Adaptive MIMO Fuzzy Compensate Fuzzy Sliding Mode Algorithm: Applied to Second Order Nonlinear System

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Abstract

This research is focused on proposed adaptive fuzzy sliding mode algorithms with the adaptation laws derived in the Lyapunov sense. The stability of the closed-loop system is proved mathematically based on the Lyapunov method. Adaptive MIMO fuzzy compensate fuzzy sliding mode method design a MIMO fuzzy system to compensate for the model uncertainties of the system, and chattering also solved by linear saturation method. Since there is no tuning method to adjust the premise part of fuzzy rules so we presented a scheme to online tune consequence part of fuzzy rules. Classical sliding mode control is robust to control model uncertainties and external disturbances. A sliding mode method with a switching control low guarantees the stability of the certain and/or uncertain system, but the addition of the switching control low introduces chattering into the system. One way to reduce or eliminate chattering is to insert a boundary layer method inside of a boundary layer around the sliding surface. Classical sliding mode control method has difficulty in handling unstructured model uncertainties. One can overcome this problem by combining a sliding mode controller and artificial intelligence (e.g. fuzzy logic). To approximate a time-varying nonlinear dynamic system, a fuzzy system requires a large amount of fuzzy rule base. This large number of fuzzy rules will cause a high computation load. The addition of an adaptive law to a fuzzy sliding mode controller to online tune the parameters of the fuzzy rules in use will ensure a moderate computational load. The adaptive laws in this algorithm are designed based on the Lyapunov stability theorem. Asymptotic stability of the closed loop system is also proved in the sense of Lyapunov.

Keywords: Adaptive Fuzzy Sliding Mode Algorithm, Lyapunov Based, Adaptive MIMO Fuzzy Compensate Fuzzy Sliding Mode Algorithm, Chattering Phenomenon, Sliding Surface, Fuzzy logic Controller, Adaptive law.

1. INTRODUCTION

The first person who used the word robot was Karel Capek in 1920 in his satirical play, R.U.R (Rossum's Universal Robots). The first person who used the word robotics was the famous author, Issac Asimov along with three fundamental rules. Following World War II, the first industrial robot manipulator have been installation at General Motors in 1962 for the automation. In 1978 the PUMA (Programmable Universal Machine for Assembly) and in 1979 the SCARA (Selective Compliance Assembly Robot Arm) were introduced and they were quickly used in research laboratories and industries. According to the MSN Learning & Research," 700000 robots were in the industrial world in 1995 and over 500000 were used in Japan, about 120000 in Western Europe, and 60000 in the United States [1, 6]." Research about mechanical parts and control methodologies in robotic system is shown; the mechanical design, type of actuators, and type of systems drive play important roles to have the best performance controller. More over types of kinematics chain, i.e., serial Vs. parallel manipulators, and types of connection between link and join actuators, i.e., highly geared systems Vs. direct-drive systems are played important roles to select and design the best acceptable performance controllers[6]. A serial link PUMA 560robot is a sequence of joints and links which begins with a base frame and ends with an end-effector. This type of robot manipulators, comparing with the load capacitance is more weightily because each link must be supported the weights of all next links and actuators between the present link and end-effector[6]. Serial robot manipulators have been used in automotive industry, medical application, and also in research laboratories. One of the most important classifications in controlling the robot manipulator is how the links have connected to the actuators. This classification divides into two main groups: highly geared (e.g., 200 to 1) and direct drive (e.g., 1 to 1). High gear ratios reduce the nonlinear coupling dynamic parameters in robot manipulator. In this case, each joint is modeled the same as SISO systems. In high gear robot manipulators which generally are used in industry, the couplings are modeled as a disturbance for SISO systems. Direct drive increases the coupling of nonlinear dynamic parameters of robot manipulators. This effect should be considered in the design of control systems. As a result some control and robotic researchers' works on nonlinear robust controller design[2]. Although PUMA robot manipulator is high gear but this research focuses on design MIMO controller.

In modern usage, the word of control has many meanings, this word is usually taken to mean regulate, direct or command. The word feedback plays a vital role in the advance engineering and science. The conceptual frame work in Feed-back theory has developed only since world war II. In the twentieth century, there was a rapid growth in the application of feedback controllers in process industries. According to Ogata, to do the first significant work in three-term or PID controllers which Nicholas Minorsky worked on it by automatic controllers in 1922. In 1934, Stefen Black was invention of the feedback amplifiers to develop the negative feedback amplifier[1, 6]. Negative feedback invited communications engineer Harold Black in 1928 and it occurs when the output is subtracted from the input. Automatic control has played an important role in advance science and engineering and its extreme importance in many industrial applications, i.e., aerospace, mechanical engineering and robotic systems. The first significant work in automatic control was James Watt's centrifugal governor for the speed control in motor engine in eighteenth century[2]. There are several methods for controlling a robot manipulator, which all of them follow two common goals, namely, hardware/software implementation and acceptable performance. However, the mechanical design of robot manipulator is very important to select the best controller but in general two types schemes can be presented, namely, a joint space control schemes and an operation space control schemes[1]. Joint space and operational space control are closed loop controllers which they have been used to provide robustness and rejection of disturbance effect. The main target in joint space controller is to design a feedback controller which the actual motion ($q_a(t)$) and desired motion ($q_d(t)$) as closely as possible. This control problem is classified into two main groups. Firstly, transformation the desired motion $X_d(t)$ to joint variable $q_d(t)$ by inverse kinematics of robot manipulators[6]. This control include simple PD control, PID control, inverse dynamic control, Lyapunov-based control, and passivity based control that explained them in the following section. The main target in operational space controller is to design a feedback controller to allow the actual end-effector motion $X_a(t)$ to track the desired endeffector motion $X_d(t)$. This control methodology requires a greater algorithmic complexity and the inverse kinematics used in the feedback control loop. Direct measurement of operational space variables are very expensive that caused to limitation used of this controller in industrial robot manipulators[6]. One of the simplest ways to analysis control of multiple DOF robot manipulators are analyzed each joint separately such as SISO systems and design an independent joint controller for each joint. In this controller, inputs only depends on the velocity and displacement of the corresponding joint and the other parameters between joints such as coupling presented by disturbance input. Joint space controller has many advantages such as one type controllers design for all joints with the same formulation, low cost hardware, and simple structure.

