Online Tuning Chattering Free Sliding Mode Fuzzy Control Design: Lyapunov Approach

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Abstract

This paper expands a sliding mode fuzzy controller which sliding surface gain is on-line tuned by minimum fuzzy inference algorithm. The main goal is to guarantee acceptable trajectories tracking between the second order nonlinear system (robot manipulator) actual and the desired trajectory. The fuzzy controller in proposed sliding mode fuzzy controller is based on Mamdani's fuzzy inference system (FIS) and it has one input and one output. The input represents the function between sliding function, error and the rate of error. The outputs represent torque, respectively. The fuzzy inference system methodology is on-line tune the sliding surface gain based on error-based fuzzy tuning methodology. Pure sliding mode fuzzy controller has difficulty in handling unstructured model uncertainties. To solve this problem applied fuzzy-based tuning method to sliding mode fuzzy controller for adjusting the sliding surface gain (λ). Since the sliding surface gain (λ) is adjusted by fuzzy-based tuning method, it is nonlinear and continuous. Fuzzy-based tuning sliding mode fuzzy controller is stable model-free controller which eliminates the chattering phenomenon without to use the boundary layer saturation function. Lyapunov stability is proved in fuzzy-based tuning sliding mode fuzzy controller based on switching (sign) function.

This controller has acceptable performance in presence of uncertainty (e.g., overshoot=0%, rise time=0.8 second, steady state error = 1e-9 and RMS error=1.8e-12).

Keywords: robot manipulator, sliding mode controller, sliding mode fuzzy controller, fuzzy on-line tune sliding mode fuzzy controller, Lyapunov- based, fuzzy inference system.

1. INTRODUCTION, BACKGROUND and MOTIVATION

Motivation and background: PUMA 560 robot manipulator is a 6 DOF serial robot manipulator. From the control point of view, robot manipulator divides into two main parts i.e. kinematics and dynamic parts. The dynamic parameters of this system are highly nonlinear [1-10]. Sliding mode controller (SMC) is a significant nonlinear controller under condition of partly uncertain dynamic parameters of system [1, 6-30]. This controller is used to control of highly nonlinear systems especially for robot manipulators, because this controller is a robust and stable [41-51]. Conversely, pure sliding mode controller is used in many applications; it has two important drawbacks namely; chattering phenomenon, and nonlinear equivalent dynamic formulation in uncertain dynamic parameter [52-60]. The chattering phenomenon problem can be reduced by using linear saturation boundary layer function in sliding mode control law. Lyapunov stability is proved in pure sliding mode controller based on switching (sign) function [59-60]. The nonlinear equivalent dynamic formulation problem in uncertain system can be solved by using artificial intelligence theorem. Fuzzy logic theory is used to estimate the system dynamic [31-40]. However fuzzy logic controller is used to control complicated nonlinear dynamic systems, but it cannot guarantee stability and robustness [31-40]. Fuzzy logic controller is used in adaptive methodology and this method is also can applied to nonlinear conventional control methodology to improve the stability, increase the robustness, reduce the fuzzy rule base and estimate the system's dynamic parameters [31-40]. To reduce the fuzzy rule base with regards to improve the stability and robustness sliding mode fuzzy controller is introduced. In sliding mode fuzzy controller sliding mode controller is applied to fuzzy logic controller to reduce the fuzzy rules and increase the stability and robustness [61-80]. The main drawback in sliding mode fuzzy controller is calculation the value of sliding surface slope coefficient pri-defined very carefully. To estimate the system dynamics, fuzzy inference system is introduced. Most of researcher is applied fuzzy logic theorem in sliding mode controller to design a model free controller. Pure sliding mode controller and sliding mode fuzzy controller have difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining fuzzy sliding mode controller or sliding mode fuzzy controller and adaption law which this method can helps improve the system's tracking performance by online tuning method [61-82]. It is possible to solve this problem by combining sliding mode fuzzy controller and fuzzy-based tuning which this method can helps improve the system's tracking performance by online tuning method. This method is based on resolve the on line sliding surface slope as well as improve the output performance by tuning the sliding surface slope coefficient. The sliding surface gain ($\boldsymbol{\lambda}$) of this controller is adjusted online depending on the last values of error (e) and change of error ($\dot{e}$) by sliding surface slope updating factor (α). Fuzzy-based tuning sliding mode fuzzy controller is stable model-free controller which does not need to limits the dynamic model of robot manipulator and eliminate the chattering phenomenon without to use the boundary layer saturation function. Lyapunov stability is proved in fuzzy-based tuning sliding mode fuzzy controller based on switching (sign) function.

Literature Review

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]. 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]. 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, Weng and 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 most exceptional stability and robustness. Sliding mode fuzzy controller has the two most important advantages: reduce the number of fuzzy rule base and increase robustness and stability. Conversely sliding mode fuzzy controller has the above advantages, define the sliding surface slope coefficient very carefully is the main disadvantage of this controller. 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. However this controller's response is very fast and robust but it has chattering phenomenon. 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 control of robot manipulator 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: artificial intelligence controller (neuro-fuzzy) 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 in 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 controller in presence of nonlinear dynamic part is significantly growing as nonlinear control applications. For instance, the applications of fuzzy logic on sliding mode controller have reported in [24, 41-45]. Fuzzy sliding mode controller (FSMC) is a nonlinear controller based on sliding mode method when fuzzy logic methodology applied to sliding mode controller to reduce the high frequency oscillation (chattering) and compensate the dynamic model of uncertainty based on nonlinear dynamic model [42-43]. Temeltas [46] has proposed fuzzy adaption techniques and applied to SMC to have robust controller and solves the chattering problem. In this method however system's performance is better than sliding mode controller but it is depended on nonlinear dynamic equations. Hwang and Chao [47] have proposed a Tagaki-Sugeno (TS) fuzzy model based sliding mode controller based on neuro-fuzzy based linear state-space to estimate the uncertainties. A MIMO fuzzy sliding mode controller to reduces the chattering phenomenon and estimate the nonlinear equivalent part has been presented for a robot manipulator [42]. Sliding mode fuzzy controller (SMFC) is an artificial intelligence controller based on fuzzy logic methodology when, sliding mode controller is applied to fuzzy logic controller to reduce the fuzzy rules and refine the stability of close loop system in fuzzy logic controller [23, 48-50]. 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. In comparison, to reduce the number of fuzzy rule base, increase the robustness and stability sliding mode fuzzy controller is more suitable than fuzzy logic controller [52]. 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 [75]. 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. Hsu et al. [54] have presented traditional adaptive fuzzy sliding mode control which can update fuzzy rules to compensate nonlinear parameters and guarantee the stability robot manipulator controller. Hsueh et al. [43] have presented traditional self tuning sliding mode controller which can resolve the chattering problem without 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 pure sliding mode controller and fuzzy logic controller, as a result it is used to adjust and tune coefficient. Adaptive fuzzy sliding mode controller is used to many applications. This controller is based on online tuning the parameters and caused to improve the trajectory [40, 55-57]. The adaptive sliding mode controller is used to estimate the unknown dynamic parameters and external disturbances. For instance, the applications of adaptive fuzzy sliding mode controller to control the robot manipulators have been reported in [24, 29, 45]. Generally, adaptive fuzzy sliding mode control of robot manipulator is classified into two main groups' i.e. multi-input multi-output (MIMO) and single-input single-output (SISO) fuzzy systems. Yoo and Ham [58] have proposed a MIMO fuzzy system to help the compensation and estimation the torque coupling. In $\boldsymbol{n-DOF}$ robot manipulator with $\boldsymbol{k}$ membership function for each input variable, the number of fuzzy rules for each joint is equal to $\boldsymbol{3k^{2n}}$ that causes to high computation load and also this controller has chattering. This method can only tune the consequence part of the fuzzy rules. Guo and Woo [60] have proposed a SISO fuzzy controller to compensate the switching terms. The number of fuzzy rules is reduced ($\boldsymbol{K_2}$) with regard to reduce the chattering. Lin and Hsu [61] have proposed a methodology to tuning consequence and premise part of fuzzy rules to reduce the chattering based on tuning the membership function. In this method the number of fuzzy rules equal to $\boldsymbol{K_2}$ with low computational load but chattering is expected. Shahnazi et al., have proposed a SISO PI direct adaptive fuzzy sliding mode controller based on Lin and Hsu algorithm to reduce or eliminate chattering with $\boldsymbol{K_2}$ fuzzy rules numbers. The bounds of PI controller and the parameters are online adjusted by low adaption computation and tune the membership function[44]. Medhafer et al. [59] have proposed an indirect adaptive fuzzy sliding mode controller to control robot manipulator. This MIMO algorithm, applies to partly estimate the nonlinear dynamic parameters.

Contributions

Sliding mode controller is used to control of highly nonlinear systems especially for robot manipulators. The first problem of the pure sliding mode controller with switching function was chattering phenomenon in certain and uncertain systems. The nonlinear equivalent dynamic problem in uncertain system is the second challenge in pure sliding mode controller. To eliminate the PUMA robot manipulator's dynamic of system, 7 rules Mamdani inference system is design and applied to sliding mode methodology with switching function. This methodology is worked based on applied fuzzy logic in equivalent nonlinear dynamic part to eliminate unknown dynamic parameters. Pure sliding mode controller has difficulty in handling unstructured model uncertainties. This research is solved this problem by combining sliding mode fuzzy controller and fuzzy-based tuning. It is based on resolve the on line sliding surface gain ($\boldsymbol{\lambda}$) as well as improve the output performance. The sliding surface gain ($\boldsymbol{\lambda}$) of this controller is adjusted online depending on the last values of error (e) and change of error ($\dot{e}$) by sliding surface slope updating factor (α). Fuzzy-based tuning sliding mode fuzzy controller is stable model-free controller which does not need to limits the dynamic model of robot manipulator and eliminate the chattering phenomenon without to use the boundary layer saturation function. Lyapunov stability is proved in fuzzy-based tuning sliding mode fuzzy controller based on switching (sign) function.

