



AENSI Journals

Journal of Applied Science and Agriculture

ISSN 1816-9112

Journal home page: www.aensiweb.com/jasa/index.html



Design for Integration of Slide- Fuzzy Mode Controller Based on the Strategy of Mobile Slide Level for Two-Chain Robotic Automated Arm

¹O. Rahmani, ²A. Taherkhani, ¹M. Rahmani, ¹T. Karimiyan

¹Department of Electrical Engineering, Takestan Branch, Islamic Azad University, Takestan, Iran.

²Department of Physics, Faculty of Science, Takestan branch, Islamic Azad University, Takestan, Iran.

ARTICLE INFO

Article history:

Received 11 June 2014

Received in revised form 25 July 2014

Accepted 20 September 2014

Available online 1 October 2014

Key words:

Fuzzy control, Sliding Mode, Robot, Integration Control

ABSTRACT

The sliding displacement includes two phases i.e. approaching phase and sliding phase. Several problems may be exposed in both phases. In sliding phase, the nature of transformation in controlling rule may cause the adverse collision phenomenon where its high frequency fluctuations may lead to non-modeled kinetics in this system. This may destroy the system under the control. In this article, a Fuzzy-Sliding Mode Controller (FSMC) is introduced to solve this problem. Similarly, during approaching phase, Sliding Mode System is sensitive to parametric uncertainties and external turbulences. Fuzzy- Sliding Mode Controller (FSMC) has been prepared along with Mobile Sliding Surface (MSS) to minimize and or remove the approaching phase as possible in this essay.

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To Cite This Article: O. Rahmani, A. Taherkhani, M. Rahmani, T. Karimiyan., Design for Integration of Slide- Fuzzy Mode Controller Based on the Strategy of Mobile Slide Level for Two-Chain Robotic Automated Arm. *J. Appl. Sci. & Agric.*, 9(16): 80-87, 2014

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 (Kelly, R. and V. Santibañez, 1996; Santibañez, V. and R. Kelly, 1997). 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 (....., 1998; Laib, A., 2000). 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) (Choi, S.B., *et al.*, 1994; Choi, S.B., 1993). 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 (Spong, M. and M. Vidyasagar, 1989).

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

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 Coriolis 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.

Corresponding Author: O. Rahmani, Department of Electrical Engineering, Takestan Branch, Islamic Azad University, Takestan, Iran.

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 (Cai, L. and G. Song, 1994; Wang, J., 2001).

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

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

$$\operatorname{sat}(\tau_i; f_{si}) = \begin{cases} f_{si} & \tau_i > f_{si} \\ \tau_i & -f_{si} \leq \tau_i \leq f_{si} \\ -f_{si} & \tau_i < -f_{si} \end{cases} \quad (3)$$

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 $M(\dot{q})$ of the inertia matrix satisfy

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

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

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

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

$$\sup\{|g_i(q)|\} \leq \bar{g}_i \quad \bar{g}_i \geq 0$$

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

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

We assume that each actuator satisfies the following condition

$$\tau^{max} > \bar{g}_i + f_{si} \quad (4)$$

G and M matrix is present as the following

$$C = \hat{C} + \Delta C \quad (5)$$

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

$$s = \dot{e} + \lambda e \quad (6)$$

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:

$$\dot{q}_r = \dot{q}_d - \lambda e \quad (7)$$

We may define slide surface as following:

$$s = \dot{q} - \dot{q}_r \quad (8)$$

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

$$\frac{1}{2} \frac{d}{dt} [s^T M s] < -\eta (s^T s)^{1/2} \quad (9)$$

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

$$\boldsymbol{\tau} = \hat{\boldsymbol{\tau}} - K \operatorname{sgn}(s) \quad (10)$$

That,

$$\hat{\boldsymbol{\tau}} = M \ddot{q}_r + \hat{C} \dot{q}_r + G \quad (11)$$

and,

$$K_i \geq \|\Delta C \dot{q}_r\| + \Gamma_i \quad (12)$$

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

$$\Gamma_i \geq F_{up} + \eta_i \quad (13)$$

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

$$V = \frac{1}{2} s^T M s \quad (14)$$

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

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

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

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

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

$$\dot{V} = s^T (\tau - C \dot{q}_r - G - F - M \ddot{q}_r) \quad (17)$$

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

$$\dot{V} = -s^T (\Delta C \dot{q}_r + F) - \sum_{i=1}^n K_i |s_i| \quad (18)$$

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

$$\dot{V} \leq - \sum_{i=1}^n \eta_i |s_i| \quad (19)$$

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

$$\text{sgn}\left(\frac{s}{\phi}\right) = \begin{cases} \text{sgn}\left(\frac{s}{\phi}\right) & |s| \geq |\phi| \\ \frac{s}{\phi} & |s| < |\phi| \end{cases} \quad (20)$$

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

$$\text{IF } x_1 \text{ is } A_1^{l_1} \text{ and } x_2 \text{ is } A_2^{l_2} \text{ THEN } y^l \text{ is } B^{l_1 l_2} \quad (21)$$

Where

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

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 $y \in v$ exists an input membership function $\mu_{A_j^{l_j}}(x_j)$ and output membership function $\mu_{B^{l_1 l_2}}(y)$, respectively, with $l_j = -(N_1 - 1)/2, \dots, -(N_j - 1)/2$

; $j = 1, 2$; 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 $l = -(N - 1)/2, \dots, -(N - 1)/2$.

In the remainder of this paper, we consider the SFC class of fuzzy controllers studied in (Calcev, G., 1998; Calcev, G., *et al.*, 1998), 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.

