Design Adaptive Fuzzy Inference Sliding Mode Algorithm: Applied to Robot Arm

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Abstract

The developed control methodology can be used to build more efficient intelligent and precision mechatronic systems. Three degrees of freedom robot arm is controlled by adaptive sliding mode fuzzy algorithm fuzzy sliding mode controller (SMFAFSMC). This plant has 3 revolute joints allowing the corresponding links to move horizontally. Control of robotic manipulator is very important in field of robotic, because robotic manipulators are Multi-Input Multi-Output (MIMO), nonlinear and most of dynamic parameters are uncertainty. Design strong mathematical tools used in new control methodologies to design adaptive nonlinear robust controller with acceptable performance in this controller is the main challenge. Sliding mode methodology is a nonlinear robust controller which can be used in uncertainty nonlinear systems, but pure sliding mode controller has chattering phenomenon and nonlinear equivalent part in uncertain system therefore the first step is focused on eliminate the chattering and in second step controller is improved with regard to uncertainties. Sliding function is one of the most important challenging in artificial sliding mode algorithm which this problem in order to solved by on-line tuning method. This paper focuses on adjusting the sliding surface slope in fuzzy sliding mode controller by sliding mode fuzzy algorithm.

Keywords: Mechatronic System, Robot arm, Adaptive Method, Sliding mode Fuzzy Algorithm, Fuzzy Sliding Mode Algorithm, Robust Controller, Fuzzy Logic, Sliding Mode Controller, Sliding Surface Slope, Sliding Function, Adaptive Sliding Mode Fuzzy algorithm Fuzzy Sliding Mode Controller.

1. INTRODUCTION

A robot system without any controllers does not to have any benefits, because controller is the main part in this sophisticated system. The main objectives to control of robot manipulators are stability and robustness. Lots of researchers work on design the controller for robotic manipulators to have the best performance. Control of any systems divided in two main groups: linear and nonlinear controller [1].

However, one of the important challenging in control algorithms is design linear behavior controller to easier implementation for nonlinear systems but these algorithms have some limitation such as controller working area must to be near the system operating point and this adjustment is very difficult specially when the dynamic system parameters have large variations and when the system has hard nonlinearities [1-4]. Most of robot manipulators which work in industry are usually controlled by linear PID controllers. But the robot manipulator dynamic functions are, nonlinear with strong coupling between joints (low gear ratio), structure and unstructured uncertainty and Multi- Inputs Multi-Outputs (MIMO) which, design linear controller is very difficult especially if the velocity and acceleration of robot manipulator be high and also when the ratio between joints gear be small [2]. To eliminate above problems in physical systems most of control researcher go toward to select nonlinear robust controller.

One of the most important powerful nonlinear robust controllers is Sliding Mode Controller (SMC). However Sliding mode control methodology was first proposed in the 1950 but this controller has been analyzed by many researchers in recent years. The main reason to select this controller in wide range area is have an acceptable control performance and solve some main challenging topics in control such as resistivity to the external disturbance and uncertainty. However, this controller has above advantages but, pure sliding mode controller has following disadvantages i.e.chattering problem, sensitive and equivalent dynamic formulation [3, 5-15].

After the invention of fuzzy logic theory in 1965 by Zadeh [16], this theory was used in wide range area because Fuzzy Logic Controller (FLC) is one of the most important applications of fuzzy logic theory. This controller can be used to control of nonlinear, uncertain and noisy systems. However pure FLC works in many engineering applications but, it cannot guarantee two most important challenges in control, namely, stability and acceptable performance [16-25]. Some researchers applied fuzzy logic methodology in sliding mode controllers (FSMC) to reduce the chattering and solve the nonlinear dynamic equivalent problems in pure sliding mode controller and the other researchers applied sliding mode methodology in fuzzy logic controller (SMFC) to improve the stability of systems, therefore FSMC is a controller based on SMC but SMFC works based on FLC [26-40].

Adaptive control used in systems whose dynamic parameters are varying and/or have unstructured disturbance and need to be training on line. Adaptive fuzzy inference system provide a good knowledge tools for adjust a complex uncertain nonlinear system with changing dynamics to have an acceptable performance. Combined adaptive method to artificial sliding mode controllers can help to controllers to have a better performance by online tuning the nonlinear and time variant parameters [26-40].

This paper is organized as follows: In section 2, dynamic formulation of robot manipulator is presented. Detail of mamdani fuzzy inference estimator is introduce and applied to sliding mode methodology is presented in section 3. In section 4, design adaptive methodology and applied to propose method is presented. In section 5, the simulation result is presented and finally in section 6, the conclusion is presented.

