Adaptive Sliding Mode Controller for Robotic Manipulator Tracking Control with Fuzzy Design

Monisha Pathak, Mrinal Buragohain

Abstract: This paper introduces an adaptive sliding mode controller design based on fuzzy compensation for efficient robotic manipulator tracking control. This work introduces design of Adaptive Fuzzy Controller based on sliding control principles for Robotic Manipulators. In the work, an adaptive fuzzy sliding mode control algorithm is proposed for tracking control of robot manipulators. The fuzzy system uses a set of fuzzy rules, the parameters of which are modified in real-time by adaptive laws, to approximate unknown nonlinearities. This makes it easier to direct the nonlinear system's output to follow a specific trajectory. An adaptive control algorithm based on the adaptive fuzzy model is created using the Lyapunov approach. Both the chattering and the stable performance are assured.

Keywords: Sliding Mode Control, Fuzzy Logic Control; Robot Manipulator; Adaptive Control

I. INTRODUCTION

Robot manipulators have been widely employed in industrial, medical and other applications, particularly for precise positioning and path tracking. The robot manipulators are heavily coupled, nonlinear systems, and their features and responses are severely affected by time variable factors and uncertainties. As a result, to handle such complexities, these systems require an effective and robust controller, which is a significant issue for researchers [3]. It is critical to offer effective control to the end effector of a robotic manipulator for precise trajectory tracking execution.

To handle such systems with uncertainties Sliding Mode Control (SMC) is one of the most robust and powerful control approach[18]. It has appealing characteristics such as reduced order compensated dynamics, insensitive to matched uncertainty, and robustness to disturbance. In the area of control theory, the introduction of fuzzy logic has greatly increased the application of controllers to control nonlinear, complex systems. Due to various advantages over traditional methodologies, such as the inclusion of human experience, a flexible model free approach, and so on, the fuzzy logic control (FLC) opens up new frontiers in the field of control theory[1,2].The advantage of intelligent control is the precise approximation[16] of any nonlinear function by neural networks and fuzzy systems. It is best to use an adaptive intelligent controller when the dynamics of the system are unknown and highly nonlinear. Particularly, controlling robot manipulators using neural networks (NN) and fuzzy logic has drawn a lot of interest, and a number of pertinent plans and techniques have been created and investigated[4-15].

This work introduces design of Adaptive Fuzzy Controller based on sliding control principles. In the work, an adaptive fuzzy sliding mode control algorithm is proposed for tracking control of robot manipulators. Unknown nonlinearities are approximated by the fuzzy system using a set of fuzzy rules, the parameters of which are changed in real time by adaptive laws. This makes directing the output of the nonlinear system to follow a particular trajectory simpler. The Lyapunov synthesis technique is used to develop an adaptive control algorithm based on the adaptive fuzzy model. Robust performance is possible while the chattering action is reduced. The proposed control algorithm's stability analysis is offered.

This paper's structure is as follows: The system model, its attributes, and some presumptions are all introduced in Section II. The control law design and stability analysis are presented in Section III. In Section IV, the control rule is verified using a simulation on a 2DOF manipulator. In Section V, a conclusion is reached.

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*** Correspondence Author**

Monisha Pathak*, Department of Instrumentation Engineering, Jorhat Engineering College, Jorhat (Assam), India. E-mail: mamup@yahoo.co.in

Dr. Mrinal Buragohain, Department of Electrical Engineering, Jorhat Engineering College, Jorhat (Assam), India. E-mail: mrinalburagohain@gmail.com

II. PRELIMINARY

Consider the dynamics of n link robot manipulators as [3]

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

where $q, \dot{q}$ and $\ddot{q} \in R^n$ are vectors of angular position, angular velocity and angular acceleration of the joints respectively. In addition, $M(q) \in R^{n\times n}$ stands for the inertia matrix, and $C(q,\dot{q})\dot{q} \in R^n$ stands for the centrifugal coriolis torque vector. Furthermore, $G(q) \in R^n$ stands for the gravitational vector, $F_r(\dot{q}) \in R^n$ for friction, $\tau \in R^n$ for joint torque vector, and τ_d for unknown disturbance. The robot manipulator dynamics given in (1) has the following properties.

