Novel Artificial Control of Nonlinear Uncertain System: Design a Novel Modified PSO SISO Lyapunov Based Fuzzy Sliding Mode Algorithm

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Abstract

This research is focused on novel particle swarm optimization (PSO) SISO Lyapunov based fuzzy estimator sliding mode algorithms derived in the Lyapunov sense. The stability of the closed-loop system is proved mathematically based on the Lyapunov method. PSO SISO fuzzy compensate sliding mode method design a SISO fuzzy system to compensate for the dynamic model uncertainties of the nonlinear dynamic system and chattering also solved by nonlinear fuzzy saturation like method. Adjust the sliding function is played important role to reduce the chattering phenomenon and also design acceptable estimator applied to nonlinear classical controller so PSO method is used to off-line tuning. 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 nonlinear (fuzzy) boundary like 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 applied fuzzy inference system into sliding mode algorithm to design and estimate model-free nonlinear dynamic equivalent part. 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 PSO method to a fuzzy sliding mode controller to tune the parameters of the fuzzy rules in use will ensure a moderate computational load. The PSO method in this algorithm is designed based on the PSO stability theorem. Asymptotic stability of the closed loop system is also proved in the sense of Lyapunov.

Keywords: Particle Swarm Optimization, Lyapunov Based Fuzzy Estimator Sliding Mode Algorithms, Nonlinear Fuzzy Saturation like Method, Sliding Mode Controller, Chattering Phenomenon.

1. INTRODUCTION

Robot manipulators have many applications in aerospace, manufacturing, automotive, medicine and other industries. Robot manipulators consist of three main parts: mechanical, electrical, and control. In the mechanical point of view, robot manipulators are collection of serial or parallel links which have connected by revolute and/or prismatic joints between base and end-effector frame. The robot manipulators electrical parts are used to links motion. Control part is used to adjust the timing between the subparts of robot manipulator to reach the best performance (trajectory) [1].

It is a well known fact, the aim of science and modern technology has making an easier life. Conversely, modern life includes complicated technical systems which these systems (e.g., robot manipulators) are nonlinear, time variant, and uncertain in measurement, they need to have controlled. Consequently it is hard to design accurate models for these physical systems because they are uncertain. At present, in some applications robot manipulators are used in unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design nonlinear robust controller with an acceptable performance (e.g., minimum error, good trajectory, disturbance rejection) [1-8].

Sliding mode controller (SMC) is one of the influential nonlinear controllers in certain and uncertain systems which are used to present a methodical solution for two main important controllers' challenges, which named: stability and robustness. Conversely, this controller is used in different applications; sliding mode controller has subsequent drawbacks i.e. chattering phenomenon, and nonlinear equivalent dynamic formulation in uncertain systems[1-2]. 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, 9-20]. Sliding mode controller is divided into two main sub controllers: discontinues controller($\boldsymbol{U_{dis}}$) and equivalent controller($\boldsymbol{U_{eq}}$). 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 [31-40]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]; [48-62]. 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.
The tuning-gain block has been designed at each input/output stage. The PSO has been used to obtain the optimal value of the sliding surface slope. Off-line control method (e.g., PSO) is used in systems whose dynamic parameters are varying and need to be trained off line. In general states PSO algorithm can be tuned classical controller coefficient and fuzzy coefficient or membership function. PSO fuzzy inference system provide a good knowledge tools to adjust a complex uncertain nonlinear system with changing dynamics to have an acceptable performance [63-65] Combined PSO method to artificial sliding mode controllers can help the controllers to have a better performance by off-line tuning the nonlinear and time variant parameters [63-65].

In this research we will highlight the SISO PSO fuzzy sliding mode algorithm with estimates the equivalent part derived in the Lyapunov sense. This algorithm will be analyzed and evaluated on robotic manipulators. Section 2, serves as an introduction to the classical sliding mode control algorithm and its application to a two degree of-freedom robot manipulator, describe the objectives and problem statements. Part 3, introduces and describes the methodology algorithms and proves Lyapunov stability. Section 4 presents the simulation results of this algorithm applied to a 2 degree-of-freedom robot manipulator and the final section is describe the conclusion.

