Designing of Incorporating Fuzzy-Sliding Mode Controller Based on Strategy Moving Sliding Surface for Two-Link Robot Manipulator

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Abstract: Sliding movement includes two phases; reaching phase and Sliding phase. In both phases problems are encountered. In sliding phase, the switching nature of control law leads to the undesirable chattering phenomenon whose high frequency oscillations excite the un-modeled dynamics of the system; this might damage the system under control .In this paper, as a solution to these problems one incorporating fuzzy-sliding mode controller (FSMC) is introduced. Also, during reaching phase, SMC is sensitive to parametric uncertainties and external disturbances. Throughout this paper a sliding mode fuzzy controller with moving switching surface (MSS) is provided to minimize or possibly eliminate the reaching phase.
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1. Introduction

The robot manipulator dynamics is inherently nonlinear time-varying and has many uncertainties, such as payload parameters, frictions and disturbances. A well known approach to the control of uncertain system by nonlinear feedback laws is the sliding mode control [6-10]. Sliding mode control is a powerful control technology, which could handle the worst-case control environment. In a sliding mode control system, the control law is designed to drive the system states toward a specific sliding surface. Conventional sliding mode control introduces a static linear sliding surface with constant gain as the error variable in order to obtain globally asymptotically stable controllers for robot manipulators [11-13]. As the sliding surface is hit, the system response is governed by the surface; consequently the robustness to the Parameter variations or disturbances is achieved. In spite of the robust characteristics of controller, this controller has problems. One of the problems of the sliding mode control is the chattering phenomenon. Many techniques have proposed to eliminate these problems, as to define a bounded layer surrounding the sliding surface, but it leads to increase stability error. Further to this, in sliding mode control, the system only in Sliding phase is resistant to uncertainty and disturbance, while in reaching phase it is sensitive them. In this paper, a fuzzy sliding mode control (FSMC) is proposed to control of the chattering phenomenon. The fuzzy sliding mode control is applied in around the sliding surface. So one of the methods to minimize or eliminate the reaching phase is to use a moving switching surface (MSS) [2-3]. This paper resorts to fuzzy logic for designing of this moving surface. In next part of this paper the robot manipulator dynamics equations has presented then a sliding mode controller and a fuzzy controller has been designed for the robot manipulator. To this end, a incorporating fuzzy-sliding mode controller and a moving sliding surface with using of fuzzy technique has been designed.

2. The robot manipulator model

The dynamics of a serial –link robot can be written as [14]

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

Where, $M(q) \in R^{n\times n}$ is the symmetric positive–definite manipulator inertia matrix. $C(q,\dot{q})) \in R^{n\times n}$ is the vector of centripetal and Carioles torques, $G(q) \in R^{n}$ is the vector of gravitational torques. Also, $q, \dot{q}, \ddot{q} \in R^{n}$ are vectors of location, velocity and angular acceleration of robot links respectively.

The friction torque $F(\dot{q},\tau)$ is assumed to dissipate energy at all nonzero velocities and, therefore, its entries are bounded within the first and third quadrants. This feature allows considering the common Coulomb, viscous and static friction models [15] and [16]

$$f_i(\dot{q},\tau_i) = b_i\dot{q}_i + f_{ci}sgn(\dot{q}_i) + [1 - sgn(\dot{q}_i)]sat(\tau_i; f_{si}) \tag{2}$$

Where, b_i, f_{ci} and f_{si} denote the coefficients of the viscous, Coulomb, and static friction, respectively, with $i = 1,2,\ldots,n$, The $sat(.;.)$ function is defined as follows

(3)

$$sat(\tau_i; f_{si}) = \begin{cases} f_{si} & \tau_i > f_{si} \\ \tau_i & -f_{si} \le \tau_i \le f_{si} \\ -f_{si} & \tau_i < -f_{si} \end{cases}$$

We assume the robot links are joined together with revolute joints. Three important properties are the following.