Paper Outline
Section 2, is served as an introduction to the sliding mode controller formulation algorithm and its application to control of robot manipulator, dynamic of robot manipulator and proof of stability. Part 3, introduces and describes the methodology (design fuzzy-based tuningerror-based sliding mode fuzzy controller) algorithms and proves Lyapunov stability. Section 4 presents the simulation results and discussion of this algorithm applied to a robot arm and the final section is describing the conclusion.

2. THEOREM
Dynamic formulation: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 4, 15-29, 63-74]:

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

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. This robot manipulator dynamic equation can also be written in a following form [1-29]:

$$\boldsymbol{\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q)} \tag{2}$$

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 (2) 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 [3, 41-62]:

$$\boldsymbol{\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\}} \tag{3}$$

This technique is very attractive from a control point of view.

Sliding mode methodology: Consider a nonlinear single input dynamic system is defined by [6]:

$$\boldsymbol{x^{(n)} = f(\vec{x}) + b(\vec{x})u} \tag{4}$$

Where u is the vector of control input, $\boldsymbol{x^{(n)}}$ is the $\boldsymbol{n^{th}}$ derivation of $\boldsymbol{x}$, $\boldsymbol{x = [x, \dot{x}, \ddot{x}, \dots, x^{(n-1)}]^T}$ is the state vector, $\boldsymbol{f(x)}$ is unknown or uncertainty, and $\boldsymbol{b(x)}$ is of known *sign* function. The main goal to design this controller is train to the desired state; $\boldsymbol{x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d{}^{(n-1)}]^T}$, and trucking error vector is defined by [6]:

$$\boldsymbol{\widetilde{x} = x - x_d = [\widetilde{x}, \dots, \widetilde{x}^{(n-1)}]^T} \tag{5}$$

A time-varying sliding surface $\boldsymbol{s(x,t)}$ in the state space $\boldsymbol{R^n}$ is given by [6]:

$$\boldsymbol{s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\,\widetilde{x} = 0} \tag{6}$$

where λ is the positive constant. To further penalize tracking error, integral part can be used in sliding surface part as follows [6]:

$$\boldsymbol{s(x,t)} = (\frac{d}{dt} + \boldsymbol{\lambda})^{\boldsymbol{n-1}} \left(\int_0^t \boldsymbol{\widetilde{x}\,dt}\right) = \boldsymbol{0} \tag{7}$$

The main target in this methodology is kept the sliding surface slope $\boldsymbol{s(x,t)}$ near to the zero. Therefore, one of the common strategies is to find input $\boldsymbol{U}$ outside of $\boldsymbol{s(x,t)}$ [6].

$$\boldsymbol{\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)|} \tag{8}$$

where ζ is positive constant.

$$\text{If }\ \mathbf{S(0)>0} \rightarrow \frac{d}{dt}S(t) \le -\zeta \tag{9}$$

To eliminate the derivative term, it is used an integral term from t=0 to t=$\boldsymbol{t_{reach}}$

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt} S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \to S\,(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \tag{10}$$

Where t_{reach} is the time that trajectories reach to the sliding surface so, suppose $S(t_{reach} = 0)$ defined as

$$0 - S(0) \le -\eta(t_{reach}) \to t_{reach} \le \frac{S(0)}{\zeta} \tag{11}$$

and

$$if\ S(0) < 0 \to 0 - S(0) \le -\eta(t_{reach}) \to S(0) \le -\zeta(t_{reach}) \to t_{reach} \le \frac{|S(0)|}{\eta} \tag{12}$$

Equation (12) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \to error(x - x_d) = 0 \tag{13}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda) \quad \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{14}$$

The derivation of S, namely, $\dot{S}$ can be calculated as the following;

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{15}$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \ \to \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \tag{16}$$

Where f is the dynamic uncertain, and also since $S = 0\ and\ \dot{S} = 0$, to have the best approximation ,$\hat{U}$ is defined as

$$\hat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \tag{17}$$

A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law:

$$U_{dis} = \hat{U} - K(\vec{x}, t) \cdot \mathrm{sgn}(s) \tag{18}$$

where the switching function $\mathbf{sgn}(S)$ is defined as [1, 6]

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{19}$$

and the $K(\vec{x}, t)$ is the positive constant. Suppose by (8) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt} s^2(x,t) = \dot{S} \cdot S = \left[f - \hat{f} - K\mathrm{sgn}(s)\right] \cdot S = \left(f - \hat{f}\right) \cdot S - K|S| \tag{20}$$

and if the equation (12) instead of (11) the sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x}\, dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{21}$$

in this method the approximation of U is computed as [6]

$$\hat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{22}$$

Based on above discussion, the sliding mode control law for multi degrees of freedom robot manipulator is written as [1, 6]:

$$\tau = \tau_{eq} + \tau_{dis} \tag{23}$$

Where, the model-based component τ_{eq} is the nominal dynamics of systems and τ_{eq} for first 3 DOF PUMA robot manipulator can be calculate as follows [1]:

$$\tau_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \tag{24}$$

and τ_{dis} is computed as [1];

$$\boldsymbol{\tau_{dis}} = \boldsymbol{K} \cdot \mathbf{sgn}(\boldsymbol{S}) \tag{25}$$

by replace the formulation (25) in (23) the control output can be written as;

$$\boldsymbol{\tau} = \boldsymbol{\tau_{eq}} + \boldsymbol{K}.\mathbf{sgn}(\boldsymbol{S}) \tag{26}$$

By (26) and (24) the sliding mode control of PUMA 560 robot manipulator is calculated as;

$$\boldsymbol{\tau} = \left[\boldsymbol{M^{-1}}(\boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G}) + \dot{\boldsymbol{S}}\right]\boldsymbol{M} + \boldsymbol{K} \cdot \mathbf{sgn}(\boldsymbol{S}) \tag{27}$$

where $S = \lambda e + \dot{e}$ in PD-SMC and $S = \lambda e + \dot{e} + (\frac{\lambda}{2})^2 \sum e$ in PID-SMC.

Proof of Stability: the lyapunov formulation can be written as follows,

$$\boldsymbol{V} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{S^T}.\boldsymbol{M}.\boldsymbol{S} \tag{28}$$

the derivation of V can be determined as,

$$\dot{\boldsymbol{V}} = \frac{1}{2}\boldsymbol{S^T}.\dot{\boldsymbol{M}}.\boldsymbol{S} + \boldsymbol{S^T}\ \boldsymbol{M}\dot{\boldsymbol{S}} \tag{29}$$

the dynamic equation of IC engine can be written based on the sliding surface as

$$\boldsymbol{M}\dot{\boldsymbol{S}} = -\boldsymbol{VS} + \boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G} \tag{30}$$

it is assumed that

$$\boldsymbol{S^T}\left(\dot{\boldsymbol{M}} - \mathbf{2}\boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G}\right)\boldsymbol{S} = \mathbf{0} \tag{31}$$

by substituting (30) in (29)

$$\dot{\boldsymbol{V}} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{S^T}\dot{\boldsymbol{M}}\boldsymbol{S} - \boldsymbol{S^T}\boldsymbol{B} + \boldsymbol{CS} + \boldsymbol{S^T}\left(\boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{CS} + \boldsymbol{G}\right) = \boldsymbol{S^T}\left(\boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{CS} + \boldsymbol{G}\right) \tag{32}$$

suppose the control input is written as follows

$$\widehat{\boldsymbol{U}} = \widehat{\boldsymbol{U}_{\boldsymbol{Nonlinear}}} + \widehat{\boldsymbol{U}_{\boldsymbol{dis}}} = \left[\widehat{\boldsymbol{M^{-1}}}(\boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G}) + \dot{\boldsymbol{S}}\right]\widehat{\boldsymbol{M}} + \boldsymbol{K}.\boldsymbol{sgn}(\boldsymbol{S}) + \boldsymbol{B} + \boldsymbol{CS} + \boldsymbol{G} \tag{33}$$

by replacing the equation (33) in (32)

$$\dot{\boldsymbol{V}} = \boldsymbol{S^T}(\boldsymbol{M}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G} - \widehat{\boldsymbol{M}}\dot{\boldsymbol{S}} - \widehat{\boldsymbol{B} + \boldsymbol{C}}\boldsymbol{S} + \boldsymbol{G} - \boldsymbol{Ksgn}(\boldsymbol{S}) = \boldsymbol{S^T}\left(\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}} + \widetilde{\boldsymbol{B} + \boldsymbol{C}}\boldsymbol{S} + \boldsymbol{G} - \boldsymbol{Ksgn}(\boldsymbol{S})\right) \tag{34}$$

it is obvious that

$$\left|\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}} + \widetilde{\boldsymbol{B} + \boldsymbol{C}}\boldsymbol{S} + \boldsymbol{G}\right| \leq \left|\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}}\right| + \left|\widetilde{\boldsymbol{B} + \boldsymbol{C}}\boldsymbol{S} + \boldsymbol{G}\right| \tag{35}$$

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

$$\boldsymbol{K_u} = \left[\left|\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}}\right| + \left|\boldsymbol{B} + \boldsymbol{CS} + \boldsymbol{G}\right| + \boldsymbol{\eta}\right]_{\boldsymbol{i}}, \boldsymbol{i} = \mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{4}, \ldots \tag{36}$$

the equation (11) can be written as

$$\boldsymbol{K_u} \geq \left|\left[\widetilde{\boldsymbol{M}}\dot{\boldsymbol{S}} + \boldsymbol{B} + \boldsymbol{CS} + \boldsymbol{G}\right]_{\boldsymbol{i}}\right| + \boldsymbol{\eta_i} \tag{37}$$

therefore, it can be shown that

$$\dot{\boldsymbol{V}} \leq -\sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{\eta_i}\left|\boldsymbol{S_i}\right| \tag{38}$$

Consequently the equation (38) guaranties the stability of the Lyapunov equation. Figure 1 is shown pure sliding mode controller, applied to robot arm.