2. APPLICATION: ROBOT MANIPULATOR DYNAMIC FORMULATION

The equation of an *n-DOF* robot manipulator governed by the following equation [1, 4, 33-40]:

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

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 [33-40]:

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

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, 33-40]:

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

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

3. MAMDANI FUZZY INFERENCE ESTIMATOR SLIDING MODE METHODOLOGY

Sliding mode controller (SMC) is a influential nonlinear, stable and robust controller which it 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, 5-11, 33-40]. A time-varying sliding surface $s(x,t)$ is given by the following equation:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\,\tilde{x} = 0 \tag{4}$$

where λ is the constant and it is positive. The derivation of S, namely, $\dot{S}$ can be calculated as the following formulation [5-11, 33-40]:

$$\dot{S} = (\ddot{\mathbf{x}} - \ddot{\mathbf{x}}_{\mathrm{d}}) + \boldsymbol{\lambda}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathrm{d}}) \tag{5}$$

The control law for a multi degrees of freedom robot manipulator is written as:

$$U = U_{eq} + U_r \tag{6}$$

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

$$U_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \tag{7}$$

Where $M(q)$ is an inertia matrix which it is symmetric and positive, $V(q,\dot{q}) = B + C$ is the vector of nonlinearity term and $G(q)$ is the vector of gravity force and U_r with minimum chattering based on [33-40] is computed as;

$$U_r = K \cdot (\mathrm{mu} + \mathrm{b})\left({S}/{\emptyset}\right) \tag{8}$$

Where $\emptyset_u = mu + b = saturation_{fuction}$ is a dead zone (saturation) function and, u and b are unlimited coefficient, by replace the formulation (5) in (3) the control output can be written as;

$$U = U_{eq} + K.(\mathrm{mu} + \mathrm{b})\left({S}/{\emptyset}\right) = \begin{cases} U_{eq} + K.\mathrm{sgn}(S) & ,|S| \geq \emptyset \\ U_{eq} + K.{S}/{\emptyset} & ,|S| < \emptyset \end{cases} \tag{9}$$

Where the function of $sgn(S)$ defined as;

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{10}$$

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) [16-25, 33-40].

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

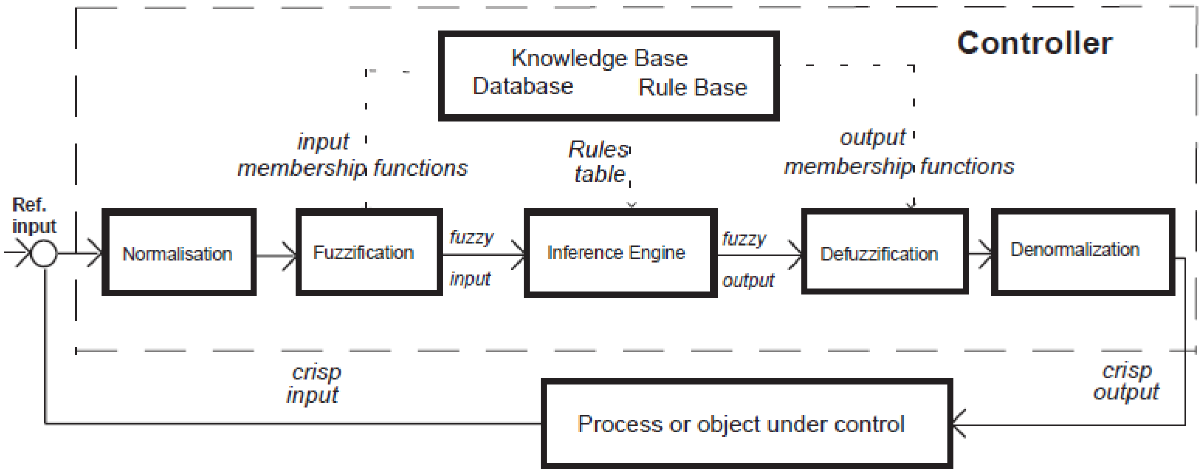

FIGURE 1: Block diagram of a fuzzy controller with details.

The fuzzy system can be defined as below [40]

$$f(x) = U_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = \psi(S) \tag{11}$$

where $\theta = (\theta^1, \theta^2, \theta^3, \ldots \ldots, \theta^M)^T, \zeta(x) = (\zeta^1(x), \zeta^2(x), \zeta^3(x), \ldots \ldots, \zeta^M(x))^T$

$$\zeta^1(x) = \frac{\sum_i \mu_{(xi)} x_i}{\sum_i \mu_{(xi)}} \tag{12}$$

where $\theta = (\theta^1, \theta^2, \theta^3, \ldots \ldots, \theta^M)$ is adjustable parameter in (8) and $\mu_{(xi)}$ is membership function.

error base fuzzy controller can be defined as

$$U_{fuzzy} = \psi(S) \tag{13}$$

In this work the fuzzy controller has one input which names; sliding function. Fuzzy controller with one input is difficult to implementation, because it needs large number of rules, to cover equivalent part estimation [16-25]. In this fuzzy inference system researcher is defined 7 linguistic variables. As a summary the design of fuzzy inference system estimator 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 deffuzzification [16-18].

Fuzzification: the first step in fuzzification is determine inputs and outputs which, it has one input; namely sliding function (S) and one output ($\emptyset$). The sliding function ($S = \lambda e + \dot{e}$) which related to the difference between desired and actual output position and the difference between desired and actual velocity. The second step is chosen an appropriate membership function for inputs and output which, for simplicity in implementation and also to have an acceptable performance the researcher is selected the triangular membership function which it is shown in Figure 2. The third step is chosen the correct labels for each fuzzy set which, in this research namely as linguistic variable. The linguistic variables for input are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and the linguistic variables to find the output are; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR), Large Right (LR).