Property A:

The inertia matrix $M(q)$ is bounded, symmetric and positive definite i.e

$$m_l\|x\|^2 \le x^T M(q)x \le m_u\|x\|^2$$

Where $0 < m_l < m_u$ are the bounds of $M(q)$ that may be computed for any given arm.

Property B:

Matrix $\dot{M}(q) - 2C(q,\dot{q})$ is a skew symmetric matrix. i.e.,

$$x^T[\dot{M}(q) - 2C(q,\dot{q})]x = 0, \quad \forall x \neq 0 \qquad (4)$$

Assumption a: The all joints of the manipulator are revolute.
Assumption b: $q, \dot{q}, \ddot{q}$ are all continuous and bounded.

III. ADAPTIVE FUZZY SLIDING MODE CONTROLLER DESIGN

Let us rewrite eq (1) as

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + U(q,\dot{q},\ddot{q}) = \tau \quad (2)$$

where $U(q,\dot{q},\ddot{q})$ is an unknown nonlinear function consisting of friction force F_r and disturbance τ_d and uncertainties. Assume $M(q)$ and $C(q,\dot{q})$ and $G(q)$ are known. Now for a desired trajectory q_d the tracking error is $e = q - q_d$.

Define sliding mode function as

$$s = \dot{e} + \lambda e \qquad (3)$$

And

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

where λ is a positive definite matrix. Now,

$$s = \dot{q} - \dot{q}_d + \lambda e$$
$$s = \dot{q} - \dot{q}_r$$
$$M\dot{s} = M\ddot{q} - M\ddot{q}_r$$
$$M\dot{s} = \tau - C\dot{q} - G - U - M\ddot{q}_r$$

Now the fuzzy system is designed as $\hat{U}(q,\dot{q},\ddot{q}|\Psi)$ to approximate unknown nonlinear function $U(q,\dot{q},\ddot{q})$. $\hat{U}(q,\dot{q},\ddot{q}|\Psi)$ is expressed as[2,17]

$$\hat{U}(q,\dot{q},\ddot{q}|\Psi) = \begin{bmatrix} \hat{U}_1(q,\dot{q},\ddot{q}|\Psi_1) \\ \hat{U}_2(q,\dot{q},\ddot{q}|\Psi_2) \\ . \\ . \\ \hat{U}_n(q,\dot{q},\ddot{q}|\Psi_n) \end{bmatrix} = \begin{bmatrix} \Psi_1^T u(q,\dot{q},\ddot{q}) \\ \Psi_2^T u(q,\dot{q},\ddot{q}) \\ . \\ . \\ \Psi_n^T u(q,\dot{q},\ddot{q}) \end{bmatrix}$$

where $u(q,\dot{q},\ddot{q})$ is fuzzy basis function vector and Ψ is parameter matrix.

The fuzzy approximation error is,

$$\varepsilon = U(q,\dot{q},\ddot{q}) - \hat{U}(q,\dot{q},\ddot{q}|\Psi^*)$$

Define Lyapunov function as

$$L(t) = \frac{1}{2}(s^T M s + \textstyle\sum_{i=1}^{n} \tilde{\Psi}_i^T \Delta_i \tilde{\Psi}_i) \qquad (4)$$

Where $\tilde{\Psi}_i = \Psi_i^* - \Psi_i$ and Ψ_i^* is the i[th] column vector of optimal parameter matrix Ψ^*. $\Delta_i > 0$. Then,

$$\dot{L}(t) = s^T M\dot{s} + \frac{1}{2}s^T \dot{M}s + \sum_{i=1}^{n}\left(\tilde{\Psi}_i^T \Delta_i \dot{\tilde{\Psi}}_i\right)$$

$$= -s^T(-\tau + C\dot{q} + G + U + M\ddot{q}_r - Cs) + \textstyle\sum_{i=1}^{n}\left(\tilde{\Psi}_i^T \Delta_i \dot{\tilde{\Psi}}_i\right)$$

$$= -s^T(-\tau + C\dot{q}_r + G + U + M\ddot{q}_r) + \textstyle\sum_{i=1}^{n}\left(\tilde{\Psi}_i^T \Delta_i \dot{\tilde{\Psi}}_i\right) \quad (5)$$

Now the adaptive fuzzy sliding mode control law is designed as

$$\tau = M(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + \hat{U}(q,\dot{q},\ddot{q}|\Psi) - Zs - Ksgn(s) \qquad (6)$$