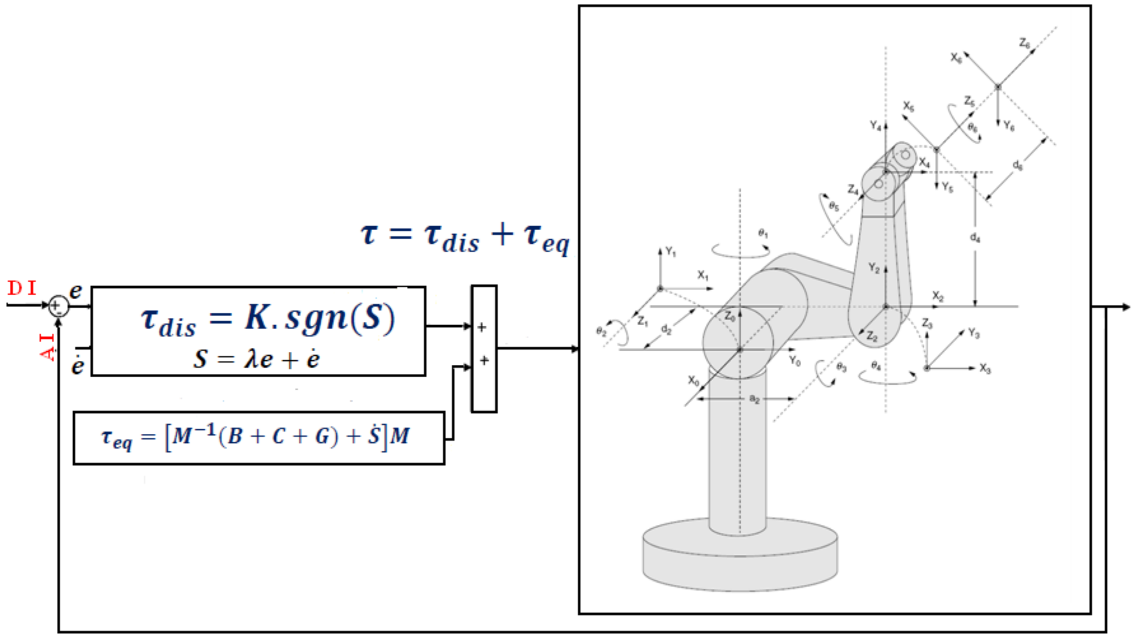

FIGURE 1: Block diagram of a sliding mode controller: applied to robot arm

3. METHODOLOGY

As shown in Figure 1, sliding mode controller is divided into two main parts: discontinuous part and equivalent part. Discontinuous part is based on switching function which this method is used to good following trajectory. Equivalent part is based on robot manipulator's dynamic formulation which these formulations are nonlinear; MIMO and some of them are unknown. Equivalent part of sliding mode controller is based on nonlinear dynamic formulations of robot manipulator. Robot manipulator's dynamic formulations are highly nonlinear and some of parameters are unknown therefore design a controller based on dynamic formulation is complicated. To solve this challenge fuzzy logic methodology is applied to sliding mode controller. Based on literature [43-44, 58-61], most of researchers are designed fuzzy model-based sliding mode controller and model-based sliding mode fuzzy controller. In this research fuzzy logic method is applied to SMC to reduce the fuzzy rule base, improve the stability and robustness. Figure 2 shows sliding mode fuzzy controller.

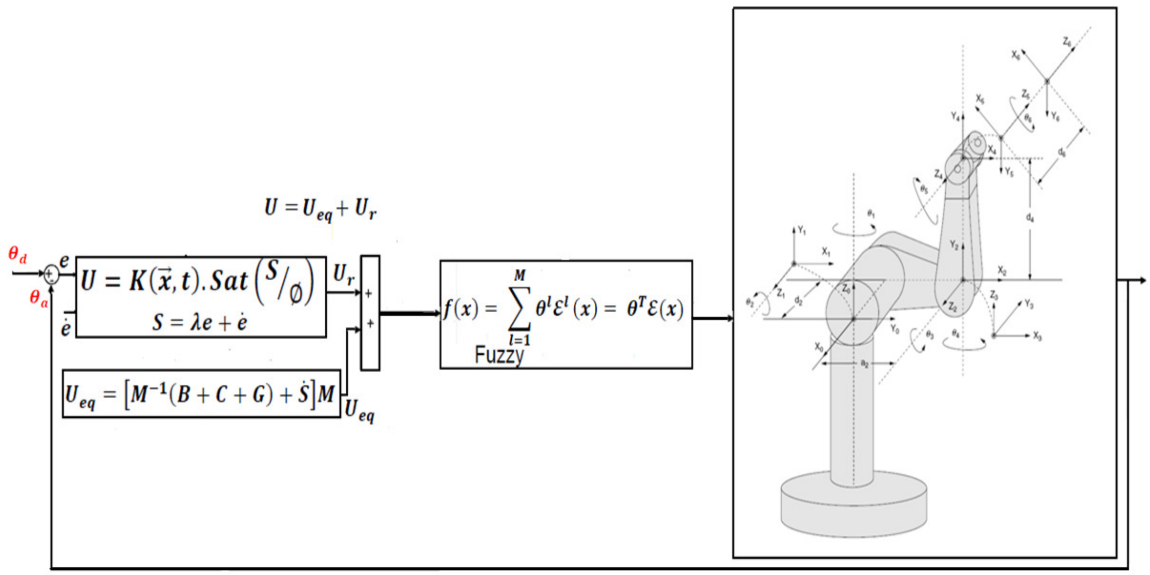

FIGURE 2: Sliding Mode Fuzzy Controller

To solve the challenge of sliding mode controller based on nonlinear dynamic formulation this research is focused on estimate the nonlinear equivalent formulation based on fuzzy logic methodology in feed forward way in this system. In this method; dynamic nonlinear equivalent part is estimated by performance/error-based fuzzy logic controller. In sliding mode fuzzy controller; error based Mamdani's fuzzy inference system has considered with one input, one output and totally 5 rules to estimate the dynamic equivalent part. In this method a model free Mamdani's fuzzy inference system has considered based on error-based fuzzy logic controller to estimate the nonlinear equivalent part. For both sliding mode controller and sliding mode fuzzy controller applications the system performance is sensitive to the sliding surface slope coefficient(λ). For instance, if large value of λ is chosen the response is very fast the system is unstable and conversely, if small value of λ is considered the response of system is very slow but system is stable. Therefore to have a good response, compute the best value sliding surface slope coefficient is very important. Eksin et. al [83] have designed mathematical model-free sliding surface slope in fuzzy sliding mode controller. In above method researchers are used saturation function instead of switching function therefore the proof of stability is very difficult. In sliding mode fuzzy controller based on (27) the PD-sliding surface is defined as follows:

$$S = \dot{e} + \lambda_1 e \tag{39}$$

where $\lambda_1 = diag[\lambda_{11}, \lambda_{12}, \lambda_{13}]$. The time derivative of S is computed;

$$\dot{S} = \ddot{q}_d + \lambda_1 \dot{e} \tag{40}$$

Based on Figure 3.5, the fuzzy error-based sliding mode controller's output is written;

$$\hat{\tau} = (\tau_{eq} + \tau_{cont})_{fuzzy\ estimator} \tag{41}$$

Based on fuzzy logic methodology

$$f(x) = U_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) \tag{42}$$

where θ^T is adjustable parameter (gain updating factor) and $\zeta(x)$ is defined by;

$$\zeta(x) = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)} \tag{43}$$

Where $\mu(x_i)$ is membership function. τ_{fuzzy} is defined as follows;

$$\tau_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = \left[M^{-1}(B + C + G) + \dot{S}\right]M + \mathbf{K.sgn\ (S)} \tag{44}$$

Based on [80-81] to compute dynamic parameters of PUMA560;

$$\tau_{fuzzy} = \begin{bmatrix} \tau_{1fuzzy} \\ \tau_{2fuzzy} \\ \tau_{3fuzzy} \end{bmatrix}, \quad M^{-1} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}^{-1}$$

$$B + C + G = \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^{\,2} + C_{13}\dot{q}_3^{\,2} \\ C_{21}\dot{q}_1^{\,2} + C_{23}\dot{q}_3^{\,2} \\ C_{31}\dot{q}_1^{\,2} + C_{32}\dot{q}_2^{\,2} \\ 0 \\ C_{51}\dot{q}_1^{\,2} + C_{52}\dot{q}_2^{\,2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

$$\dot{S} = \begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \\ \dot{S}_3 \\ \dot{S}_4 \\ \dot{S}_5 \\ \dot{S}_6 \end{bmatrix} \text{ and } M = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}$$