Property 1: The matrix $C(q,\dot{q})$ and the time derivative $\dot{M}(q)$ of the inertia matrix satisfy

$$q^T\left(\dot{M}(q) - 2C(q,\dot{q})\right)q = 0$$

Property 2: The friction torque vector $F(\dot{q},\tau)$ satisfies

$$\dot{q}^T F(\dot{q},\tau) > 0 \quad \forall \tau \in R^n$$

Property 3: The gravitational torque vector $G(q)$ is bounded such that

$$sup\{|g_i(q)|\} \le \bar{g}_i \quad \bar{g}_i \ge 0$$

Where, g_i stands for the elements of G . Assume that each joint actuator is able to supply a known maximum torque τ^{max} so that

$$|\tau_i| \le \tau^{max} \quad i = 1,2,\ldots,n$$

We assume that each actuator satisfies the following condition

(4)

$$\tau^{max} > \bar{g}_i + f_{s_i}$$

G and M matrix is present as the following

(5)

$$C = \hat{C} + \Delta C$$

3. Designing of Sliding mode Fuzzy controller

In this part, our purpose is to design a sliding mode controller that can detect desired state vector q_d with existence of uncertainty and disturbance.

3.1. Designing of sliding mode controller

The first step at the designing of sliding mode controller is choice of slide surface. With considering a robot manipulator, slide surface is defined as follows

(6)

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

Where $e = -\tilde{q} = q - q_d$ and λ are positive–definite matrixes, positive as it ensure stability $s = 0$. With defining of velocity vector as:

(7)

$$\dot{q}_r = \dot{q}_d - \lambda e$$

We may define slide surface as following:

(8)

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

For system states get to slide surface and remain in it, the following slide condition should establish [1].

(9)

$$\frac{1}{2}\frac{d}{dt}[s^T M s] < -\eta\,(s^T s)^{1/2}$$

Where η is positive–definite matrix, with defining of slide surface (2) and the following control rule for system (1), slide condition (9) is complied

(10)

$$\tau = \hat{\tau} - K sgn(s)$$

That,

(11)

$$\hat{\tau} = M\ddot{q}_r + \hat{C}\dot{q}_r + G$$

and,

(12)

$$K_i \ge \|\Delta C\dot{q}_r\| + \Gamma_i$$

$\Gamma \in R^n$ is parameter of designing and should design as

(13)

$$\Gamma_i \ge F_{up} + \eta_i$$

Prove: with utilization of Lyapunov theory is proved that the control rule (10) resists system (1). Choose the Lyapunov function candidate to be

(14)

$$V = \frac{1}{2}s^T M s$$

Because M matrix is a positive–definite matrix so providing $s \ne 0$ then $V > 0$ and with deriving from V the following equation is obtained

(15)

$$\dot{V} = s^T M\dot{s} + \frac{1}{2}s^T \dot{M} s$$

By using of equation (3) the following result is supplied

(16)

$$\dot{V} = s^T(M\ddot{q} - M\ddot{q}_r) + \frac{1}{2}s^T\dot{M}s$$

With setting (1) in (16) and using of property 1 the following result is provided

(17)

$$\dot{V} = s^T(\tau - C\dot{q}_r - G - F - M\ddot{q}_r)$$

And with applying (10) and (11) in up bond we have

(18)

$$\dot{V} = -s^T(\Delta C\dot{q}_r + F) - \sum_{i=1}^{n} K_i|s_i|$$

And then from (12), (13) and (14) the following bond is proved

(19)

$$\dot{V} \le -\sum_{i=1}^{n} \eta_i |s|_i$$

For decrease of the chattering phenomenon around slide surface, we define a bounded layer with diameter φ around slide surface. So we replace saturation function in sgn at bond (10) and we have

(20)

$$sgn\left(\frac{s}{\varphi}\right) = \begin{cases} sgn\left(\frac{s}{\varphi}\right) & |s| \geq |\varphi| \\ \frac{s}{\varphi} & |s| < |\varphi| \end{cases}$$

3.2. Designing of Fuzzy controller

In this paper, we consider a sectorial fuzzy controller studied (SFC). Two-input one-output rules will be used in the formulation of the knowledge base. The IF–THEN rules are of the following form