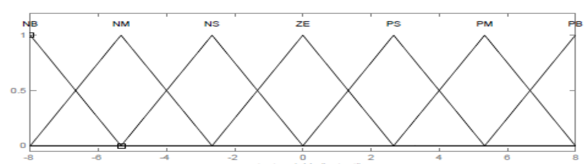

FIGURE 2: Membership function: triangular

Fuzzy Rule Base and Rule Evaluation: the first step in rule base and evaluation is provide a least structured method to derive the fuzzy rule base which, expert experience and control engineering knowledge is used because this method is the least structure of the other one and the researcher derivation the fuzzy rule base from the knowledge of system operate and/or the classical controller. Design the rule base of fuzzy inference system can play important role to design the best performance of fuzzy sliding mode controller, that to calculate the fuzzy rule base the researcher is used to heuristic method which, it is based on the behavior of the control of robot manipulator suppose that two fuzzy rules in this controller are;

F.R^1: *IF S is NB, THEN ∅ is LL* **(14)**
F.R^2: *IF e is PS THEN ∅ is ML*

The complete rule base for this controller is shown in Table 1. Rule evaluation focuses on operation in the antecedent of the fuzzy rules in fuzzy inference system. This part is used AND/OR fuzzy operation in antecedent part which AND operation is used.

TABLE 1: Rule table (Mamdani'sFIS)

S	NB	NM	NS	ZE	PS	PM	PB
∅	LL	ML	SL	Z	SR	MR	LR

Aggregation of the Rule Output (Fuzzy inference): Max-Min aggregation is used to this work which the calculation is defined as follows;

$$\mu_U(x_k,y_k,U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k,y_k,U) = max\left\{min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k,y_k),\mu_{p_m}(U)\right]\right\} \tag{15}$$

Deffuzzification: The last step to design fuzzy inference in our controller is defuzzification. This part is used to transform fuzzy set to crisp set, therefore the input for defuzzification is the aggregate output and the output of it is a crisp number. In this design the Center of gravity method (COG) is used and calculated by the following equation [25];

$$COG(x_k,y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \mu_u(x_k,y_k,U_i)}{\sum_i \sum_{j=1}^{r} \mu_u(x_k,y_k,U_i)} \tag{16}$$

The fuzzy division can be reached the best state when $S.\dot{S} < 0$ and the error is minimum by the following formulation

$$\theta^* = \arg\min\,[Sup_{x\in U}|\sum_{l=1}^{M} \theta^T \zeta(x) - U_{equ}|] \tag{17}$$

Where $\theta^*$is the minimum error, $sup_{x\in U}|\sum_{l=1}^{M} \theta^T \zeta(x) - \tau_{equ}|$ is the minimum approximation error.

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l [\mu_A(S_j)]}{\sum_{l=1}^{M} [\mu_A(S_j)]} = \theta_j^T \zeta_j(S_j) \tag{18}$$

Where $\zeta_j(S_j) = [\zeta_j^1(S_j), \zeta_j^2(S_j), \zeta_j^3(S_j), \ldots\ldots, \zeta_j^M(S_j)]^T$

$$\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)} \tag{19}$$

where the $\gamma_{s_j}$is the positive constant.

According to the nonlinear dynamic equivalent formulation of robot manipulator the nonlinear equivalent part is estimated by (8)

$$[M^{-1}(B+C+G)+\dot{S}]M = \sum_{l=1}^{M} \theta^T \zeta(x) - \lambda S - K \tag{20}$$

Based on (3) the formulation of proposed fuzzy sliding mode controller can be written as;

$$U = U_{eq_{fuzzy}} + U_r \tag{21}$$

Where $U_{eq_{fuzzy}} = [M^{-1}(B + C + G) + \dot{S}]M + \sum_{l=1}^{M} \theta^T \zeta(x) + K$
Figure 3 is shown the proposed fuzzy sliding mode controller.