Therefore, the error-based fuzzy sliding mode controller for PUMA robot manipulator is calculated by the following equation;

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \end{bmatrix} = \left(\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} + \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} \ \mathbf{sgn} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} \right)_{fuzzy\ estimate} \tag{45}$$

As mentioned in Figure 2, the design of error-based fuzzy to estimate the equivalent part based on Mamdani's fuzzy inference method has four steps, namely, fuzzification, fuzzy rule base and rule evaluation, aggregation of the rule output (fuzzy inference system) and defuzzification. In most of industrial robot manipulators, controllers are still usually classical linear, but the manipulator dynamics is highly nonlinear and have uncertain or variation in parameters (e.g., structure and unstructured), as a result design a classical linear controllers for this system is very difficult and sometimes impossible. The first solution is to make the robust algorithm in order to reduce the uncertainty problems in a limit variation (e.g., sliding mode controller and computed torque like controller). Conversely the first solution is used in many applications it has some limitations such as nonlinear dynamic part in controller. The second solution is applied artificial intelligence method (e.g., fuzzy logic) in conventional nonlinear method to reduce or eliminate the challenges. However the second solution is a superior to reduce or eliminate the dynamic nonlinear part with respect to have stability and fairly good robustness but it has a robust in a limit variation. The third solution is used the on-line sliding mode fuzzy controller (e.g., fuzzy-based tuning sliding surface slope in sliding mode fuzzy controller). Adaptive (on-line) control is used in systems whose dynamic parameters are varying and need to be training on line. Sliding mode fuzzy controller has difficulty in handling unstructured model uncertainties and this controller's performance is sensitive to sliding surface slope coefficient. It is possible to solve above challenge by combining fuzzy-based tuning method and sliding mode fuzzy controller which this methodology can help to improve system's tracking performance by on-line tuning (fuzzy-based tuning) method. Based on above discussion, compute the best value of sliding surface slope coefficient has played important role to improve system's tracking performance especially the system parameters are unknown or uncertain. This problem is solved by tuning the surface slope coefficient ($\boldsymbol{\lambda}$) of the error-based fuzzy sliding mode controller continuously in real-time. In this methodology, the system's performance is improved with respect to the classical sliding mode controller and sliding mode fuzzy controller. Figure 3 shows the fuzzy-based tuning sliding mode fuzzy controller.

Based on (44) to adjust the sliding surface slope coefficient we define $\hat{f}(x|\lambda)$ as the fuzzy based tuning.

$$\hat{\boldsymbol{f}}(\boldsymbol{x}|\boldsymbol{\lambda}) = \boldsymbol{\lambda}^{T}\boldsymbol{\zeta}(\boldsymbol{x}) \quad \textbf{(46)}$$

If minimum error ($\boldsymbol{\lambda}^*$) is defined by;

$$\boldsymbol{\lambda}^* = \boldsymbol{arg\,min}\,[(\boldsymbol{Sup}|\hat{\boldsymbol{f}}(\boldsymbol{x}|\boldsymbol{\lambda}) - \boldsymbol{f}(\boldsymbol{x})|)] \quad \textbf{(47)}$$

Where λ^T is adjusted by an adaption law and this law is designed to minimize the error's parameters of $\boldsymbol{\lambda} - \boldsymbol{\lambda}^*$. adaption law in fuzzy-based tuning sliding mode fuzzy controller is used to adjust the sliding surface slope coefficient. Fuzzy-based tuning part is a supervisory controller based on Mamdani's fuzzy logic methodology. This controller has two inputs namely; error (e) and change of error $(\dot{e})$ and an output namely; gain updating factor(α). As a summary design a fuzzy-based tuning based on fuzzy logic method in fuzzy based tuning sliding mode fuzzy controller has five steps:

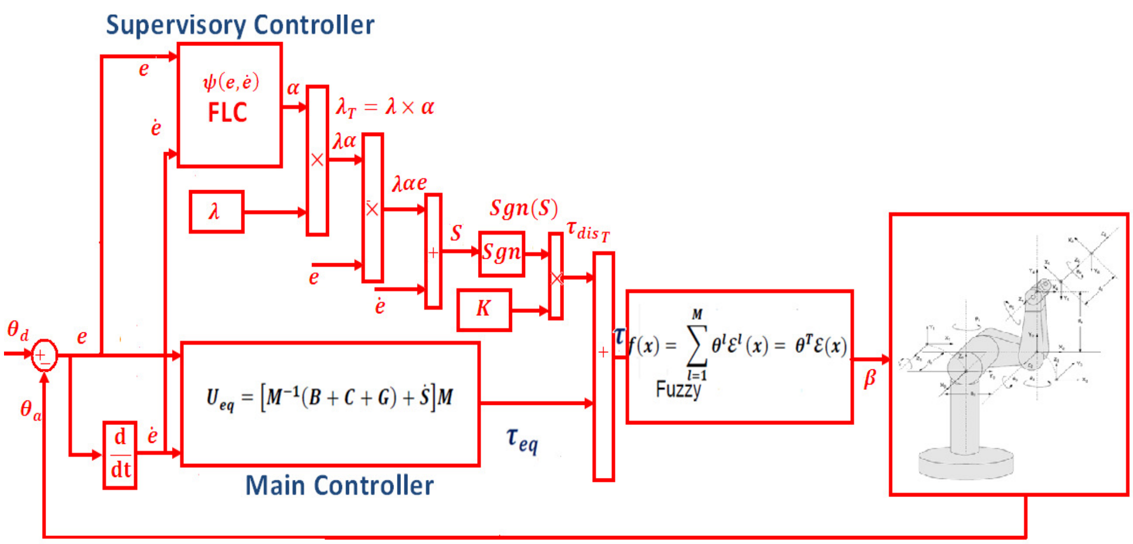

FIGURE 3 : Fuzzy based tuning Sliding Mode Fuzzy Controller

1. Determine Inputs and Outputs

it has two inputs error and change of error $(e, \dot{e})$ and the output name's is sliding surface slope updating factor (α).

2. Find linguistic Variable

The linguistic variables for error(e) are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and it is quantized into thirteen levels represented by: -1, -0.83, -0.66, -0.5, -0.33, -0.16, 0, 0.16, 0.33, 0.5, 0.66, 0.83, 1, the linguistic variables for change of error$(\dot{e})$ are ;Fast Left (FL), Medium Left (ML), Slow Left (SL),Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR), and it is quantized in to thirteen levels represented by: -6, -5, -0.4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, and the linguistic variables for sliding surface slope updating factor (α) are; Zero (ZE), Very Small (VS), Small (S), Small Big (SB), Medium Big (MB), Big (B), and Very Big (VB) and they are defined on $[0.5,1]$ and quantized into thirteen levels respected by: 0.5, 0.5417, 0.583, 0.625, 0.667, 0.7087, 0.7503, 0.792, 0.834, 0.876, 0.917, 0.959, 1.

3. Type of membership function: In this research triangular membership function is selected because it has linear equation with regard to has a high-quality response.

4. Design fuzzy rule table: the rule base for sliding surface slope updating factor of fuzzy-based tuning error-based fuzzy sliding mode controller is based on

F.R[1]: *IF e is NB and $\dot{e}$ is NB, THEN α is VB.* **(48)**

The complete rule base for supervisory controller is shown in Table 1.

5. Defuzzification: COG method is used to defuzzification in this research.

e \ $\dot{e}$	FL	ML	SL	Z	SR	MR	FR
NB	VB	VB	VB	B	SB	S	ZE
NM	VB	VB	B	B	MB	S	VS
NS	VB	MB	B	VB	VS	S	VS
Z	S	SB	MB	ZE	MB	SB	S
PS	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
PB	ZE	S	SB	B	VB	VB	VB

TABLE 1: Fuzzy rule base for sliding surface slope updating factor (α)

Based on Figure 3, supervisory controller is a controller to solve the unstructured uncertainties and tuning the sliding surface slope coefficient. This controller consists of two parts: fuzzy logic controller and scaling factor. Fuzzy logic controller is a Mamdani's error base inference system which has error (e) and change of error ($\dot{e}$) as inputs and sliding surface slope updating factor (α) as output. Each inputs has seven linguistic variables thus the controller's output has 49 rules, the output is defined between [0.5 1] and it is quantized into thirteen levels. Sliding surface slope updating factor (α) is used to tuning the main controller to give the best possible results. It is required because the robot manipulator's dynamic equations are highly nonlinear, the rules formulated in fuzzy sliding mode controller through user experience are not always correct under defined and also to unstructured uncertainties. It is independent of robot manipulator dynamic parameters and depends only on current system's performance; it is based on error and change of error. In this method the actual sliding surface slope coefficient ($\boldsymbol{\lambda}$) is obtained by multiplying the sliding surface with sliding surface slope updating factor (α). The sliding surface slope updating factor (α) is calculated on-line by 49 rules Mamdani's error-based fuzzy logic methodology. To limitation the error between [-1 1] and change of error between [-6 6], the best values for scaling factors are; $K_\alpha = 1.5$ and $K_\beta = 3$ based on Table 2.