(21)

$$\textbf{IF } x_1 \text{ is } A_1^{l_1} \text{ and } x_2 \text{ is } A_2^{l_2} \textbf{ THEN } y^l \text{ is } B^{l_1 l_2}$$

Where

$x = [x_1 \quad x_2]^T = [e \quad \dot{e}]^T \in u = u_1 \times u_2 \subset R^2$

For each input fuzzy set $A_j^{l_j}$ in $x_j \in u_j$ and output fuzzy set $B^{l_1 l_2}$ in $y \subset V$ exists an input membership function $\mu_{A_j^{l_j}}(x_j)$ and output membership function $\mu_{B^{l_1 l_2}}(x_j)$, respectively, with $l_j = -(N_1 - 1)/2, \ldots, -(N_j - 1)/2$; $j = 1,2$; N_j being an odd number of membership functions associated to the input *j*. The total number of rules *M* is defined by the number of membership functions of each input $M = N_1 \times N_2$. The output variable of a fuzzy logic controller FLC can have associated an odd number, say *N*, of membership functions $\mu_{B^l}(y)$, with $l = -(N-1)/2, \ldots, -(N-1)/2$.

In the remainder of this paper, we consider the SFC class of fuzzy controllers studied in [4] and [5], where we have selected the following specifications: Singleton fuzzifier, N_j (odd) triangular membership functions for each input, with $j = 1,2$ (see Fig.1), *N* (odd) singleton membership functions for the output, (see Fig. 2), rule base defined by (18) for two inputs, (table.1), product inference, and center average defuzzifier.

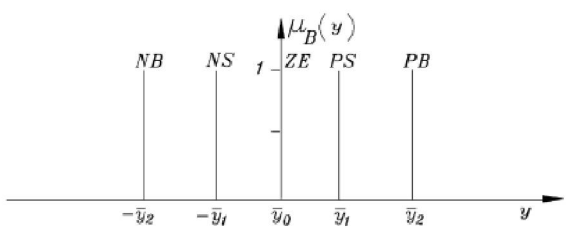

Figure. 1. Input membership functions

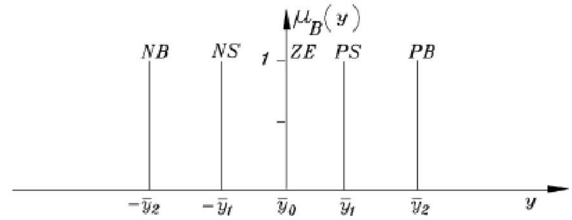

Figure. 2. Output membership functions

Table 1. Look-up the fuzzy rule base

x_2 \ x_1	NB	NS	ZE	PS	PB
NB	NB	NB	NS	ZE	ZE
NS	NB	NB	NS	ZE	ZE
ZE	NS	NS	ZE	PS	PS
PS	ZE	ZE	PS	PB	PB
PB	ZE	ZE	PS	PB	PB

3.3. Designing of incorporating controller

Because of we can synchronously use from premium of fuzzy and sliding mode controllers and minimize detects each of their, we propose the following incorporating controller:

(22)

$$\tau = \begin{cases} \hat{\tau} - Ksgn(s) & |\tilde{q}_i| \geq \alpha \\ \varphi(\tilde{q}, \dot{\tilde{q}}) + G(q) & |\tilde{q}_i| < \alpha \end{cases}$$

Where in this bond α is a positive parameter. in case $|\tilde{q}_i| \geq \alpha$, sliding mode controller works and fuzzy mode controller acts provided that $|\tilde{q}_i| < \alpha$. So the used controller will be as a robust sliding mode controller. Also the chattering phenomenon happens surrounding the sliding surface $(s = 0)$ that it excite both high frequency oscillations the un-modeled dynamics of the system and it cause to increase input torque. So we apply the fuzzy sliding mode control in around the sliding surface for conquest of this problem.