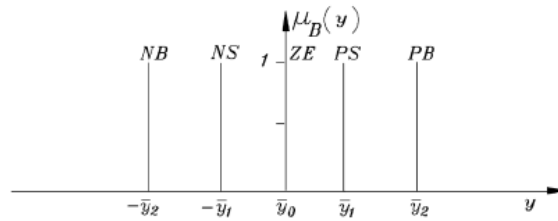


Fig. 1: Input membership functions.

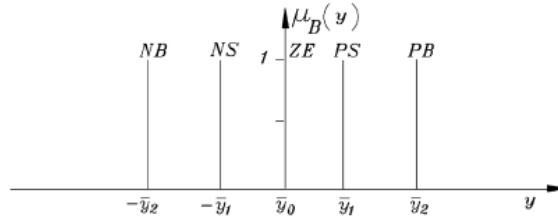


Fig. 2: Output membership functions.

Table 1: Look-up the fuzzy rule base.

$x_2 \backslash x_1$	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:

$$\tau = \begin{cases} \tilde{\tau} - Ksgn(s) & |\tilde{q}_i| \geq \alpha \\ \varphi(\tilde{q}, \dot{\tilde{q}}) + G(q) & |\tilde{q}_i| < \alpha \end{cases} \tag{22}$$

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.

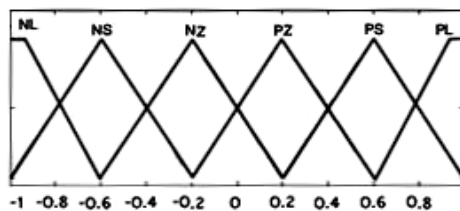


Fig. 3: membership functions for inputs \tilde{q} and $\dot{\tilde{q}}$.

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) (Choi, S.B., *et al.*, 1994; Choi, S.B., *et al.*, 1993). In attention to studied robot that is a two-link robot, equation of moving sliding surface is defined as

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

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

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

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

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

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

$$m_1 = 10 \quad \hat{m}_2 = 5 \quad l_1 = 1 \quad l_2 = 0.5 \quad l_{c1} = 0.5 \quad \hat{l}_{c2} = 0.25$$

$$l_1 = 10/12 \quad \hat{l}_2 = 5/12$$

$$0 \leq \Delta m_2 \leq 2 \quad 0 \leq \Delta l_{c2} \leq 0.25 \quad 0 \leq \Delta l_2 \leq 0.5$$

Desired vector is:

$$q_d = [\pi \quad -\pi]^T \quad (27)$$

Designing parameters of sliding mode controller are:

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

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.

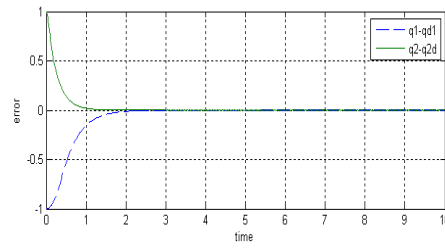


Fig. 4: Detection error of sliding mode controller.

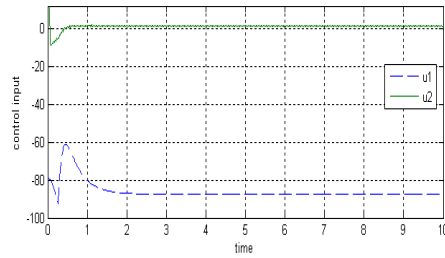


Fig. 5: Control inputs of sliding mode controller

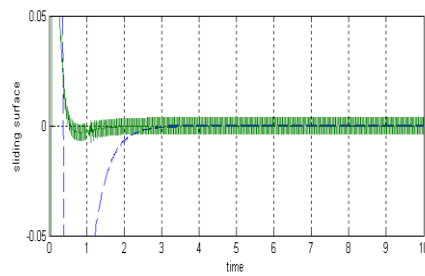


Fig. 6: Sliding surface of sliding mode controller.

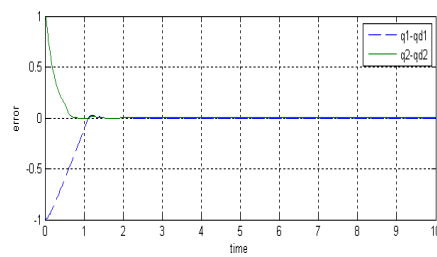


Fig. 7: Detection error of incorporating fuzzy-sliding mode controller.

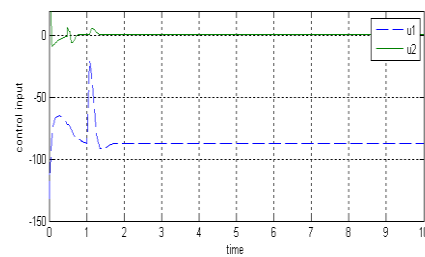


Fig. 8: control inputs of incorporating fuzzy-sliding mode controller.

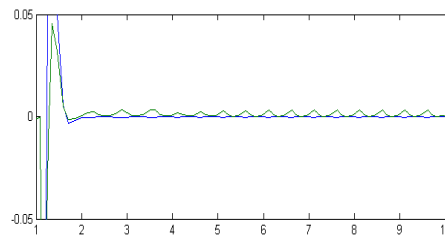


Fig. 9: Sliding surface of incorporating fuzzy-sliding mode controller.

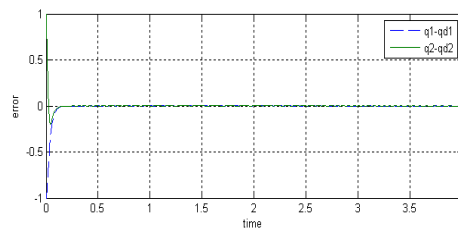


Fig. 10: Detection error of sliding mode controller with moving surface.

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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