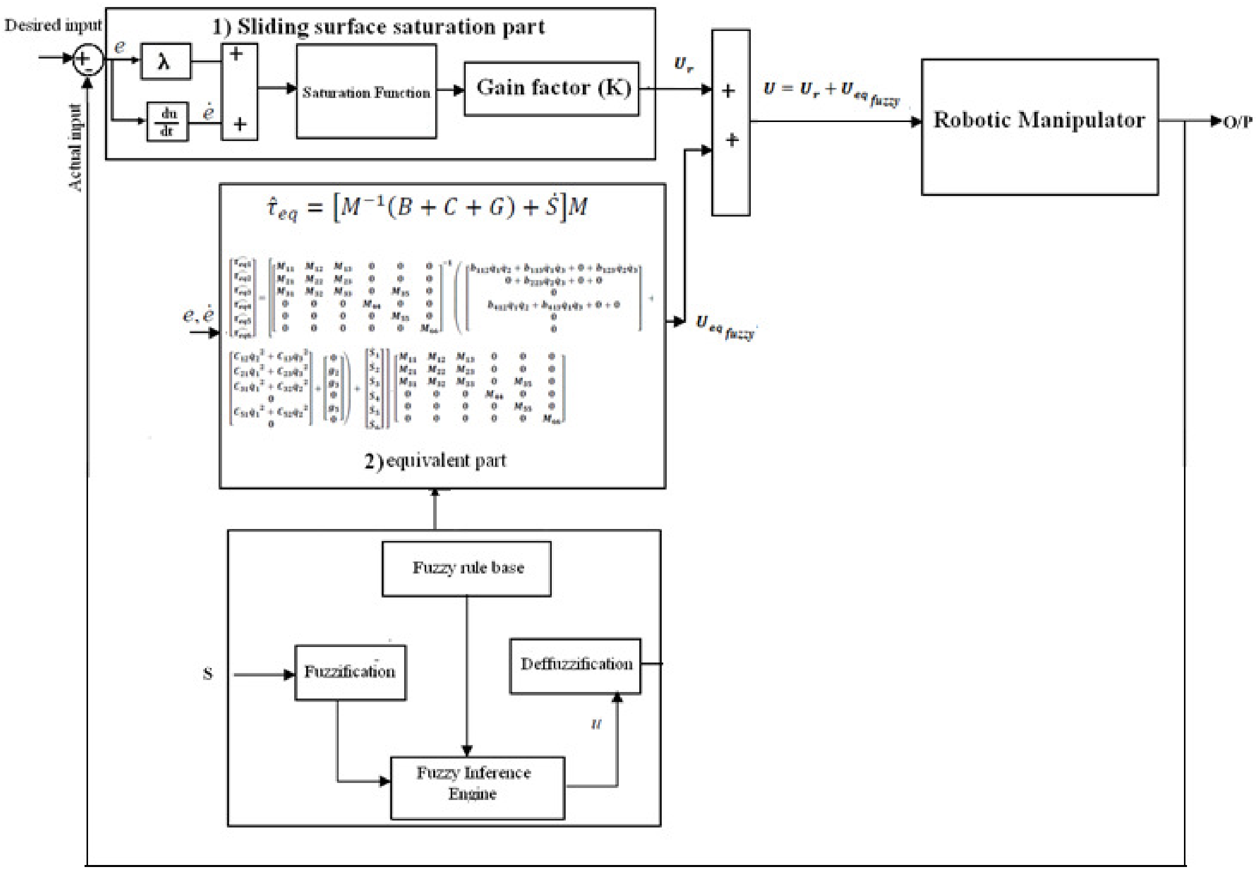

FIGURE 3: Proposed fuzzy sliding mode algorithm: applied to robot manipulator

4. DESIGN ADAPTIVE SLIDING MODE FUZZY ALGORITM: APPLIED TO PROPOSED METHODOLOGY

However proposed FSMC has satisfactory performance but calculate the sliding surface slope by try and error or experience knowledge is very difficult, particularly when system has uncertainties; sliding mode fuzzy self tuning sliding function fuzzy sliding mode controller is recommended.

$$U_{SF} = \psi\left(K \cdot (mx + b) \cdot \left({}^{S}/_{\emptyset}\right)\right) \tag{22}$$

Where U_{SF} is sliding mode fuzzy output function. The adaption low is defined as

$$\dot{\theta}_j = \gamma_{sj} S_j \zeta_j(S_j) \tag{23}$$

where the γ_{sj} is the positive constant and $\zeta_j(S_j) = [\zeta_j^1(S_j), \zeta_j^2(S_j), \zeta_j^3(S_j), \ldots\ldots, \zeta_j^M(S_j)]^T$

$$\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)} \tag{24}$$

As a result proposed method is very stable with a good performance. Figure 4 is shown the block diagram of proposed adaptive sliding mode fuzzy applied to fuzzy sliding mode controller.

The fuzzy system can be defined as below

$$f(x) = \tau_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = \psi(e, \dot{e}) \quad (25)$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots \dots, \theta^M)^T, \zeta(x) = (\zeta^1(x), \zeta^2(x), \zeta^3(x), \dots \dots, \zeta^M(x))^T$

$$\zeta^1(x) = \frac{\sum_i \mu_{(xi)} x_i}{\sum_i \mu_{(xi)}} \quad (26)$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots \dots, \theta^M)$ is adjustable parameter in (25) and $\mu_{(xi)}$ is membership function.
error base fuzzy controller can be defined as