2. OBJECTIVES, PROBLEM STATEMENTS AND SLIDING MODE FORMULATION

When system works with various parameters and hard nonlinearities design linear controller technique is very useful in order to be implemented easily but it has some limitations such as working near the system operating point[2-20]. Sliding mode 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: chattering problem; which caused the high frequency oscillation in the controllers output and equivalent dynamic formulation; calculate the equivalent control formulation is difficult because it depends on the dynamic equation [20]. Conversely pure FLC works in many areas, it cannot guarantee the basic requirement of stability and acceptable performance[30-40]. Although both SMC and FLC have been applied successfully in many applications but they also have some limitations. The linear boundary layer method is used to reduce or eliminate the chattering and fuzzy estimator is used instead of dynamic equivalent equation to implement easily and avoid mathematical model base controller. To reduce the effect of uncertainty in proposed method, self tuning sliding mode fuzzy method is applied in fuzzy sliding mode controller in robot manipulator in order to solve above limitation.
The dynamic equation of an n-link robot manipulator is define as [53-62]

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

Where $q \in R^n$ is the vector of joint position, $M(q) \in R^{n\times n}$ is the inertial matrix, $C(q,\dot{q}) \in R^n$ is the matrix of Coriolis and centrifugal forces, $G(q) \in R^n$ is the gravity vector and $\tau \in R^n$ is the vector of joint torques.
This work focuses on two-degree-of-freedom robot manipulator.
The dynamics of this robotic manipulator is given by [1, 6, 9-14]

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

Where

$$M(q) = \begin{bmatrix} m_1 l^2 + 2m_2 l^2 + 2m_2 l^2 \cos q_2 & m_2 l^2 + m_2 l^2 \cos q_2 \\ m_2 l^2 + m_2 l^2 \cos q_2 & m_2 l^2 \end{bmatrix} \quad \textbf{(3)}$$

$$C(q,\dot{q}) = \begin{bmatrix} -2m_2 l^2 \dot{q}_1 \dot{q}_2 \sin q_2 - m_2 l^2 \dot{q}_2^2 \sin q_2 \\ m_2 l^2 \dot{q}_1^2 \sin q_2 \end{bmatrix} \quad (4)$$

Our target is to track the desired trajectories q_d of the robotic manipulators (2) by using a sliding mode controller. We extract $\dot{q}$ from $C(q,\dot{q})$ in (2) and rewrite (2) as

$$\tau = M(q)\ddot{q} + c(q,\dot{q})\dot{q} \quad (5)$$

Where

$$C(q,\dot{q}) = \begin{bmatrix} -m_2 l^2 \dot{q}_2 \sin q_2 - m_2 l^2 \dot{q}_1 \sin q_2 - m_2 l^2 \dot{q}_2 \sin q_2 \\ m_2 l^2 \dot{q}_1 \sin q_2 & 0 \end{bmatrix} \quad (6)$$

We define the tracking error as

$$e = q - q_d \quad (7)$$

Where $q = [q_1, q_2]^T$, $q_d = [q_{1d}, q_{2d}]^T$. The sliding surface is expressed as

$$s = \dot{e} + \lambda e \quad (8)$$

Where $\lambda = diag[\lambda_1, \lambda_2]$, λ_1 and λ_2 are chosen as the bandwidth of the robot controller.
We need to choose τ to satisfy the sufficient condition (9). We define the reference state as

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) = \dot{S}\cdot S = [f - \hat{f} - K\operatorname{sgn}(s)]\cdot S = (f - \hat{f})\cdot S - K|S| \quad (9)$$

$$\dot{q}_e = \dot{q} - s = \dot{q}_d - \lambda e \quad (10)$$

Now we pick the control input τ as

$$\tau = M^{\wedge}\ddot{q}_r + C_1^{\wedge}\dot{q}_r - As - Ksgn(s) \quad (11)$$

Where $M^{\wedge}$ and $C_1^{\wedge}$ are the estimations of $M(q)$ and $C_1(q,\dot{q})$; $A = diag[a_1, a_2]$ and $K = diag[k_1, k_2]$ are diagonal positive definite matrices. From (7) and (11), we can get

$$M\dot{s} + (C_1 + A)s = \Delta f - Ksgn(s) \quad (12)$$

Where $\Delta f = \Delta M\ddot{q}_r + \Delta C_1\dot{q}_r$, $\Delta M = M^{\wedge} - M$ and $\Delta C_1 = C_1^{\wedge} - C_1$. We assume that the bound $|\Delta f_i|_{bound}$ of $\Delta f_i (i = 1,2)$ is known. We choose K as

$$K_i \geq |\Delta f_i|_{bound} \quad (13)$$

We pick the Lyapunov function candidate to be

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

Since M is positive symmetric definite, $V > 0$ for $s \neq 0$. Take the derivative of M with respect to time in (6) and we get

$$\dot{M} = \begin{bmatrix} -2]m_2 l^2 \dot{q}_2 \sin q_2 - m_2 l^2 \dot{q}_2 \sin q_2 \\ -m_2 l^2 \dot{q}_2 \sin q_2 & 0 \end{bmatrix} \quad (15)$$