A nonlinear methodology is used for nonlinear uncertain systems (e.g., robot manipulators) to have an acceptable performance. These controllers divided into six groups, namely, feedback linearization (computed-torque control), passivity-based control, sliding mode control (variable structure control), artificial intelligence control, lyapunov-based control and adaptive control[1-20]. Sliding mode controller (SMC) is a powerful nonlinear controller which has been analyzed by many researchers especially in recent years. This theory was first proposed in the early 1950 by Emelyanov and several co-workers and has been extensively developed since then with the invention of high speed control devices [1-3, 6, 14]. The main reason to opt for this controller is its acceptable control performance in wide range and solves two most important challenging topics in control which names, stability and robustness [7, 17-20]. Sliding mode controller is divided into two main sub controllers: discontinues controller(τ_{dis}) and equivalent controller(τ_{eq}). Discontinues controller causes an acceptable tracking performance at the expense of very fast switching. In the theory of infinity fast switching can provide a good tracking performance but it also can provide some problems (e.g., system instability and chattering phenomenon). After going toward the sliding surface by discontinues term, equivalent term help to the system dynamics match to the sliding surface[1, 6]. However, this controller used in many applications but, pure sliding mode controller has following challenges: chattering phenomenon, and nonlinear equivalent dynamic formulation [20]. Chattering phenomenon can causes some problems such as saturation and heat the mechanical parts of robot manipulators or drivers. To reduce or eliminate the chattering, various papers have been reported by many researchers which classified into two most important methods: boundary layer saturation method and estimated uncertainties method [1, 10-14]. In boundary layer saturation method, the basic idea is the discontinuous method replacement by saturation (linear) method with small neighborhood of the switching surface. This replacement caused to increase the error performance against with the considerable chattering reduction. Slotine and Sastry have introduced boundary layer method instead of discontinuous method to reduce the chattering[21]. Slotine has presented sliding mode with boundary layer to improve the industry application [22]. R. Palm has presented a fuzzy method to nonlinear approximation instead of linear approximation inside the boundary layer to improve the chattering and control the result performance[23]. Moreover, C. C. Weng and W. S. Yu improved the previous method by using a new method in fuzzy nonlinear approximation inside the boundary layer and adaptive method[24]. As mentioned [24]sliding mode fuzzy controller (SMFC) is fuzzy controller based on sliding mode technique to simple implement, most exceptional stability and robustness. Conversely above method has the following advantages; reducing the number of fuzzy rule base and increasing robustness and stability, the main disadvantage of SMFC is need to define the sliding surface slope coefficient very carefully. To eliminate the above problems control researchers have applied artificial intelligence method (e.g., fuzzy logic) in nonlinear robust controller (e.g., sliding mode controller) besides this technique is very useful in order to implement easily. Estimated uncertainty method used in term of uncertainty estimator to compensation of the system uncertainties. It has been used to solve the chattering phenomenon and also nonlinear equivalent dynamic. If estimator has an acceptable performance to compensate the uncertainties, the chattering is reduced. Research on estimated uncertainty to reduce the chattering is significantly growing as their applications such as industrial automation and robot manipulator. For instance, the applications of artificial intelligence, neural networks and fuzzy logic on estimated uncertainty method have been reported in [25-28]. Wu et al. [30] have proposed a simple fuzzy estimator controller beside the discontinuous and equivalent control terms to reduce the chattering. Their design had three main parts i.e. equivalent, discontinuous and fuzzy estimator tuning part which has reduced the chattering very well. Elmali et al. [27]and Li and Xu [29]have addressed sliding mode control with perturbation estimation method (SMCPE) to reduce the classical sliding mode chattering. This method was tested for the tracking control of the first two links of a SCARA type HITACHI robot. In this technique, digital controller is used to increase the system's response quality. Conversely this method has the following advantages; increasing the controller's response speed and reducing dependence on dynamic system model by on-line control, the main disadvantage are chattering phenomenon and need to improve the performance.

In recent years, artificial intelligence theory has been used in sliding mode control systems. Neural network, fuzzy logic, and neuro-fuzzy are synergically combined with nonlinear classical controller and used in nonlinear, time variant, and uncertainty plant (e.g., robot manipulator). Fuzzy logic controller (FLC) is one of the most important applications of fuzzy logic theory. This controller can be used to control nonlinear, uncertain, and noisy systems. This method is free of some model-based techniques as in classical controllers. As mentioned that fuzzy logic application is not only limited to the modelling of nonlinear systems [31-36]but also this method can help engineers to design easier controller. Control robot arm manipulators using classical controllers are based on manipulator dynamic model. These controllers often have many problems for modelling. Conventional controllers require accurate information of dynamic model of robot manipulator, but these models are multi-input, multi-output and non-linear and calculate accurate model can be very difficult. When the system model is unknown or when it is known but complicated, it is difficult or impossible to use classical mathematics to process this model[32]. The main reasons to use fuzzy logic technology are able to give approximate recommended solution for unclear and complicated systems to easy understanding and flexible. Fuzzy logic provides a method which is able to model a controller for nonlinear plant with a set of IF-THEN rules, or it can identify the control actions and describe them by using fuzzy rules. It should be mentioned that application of fuzzy logic is not limited to a system that's difficult for modeling, but it can be used in clear systems that have complicated mathematics models because most of the time it can be shortened in design but there is no high quality design just sometimes we can find design with high quality. Besides using fuzzy logic in the main controller of a control loop, it can be used to design adaptive control, tuning parameters, working in a parallel with the classical and non classical control method [32]. The applications of artificial intelligence such as neural networks and fuzzy logic in modelling and control are significantly growing especially in recent years. For instance, the applications of artificial intelligence, neural networks and fuzzy logic, on robot arm control have reported in [37-39]. Wai et al. [37-38]have proposed a fuzzy neural network (FNN) optimal control system to learn a nonlinear function in the optimal control law. This controller is divided into three main groups: arterial intelligence controller (fuzzy neural network) which it is used to compensate the system's nonlinearity and improves by adaptive method, robust controller to reduce the error and optimal controller which is the main part of this controller. Mohan and Bhanot [40] have addressed comparative study between some adaptive fuzzy, and a new hybrid fuzzy control algorithm for manipulator control. They found that self-organizing fuzzy logic controller and proposed hybrid integrator fuzzy give the best performance as well as simple structure. Research on combinations of fuzzy logic systems with sliding mode method is significantly growing as nonlinear control applications. For instance, the applications of fuzzy logic on sliding mode controller have reported in [24, 41-45]. Research on applied fuzzy logic methodology in sliding mode controller (FSMC) to reduce or eliminate the high frequency oscillation (chattering), to compensate the unknown system dynamics and also to adjust the linear sliding surface slope in pure sliding mode controller considerably improves the robot manipulator control process [42-43]. H.Temeltas [46] has proposed fuzzy adaption techniques for SMC to achieve robust tracking of nonlinear systems and solves the chattering problem. Conversely system's performance is better than sliding mode controller; it is depended on nonlinear dynamic equqation. C. L. Hwang *et al.* [47]have proposed a Tagaki-Sugeno (TS) fuzzy model based sliding mode control based on *N* fuzzy based linear state-space to estimate the uncertainties. A multi-input multi-output FSMC reduces the chattering phenomenon and reconstructs the approximate the unknown system has been presented for a robot manipulator [42]. Investigation on applied sliding mode methodology in fuzzy logic controller (SMFC) to reduce the fuzzy rules and refine the stability of close loop system in fuzzy logic controller has grown specially in recent years as the robot manipulator control [23]; [48-50, 53]. Lhee et al. [48]have presented a fuzzy logic controller based on sliding mode controller to more formalize and boundary layer thickness. Emami *et al.* [51]have proposed a fuzzy logic approximate inside the boundary layer. H.K.Lee *et al.* [52] have presented self tuning SMFC to reduce the fuzzy rules, increase the stability and to adjust control parameters control automatically. However the application of FSMC and SMFC are growing but the main SMFC drawback compared to FSMC is calculation the value of sliding surface λ pri-defined very carefully. Moreover, the advantages of SMFC compared to FLC reduce the number of fuzzy rule base and increase the robustness and stability. At last FSMC compare to the SMFC is more suitable for implementation action.

In various dynamic parameters systems that need to be training on-line adaptive control methodology is used. Adaptive control methodology can be classified into two main groups, namely, traditional adaptive method and fuzzy adaptive method. Fuzzy adaptive method is used in systems which want to training parameters by expert knowledge. Traditional adaptive method is used in systems which some dynamic parameters are known. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, adaptive method is applied to artificial sliding mode controller. F Y Hsu et al. [54]have presented adaptive fuzzy sliding mode control which can update fuzzy rules to compensate nonlinear parameters and guarantee the stability robot manipulator controller. Y.C. Hsueh et al. [43] have presented self tuning sliding mode controller which can resolve the chattering problem without to using saturation function. For nonlinear dynamic systems (e.g., robot manipulators) with various parameters, adaptive control technique can train the dynamic parameter to have an acceptable controller performance. Calculate several scale factors are common challenge in classical sliding mode controller and fuzzy logic controller, as a result it is used to adjust and tune coefficient. Research on adaptive fuzzy control is significantly growing, for instance, different adaptive fuzzy controllers have been reported in [40, 55-57].