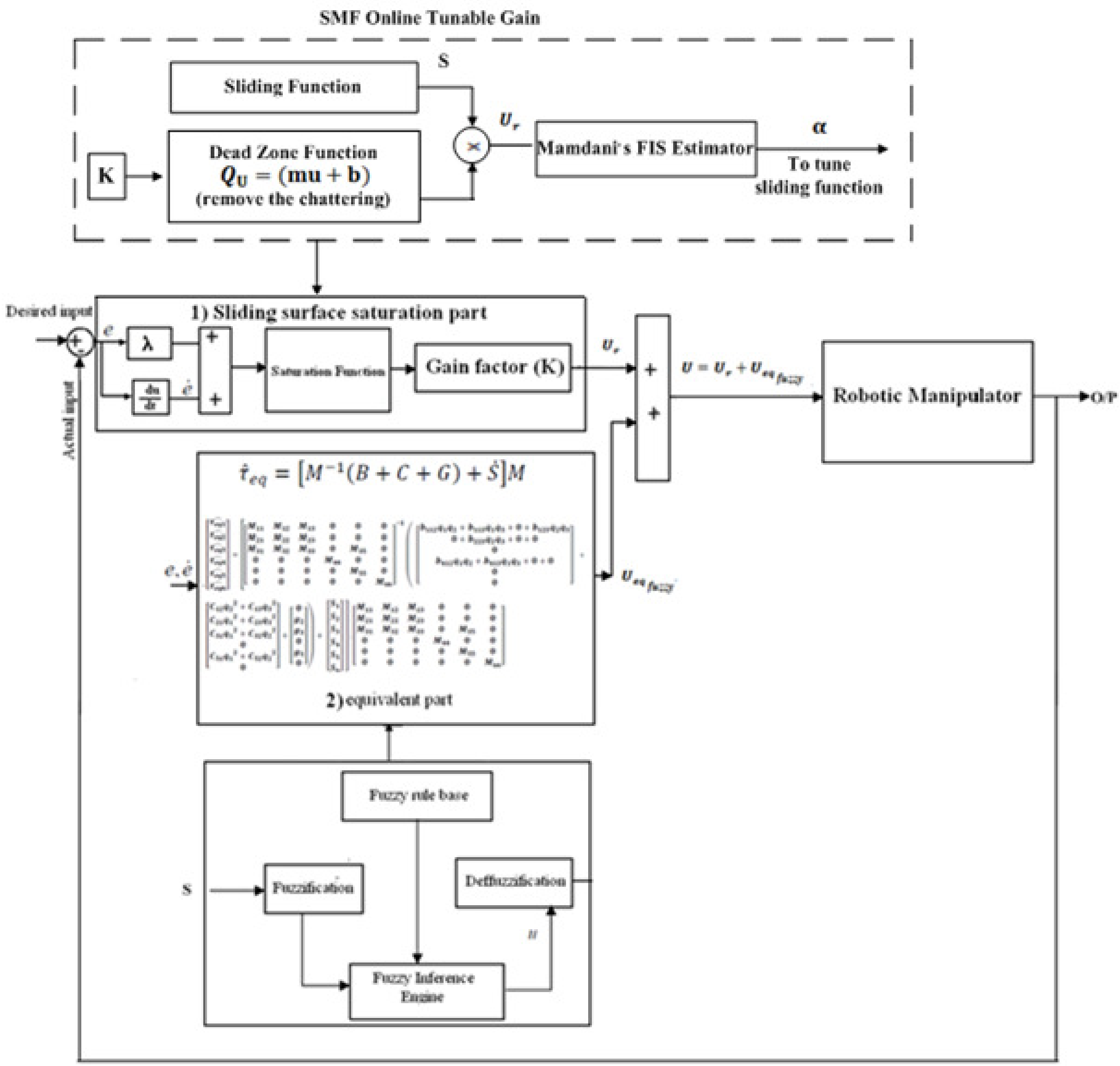

FIGURE 4: Proposed adaptive sliding fuzzy tune FSMC algorithm: applied to robot arm

$$\tau_{fuzzy} = \psi(e, \dot{e}) \quad (27)$$

According to the formulation in sliding mode algorithm

$$if\ S = 0\ then\ \dot{e} = \lambda e \tag{28}$$

the fuzzy division can be reached the best state when $S.\dot{S} < 0$ and the error is minimum by the following formulation

$$\theta^* = \arg\min\left[Sup_{x \in U}\left|\sum_{l=1}^{M} \theta^T \zeta(x) - \tau_{equ}\right|\right] \tag{29}$$

Where θ^* is the minimum error, $sup_{x \in U}\left|\sum_{l=1}^{M} \theta^T \zeta(x) - \tau_{equ}\right|$ is the minimum approximation error. The adaptive controller is used to find the minimum errors of $\theta - \theta^*$.

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l [\mu_A(S_j)]}{\sum_{l=1}^{M} [\mu_A(S_j)]} = \theta_j^T \zeta_j(S_j) \tag{30}$$

Where $\zeta_j(S_j) = [\zeta_j^1(S_j), \zeta_j^2(S_j), \zeta_j^3(S_j), \ldots\ldots, \zeta_j^M(S_j)]^T$

$$\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)} \tag{31}$$

the adaption low is defined as

$$\dot{\theta}_j = \gamma_{sj} S_j \zeta_j(S_j) \tag{32}$$

where the γ_{sj} is the positive constant.
According to the formulation in fuzzy sliding and also sliding mode fuzzy

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) = \sum_{l=1}^{M} \theta^T \zeta(x) - \lambda S - K \tag{33}$$

