the control law .Let the Lyapunov function candidate-

$$V_L = \left(\frac{1}{2}\right)\left(s^T M s + \sum_i^n \tilde{\sigma}_{k_i}^T \tilde{\sigma}_{k_i}\right)^2$$
(39)

Differentiating equation (36) we can obtain-

$$\dot{V}_L = \frac{1}{2}\left[\dot{s}^T M s + s^T \dot{M} s + s^T M \dot{s} + \sum_{i=0}^n \dot{\tilde{\sigma}}_{k_i}^T \tilde{\sigma}_{k_i} \tilde{\sigma}_{k_i}^T \dot{\tilde{\sigma}}_{k_i}\right]$$
(40)

$$= s^T M \dot{s} + \sum_{i=1}^n \tilde{\sigma}_{k_i}^T \dot{\tilde{\sigma}}_{k_i}$$

$$= s^T \left[P - \frac{\dot{M}}{2} + \Delta f - K_f\right] + \sum_{i=0}^n \tilde{\sigma}_{k_i}^T \dot{\tilde{\sigma}}_{k_i}$$

$$= s^T\left(P - \frac{\dot{M}}{2}\right) + \sum_{i=1}^n (s_i[\Delta f + K_f]) + \sum_{i=0}^n \tilde{\sigma}_{k_i}^T \dot{\tilde{\sigma}}_{k_i}$$
(41)

Substituting equation (34) to (38) yields

$$\dot{V}_L = s^T\left(P - \frac{\dot{M}}{2}\right) + \sum_{i=1}^n \left(s_i\left[\Delta f - \sigma_{K_{id}}^T \chi_{k_i}(s_i)\ \right]\right) + \sum_{i=0}^n \tilde{\sigma}_{k_i}^T\left(-s_i \chi_{k_i}(s_i) + \dot{\tilde{\sigma}}_{k_i}\right)$$
(42)

Applying $\dot{\sigma}_{k_i} = \dot{\tilde{\sigma}}_{k_i}$ and control law (35) to (39)

The derivative of Lyapunov function becomes

$$\dot{V}_L = s^T\left(P - \frac{\dot{M}}{2}\right) + \sum_{i=1}^n \left(s_i\left[\Delta f - \sigma_{K_{id}}^T \chi_{k_i}(s_i)\ \right]\right)$$
(43)

$$\leq s^T\left(P - \frac{\dot{M}}{2}\right) + \sum_{i=1}^n \left(|s_i|\left|\Delta f - \sigma_{K_{id}}^T \chi_{k_i}(s_i)\right|\right)$$
(44)

From equation (32) η_i can be chosen small as possible as

$$\left|\Delta f - \sigma_{K_{id}}^T \chi_{k_i}(s_i)\right| \leq \eta_i \leq \rho_i |s_i|$$
(45)

Where 0<ρ_i<1. Now multiplying (42) by s_i

$$|s_i|\left|\Delta f - \sigma_{K_{id}}^T \chi_{k_i}(s_i)\right| \leq \rho_i |s_i|^2 = \rho_i {s_i}^2$$
(46)

Hence, one can obtain

$$\dot{V} = s^T\left(P - \frac{\dot{M}}{2}\right) + \sum_{i=1}^n \rho_i {s_i}^2$$
(47)

The right hand side of the above equation is

$$\sum_{i=1}^n (-b_i + \rho_i){s_i}^2 = s^T(A - \phi)s$$
(48)

Where $\emptyset = \mathrm{diag}[\rho_1, \rho_2, \ldots\ldots\ldots, \rho_n]$.since $b_i > \rho_i$,$i = 1,2, \ldots.. n$, and $(A - \phi)$ is a positive matrix, it is now clear

$$\dot{V} \leq \sum_{i=1}^n (-b_i {s_i}^2 + \rho_i {s_i}^2) = s^T(A - \phi)s \leq 0$$
(49)

$(A - \phi)$ is positive matrix and $\dot{V}$=0 implies s=0.therefor control law ensures validity of sliding mode control enhanced by fuzzy logic algorithm .so in other words

$$\lim_{t\to\infty} s = \lim_{t\to\infty}(\dot{e} + \Lambda e)$$
(50)

This implies

$$\lim_{t\to\infty} q = q_d$$
(51)

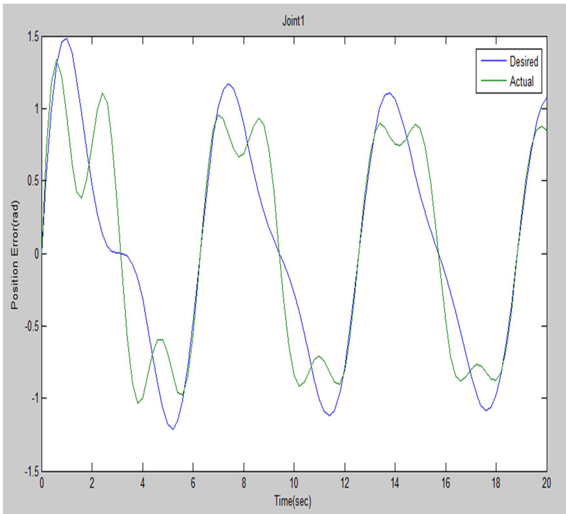
3. Simulation results and discussion

A systematic methodology for the development of a fuzzy logic controller for joint position control of serial link manipulator of robot has been developed. This reduces the signal error. Human beings give the control information based on their perception. But joint position controller based on fuzzy logic provides, efficient result with simple procedure. The result so obtained by fuzzy logic controller is thus much more accurate. The proposed design process is much simpler as compared to other methods reported for finding the actual joint positions and the saturated joint positions. The formulation and implementation of membership functions and rules are given for signal error.