From (11) and (15) we get

$$\dot{M} - 2C_1 = \begin{bmatrix} 0 & 2m_2 l^2 \dot{q}_1 \sin q_2 + m_2 l^2 \dot{q}_2 \sin q_2 \\ -2m_2 l^2 \dot{q}_1 \sin q_2 - m_2 l^2 \dot{q}_2 \sin q_2 & 0 \end{bmatrix} \quad (16)$$

Which is a skew-systemmetric matrix satisfying

$$s^T(\dot{M} - 2C_1)s = 0 \quad (17)$$

Then $\dot{V}$ becomes

$$\begin{aligned} \dot{V} &= s^T M\dot{s} + \frac{1}{2}s^T \dot{M}s \\ &= s^T(M\dot{s} + C_1 s) \\ &= s^T[-As + \Delta f - Ksgn(s)] \\ &= \sum_{i=1}^{2}(s_i[\Delta f_i - K_i sgn(s_i)]) - s^T As \end{aligned} \quad (18)$$

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

$$\dot{V} = \sum_{i=1}^{2} (s_i[\Delta f_i - K_i sgn(s_i)]) - s^T A s \le -s^T As < 0 \quad (s \neq 0) \tag{19}$$

To attenuate chattering problem, we introduce a saturation function in the control law instead of the sign function in (9). The control law becomes

$$\tau = \hat{M}\ddot{q}_r + \hat{C}_1\dot{q}_r - As - Ksat(s/\Phi) \tag{20}$$

In this classical sliding mode control method, the model of the robotic manipulator is partly unknown. To attenuate chattering, we use the saturation function described in (20). Our control law changes to

$$\tau = \hat{M}\ddot{q}_r + \hat{C}_1\dot{q}_r - As - Ksat(s) \tag{21}$$

The main goal is to design a position controller for robot manipulator with acceptable performances (e.g., trajectory performance, torque performance, disturbance rejection, steady state error and RMS error). Robot manipulator has nonlinear dynamic and uncertain parameters consequently; following objectives have been pursuit in the mentioned study.

- To develop a chattering in a position pure sliding mode controller against uncertainties.
- To design and implement a position fuzzy estimator sliding mode controller in order to solve the equivalent problems in the pure sliding mode control.
- To develop a position sliding mode fuzzy adaptive fuzzy sliding mode controller in order to solve the disturbance rejection.

Figure 1 is shown the classical sliding mode methodology with linear saturation function to eliminate the chattering.

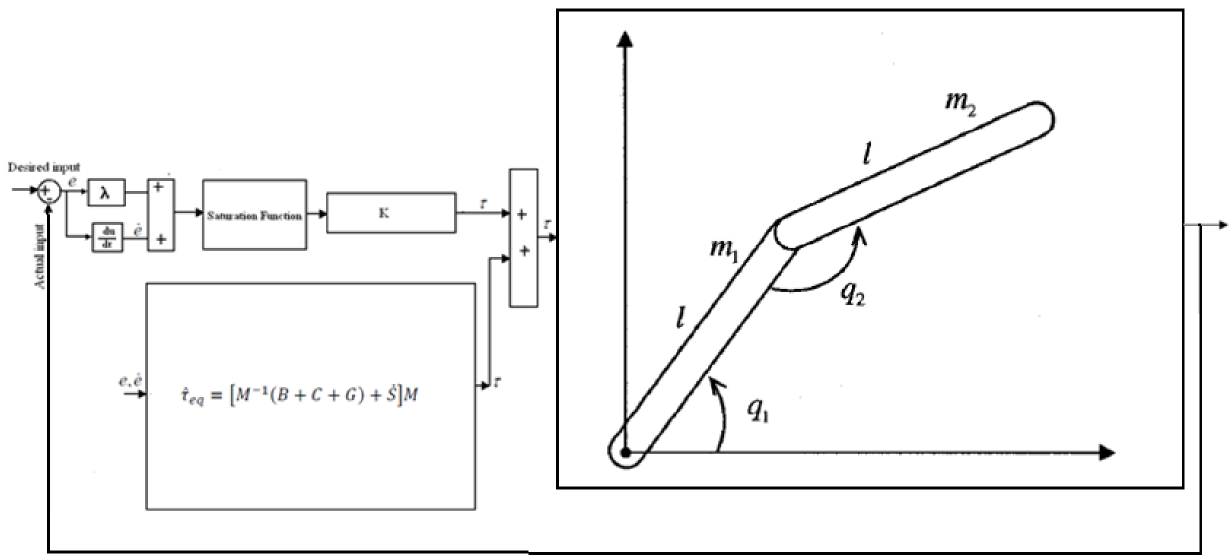

FIGURE 1: Classical sliding mode controller: applied to two-link robotic manipulator