Where $Z = diag(z_i)$, $z_i > 0$ and $K = diag(k_i)$, $k_i \ge |\varepsilon_i|$, $i = 1,2,\dots\dots,n$

And the adaptive rule is define as

$$\dot{\Psi}_i = -\Delta_i^{-1} s_i\, u(q,\dot{q},\ddot{q}) \; i = 1,2,\dots\dots,n \qquad (7)$$

Now from (4), (6) and (7) we get,

$$\dot{L}(t) \le -s^T Z s \le 0 \qquad (8)$$

Considering fuzzy system $\hat{U}(q,\dot{q},\ddot{q}|\Psi)$, for n joint manipulator, for each joint the number of input variables is 3. For each input variable, if m membership functions are designed, then the fuzzy compensator needs m^{3n} fuzzy rules. This causes excessive computation. To solve this problem, to reduce the number of fuzzy rules, independent design should be used. i.e. if we consider fuzzy compensation with only frictional force, then $U(q,\dot{q},\ddot{q}) = U(\dot{q})$. Then to approximate $U(q,\dot{q},\ddot{q})$, fuzzy system can be designed as $\hat{U}(\dot{q}|\Psi)$. Then from (6), the control law becomes,

$$\tau = M(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + \hat{U}(\dot{q}|\Psi) - Zs - Ksgn(s)$$

And from (7) the adaptive law is

$$\dot{\psi}_i = -\Delta_i^{-1} s_i\, u(\dot{q}) \quad , i = 1,2,\dots\dots,n$$

And the fuzzy system is given by

$$\hat{U}(\dot{q}|\psi) = \begin{bmatrix} \hat{U}_1(\dot{q}_1) \\ \hat{U}_2(\dot{q}_2) \\ . \\ . \\ \hat{U}_n(\dot{q}_n) \end{bmatrix} = \begin{bmatrix} \psi_1^T u^1(\dot{q}_1) \\ \psi_2^T u^2(\dot{q}_2) \\ . \\ . \\ \psi_n^T u^n(\dot{q}_n) \end{bmatrix}$$

IV. SIMULATION RESULTS

Consider the dynamics of two-link manipulator as follows:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F_r(\dot{q}) + \tau_d = \tau$$

Where

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

And,

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$$M_{11} = (m_1 + m_2)l_1^2 + m_2 l_2^2 + 2m_2 l_1 l_2 \cos(q_2)$$

$$M_{12} = M_{21} = m_2 l_2^2 + m_2 l_1 l_2 \cos(q_2)$$

$$M_{22} = m_2 l_2^2$$

$$C(q,\dot{q})\dot{q} = \begin{pmatrix} -m_2 l_1 l_2 \sin(q_2)\,\dot{q}_2^2 - 2m_2 l_1 l_2 \sin(q_2)\,\dot{q}_1 \dot{q}_2 \\ m_2 l_1 l_2 \sin(q_2)\,\dot{q}_2^2 \end{pmatrix}$$

$$G(q) = \begin{pmatrix} (m_1 + m_2) l_1 g cos(q_1) + m_2 l_2 g cos(q_1 + q_2) \\ m_2 l_2 g cos(q_1 + q_2) \end{pmatrix}$$

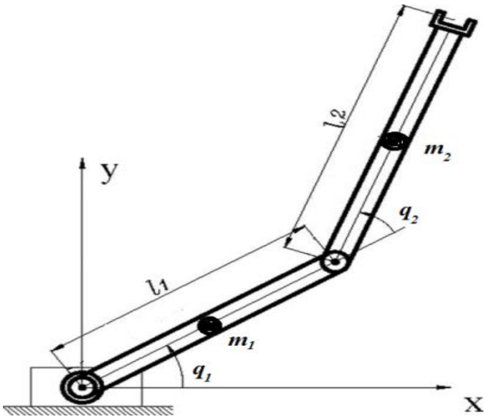

Figure 1

The manipulator and the associated variables are shown in Figure 1. Here $q = [q_1, q_2]^T$ is the angular position vector where q_1 and q_2 are the angular positions of joints 1 and 2, $\tau = [\tau_1\ ,\ \tau_2]^T$ is the applied torque, and $[q_1\ \ \dot{q}_1\ \ q_2\ \ \dot{q}_2]^T = [0,0,0,0]^T$ is the initial states of the manipulator and $l_1 = 1m,\ l_2 = 0.85m\ ,\ m_1 = 1kg\ \ ,\ m_2 = 1.5kg$. The desired trajectory are $q_{d1} = 0.5sint$ and $q_{d2} = 0.5sint$.
The fuzzy membership function is defined as