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

$$M\dot{S} = -VS + M\dot{S} + VS + G - \tau \tag{34}$$

It is supposed that

$$S^T(\dot{M} - 2V)S = 0 \tag{35}$$

it can be shown that

$$M\dot{S} + (V + \lambda)S = \Delta f - K \tag{36}$$

where $\Delta f = [M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q)] - \sum_{l=1}^{M} \theta^T \zeta(x)$
as a result $\dot{V}$ is became

$$\begin{aligned}
\dot{V} &= \frac{1}{2} S^T \dot{M} S - S^T V S + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= S^T(-\lambda S + \Delta f - K) + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j(\Delta f_j - K_j)] - S^T \lambda S + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j(\Delta f_j - \theta_j^T \zeta_j(S_j))] - S^T \lambda S + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j(\Delta f_j - (\theta_j^*)^T \zeta_j(S_j) + \phi_j^T \zeta_j(S_j))] - S^T \lambda S + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j(\Delta f_j - ((\theta_j^*)^T \zeta_j(S_j))] - S^T \lambda S)] + \sum (\frac{1}{\gamma_{sj}} \phi_j^T [\gamma_{sj} \zeta_j(S_j) S_j + \dot{\phi}_j])
\end{aligned}$$

where $\dot{\theta}_j = \gamma_{sj} S_j \zeta_j(S_j)$ is adaption law, $\dot{\phi}_j = -\dot{\theta}_j = -\gamma_{sj} S_j \zeta_j(S_j)$, consequently $\dot{V}$ can be considered by

$$\dot{V} = \sum_{j=1}^{m} [S_j \, \Delta f_j - \left(((\theta_j^*)^T \zeta_j(S_j)) \right)] - S^T \lambda S \quad \textbf{(37)}$$

the minimum error can be defined by

$$e_{mj} = \Delta f_j - \left(((\theta_j^*)^T \zeta_j(S_j)) \right) \quad \textbf{(38)}$$

$\dot{V}$ is intended as follows

$$\begin{aligned} \dot{V} &= \sum_{j=1}^{m} [S_j \, e_{mj}] - S^T \lambda S \\ &\le \textstyle\sum_{j=1}^{m} |S_j \,||e_{mj}| - S^T \lambda S \\ &= \sum_{j=1}^{m} |S_j \,||e_{mj}| - \lambda_j S_j^{\,2} \\ &= \sum_{j=1}^{m} |S_j \,|(|e_{mj}| - \lambda_j S_j) \end{aligned} \quad \textbf{(39)}$$

For continuous function $g(x)$, and suppose $\varepsilon > 0$ it is defined the fuzzy logic system in form of (27) such that

$$Sup_{x \in U} |f(x) - g(x)| < \epsilon \quad \textbf{(40)}$$

the minimum approximation error (e_{mj}) is very small.

$$if \;\; \lambda_j = \alpha \quad that \quad \alpha |S_j| > e_{mj} \; (S_j \ne 0) \quad then \quad \dot{V} < 0 \; for \; (S_j \ne 0) \quad \textbf{(41)}$$

5 SIMULATION RESULTS

PD sliding mode controller (PD-SMC), proposed PD fuzzy sliding mode controller (PD FSMC) and proposed adaptive sliding mode fuzzy algorithm Fuzzy Sliding Mode Controller (SMFAFSMC) were tested to Step response trajectory. This simulation applied to three degrees of freedom robot arm therefore 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. Trajectory performance, torque performance, disturbance rejection, steady state error and RMS error are compared in these controllers. It is noted that, these systems are tested by band limited white noise with a predefined 40% of relative to the input signal amplitude which the sample time is equal to 0.1. This type of noise is used to external disturbance in continuous and hybrid systems.

Tracking Performances: Figure 5 is shown tracking performance for first, second and third link in SMC, FSMC and SMFAFSMC without disturbance for sinus trajectories. By comparing sinus response trajectory without disturbance in SMC, FSMC and SMFAFSMC it is found that the SMC's and FSMC's overshoot (4%) is higher than SMFAFSMC (0%), although all of them have about the same rise time.