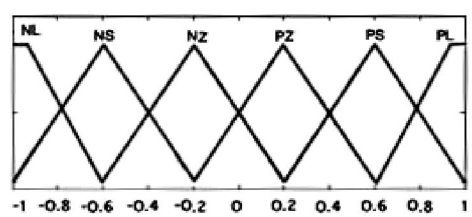

Figure. 3. membership functions for inputs $\tilde{q}$ and $\dot{\tilde{q}}$

4. Designing of moving sliding surface

In sliding mode control, the system only in Sliding phase is resistant to uncertainty and disturbance, while in reaching phase it is sensitive them and this is one of the problems of the classical sliding mode controller. . So one of the methods to minimize or eliminate the reaching phase is to use a moving switching surface (MSS) [2-3]. In attention to studied robot that is a two-link robot, equation of moving sliding surface is defined as

$$s(e,\dot{e},t) = \dot{e} + \lambda e - \gamma \tag{23}$$

Surface rotation occurs along with $\lambda(t)$ which is surface slope and shifting along with the changes in $\gamma(t)$. In two degree systems if the representative point (RP) is the first or third quarter, we will shift the surface slope and in case RP is in the second or fourth quarter we rotate it. According to the above mentioned statements the control rule for sliding mode with bonded layer and moving sliding surface is as follows

$$\tau = \hat{\tau} - K\ sat\left(\frac{\dot{e} + \lambda e - \gamma}{\varphi}\right) \tag{24}$$

For setting $\lambda(t)$ and $\gamma(t)$, we use fuzzy logic and consider it as a function of errors and errors variation. Having two inputs and two outputs, the simple sognoy rule of IF-THEN will be

$$IF\ \tilde{q}\ is\ A_i\ and\ \dot{\tilde{q}}\ is\ B_i\ THEN$$

$$\tau = \hat{\tau} - K\ sat\left(\frac{\dot{e} + \lambda_i e - \gamma_i}{\varphi}\right) \tag{25}$$

In order to determine λ_i, γ_i, first we define six membership function $\{NL, PS, PZ, NZ, NS, NL\}$ for each $\tilde{q}, \dot{\tilde{q}}$ input (see Fig 4). Based on sliding mode control, sognoy rule base is regarded for calculating λ_i, γ_i. This is shown in tables 2 and 3.

Table 2. Look-up the fuzzy rule base for λ_i

$\dot{e}$ \ e	PL	PS	PZ	NZ	NS	NL
PL	0/6	0/6	0/6	0/6	0/6	0/6
PS	0/6	0/6	0/6	5	5	5
PZ	0/6	0/6	5	8	8	8
NZ	8	8	8	5	0/6	0/6
NS	5	5	5	0/6	0/6	0/6
NL	0/6	0/6	0/6	0/6	0/6	0/6

Table 3. Look-up the fuzzy rule base for γ_i

$\dot{e}$ \ e	PL	PS	PZ	NZ	NS	NL
PL	-10	-8	-4	0	0	0
PS	-8	-4	-2	0	0	0
PZ	-3	-2	0	0	0	0
NZ	0	0	0	0	2	4
NS	0	0	0	0	4	8
NL	0	0	0	4	6	10

5. Results

The proposed methods in this paper were applied to a robot with the following parameters

$$m_1 = 10\ \ \hat{m}_2 = 5\ \ l_1 = 1\ \ l_2 = 0.5\ \ l_{c_1} = 0.5\ \ \hat{l}_{c_2} = 0.25 \tag{26}$$

$$I_1 = {}^{10}/_{12}\ \ \hat{I}_2 = {}^{5}/_{12}$$

$$0 \le \Delta m_2 \le 2\ \ 0 \le \Delta l_{c_2} \le 0.25\ \ 0 \le \Delta I_2 \le 0.5$$

Desired vector is:

$$q_d = [\pi\ \ -\pi]^T \tag{27}$$

Designing parameters of sliding mode controller are:

$$\lambda = \begin{bmatrix} 2 & 0 \\ 0 & 4 \end{bmatrix}\quad K = \begin{bmatrix} 75 & 0 \\ 0 & 110 \end{bmatrix} \tag{28}$$

Bearing in mind that if input torques exceed a certain amount the problem of link saturation will show up, so we will face limitations in applying input torques. For the simulated robotic model, the maximum applied torques is 150 to the first link and 15 to the second.