2. PROBLEM STATEMENT AND FORMULATION CHALLENGE

One of the significant challenges in control algorithms is a linear behavior controller design for nonlinear systems. When system works with various parameters and hard nonlinearities this technique is very useful in order to be implemented easily but it has some limitations such as working near the system operating point[2]. Some of robot manipulators which work in industrial processes are controlled by linear PID controllers, but the design of linear controller for robot manipulators is extremely difficult because they are nonlinear, uncertain and MIMO[1, 6]. To reduce above challenges the nonlinear robust controllers is used to systems control. One of the powerful nonlinear robust controllers is sliding mode controller (SMC), although this controller has been analyzed by many researchers but the first proposed was in the 1950 [7].This controller is used in wide range areas such as in robotics, in control process, in aerospace applications and in power converters because it has an acceptable control performance and solve some main challenging topics in control such as resistivity to the external disturbance. Even though, this controller is used in wide range areas but, pure sliding mode controller has the following disadvantages: Firstly, chattering problem; which caused the high frequency oscillation in the controllers output. Secondly, equivalent dynamic formulation; calculate the equivalent control formulation is difficult because it depends on the dynamic equation [20]. On the other hand, after the invention of fuzzy logic theory in 1965, this theory was used in wide range applications that fuzzy logic controller (FLC) is one of the most important applications in fuzzy logic theory because the controller has been used for nonlinear and uncertain (e.g., robot manipulator) systems controlling. Conversely pure FLC works in many areas, it cannot guarantee the basic requirement of stability and acceptable performance[8]. Although both SMC and FLC have been applied successfully in many applications but they also have some limitations. The boundary layer method is used to reduce or eliminate the chattering and proposed method focuses on substitution error-base fuzzy logic system instead of dynamic equivalent equation to implement easily and avoid mathematical model base controller. To reduce the effect of uncertainty in proposed method, MIMO adaptive method is applied in fuzzy sliding mode controller in PUMA 560 robot manipulator.

The dynamic formulation of robot manipulate can be written by the following equation

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

the lyapunov formulation can be written as follows,

$$V = \frac{1}{2}S^T.M.S \tag{2}$$

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2}S^T.\dot{M}.S + S^T M\dot{S} \tag{3}$$

the dynamic equation of robot manipulator can be written based on the sliding surface as

$$M\dot{S} = -VS + M\dot{S} + VS + G - \tau \tag{4}$$

it is assumed that

$$S^T(\dot{M} - 2V)S = 0 \tag{5}$$

by substituting (4) in (3)

$$\dot{V} = \frac{1}{2}S^T \dot{M}S - S^T VS + S^T\left(M\dot{S} + VS + G - \tau\right) = S^T\left(M\dot{S} + VS + G - \tau\right) \tag{6}$$

suppose the control input is written as follows

$$\hat{\tau} = \widehat{\tau_{eq}} + \widehat{\tau_{dis}} = \left[\hat{M}^{-1}\left(\hat{V} + \hat{G}\right) + \dot{S}\right]\hat{M} + K.sgn(S) + K_v S \tag{7}$$

by replacing the equation (7) in (6)

$$\dot{V} = S^T(M\dot{S} + VS + G - \hat{M}\dot{S} - \hat{V}S - \hat{G} - K_v S - Ksgn(S) = S^T\left(\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K_v S - Ksgn \tag{8}$$

it is obvious that

$$\left|\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K_v S\right| \le \left|\tilde{M}\dot{S}\right| + \left|\tilde{V}S\right| + \left|\tilde{G}\right| + |K_v S| \tag{9}$$

the Lemma equation in robot manipulator system can be written as follows

$$K_u = \left[\left|\tilde{M}\dot{S}\right| + |VS| + \|G| + |K_v S| + \eta\right]_i, i = 1,2,3,4,\dots \tag{10}$$

the equation (5) can be written as

$$K_u \ge \left|\left[\tilde{M}\dot{S} + VS + G - K_v S\right]_i\right| + \eta_i \tag{11}$$

therefore, it can be shown that

$$\dot{V} \le -\sum_{i=1}^{n} \eta_i |S_i| \tag{12}$$

Based on above discussion, the control law for a multi degrees of freedom robot manipulator is written as:

$$U = U_{eq} + U_r \tag{13}$$

Where, the model-based component U_{eq} is the nominal dynamics of systems and U_{eq} can be calculate as follows:

$$U_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \tag{14}$$

and U_{sat} is computed as;

$$U_{sat} = K \cdot \text{sat}\left({S}/{\emptyset}\right) \tag{15}$$

by replace the formulation (15) in (13) the control output can be written as;

$$U = U_{eq} + K.\text{sat}\left({S}/{\emptyset}\right) = \begin{cases} U_{eq} + K.\text{sgn}(S) & , |S| \ge \emptyset \\ U_{eq} + K.{S}/{\emptyset} & , |S| < \emptyset \end{cases} \tag{16}$$

By (16) and (14) the sliding mode control of PUMA 560 robot manipulator is calculated as;

$$U = \left[M^{-1}(B + C + G) + \dot{S}\right]M + K \cdot \text{sat}\left({S}/{\emptyset}\right) \tag{17}$$

3. DESIGN ADAPTIVE MIMO FUZZY COMPENSATE FUZZY SLIDING MODE ALGORITHM

Zadeh introduced fuzzy sets in 1965. After 40 years, fuzzy systems have been widely used in different fields, especially on control problems. Fuzzy systems transfer expert knowledge to mathematical models. Fuzzy systems used fuzzy logic to estimate dynamics of our systems. Fuzzy controllers including fuzzy if-then rules are used to control our systems. However the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of;

- Input fuzzification (binary-to-fuzzy[B/F]conversion)
- Fuzzy rule base (knowledge base)
- Inference engine
- Output defuzzification (fuzzy-to-binary[F/B]conversion) [30-40].

The basic structure of a fuzzy controller is shown in Figure 1.

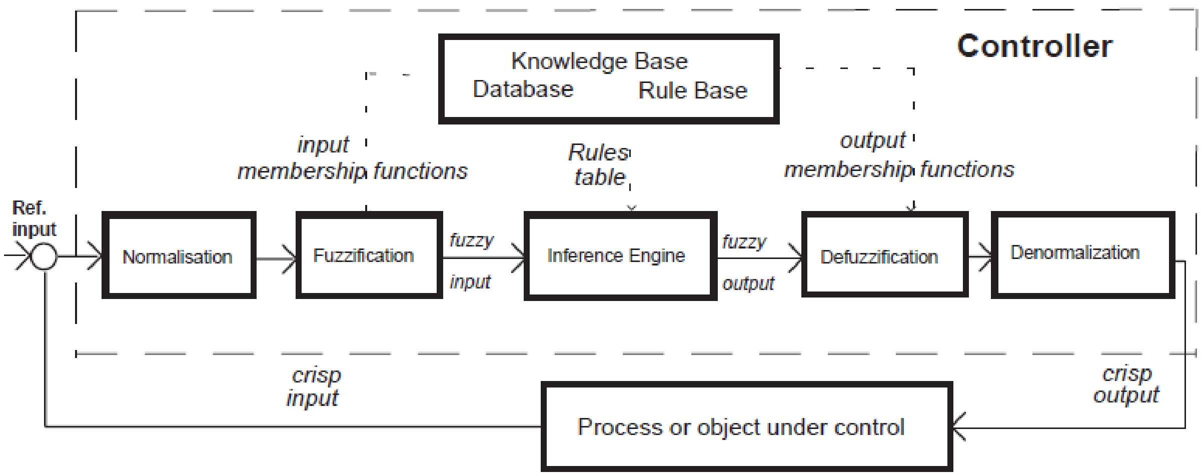

FIGURE 1: Block diagram of a fuzzy controller with details.