k_α	k_β	e_{band}	$\dot{e}_{band}$	α_{band}
0.25	0.5	$[-0.166 \quad 0.18]$	$[-0.98 \quad 1.1]$	$[-0.1 \quad 0.1]$
0.5	1	$[-0.332 \quad 0.37]$	$[-1.96 \quad 2.2]$	$[-0.05 \quad 0.2]$
0.75	1.5	$[-0.498 \quad 0.54]$	$[-2.94 \quad 3.3]$	$[0 \quad 0.3]$
1	2	$[-0.664 \quad 0.733]$	$[-3.92 \quad 4.4]$	$[0.12 \quad 0.38]$
1.25	2.5	$[-0.83 \quad 0.9]$	$[-4.9 \quad 5.5]$	$[0.3 \quad 0.85]$
1.5	3	$[-0.995 \quad 1.1]$	$[-5.88 \quad 6.6]$	$[0.49 \quad 1.01]$
1.75	3.5	$[-1.162 \quad 1.26]$	$[-6.86 \quad 7.7]$	$[0.58 \quad 1.38]$
2	4	$[-1.328 \quad 1.44]$	$[-7.84 \quad 8.8]$	$[0.63 \quad 1.6]$

TABLE 2: Best value of k_α and k_β to tuning the α

Table 3 shows the sliding surface slope updating factor (α) lookup table in fuzzy-based tuning part by COG defuzzification method. It has 169 cells to shows the fuzzy-based tuning to on-line tuning the sliding surface slope coefficient. For instance if $e = -1$ and $\dot{e} = -3.92$ then the output=0.5. Based on Table 3.3 if two fuzzy rules are defined by

$$F.R^1: if\ e\ is\ NB \quad and \quad \dot{e}\ is\ ML \quad then \quad \alpha\ is\ VB$$
$$F.R^2: if\ e\ is\ NB \quad and \quad \dot{e}\ is\ FL \quad then \quad \alpha\ is\ VB$$

If all input fuzzy activated by crisp input values $e = -1$ and $\dot{e} = -3.92$ and fuzzy set to compute NB, ML and FL are defined as

$$e_{(NB)} = \{(0,-1.5),(0.25,-1.375),(0.5,-1.25),(0.75,-1.125),(1,-1),(0.75,-0.875),(0.5,-0.75),(0.25,-0.625),(0,-0.5)$$
$$\dot{e}_{(ML)} = \{(0,-5.8),(0.25,-5.17),(0.5,-4.55),(0.75,-3.92),(1,-3.3),(0.75,-2.67),(0.5,-2.05),(0.25,-1.42),(0,-0.83)$$
$$\dot{e}_{(FL)} = \{(0,-7.5),(0.25,-6.88),(0.5,-6.25),(0.75,-5.57),(1,-5),(0.75,-4.30),(0.5,-3.92),(0.25,-3.12),(0,-2.5)$$

$\dot{e}$ → / e ↓	Membership Function (τ)												
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-1	-92	-92	-92	-92	-90	-90	-80	-77	-70	-55	-50	-20	0
-0.83	-92	-92	-92	-92	-80	-77	70	-55	-50	-30	-25	0	0
-0.66	-92	-92	-92	-80	-77	-77	-70	-55	-50	-25	0	0	25
-0.5	-92	-92	-71	-57	-43	-28	-28	-28	-25	0	0	25	43
-0.33	-92	-71	-57	-43	-28	-25	-25	-25	0	0	25	43	57
-0.16	-71	-57	-43	-28	-25	-25	0	0	0	14	28	43	57
0	-71	-57	-43	-28	-25	0	0	0	14	28	43	43	71
0.16	-43	-28	-25	0	0	0	0	14	14	28	43	57	70
0.33	-28	-25	0	0	0	14	14	14	28	43	57	71	84
0.5	-25	0	0	0	14	28	28	28	43	57	70	84	92
0.66	0	0	0	14	28	43	43	43	57	70	84	92	92
0.83	0	0	14	28	43	57	57	57	70	92	92	92	92
1	0	14	28	43	57	71	92	92	92	92	92	92	92

TABLE 3: Sliding surface slope updating factor (α): Fuzzy-based tuning fuzzy sliding mode controller lookup table by COG method

while $\alpha_{(VB)} = \{(0,0.4165),(0.25,0.4403),(0.5,0.4641),(0.75,0.4879),(1,0.5),$
$(0.75,0.5238),(0.5,0.5476),(0.25,0.5714),(0,0.5834)\}$

In this controller AND fuzzy operation is used therefore the output fuzzy set is calculated by using individual rule-base inference. The activation degrees is computed as

Table 4 shows the fuzzy equivalent torque performance $(\tau_{eq\ fuzzy})$ lookup table in fuzzy-based tuning error-based fuzzy sliding mode controller by COG defuzzification method.

$\dot{e}$ → / e ↓	**Membership Function**												
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-1	-85	-85	-85	-85	-84	-84	-83	-71	-57	-43	-28	-14	0
-0.83	-85	-85	-85	-85	-71	-57	-56	-57	-43	-28	-14	0	0
-0.66	-85	-85	-85	-71	-57	-43	-43	-43	-28	-14	0	0	14
-0.5	-85	-85	-71	-57	-43	-28	-28	-28	-14	0	0	14	28
-0.33	-85	-71	-57	-43	-28	-14	-14	-14	0	0	14	28	43
-0.16	-71	-57	-43	-28	-14	-14	0	0	0	14	28	43	57
0	-71	-57	-43	-28	-14	0	0	0	14	28	43	43	71
0.16	-43	-28	-14	0	0	0	0	14	14	28	43	57	70
0.33	-28	-14	0	0	0	14	14	14	28	43	57	71	84
0.5	-14	0	0	0	14	28	28	28	43	57	70	84	85
0.66	0	0	0	14	28	43	43	43	57	70	84	85	85
0.83	0	0	14	28	43	57	57	57	70	85	85	85	85
1	0	14	28	43	57	71	85	85	85	85	85	85	85

TABLE 4: Fuzzy equivalent torque performance ($\tau_{eq\,fuzzy}$): Fuzzy-based tuning fuzzy sliding mode controller lookup table by COG method

$$\mu_{FR_1} = \min\left[\mu_{e(N.B)}(-1), \mu_{\dot{e}(M.L)}(-3.92)\right] = \min[1,0.75] = 0.75$$
$$\mu_{FR_2} = \min\left[\mu_{e(N.B)}(-1), \mu_{\dot{e}(F.L)}(-3.92)\right] = \min[1,0.5] = 0.5$$

The activation degrees of the consequent parts for $F.R^1$ and $F.R^2$ are computed as:

$$\mu_{FR_1}(-1,-3.92,\alpha) = \min\left[\mu_{FR_1}(-1,-3.92), \mu_{\alpha(VB)}\right] = \min\left[0.75, \mu_{\alpha(VB)}\right]$$
$$\mu_{FR_2}(-1,-3.92,\alpha) = \min\left[\mu_{FR_2}(-1,-3.92), \mu_{\alpha(VB)}\right] = \min\left[0.5, \mu_{\alpha(VB)}\right]$$

Fuzzy set $\alpha_{L.L(1)}$ and $\alpha_{L.L(2)}$ have nine elements:

$$F.F^1(-1,-3.92,\alpha) = \{(0,0.4165),(0.25,0.4403),(0.5,0.4641),(0.75,0.4879),(1,0.5),(0.75,0.5238),(0.5,0.5476),(0.25,0.5714),(0,0.5834)\}$$

$$F.F^2(-1,-3.92,T) = \{(0,0.4165),(0.25,0.4403),(0.5,0.4641),(0.75,0.4879),(1,0.5),(0.75,0.5238),(0.5,0.5476),(0.25,0.5714),(0,0.5834)\}$$

Max-min aggregation is used to find the output of fuzzy set:

$$\mu_{U_{12}}(-1,-3.92,\alpha) = \mu_{\bigcup_{i=1}^{2} FR^1}(-1,-3.92,\alpha) = \max\{\mu_{FR}^1(-1,-3.92,\alpha)_{VB}\ ,\mu_{FR}^2(-1,-3.92,\alpha)_{VB}\ \}$$

$$U_{12} = \{(0,0.4165),(0.25,0.4403),(0.5,0.4641),(0.75,0.4879),(0.75,0.5),(0.75,0.5238),(0.5,0.5476),(0.25,0.5714),(0,0.5834)\}$$

The COG defuzzification is selected as;

$COG = (0.25\times 0.4403) + (0.5\times 0.4641) + (0.75\times 0.4879) + (0.75\times 0.5) + (0.75\times 0.5238) + (0.5\times 0.5476) + (0.25\times 0.5714)[0.25+0.5+0.75+0.75+0.75+0.5+0.25]^{-1} = \frac{1.875}{3.75} = 0.5$

Based on Tables 1, 3 and 4 where $e=-1$ and $\dot{e}=-3.92$ and fuzzy set to compute NB, ML and FL are defined as

$e_{(NB)} = \{(0,-1.5),(0.25,-1.375),(0.5,-1.25),(0.75,-1.125),(1,-1),(0.75,-0.875),$
$(0.5,-0.75),(0.25,-0.625),(0,-0.5)$
$\dot{e}_{(ML)} = \{(0,-5.8),(0.25,-5.17),(0.5,-4.55),(0.75,-3.92),(1,-3.3),(0.75,-2.67),$
$(0.5,-2.05),(0.25,-1.42),(0,-0.83)$
$\dot{e}_{(FL)} = \{(0,-7.5),(0.25,-6.88),(0.5,-6.25),(0.75,-5.57),(1,-5),(0.75,-4.30),$
$(0.5,-3.92),(0.25,-3.12),(0,-2.5)$
while $T_{(LL)} = \{(0,-123),(0.25,-113.5),(0.5,-104),(0.75,-94.5),(1,-85),(0.75,-75.5),$
$(0.5,-66),(0.25,-56.5),(0,-47)$. Based on 2.63 the activation degrees is computed as

$$\mu_{FR_1} = \min\left[\mu_{e(N.B)}(-1),\mu_{\dot{e}(M.L)}(-3.92)\right] = \min[1,0.75] = 0.75$$

$$\mu_{FR_2} = \min\left[\mu_{e(N.B)}(-1),\mu_{\dot{e}(F.L)}(-3.92)\right] = \min[1,0.5] = 0.5$$