3. METHODOLOGY: DESIGN A NOVEL PSO SISO LYAPUNOV BASED FUZZY ESTIMATOR SLIDING MODE ALGORITHM

First part is focuses on design chattering free sliding mode methodology using nonlinear saturation like algorithm. A time-varying sliding surface $s(x,t)$ is given by the following equation:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\tilde{x} = 0 \tag{22}$$

where λ is the constant and it is positive. The derivation of S, namely, $\dot{S}$ can be calculated as the following formulation [5-16, 41-62]:

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{23}$$

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

$$U = U_{eq} + U_r \tag{24}$$

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

$$U_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \tag{25}$$

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 [9-16] is computed as;

$$U_r = K \cdot (\mathrm{mu} + \mathrm{b}) \left(S/_{\emptyset}\right) \tag{26}$$

Where $\emptyset_u = mu + b = Linear\ saturation_{fuction}$ 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;

$$U = U_{eq} + K.(\mathrm{mu} + \mathrm{b})\left(S/_{\emptyset}\right) = \begin{cases} U_{eq} + K.\mathrm{sgn}(S) & ,|S| \geq \emptyset \\ U_{eq} + K.S/_{\emptyset} & ,|S| < \emptyset \end{cases} \tag{27}$$

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

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{28}$$

Fuzzy logic is a multivalued logic, which can transfer mathematical equation of nonlinear dynamic parameter to expert mathematical knowledge [31]. A block diagram of fuzzy controller is shown in Figure 2. Even though the application area for fuzzy logic control is really wide, the basic form for all command types of controllers still consists of: Input fuzzification (binary-to-fuzzy [B/F] conversion), Fuzzy rule base, Inference engine, and Output deffuzzification (fuzzy-to-binary [F/B] conversion) [32-35].

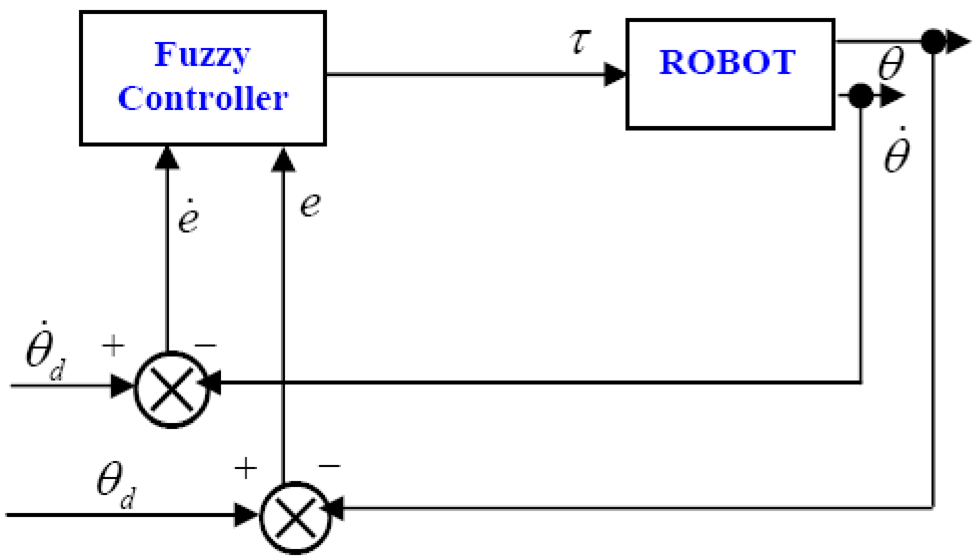

FIGURE 2: Fuzzy controller block diagram [40]

The basic structure of a fuzzy controller is shown in Figure 3.