Conventional control methods use mathematical models to controls systems. Fuzzy control methods replace the mathematical models with fuzzy if then-rules and fuzzy membership function to controls systems. Both fuzzy and conventional control methods are designed to meet system requirements of stability and convergence. When mathematical models are unknown or partially unknown, fuzzy control models can used fuzzy systems to estimate the unknown models. This is called the model-free approach [31, 35]. Conventional control models can use adaptive control methods to achieve the model-free approach. When system dynamics become more complex, nonlinear systems are difficult to handle by conventional control methods. Fuzzy systems can approximate arbitrary nonlinear systems. In practical problems, systems can be controlled perfectly by expert. Experts provide linguistic description about systems. Conventional control methods cannot design controllers combined with linguistic information. When linguistic information is important for designing controllers, we need to design fuzzy controllers for our systems. Fuzzy control methods are easy to understand for designers. The design process of fuzzy controllers can be simplified with simple mathematical models. Adaptive control uses a learning method to self-learn the parameters of systems. For system whose dynamics are varying, adaptive control can learn the parameters of system dynamics. In traditional adaptive control, we need some information about our system such as the structure of system or the order of the system. In adaptive fuzzy control we can deal with uncertain systems. Due to the linguistic characteristic, adaptive fuzzy controllers behave like operators: adaptively controlling the system under various conditions. Adaptive fuzzy control provides a good tool for making use of expert knowledge to adjust systems. This is important for a complex unknown system with changing dynamics. We divide adaptive fuzzy control into two categories: direct adaptive fuzzy control and indirect adaptive fuzzy control. A direct adaptive fuzzy controller adjusts the parameters of the control input. An indirect adaptive fuzzy controller adjusts the parameters of the control system based on the estimated dynamics of the plant.
We define fuzzy systems as two different types. The firs type of fuzzy systems is given by

$$f(x) = \sum_{l=1}^{M} \theta^l \varepsilon^l(x) = \theta^T \varepsilon(x) \tag{18}$$

Where $\theta = (\theta^1, \dots, \theta^M)^T, \varepsilon(x) = (\varepsilon^1(x), \dots, \varepsilon^M(x))^T$, and $\varepsilon^l(x) =: \prod_{i=1}^{n} \frac{\mu_{A_i^l}(x_i)}{} \sum_{l=1}^{M} (\prod_{i=1}^{n} \mu_{A_i^l}(x_i))$. $\theta^1, \dots, \theta^M$ are adjustable parameters in (18) . $\mu_{A_1^1}(x_1), \dots, \mu_{A_n^m}(x_n)$ are given membership functions whose parameters will not change over time.

The second type of fuzzy systems is given by

$$f(x) = \frac{\sum_{l=1}^{M} \theta^l \left[\prod_{i=1}^{n} \exp\left(-\left(\frac{x_i - \alpha_i^l}{\delta_i^l}\right)^2\right)\right]}{\sum_{l=1}^{M} \left[\prod_{i=1}^{n} \exp\left(-\left(\frac{x_i - \alpha_i^l}{\delta_i^l}\right)^2\right)\right]} \quad \textbf{(19)}$$

Where θ^l , α_i^l *and* δ_i^l are all adjustable parameters.
From the universal approximation theorem, we know that we can find a fuzzy system to estimate any continuous function. For the first type of fuzzy systems, we can only adjust θ^l in (18). We define $f^{\wedge}(x|\theta)$ as the approximator of the real function $f(x)$.

$$f^{\wedge}(x|\theta) = \theta^T \varepsilon(x) \quad \textbf{(20)}$$

We define θ^* as the values for the minimum error:

$$\theta^* = \arg\min_{\theta \in \Omega} \left[\sup_{x \in U} |f^{\wedge}(x|\theta) - g(x)|\right] \quad \textbf{(21)}$$

Where Ω is a constraint set for θ. For specific x ,$sup_{x \in U} |f^{\wedge}(x|\theta^*) - f(x)|$ is the minimum approximation error we can get.

We used the first type of fuzzy systems (18) to estimate the nonlinear system (23) the fuzzy formulation can be write as below;

$$f(x|\theta) = \theta^T \varepsilon(x) = \frac{\sum_{l=1}^{n} \theta^l [\mu_{A^l}(x)]}{\sum_{l=1}^{n} [\mu_{A^l}(x)]} \quad \textbf{(22)}$$

Where $\theta^1, \dots, \theta^n$ are adjusted by an adaptation law. The adaptation law is designed to minimize the parameter errors of $\theta - \theta^*$.
If the dynamic equation of an m-link robotic manipulator is [piltan reference]

$$M(q)\ddot{q} + c(q,\dot{q}) + G(q) = \tau \quad \textbf{(23)}$$

Where $q = [q_1, \dots, q_m]^T$ is an $m \times 1$ vector of joint position, $M(q)$ is an $m \times m$ inertial matrix, $c(q,\dot{q})$ is an $m \times 1$ matrix of Coriolis and centrifugal forces, $G(q)$ is an $m \times 1$ gravity vector and $\tau = [\tau_1, \dots, \tau_m]^T$ is an $m \times 1$ vector of joint torques. This paper proposed an adaptive fuzzy sliding mode control scheme applied to a robotic manipulator. A MIMO (multi-input multi-output) fuzzy system is designed to compensate the uncertainties of the robotic manipulator. The parameters of the fuzzy system are adjusted by adaptation laws.
The tracking error and the sliding surface state are defined as (58-64)

$$e = q - q_d \quad \textbf{(24)}$$

$$s = \dot{e} + \lambda_e \quad \textbf{(25)}$$

We define the reference state as

$$\dot{q}_r = \dot{q} - s = \dot{q}_d - \lambda e \quad \textbf{(26)}$$

$$\ddot{q}_r = \ddot{q} - \dot{s} = \ddot{q}_d - \lambda \dot{e} \quad \textbf{(27)}$$

The general MIMO if-then rules are given by

$$R^l: if\ x_1\ is\ A_1^l\ , x_2\ is\ A_2^l\ , \dots, x_n\ is\ A_n^l\ , then\ y_1 is\ B_1^l\ , \dots, y_m\ is\ B_m^l \quad \textbf{(28)}$$

Where $l = 1,2, \dots, M$ are fuzzy if-then rules; $x = (x_1, \dots, x_n)^T$ and $y = (y_1, \dots, y_n)^T$ are the input and output vectors of the fuzzy system. The MIMO fuzzy system is define as

$$f(x) = \Theta^T \varepsilon(x) \quad \textbf{(29)}$$

Where

$$\ominus^T = (\theta_1, \dots, \theta_m)^T = \begin{bmatrix} \theta_1^1, \theta_1^2, \dots, \theta_1^M \\ \theta_2^1, \theta_2^2, \dots, \theta_2^M \\ \vdots \\ \theta_m^1, \theta_m^2, \dots, \theta_m^M \end{bmatrix} \tag{30}$$