The simulation result of sliding mode controller and also controller with moving sliding surface are given in Figs.6-12. As shown in the Figs. The problem of sliding surface oscillations is solved in incorporating controller. And, sliding surface is smoother than that of sliding mode controller. In addition, sliding phase in controller with moving sliding surface is in its least possible.

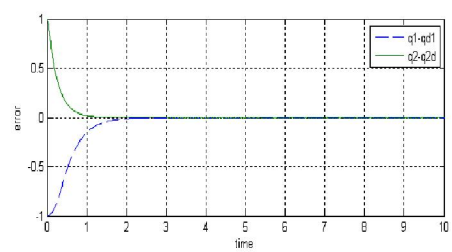

Figure. 4. Detection error of sliding mode controller

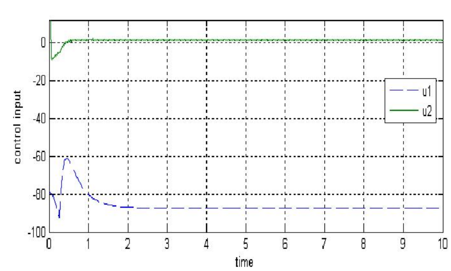

Figure 5. Control inputs of sliding mode controller

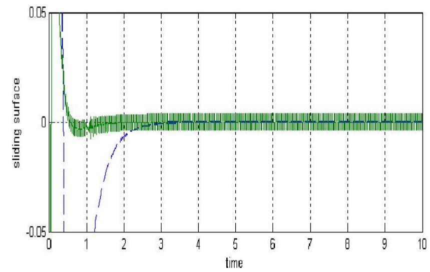

Figure. 6. Sliding surface of sliding mode controller

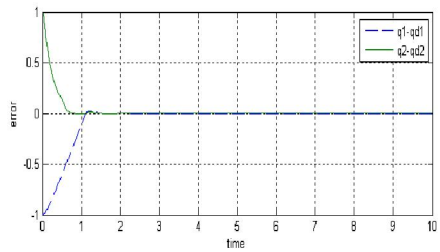

Figure. 7. Detection error of incorporating fuzzy-sliding mode controller

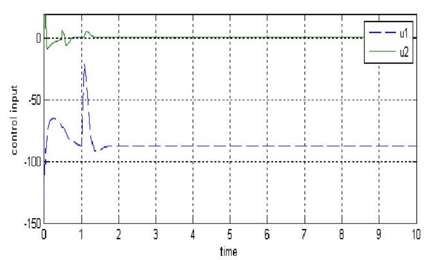

Figure. 8. control inputs of incorporating fuzzy-sliding mode controller

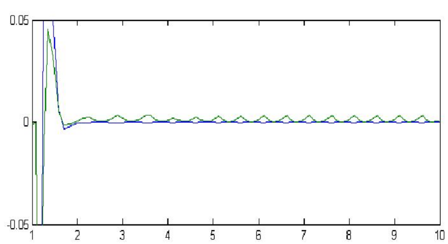
Figure. 9. Sliding surface of incorporating fuzzy-sliding mode controller

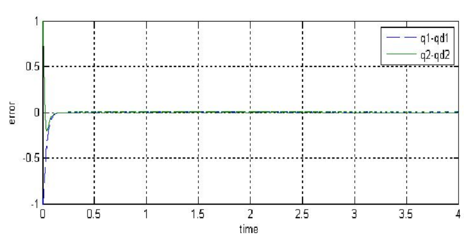

Figure. 10. Detection error of sliding mode controller with moving surface

5. Conclusion

In this paper, by using fuzzy logic two main problems of sliding mode control were removed. The first problem, sliding surface oscillation, was overcome by incorporated controller. And the second, lack of robust of controller in the reaching phase, is minimized with moving slide surface for robot manipulator link.

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