$$\mu_{A_i^l}(g_i) = \exp\left(-\left(\frac{g_i - \bar{g}_i^l}{\pi/24}\right)^2\right)$$

where $\bar{x}_i^l$ is chosen as $-\frac{\pi}{6}, -\frac{\pi}{12},\ 0\ \ ,\ \frac{\pi}{12},\ \frac{\pi}{6}$ respectively and A_i^l is designed as NB, NS, ZO, PS, PB belong to lth fuzzy rule for $i = 1,2,3,4,5$. Now the controller parameters are chosen as $\lambda = 15.I_2\ , Z = 30.I_2\ \ , K = 1.5.I_2\ \ , \varDelta_1 = \varDelta_2 = 0.0001$ The inputs of the fuzzy system are chosen as $[\dot{q}_1\ \ \dot{q}_2]$ and $\psi_i(0) = 0.1$. The friction is $F_r(\dot{q}) = [3sgn(\dot{q}_1)\ \ 3sgn(\dot{q}_2)]^T$ and the disturbance is $\tau_d = [0.1\sin(20t)\ \ \ 0.1\sin(20t)\ ]^T$ .The simulation results are shown in Figures 2 to 9.

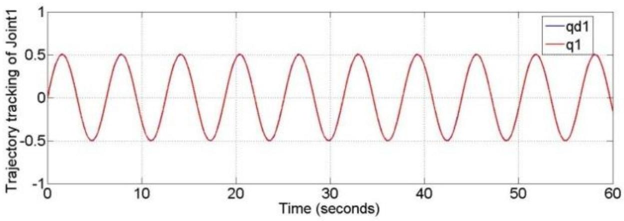

Figure 2

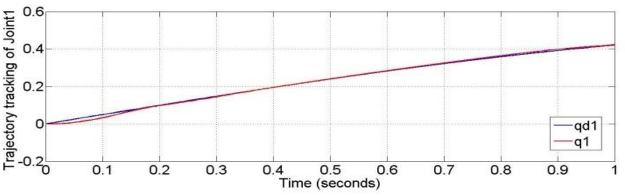

Figure 3

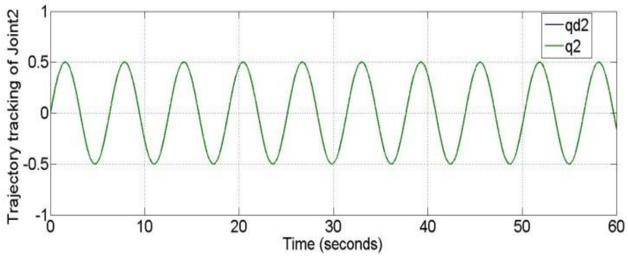

Figure 4

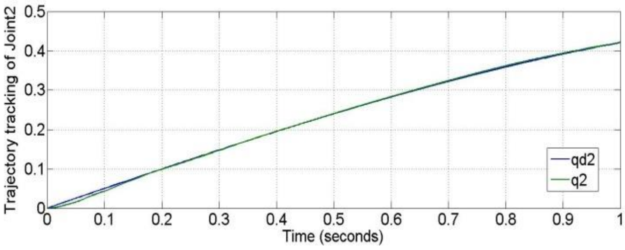

Figure 5

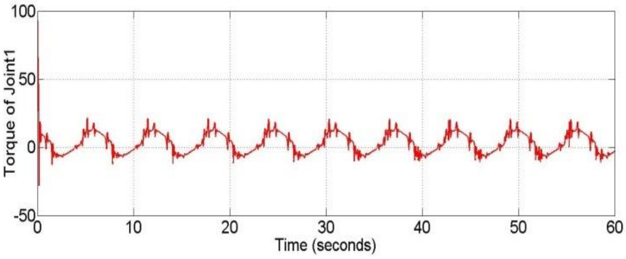

Figure 6

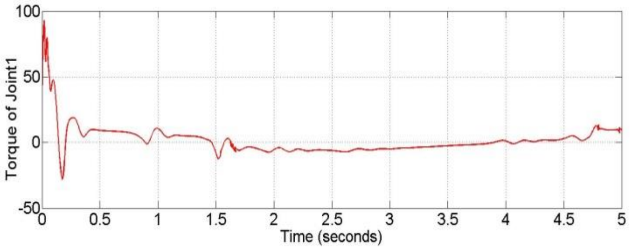

Figure 7

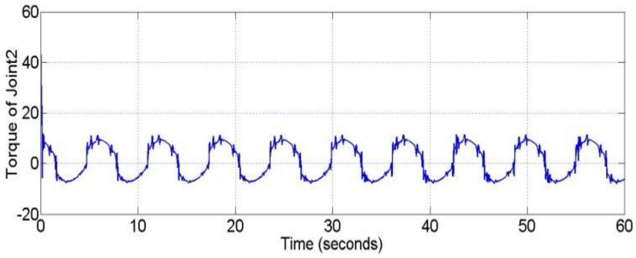

Figure 8

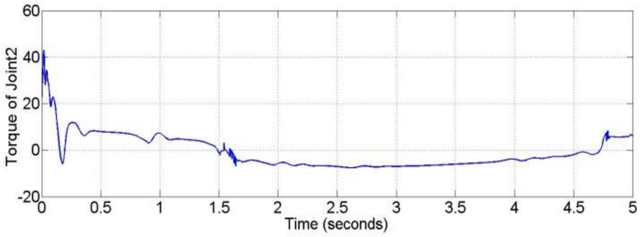

Figure 9

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V. CONCLUSION

This work presents a sliding control-based adaptive fuzzy controller design for tracking the trajectory of robotic manipulators. The work proposes an adaptive fuzzy sliding mode control algorithm for tracking control of robot manipulator where the fuzzy system uses a set of fuzzy rules whose parameters are continuously modified by adaptive laws to approximate unknown nonlinearities. The controller ensures robust performance and the chattering action is reduced satisfactorily. The controller has been implemented satisfactorily, as shown by the simulation results of a 2dof robot manipulator in the presence of uncertainties and external disturbances.

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AUTHORS PROFILE