$\varepsilon(x) = (\varepsilon^1(x), \dots, \varepsilon^M(x))^T$, $\varepsilon^1(x) = \prod_{i=1}^n \mu_{A_i^l}(x_i) / \sum_{l=1}^M (\prod_{i=1}^n \mu_{A_i^l}(x_i))$, and $\mu_{A_i^l}(x_i)$ is defined in (22). To reduce the number of fuzzy rules, we divide the fuzzy system in to three parts:

$$\begin{aligned} F^1(q,\dot{q}) &= \ominus^{1^T} \varepsilon(q,\dot{q}) \\ &= \left[\theta_1^{1^T} \varepsilon(q,\dot{q}), \dots, \theta_m^{1\ T} \varepsilon(q,\dot{q})\ \right]^T \end{aligned} \tag{31}$$

$$\begin{aligned} F^2(q,\ddot{q}_r) &= \ominus^{2^T} \varepsilon(q,\ddot{q}_r) \\ &= \left[\theta_1^{2^T} \varepsilon(q,\ddot{q}_r), \dots, \theta_m^{2\ T} \varepsilon(q,\ddot{q}_r)\ \right]^T \end{aligned} \tag{32}$$

$$\begin{aligned} F^3(q,\ddot{q}) &= \ominus^{3^T} \varepsilon(q,\ddot{q}) \\ &= \left[\theta_1^{3^T} \varepsilon(q,\dot{q}), \dots, \theta_m^{3\ T} \varepsilon(q,\ddot{q})\ \right]^T \end{aligned} \tag{33}$$

The control input is given by

$$\tau = M^{\wedge}\ddot{q}_r + C_1^{\wedge}\dot{q}_r + G^{\wedge} + F^1(q,\dot{q}) + F^2(q,\ddot{q}_r) + F^3(q,\ddot{q}) - K_D s - W sgn(s) \tag{34}$$

Where $M^{\wedge}$, $C_1^{\wedge}$ are the estimations of $M(q)$ and $C_1(q,\dot{q})$; $K_D = diag\ [K_{D1}, \dots, K_{Dm}]$ and $K_{D1}, \dots, K_{Dm}$ are positive constants; $W = diag\ [W_1, \dots, W_m]$ and $W_1, \dots, W_m$ are positive constants. The adaptation law is given by

$$\begin{aligned} \dot{\theta}_j^1 &= -\Gamma_{1j} s_j \varepsilon(q,\dot{q}) \\ \dot{\theta}_j^2 &= -\Gamma_{2j} s_j \varepsilon(q,\ddot{q}_r) \\ \dot{\theta}_j^3 &= -\Gamma_{3j} s_j \varepsilon(q,\ddot{q}) \end{aligned} \tag{35}$$

Where $j = 1, \dots, m$ and $\Gamma_{1j} - \Gamma_{3j}$ are positive diagonal matrices.
The Lyapunov function candidate is presented as

$$V = \frac{1}{2} s^T M s + \frac{1}{2}\sum_{j=1}^m \frac{1}{\Gamma_{1j}} \varnothing_j^{1^T} \varnothing_j^1 + \frac{1}{2}\sum_{j=1}^m \frac{1}{\Gamma_{2j}} \varnothing_j^{2^T} \varnothing_j^2 + \frac{1}{2}\sum_{j=1}^m \frac{1}{\Gamma_{3j}} \varnothing_j^{13^T} \varnothing_j^3 \tag{36}$$

Where $\varnothing_j^1 = \varnothing_j^{1^*} - \varnothing_j^1$, $\varnothing_j^2 = \varnothing_j^{2^*} - \varnothing_j^2$ and $\varnothing_j^3 = \varnothing_j^{3^*} - \varnothing_j^3$ we define

$$F(q,\dot{q},\ddot{q}_r,\ddot{q}) = F^1(q,\dot{q}) + F^2(q,\ddot{q}_r) + F^3(q,\ddot{q}) \tag{37}$$

From (23) and (22), we get

$$M(q)\ddot{q} + C_1(q,\dot{q})\dot{q} + G(q) = M^{\wedge}\ddot{q}_r + C_1^{\wedge}\dot{q}_r + G^{\wedge} + F(q,\dot{q},\ddot{q}_r,\ddot{q}) - K_D s - W sgn(s) \tag{38}$$

Since $\dot{q}_r = \dot{q} - s$ and $\ddot{q}_r = \ddot{q} - \dot{s}$, we get

$$M\dot{s} + (C_1 + K_D)s + W sgn(s) = -\Delta F + F(q,\dot{q},\ddot{q}_r,\ddot{q}) \tag{39}$$

Then $M\dot{s} + C_1 s$ can be written as

$$M\dot{s} + C_1 s = -\Delta F + F(q,\dot{q},\ddot{q}_r,\ddot{q}) - K_D s - W sgn(s) \tag{40}$$

Where $\Delta F = \tilde{M}\ddot{q}_r + \tilde{C}_1\dot{q}_r + \tilde{G}$, $\tilde{M} = M - M^{\wedge}$, $\tilde{C}_1 = C_1 - \hat{C}_1$ and $\tilde{G} = G - G^{\wedge}$.
The derivative of V is

$$\dot{V} = s^T M\dot{s} + \frac{1}{2} s^T \dot{M} s + \sum_{j=1}^{m} \frac{1}{\Gamma_{1j}} \emptyset_j^{1^T} \dot{\emptyset}_j^1 + \sum_{j=1}^{m} \frac{1}{\Gamma_{2j}} \emptyset_j^{2^T} \dot{\emptyset}_j^2 + \sum_{j=1}^{m} \frac{1}{\Gamma_{3j}} \emptyset_j^{13^T} \dot{\emptyset}_j^3 \tag{41}$$

We know that $s^T M\dot{s} + \frac{1}{2} s^T \dot{M} s = s^T (M\dot{s} + C_1 s)$ from (2.38). Then

$$\dot{V} = -s^T[-K_D s + W sgn(s) + \Delta F - F(q, \dot{q}, \ddot{q}_r, \ddot{q})] + \sum_{j=1}^{m} \frac{1}{\Gamma_{1j}} \emptyset_j^{1^T} \dot{\emptyset}_j^1 + \sum_{j=1}^{m} \frac{1}{\Gamma_{2j}} \emptyset_j^{2^T} \dot{\emptyset}_j^2 + \sum_{j=1}^{m} \frac{1}{\Gamma_{3j}} \emptyset_j^1 \tag{42}$$

We define the minimum approximation error as

$$\omega = \Delta F - [F^1(q, \dot{q} | \ominus^{1^*}) + F^2(q, \ddot{q}_r | \ominus^{2^*}) + F^3(q, \ddot{q} | \ominus^{3^*})] \tag{43}$$