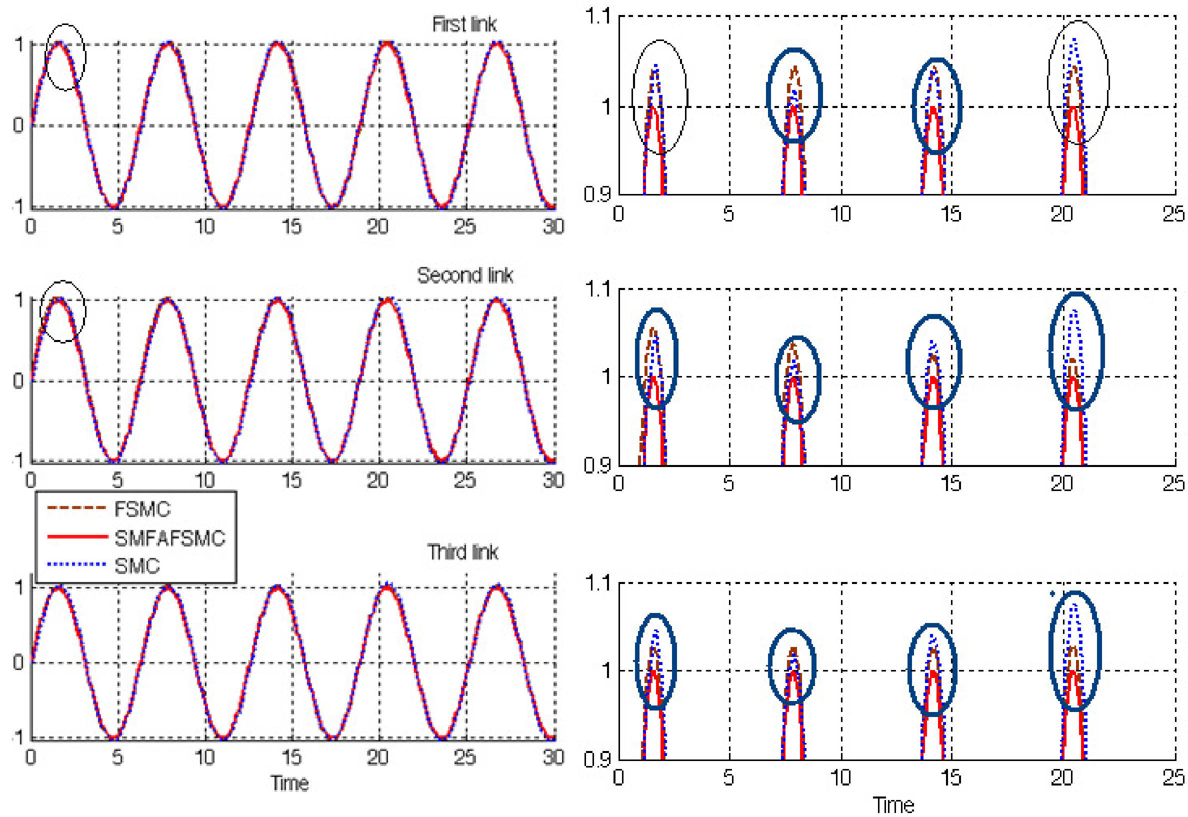

FIGURE 5: FSMC, SMFAFSMC and SMC: applied to robot manipulator.

Disturbance Rejection: Figure 6 has shown the power disturbance elimination in SMC, FSMC and SMFAFSMC. The main target in these controllers is disturbance rejection as well as reduces the chattering. A band limited white noise with predefined of 40% the power of input signal is applied to above controllers. It found fairly fluctuations in SMC and FSMC trajectory responses.

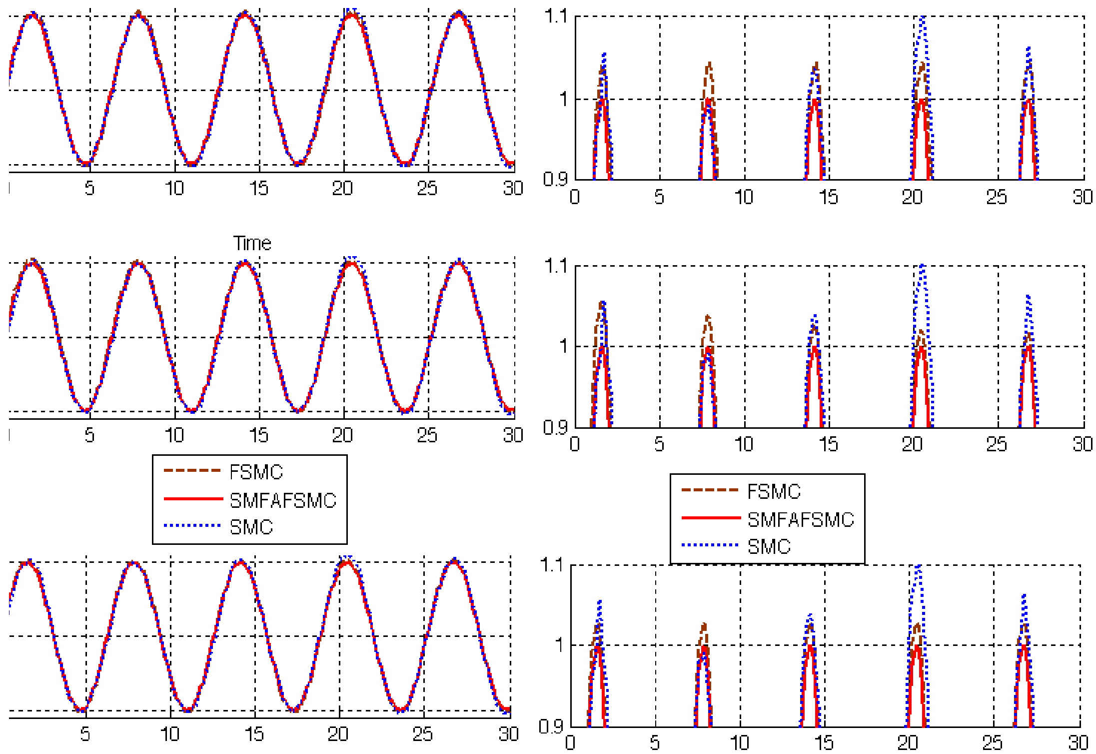

FIGURE 6: FSMC, SMFAFSMC and SMC with disturbance: applied to robot manipulator.