The activation degrees of the consequent parts for $F.R^1$ and $F.R^2$ are computed as:

$$\mu_{FR_1}(-1,-3.92,T) = \min\left[\mu_{FR_1}(-1,-3.92),\mu_{T(L.L)}\right] = \min\left[0.75,\mu_{T(L.L)}\right]$$

$$\mu_{FR_2}(-1,-3.92,T) = \min\left[\mu_{FR_2}(-1,-3.92),\mu_{T(L.L)}\right] = \min\left[0.5,\mu_{T(L.L)}\right]$$

Fuzzy set $T_{L.L(1)}$ and $T_{L.L(2)}$ have nine elements:

$F.F^1(-1,-3.92,T) = \{(0,-123),(0.25,-113.5),(0.5,-104),(0.75,-94.5),(0.75,-85),$
$(0.75,-75.5),(0.5,-66),(0.25,-56.5),(0,-47)$

$F.F^2(-1,-3.92,T) = \{(0,-123),(0.25,-113.5),(0.5,-104),(0.5,-94.5),(0.5,-85),$
$(0.5,-75.5),(0.5,-66),(0.25,-56.5),(0,-47)$

Based on 2.69, Max-min aggregation is used to find the output of fuzzy set:

$$\mu_{U_{12}}(-1,-3.92,T) = \mu_{\cup_{i=1}^{2} FR^1}(-1,-3.92,T) = \max\{\mu_{FR}^1(-1,-3.92,T)_{L.L}\,,\mu_{FR}^2(-1,-3.92,T)_{L.L}\ \}$$

$U_{12} = \{(0,-123),(0.25,-113.5),(0.5,-104),(0.75,-94.5),(0.75,-85),(0.75,-75.5),$
$(0.5,-66),(0.25,-56.5),(0,-47)\}$

Based on (2.71) the COG defuzzification is selected as;

$COG = [(0.25\times -113.5)+(0.5\times -104)+(0.75\times -94.5)+(0.75\times -85)+(0.75\times -75.5)+$
$(0.5\times -66)+(0.25\times -56.5)][0.25+0.5+0.75+0.75+0.75+0.5+0.25]^{-1} \quad = \frac{-318.75}{3.75} = -85$

Based on Figures 3.8, torque performance is calculated by;

$$\boldsymbol{\tau} = [\boldsymbol{\tau}_{equ} + (\boldsymbol{\tau}_{dis})_{tuning}]_{fuzzy} \tag{49}$$

where $(\tau_{dis})_{tuning}$ is a discontinuous part which tuning by fuzzy-based tuning method. Table 5 shows the torque performance in fuzzy-based tuning error-based fuzzy sliding mode controller look up table.

$\dot{e}$ → / e ↓	**Membership Function (τ)**												
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-1	-92	-92	-92	-92	-90	-90	-80	-77	-70	-55	-50	-20	0
-0.83	-92	-92	-92	-92	-80	-77	70	-55	-50	-30	-25	0	0
-0.66	-92	-92	-92	-80	-77	-77	-70	-55	-50	-25	0	0	25
-0.5	-92	-92	-71	-57	-43	-28	-28	-28	-25	0	0	25	43
-0.33	-92	-71	-57	-43	-28	-25	-25	-25	0	0	25	43	57
-0.16	-71	-57	-43	-28	-25	-25	0	0	0	14	28	43	57
0	-71	-57	-43	-28	-25	0	0	0	14	28	43	43	71
0.16	-43	-28	-25	0	0	0	0	14	14	28	43	57	70
0.33	-28	-25	0	0	0	14	14	14	28	43	57	71	84
0.5	-25	0	0	0	14	28	28	28	43	57	70	84	92
0.66	0	0	0	14	28	43	43	43	57	70	84	92	92
0.83	0	0	14	28	43	57	57	57	70	92	92	92	92
1	0	14	28	43	57	71	92	92	92	92	92	92	92

TABLE 5: Torque (τ) performance: Fuzzy-based tuning fuzzy sliding mode controller lookup table by COG method

Based on Figure 5, fuzzy-based tuning error-based fuzzy sliding mode controller for PUMA560 robot manipulator is calculated by the following equation;

$$\begin{bmatrix}\widehat{\tau_1}\\ \widehat{\tau_2}\\ \widehat{\tau_3}\end{bmatrix} = [\begin{bmatrix}\tau_{1eq}\\ \tau_{2eq}\\ \tau_{3eq}\end{bmatrix} + \begin{bmatrix}\lambda_1 \times \alpha_1\\ \lambda_2 \times \alpha_2\\ \lambda_3 \times \alpha_3\end{bmatrix} \begin{bmatrix}K_1\\ K_2\\ K_3\end{bmatrix} sgn \begin{bmatrix}S_1\\ S_2\\ S_3\end{bmatrix}]_{fuzzy} \quad \textbf{(50)}$$

Where $\alpha = [\alpha_1, \alpha_2, \alpha_3]$ is sliding surface slope updating factor and it is calculated based on error-based fuzzy logic methodology.

4. RESULTS AND DISCUSSION

Sliding mode controller (SMC), sliding mode fuzzy controller (SMFC) and fuzzy-based tuning sliding mode fuzzy controller (FTSMFC) were tested to Step response trajectory. In this simulation, to control position of PUMA robot manipulator the first, second, and third joints are moved from home to final position without and with external disturbance. The simulation was implemented in Matlab/Simulink environment. These controllers are tested by band limited white noise with a predefined 40% of relative to the input signal amplitude. This type of noise is used to external disturbance in continuous and hybrid systems and applied to nonlinear dynamic of these controllers. Pure sliding mode controller and sliding mode fuzzy controller have difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining sliding mode fuzzy controller and fuzzy-based tuning in a single controller method. This method can improve the system's tracking performance by online tuning method. This method is based on resolve the on line sliding surface slope as well as improve the output performance by tuning the sliding surface slope coefficient. The sliding surface gain ($\boldsymbol{\lambda}$) of this controller is adjusted online depending on the last values of error ($\boldsymbol{e}$) and change of error ($\dot{\boldsymbol{e}}$) by sliding surface slope updating factor ($\boldsymbol{\alpha}$). Fuzzy-based tuning sliding mode fuzzy controller is stable model-based controller which does not need to limits the dynamic model of robot manipulator and eliminate the chattering phenomenon without to use the boundary layer saturation function.

Tracking performances: Based on (44) in sliding mode fuzzy controller and based on (10) in sliding mode controller; controllers performance are depended on the gain updating factor (K) and sliding surface slope coefficient (λ). These two coefficients are computed by trial and error in PD-SMC and FSMC. The best possible coefficients in step SMFC are; $K_p = K_v = K_i = 18,\ \emptyset_1 = \emptyset_2 = \emptyset_3 = 0.1, and\ \lambda_1 = 3, \lambda_2 = 6, \lambda_3 = 6$ and the best possible coefficients in step SMC are; $\lambda_1 = 1, \lambda_2 = 6, \lambda_3 = 8$; $K_p = K_v = K_i = 10$; $\emptyset_1 = \emptyset_2 = \emptyset_3 = 0.1$. In fuzzy-based tuning sliding mode fuzzy controller the sliding surface gain is adjusted online depending on the last values of error (e) and change of error ($\dot{e}$) by sliding surface slope updating factor (α). Figure 4 shows tracking performance in fuzzy-based tuning sliding mode fuzzy controller (FTSMFC), sliding mode fuzzy controller (SMFC) and SMC without disturbance for step trajectory.