We plug (43) in to (42)

$$\dot{V} = -s^T[-K_D s + W sgn(s) + \Delta F - F(q, \dot{q}, \ddot{q}_r, \ddot{q})] + \sum_{j=1}^{m} \frac{1}{\Gamma_{1j}} \emptyset_j^{1^T} \dot{\emptyset}_j^1 + \sum_{j=1}^{m} \frac{1}{\Gamma_{2j}} \emptyset_j^{2^T} \dot{\emptyset}_j^2 + \sum_{j=1}^{m} \frac{1}{\Gamma_{3j}} \emptyset_j^{13^T} \dot{\emptyset}_j^3$$

$$= -s^T[-K_D s + W sgn(s) + \omega + F^1(q, \dot{q} | \ominus^{1^*}) + F^2(q, \ddot{q}_r | \ominus^{2^*}) + F^3(q, \ddot{q} | \ominus^{3^*}) - F^1(q, \dot{q}) + F^2(q, \ddot{q}_r) + F^3(q, \ddot{q})] + \sum_{j=1}^{m} \frac{1}{\Gamma_{1j}} \emptyset_j^{1^T} \dot{\emptyset}_j^1 + \sum_{j=1}^{m} \frac{1}{\Gamma_{2j}} \emptyset_j^{2^T} \dot{\emptyset}_j^2 + \sum_{j=1}^{m} \frac{1}{\Gamma_{3j}} \emptyset_j^{13^T} \dot{\emptyset}_j^3$$

$$= -s^T K_D s - s^T W sgn(s) - s^T \omega - \sum_{j=1}^{m} s_j \emptyset_j^{1^T} \varepsilon(q, \dot{q}) - \sum_{j=1}^{m} s_j \emptyset_j^{2^T} \varepsilon(q, \ddot{q}_r) - \sum_{j=1}^{m} s_j \emptyset_j^{3^T} \varepsilon(q, \ddot{q}) \sum_{j=1}^{m} \frac{1}{\Gamma_{1j}} \emptyset_j^{1^T} \dot{\emptyset}_j^1 + \sum_{j=1}^{m} \frac{1}{\Gamma_{2j}} \emptyset_j^{2^T} \dot{\emptyset}_j^2 + \sum_{j=1}^{m} \frac{1}{\Gamma_{3j}} \emptyset_j^{3^T} \dot{\emptyset}_j^3$$

$$= -s^T K_D s - s^T W sgn(s) - s^T \omega - \sum_{j=1}^{m} \emptyset_j^{1^T} (s_j \varepsilon(q, \dot{q}) - \frac{1}{\Gamma_{1j}} \dot{\emptyset}_j^1) - \sum_{j=1}^{m} \emptyset_j^{2^T} (s_j \varepsilon(q, \ddot{q}_r) - \frac{1}{\Gamma_{2j}} \dot{\emptyset}_j^2) - \sum_{j=1}^{m} \emptyset_j^{3^T} (s_j \varepsilon(q, \ddot{q}_r) - \frac{1}{\Gamma_{3j}} \dot{\emptyset}_j^3)$$

$$= -s^T K_D s - s^T W sgn(s) - s^T \omega - \sum_{j=1}^{m} \emptyset_j^{1^T} (s_j \varepsilon(q, \dot{q}) + \frac{1}{\Gamma_{1j}} \dot{\emptyset}_j^1) - \sum_{j=1}^{m} \emptyset_j^{2^T} (s_j \varepsilon(q, \ddot{q}_r) + \frac{1}{\Gamma_{2j}} \dot{\emptyset}_j^2) - \sum_{j=1}^{m} \emptyset_j^{3^T} (s_j \varepsilon(q, \ddot{q}_r) + \frac{1}{\Gamma_{3j}} \dot{\emptyset}_j^3)$$

The adaptation laws are chosen as (20). Then $\dot{V}$ becomes

$$\dot{V} = -s^T K_D s - s^T W sgn(s) - s^T \omega \tag{44}$$

$$= -\sum_{j=1}^{m} (s_j^2 K_{Dj} + W_j |s_j| + s_j \omega_j)$$

$$= -\sum_{j=1}^{m} [s_j (s_j K_{Dj} + \omega_j) + W_j |s_j|]$$

Since ω_j can be as small as possible, we can find K_{Dj} that $|s_j^2 K_{Dj}| > |\omega_j| (s_j \neq 0)$.
Therefore, we can get $s_j(s_j K_{Dj} + \omega_j) > 0$ for $s_j \neq 0$ and $\dot{V} < 0$ $(s \neq 0)$.
Figure 2 is shown the proposed method.

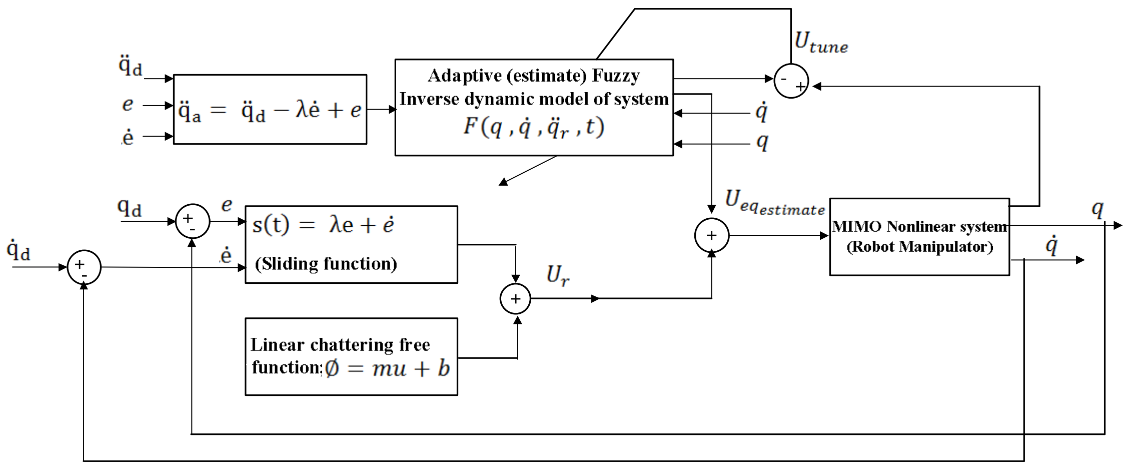

FIGURE 2: Adaptive MIMO Fuzzy Compensate Fuzzy Sliding Mode Algorithm

4. APPLICATION: ROBOT MANIPULATOR

Dynamic modelling of robot manipulators is used to describe the behaviour of robot manipulator, design of model based controller, and simulation results. The dynamic modelling describe the relationship between joint motion, velocity, and accelerations to force/torque or current/voltage and also it can be used to describe the particular dynamic effects (e.g., inertia, coriolios, centrifugal, and the other parameters) to behaviour of system. It is well known that the equation of an *n-DOF* robot manipulator governed by the following equation [36]; [58-64]:

$$M(q)\ddot{q} + N(q, \dot{q}) + g(x) = \tau \quad (45)$$

Where τ is actuation torque, $M(q)$ is a symmetric and positive define inertia matrix, $N(q, \dot{q})$ is the vector of nonlinearity term and $g(x)$ is uncertainty input. This robot manipulator dynamic equation can also be written in a following form:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) + g(x) \quad (46)$$

Where $B(q)$ is the matrix of coriolios torques, $C(q)$ is the matrix of centrifugal torques, and $G(q)$ is the vector of gravity force. The dynamic terms in equation (45) are only manipulator position. This is a decoupled system with simple second order linear differential dynamics. In other words, the component $\ddot{q}$ influences, with a double integrator relationship, only the joint variableq_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [6]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q, \dot{q})\} \quad (47)$$

In this research proposed method is applied to 2 DOF's robot manipulator with the following Where

$$M(q) = \begin{bmatrix} m_1 l^2 + 2m_2 l^2 + 2m_2 l^2 \cos q_2 & m_2 l^2 + m_2 l^2 \cos q_2 \\ m_2 l^2 + m_2 l^2 \cos q_2 & m_2 l^2 \end{bmatrix} \quad (48)$$

$$C(q, \dot{q}) = \begin{bmatrix} -2m_2 l^2 \dot{q}_1 \dot{q}_2 \sin q_2 - m_2 l^2 \dot{q}_2^2 \sin q_2 \\ m_2 l^2 \dot{q}_1^2 \sin q_2 \end{bmatrix} \quad (49)$$