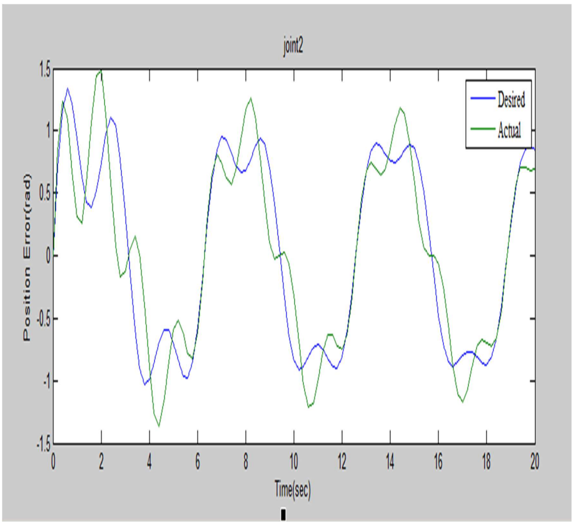
The sliding mode control enhanced by fuzzy logic algorithm for the robust trajectory tracking control of robot manipulators give Large switching input gain that causes chattering problem has been taken care of Sliding mode controller is designed to overcome this problem by using fuzzy logic algorithm using Lyapunov stability theorem, a robust stability condition has been shown to be satisfied. A four link SCARA industrial robot was selected to verify the advantage of above proposed control technique. Dynamic equation of robotic manipulator has been obtained using by Euler- Lagrange equation. A comparison between tracking the errors obtained by the proposed method and the reported by Garelli et al. [16], is shown in table 3.1. The root mean square (RMS) value of the position tracking error is computed on a trip time T of 20 (sec) using;

Table3.1 Comparison of the root mean square errors

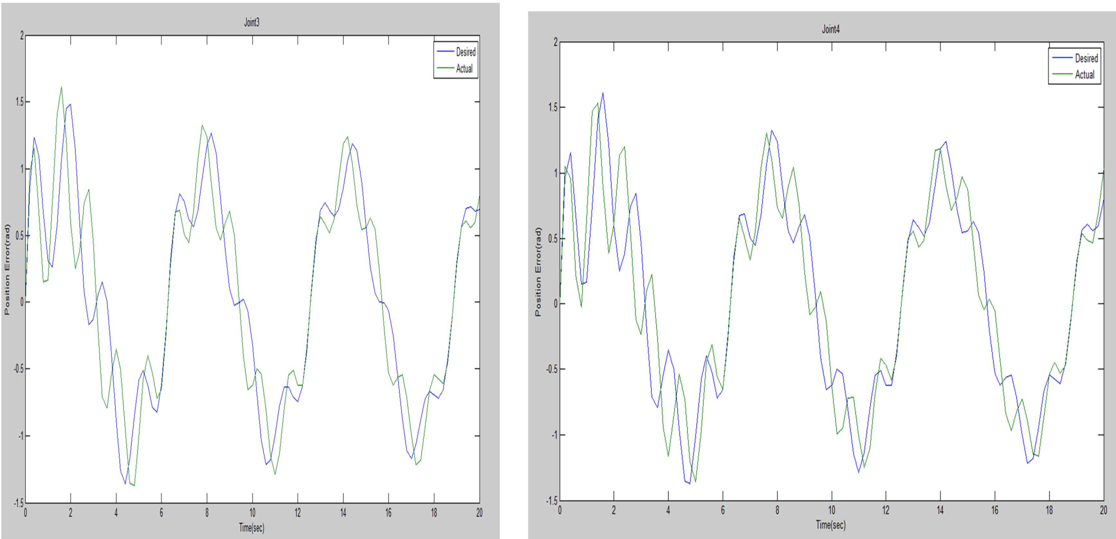
Position errors	SM Auto Regulation by Garelli et al. [16]	Proposed SMCEBFL algorithm
RMS($\{e_{p1}\}$)	0.0266	0.03438
RMS($\{e_{p2}\}$)	0.0266	0.03958
RMS($\{e_{p3}\}$)	0.0133	0.04407
RMS($\{e_{p4}\}$)	0.0531	0.04801
RMS($\{e_{p5}\}$)	0.0531	0.05151
RMS($\{e_{p6}\}$)	0.0266	0.05465
RMS($\{e_{p\mathbb{I}2}\}$)	0.0891	0.04536



(a) Error of Joint1



(b) Error of Joint 2



(c) Error of Joint3 (d) Position Error of Joint4

Figure3.1 Position error of robot during trajectory tracking

A comparison of the joint positions q and velocities$\dot{q}$, obtained by the proposed algorithm and that reported by Garelli et al.[16]is shown in figure 3.1.

4. Conclusion

This paper proposes sliding mode control enhanced by fuzzy logic algorithm for the robust trajectory tracking control of robot manipulators consider that large switching input gain that cause chattering problem while sliding mode controller works. In this study sliding mode controller is designed to overcome this problem by using fuzzy logic algorithm. The robust stability has proven with the help of Lyapunov stability theorem. Simulation shows the efficient and similar result to the previous results obtained by researcher in trajectory tracking that control the input chattering can be reduced by using proposed controller. The results show that the proposed algorithm as effective to reduce the chattering effect as the previous method proposed by other researchers.

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