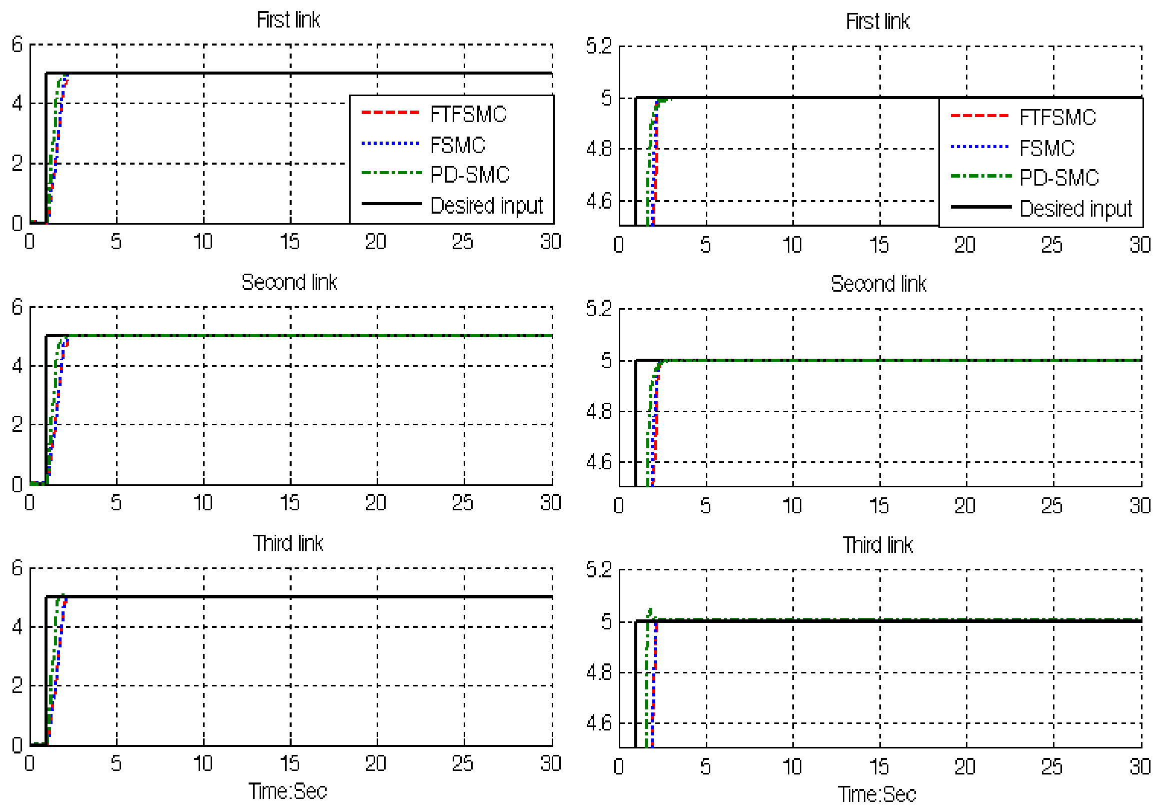

FIGURE 4: SMFC, FTSMFC, desired input and SMC for first, second and third link step trajectory performance without disturbance

Based on Figure 4 it is observed that, the overshoot in FTSMFC is 0%, in SMC's is 1% and in SMFC's is 0%, and rise time in FTSMFC's is 0.6 seconds, in SMC's is 0.483 second and in SMFC's is about 0.6 seconds. From the trajectory MATLAB simulation for FTSMFC, SMC and SMFC in certain system, it was seen that all of three controllers have acceptable performance.

Disturbance Rejection

Figure 5 shows the power disturbance elimination in FTSMFC, SMC and SMFC with disturbance for step trajectory. The disturbance rejection is used to test the robustness comparisons of these three controllers for step trajectory. A band limited white noise with predefined of 40% the power of input signal value is applied to the step trajectory. Based on Figure 5, it was seen that, STSMFC's performance is better than SMFC and SMC because FTSMFC can auto-tune the sliding surface slope coefficient as the dynamic manipulator parameter's change and in presence of external disturbance whereas SMFC and SMC cannot.

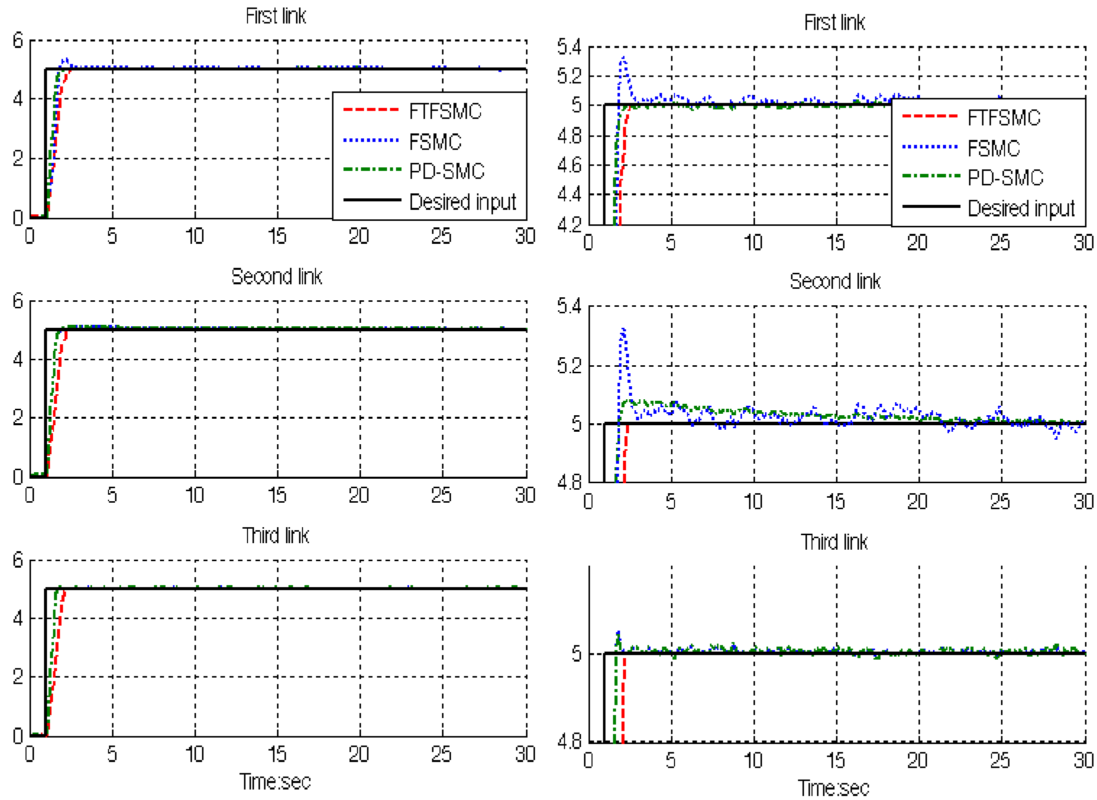

FIGURE 5: Desired input, FTSMFC, SMFC and SMC for first, second and third link trajectory with 40%external disturbance: step trajectory

Based on Figure 5; by comparing step response trajectory with 40% disturbance of relative to the input signal amplitude in FTSMFC, SMC and SMFC, FTSMFC's overshoot about **(0%)** is lower than FTSMFC's **(6%)** and SMC's (**8%**)**.** SMC's rise time **(0.5 seconds)** is lower than SMFC's **(0.7 second)** and FTSMFC's **(0.8 second).** Besides the Steady State and RMS error in FTSMFC, SMFC and SMC it is observed that, error performances in FTSMFC **(Steady State error =1.3e-12 and RMS error=1.8e-12)** are about lower than SMFC **(Steady State error =10e-4 and RMS error=0.69e-4)** and SMC's **(Steady State error=10e-4 and RMS error=11e-4).** Based on Figure 5, SMFC and SMC have moderately oscillation in trajectory response with regard to 40% of the input signal amplitude disturbance but FTSMFC has stability in trajectory responses in presence of uncertainty and external disturbance. Based on Figure 5 in presence of 40% unstructured disturbance, STSMFC's is more robust than SMFC and SMC because FTSMFC can auto-tune the sliding surface slope coefficient as the dynamic manipulator parameter's change and in presence of external disturbance whereas SMFC and SMC cannot.

Torque Performance

Figures 6 and 7 have indicated the power of chattering rejection in FTSMFC, SMC and SMFC with 40% disturbance and without disturbance.

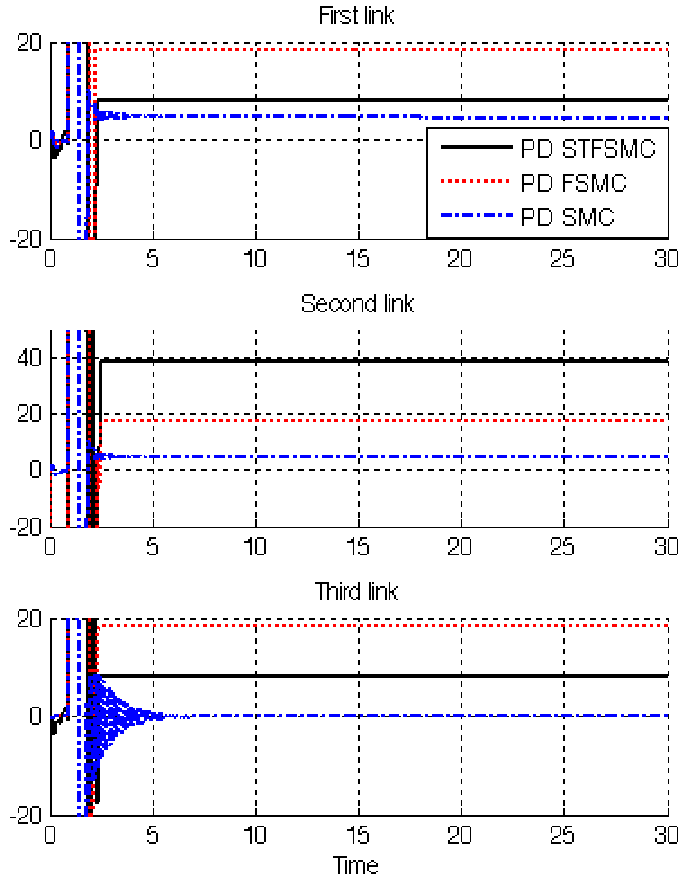

FIGURE 6: FTSMFC, SMC and SMFC for first, second and third link torque performance without disturbance

Figure 6 shows torque performance for first three links PUMA robot manipulator in FTSMFC, SMC and SMFC without disturbance. Based on Figure 6, FTSMFC, SMC and SMFC give considerable torque performance in certain system and all three of controllers eliminate the chattering phenomenon in certain system. Figure 7 has indicated the robustness in torque performance for first three links PUMA robot manipulator in FTSMFC, SMC and SMFC in presence of 40% disturbance. Based on Figure 7, it is observed that SMC and SMFC controllers have oscillation but FTSMFC has steady in torque performance. This is mainly because pure SMC and sliding mode fuzzy controller are robust but they have limitation in presence of external disturbance. The FTSMFC gives significant chattering elimination when compared to SMFC and SMC. This elimination of chattering phenomenon is very significant in presence of 40% disturbance. This challenge is one of the most important objectives in this thesis.