Take the derivative of M with respect to time in (48) and we get

$$\dot{M} = \begin{bmatrix} -2] m_2 l^2 \dot{q}_2 \sin q_2 - & m_2 l^2 \dot{q}_2 \sin q_2 \\ -m_2 l^2 \dot{q}_2 \sin q_2 & 0 \end{bmatrix} \quad (50)$$

From (50) and (48) we get

$$\dot{M} - 2C_1 = \begin{bmatrix} 0 & 2m_2 l^2 \dot{q}_1 \sin q_2 + m_2 l^2 \dot{q}_2 \sin q_2 \\ -2m_2 l^2 \dot{q}_1 \sin q_2 - m_2 l^2 \dot{q}_2 \sin q_2 & 0 \end{bmatrix} \quad (51)$$

Which is a skew-systemmetric matrix satisfying

$$s^T(\dot{M} - 2C_1)s = 0 \tag{52}$$

Then $\dot{V}$ becomes

$$\begin{aligned}\dot{V} &= s^T M\dot{s} + \frac{1}{2} s^T \dot{M} s \\ &= s^T (M\dot{s} + C_1 s) \\ &= s^T[-As + \Delta f - Ksgn(s)] \\ &= \sum_{i=1}^{2}(s_i[\Delta f_i - K_i sgn(s_i)]) - s^T As\end{aligned} \tag{53}$$

For $K_i \geq |\Delta f_i|$, we always get $s_i[\Delta f_i - K_i sgn(s_i)] \leq 0$. We can describe $\dot{V}$ as

$$\dot{V} = \sum_{i=1}^{2}(s_i[\Delta f_i - K_i sgn(s_i)]) - s^T As \leq -s^T As < 0 \quad (s \neq 0) \tag{54}$$

Figure 3 is shown 2 DOF robot manipulator which used in this research.

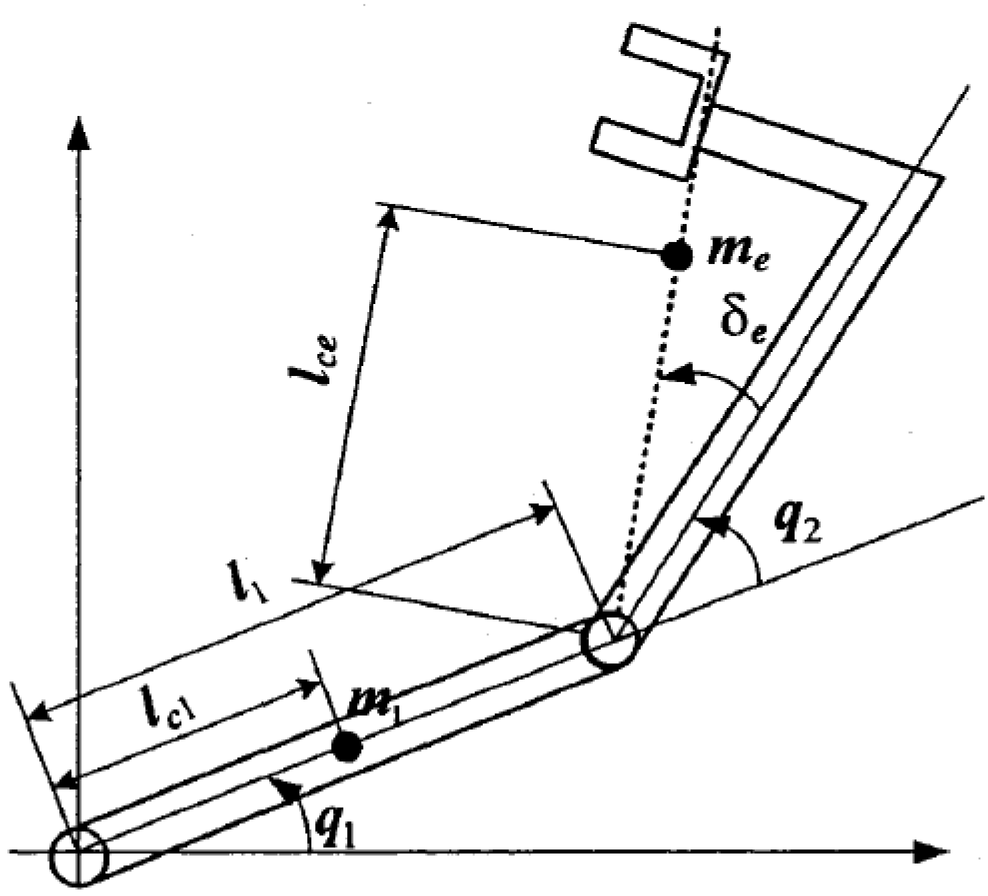

FIGURE 3: A 2-DOF serial robot manipulator

5. SIMULATION RESULT

Sliding mode controller (SMC) and adaptive MIMO fuzzy compensate fuzzy sliding mode controller (AFCFSMC) are implemented in Matlab/Simulink environment. Tracking performance, disturbance rejection and error are compared.

Tracking Performances

From the simulation for first and second trajectory without any disturbance, it was seen that both of controllers have the same performance, because these controllers are adjusted and worked on certain environment. Figure 4 is shown tracking performance in certain system and without external disturbance these two controllers.

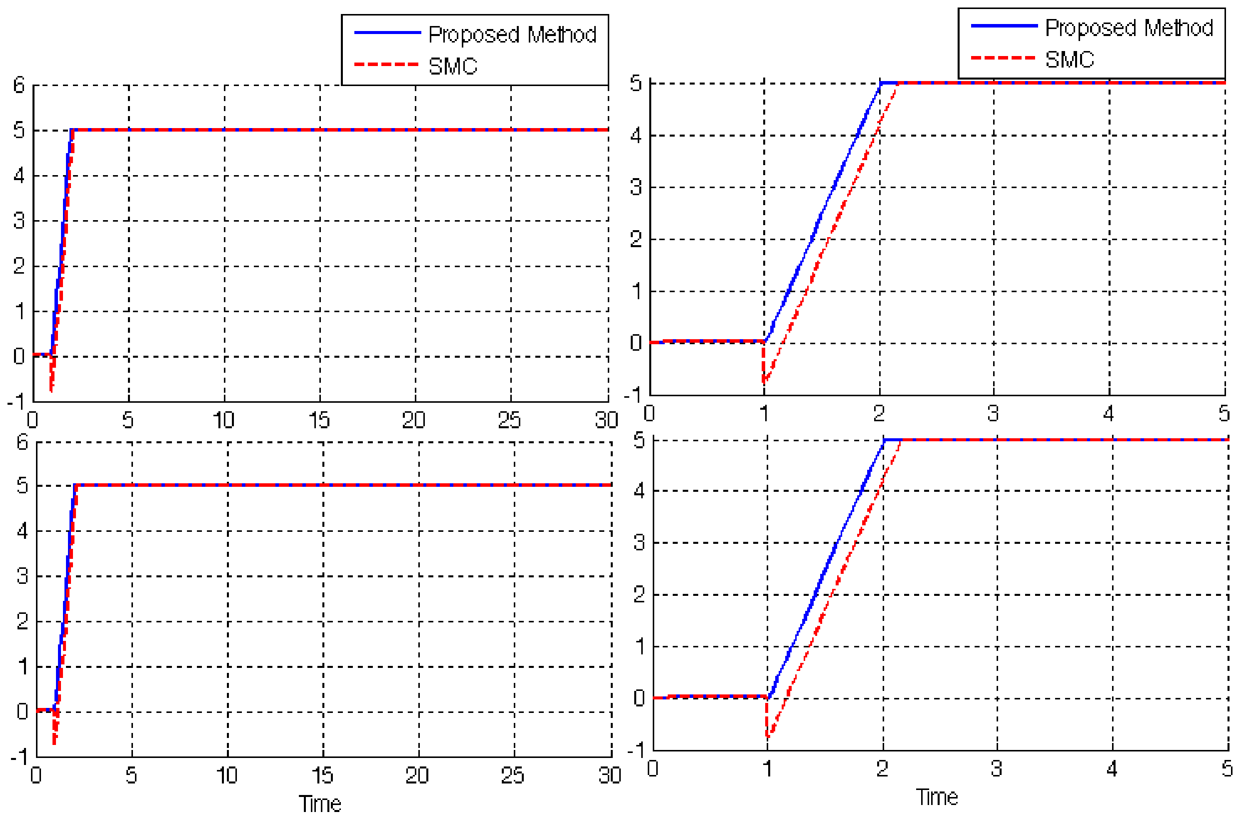

FIGURE 4: SMC Vs. AFCFSMC: applied to 2-DOF serial robot manipulator

By comparing trajectory response in above graph it is found that the AFCFSMC undershoot **(0%)** is lower than SMC **(13.8%)**, although both of them have about the same overshoot.