Mrs. Monisha Pathak, currently working as a Assistant Professor Instrumentation Engineering Department, Jorhat Engineering College, Jorhat, Assam, India, She received her Bachelor of Engineering in Instrumentation Engineering from Jorhat Engineering College, affiliated to Dibrugarh University. She pursued her Master of Engineering in Power and Control from IIT Guwahati. Her research interests include Instrumentation and Control, Nonlinear Control, Intelligent control. Some of her research publications are 1. Sliding Mode with "Adaptive Control of Robot Manipulator Trajectory Tracking using Neural Network Approximation" International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249-8958 (Online), Volume-10 Issue-6, August 2021. 2. A New Neural Network Based Sliding Mode Adaptive Controller for Tracking Control of Robot Manipulator, International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249-8958 (Online), Volume-11 Issue-2, December 2021, 3. "Control of nonlinear chemical process using sliding mode control", 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)4-6 July 2016

Dr. Mrinal Buragohain, currently working as a Professor in the Department of Electrical Engineering at Jorhat Engineering College, Jorhat received his Bachelor of Engineering in Electrical Engineering from Assam Engineering College affiliated to Gauhati University, Assam. He pursued his Master of Engineering in High Voltage Engineering from Jadavpur University, Kolkata. After this, he completed his Ph.D. with specialization in Control System in the department of Electronics and Communication Engineering at the Indian Institute of Technology, Guwahati. His research interests include soft computing application in non-linear systems and Optimal and adaptive control. Some of his Research publications are "Tracking and Synchronization of A Hyperchaotic Hyperjerk system with No Equilibria Using Back stepping Control" at International journal for Research in Engineering Application & Management, ISSN: 2454-9150, Vol-05, Issue02, May 2019, " A PID Adaptive Sliding Mode Control for an Inverted Pendulum System for an External Disturbance using Grey Wolf Optimization Technique" at International Journal of New Technologies in Science and Engineering, ISSN: 2349-0780, Vol. 5, Issue.3, 2018