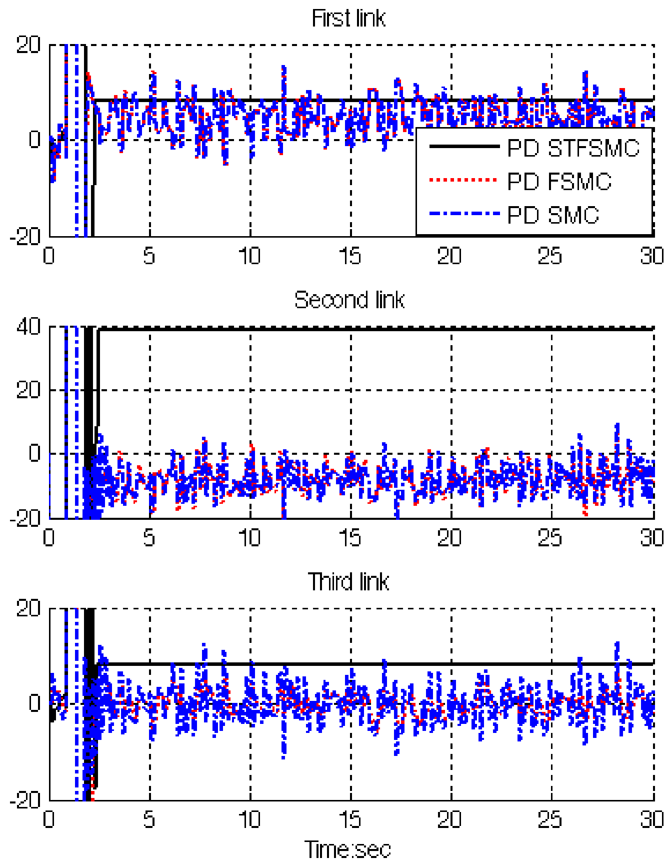

FIGURE 7: FTSMFC, SMC and SMFC for first, second and third link torque performance with40% disturbance

Based on Figure 7 it is observed that, however fuzzy tuning sliding mode fuzzy controller (FTSMFC) is a model-based controller that estimate the nonlinear dynamic equivalent formulation by fuzzy rule base but it has significant torque performance (chattering phenomenon) in presence of uncertainty and external disturbance. SMC and SMFC have limitation to eliminate the chattering in presence of highly external disturbance (e.g., 40% disturbance) but FTSMFC is a robust against to highly external disturbance.

Steady state error: Figure 8 is shown the error performance in FTSMFC, SMC and SMFC for first three links of PUMA robot manipulator**.** The error performance is used to test the disturbance effect comparisons of these controllers for step trajectory. All three joint's inputs are step function with the same step time (step time= 1 second), the same initial value (initial value=0) and the same final value (final value=5). Based on Figure 5, FTSMFC's rise time is about 0.6 second, SMC's rise time is about 0.483 second and SMFC's rise time is about 0.6 second which caused to create a needle wave in the range of 5 (amplitude=5) and the different width. In this system this time is transient time and this part of error introduced as a transient error. Besides the Steady State and RMS error in STSMFC, SMFC and SMC it is observed that, error performances in FTSMFC **(Steady State error =0.9e-12 and RMS error=1.1e-12)** are bout lower than SMFC **(Steady State error =0.7e-8 and RMS error=1e-7)** and SMC's **(Steady State error=1e-8 and RMS error=1.2e-6)**.

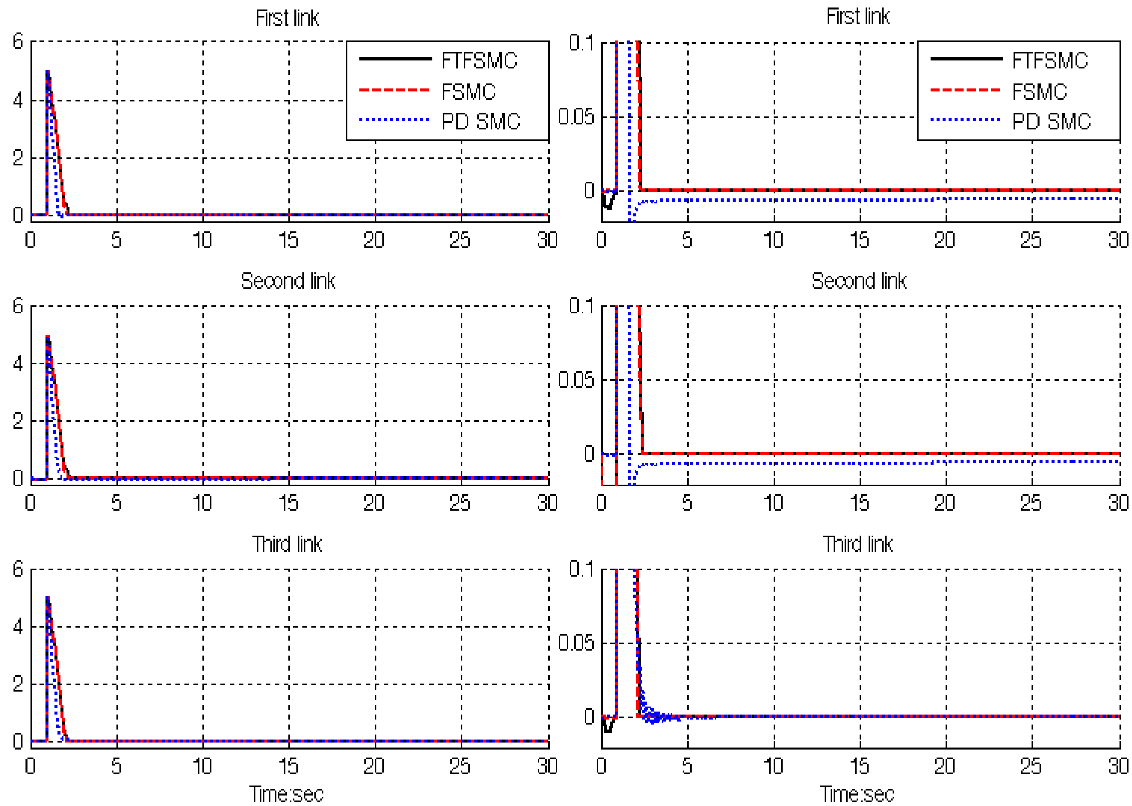

FIGURE 8: FTSMFC, SMC and SMFC for first, second and third link steady state error without disturbance: step trajectory

The FTSMFC gives significant steady state error performance when compared to SMFC and SMC. When applied 40% disturbances in FTSMFC the RMS error increased approximately 0.0164% (percent of increase the FTSMFC RMS error=$\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbanceRMS\ error} = \frac{1.8e-12}{1.1e-12} = 0.0164\%$), in SMFC the RMS error increased approximately 6.9% (percent of increase the SMFC RMS error=$\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbanceRMS\ error} = \frac{0.69e-4}{1e-7} = 6.9\%$)in SMC the RMS error increased approximately 9.17% (percent of increase the SMC RMS error=$\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbance\ RMS\ error} = \frac{11e-4}{1.2e-6} = 9.17\%$). In this part FTSMFC, SMC and SMFC have been comparatively evaluation through MATLAB simulation, for PUMA robot manipulator control. It is observed that however FTSMFC is independent of nonlinear dynamic equation of PUMA 560 robot manipulator but it can guarantee the trajectory following and eliminate the chattering phenomenon in certain systems, structure uncertain systems and unstructured model uncertainties by online tuning method.

5. CONCLUSION

Refer to this research, a position fuzzy-based tuning sliding mode fuzzy controller (FTSMFC) is proposed for PUMA robot manipulator. The nonlinear equivalent dynamic problem in uncertain system is estimated by using fuzzy logic theory. To estimate the PUMA robot manipulator system's dynamic, 5 rules Mamdani inference system is design and applied to sliding mode methodology. This methodology is based on applied fuzzy logic in equivalent nonlinear dynamic part to estimate unknown parameters. The results demonstrate that the sliding mode fuzzy controller is a model-based controllers which works well in certain and partly uncertain system. Pure sliding mode controller and sliding mode fuzzy controller have difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining sliding mode fuzzy controller and fuzzy-based tuning. Since the sliding surface gain (λ) is adjusted by fuzzy-based tuning method, it is nonlinear and continuous. The sliding surface slope updating factor (α) of fuzzy-based tuning part can be changed with the changes in error and change of error rate between half to one. Sliding surface gain is adapted on-line by sliding surface slope updating factor. In pure sliding mode controller and sliding mode fuzzy controller the sliding surface gain is chosen by trial and error, which means pure sliding mode controller and sliding mode fuzzy controller have to have a prior knowledge of the system uncertainty. If the knowledge is not available error performance and chattering phenomenon are go up. The stability and convergence of the fuzzy-based tuning sliding mode fuzzy controller based on switching function is guarantee and proved by the Lyapunov method. The simulation results exhibit that the fuzzy-based tuning sliding mode fuzzy controller works well in various situations. Based on theoretical and simulation results, it is observed that fuzzy-based tuning sliding mode fuzzy controller is a model-free stable control for robot manipulator. It is a best solution to eliminate chattering phenomenon with switching function in structure and unstructured uncertainties.

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