Disturbance Rejection

Figure 4 has shown the power disturbance elimination in above controllers. The main targets in these controllers are disturbance rejection as well as the other responses. A band limited white noise with predefined of 40% the power of input signal is applied to controllers. It found fairly fluctuations in SMC trajectory responses.

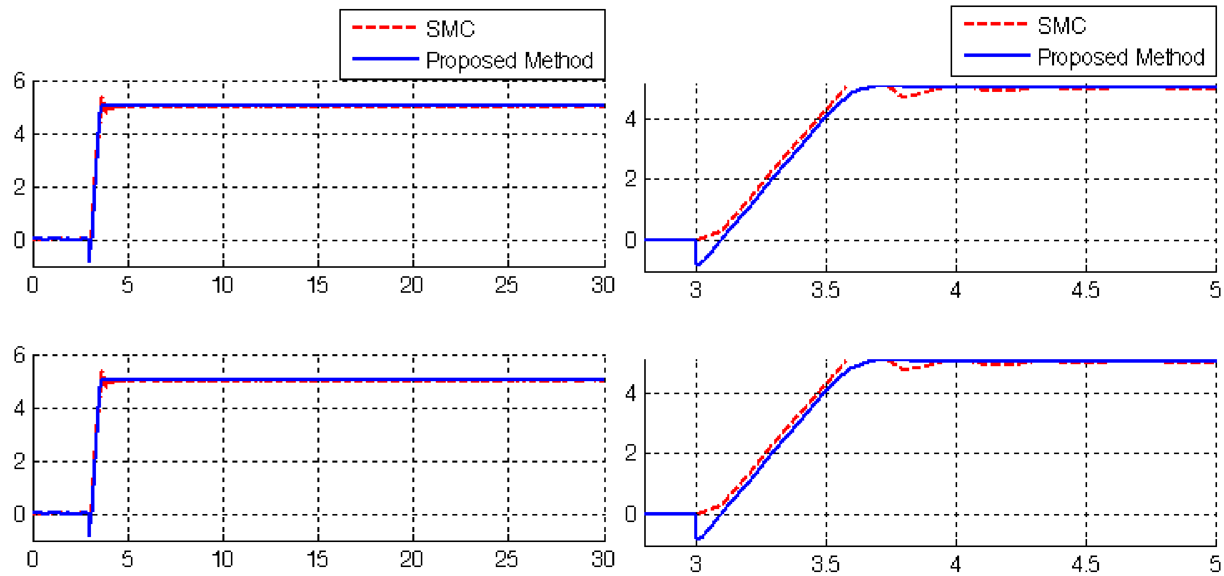

FIGURE 5: SMC Vs. AFCFSMC in presence of uncertainty and external disturbance: applied to 2-DOF serial robot manipulator

Among above graph relating to trajectory following with external disturbance, SMC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the AFCFSMC's overshoot **(0%)** is lower than SMC's **(6%)**, although both of them have about the same rise time**.**

Calculate Errors

Figure 6 has shown the error disturbance in above controllers. The controllers with no external disturbances have the same error response. By comparing the steady state error and RMS error it found that the AFCFSMC's errors (Steady State error = -0.000007 and RMS error=0.000008) are fairly less than FLC's (Steady State error $\cong \mathbf{0.0012}$ and RMS error=$\mathbf{0.0018}$), When disturbance is applied to the SMC error is about 23% growth.

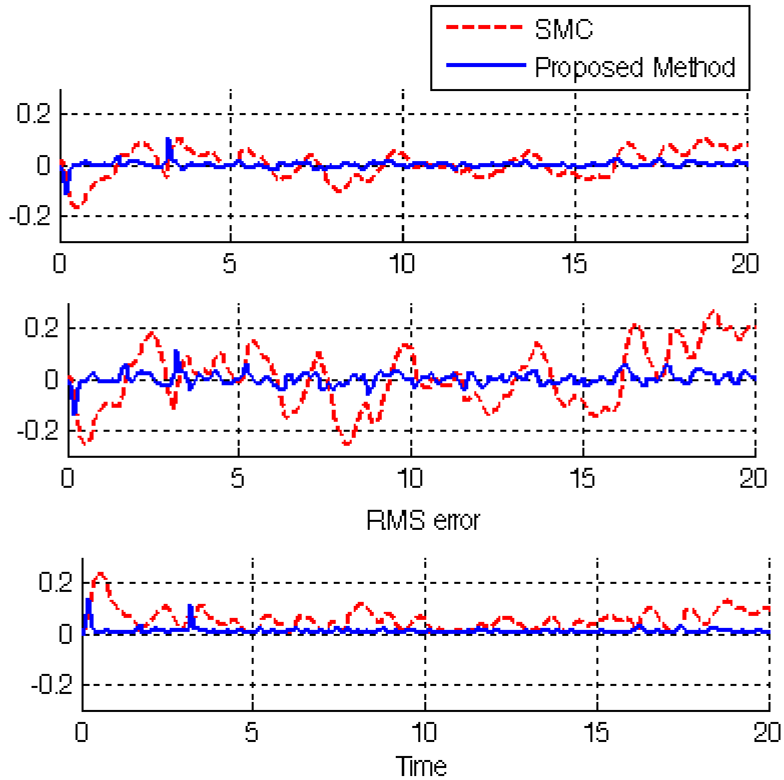

FIGURE 6: SMC Vs. AFCFSMC (error performance): applied to 2-DOF serial robot manipulator

6. CONCLUSIONS

Adaptive fuzzy sliding mode control algorithm for robot manipulators is investigated in this paper. Proposed algorithm utilizes MIMO fuzzy system to estimate the cross-coupling effects in robotic manipulator and gets perfect tracking accuracy. However, the switching control term in the control law causes chattering and there is no methodology to tune the premise part of the fuzzy rules. Proposed algorithm attenuated the chattering problem very well by substituting a fuzzy compensator and saturation function for the switching control term. The number of fuzzy rules is also reduced by abandoning MIMO fuzzy systems and SISO fuzzy systems instead. But we still need to predefine the premise part of the fuzzy rules. The stability and the convergence of this algorithms for the m-link robotic manipulator is proved theoretically using Lyapunov stability theory. Proposed algorithm has predefined adaptation gains in the adaptation laws which are highly related to the performance of our controllers. In this method the tuning part is applied to consequence part, in the case of the m-link robotic manipulator, if we define k_1 membership functions for each input variable, the number of fuzzy rules applied for each joint is $3k_1^{2m}$ and eliminate the chattering.

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