Among above graph relating to trajectory following with external disturbance, FLC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the SMC's and FSMC's overshoot (9%) is higher than SMFAFSMC (0%).

Error Calculation: Although SMC and FSMC have the same error rate but SMFAFSMC has a better performance in presence of external disturbance (refer to Table 2 and Figure 7), they have oscillation tracking which causes chattering phenomenon. As it is obvious in Table.2 FSMC is a SMC which estimate the equivalent part so FSMC have acceptable performance with regard to SMC in presence of certain and uncertainty. Figure 7 is shown steady state and RMS error in SMC and FSMC and SMFAFSMC in presence of external disturbance.

TABLE 2: RMS Error Rate of Presented controllers

RMS Error Rate	**SMC**	**FSMC**	**SMFAFSMC**
Without Noise	**1e-3**	**0.6e-3**	**0.6e-6**
With Noise	**0.012**	**0.0012**	**0.65e-6**

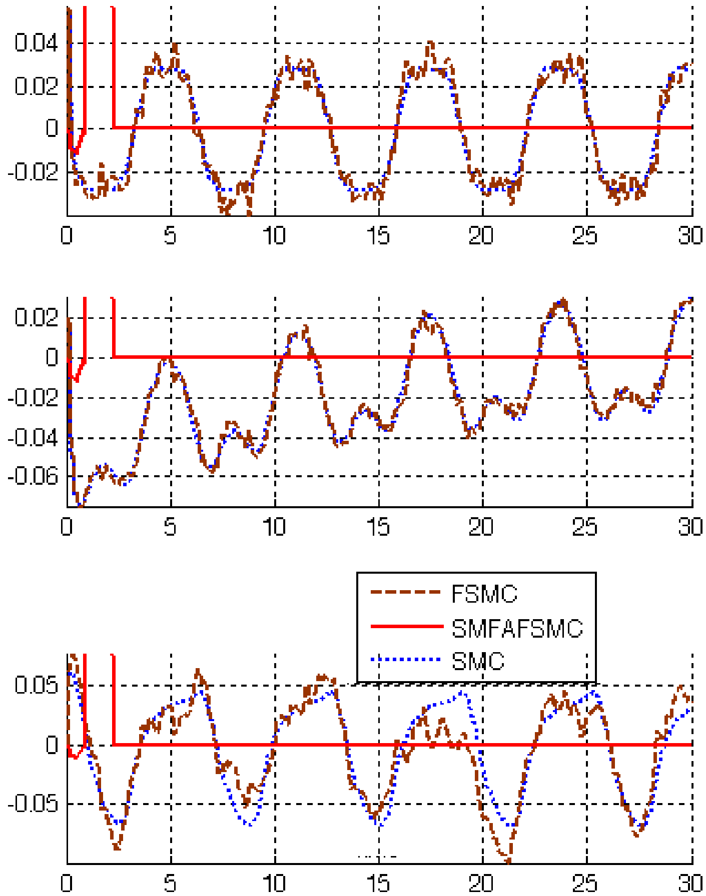

FIGURE 7: FSMC, SMFAFSMC and SMC steady state error with external disturbance: applied to robot manipulator

In these methods if integration absolute error (IAE) is defined by (15), table 3 is shown comparison between these two methods.

$$IAE = \int_0^{\infty} |e(t)|\, dt \quad \textbf{(42)}$$

Table 3: Calculate IAE

Method	Traditional SMC	FSMC	SMFAFSMC
IAE	490.1	409	210

6 CONCLUSIONS

In this research, a sliding mode fuzzy adaptive fuzzy sliding mode algorithm is proposed in order to design high performance robust controller in presence of structure unstructured uncertainties. The performance is improved by using the advantages of sliding mode algorithm, artificial intelligence method and adaptive algorithm while the disadvantages removed by added each method to previous method. Fuzzy logic method by adding to the sliding mode controller has covered negative points in fuzzy and sliding algorithms. Obviously robot manipulator dynamic parameters are nonlinear therefore design nonlinear robust model free controller is a main goal with regard to sliding mode and fuzzy logic methodology. This paper focuses on comparison between sliding mode controller, fuzzy sliding mode controller and adaptive sliding mode algorithm fuzzy sliding mode controller, to opt the best control method for the uncertain second order system (e.g., robot manipulator). Higher implementation quality of response and model free controller versus an acceptable performance in chattering, trajectory and error is reached by designing adaptive sliding mode fuzzy algorithm fuzzy sliding mode controller. This implementation considerably removes the chattering phenomenon and error in the presence of uncertainties. As a result, this controller will be able to control a wide range of nonlinear second order uncertain system (e.g., robot manipulator) with a high sampling rates because its easy to implement.

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