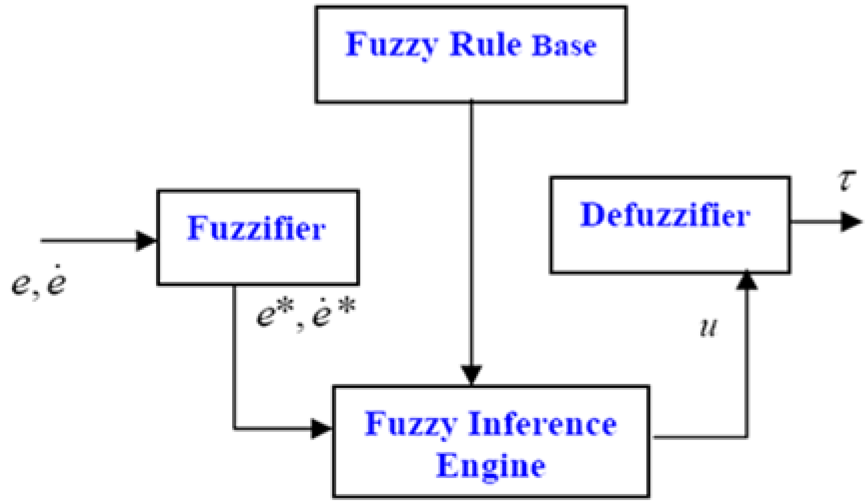

FIGURE 3: Structure of fuzzy logic controller [40]

To eliminate the chattering fuzzy inference system is used instead of linear saturation function to design nonlinear sliding function which as a summary the design of fuzzy logic controller for SMC has five steps:
Determine inputs and outputs: This controller has one input (S) and one output (α). The input is sliding function (S) and the output is coefficient which estimate the saturation function (α).
Find membership function and linguistic variable: The linguistic variables for sliding surface (S) 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 saturation coefficient (α) are; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR), Large Right (LR).
Choice of shape of membership function: In this work triangular membership function was selected.

Design fuzzy rule table: design the rule base of fuzzy logic controller can play important role to design best performance FSMC, suppose that two fuzzy rules in this controller are

F.R^1: *IF S is Z, THEN α is Z.* **(29)**
F.R^2: *IF S is (PB) THEN α is (LR).*

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

TABLE 1: Rule table for proposed FSMC

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

The control strategy that deduced by Table1 are

- If sliding surface (S) is N.B, the control applied is N.B for moving S to S=0.
- If sliding surface (S) is Z, the control applied is Z for moving S to S=0.

Defuzzification: The final step to design fuzzy logic controller is deffuzification , there are many deffuzzification methods in the literature, in this controller the COG method will be used, where this is given by

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)} \quad (30)$$

Second part is focuses on design fuzzy estimator to estimate nonlinear equivalent part. The fuzzy system can be defined as below [38-40]

$$f(x) = U_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = \psi(S) \tag{31}$$

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

$$\zeta^1(x) = \frac{\sum_i \mu_{(xi)} x_i}{\sum_i \mu_{(xi)}} \tag{32}$$

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

error base fuzzy controller can be defined as

$$U_{fuzzy} = \psi(S) \tag{33}$$

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]. Proposed method is used to a SISO fuzzy system which can approximate the residual coupling effect and alleviate the chattering. The robotic manipulator used in this algorithm is defined as below: the tracking error and the sliding surface are defined as:

$$e = q - q_d \tag{34}$$

$$s = \dot{e} + \lambda_e \tag{35}$$

We introduce the reference state as

$$\dot{q}_r = \dot{q} - s = \dot{q}_d - \lambda e \tag{36}$$

$$\ddot{q}_r = \ddot{q} - \dot{s} = \ddot{q}_d - \lambda \dot{e} \tag{37}$$

The control input is given by

$$\tau = M^{\wedge} \ddot{q}_r + C_1^{\wedge} \dot{q}_r - As - K \tag{38}$$

Where $A = diag[a_1, \dots, a_m]$ and $a_1, \dots, a_m$ are positive constants; $K = [k_1, \dots, k_m]^T$ and K_j is defined as the fuzzy gain estimated by fuzzy systems.

The fuzzy if-then rules for the jth joint of the robotic manipulator are defined as

$$R^{(l)}: if\ s_j\ is\ A_1^l\ , then\ y\ is\ B_j^l \tag{39}$$

Where $j = 1, \dots, m$ and $l = 1, \dots, M$.

We define K_j by

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l \left[\mu_{A_j^l}(s_j)\right]}{\sum_{l=1}^{M} \left[\mu_{A_j^l}(s_j)\right]} = \theta_j^T \varepsilon_j(s_j) \tag{40}$$

Where

$$\varepsilon_j(s_j) = \left[\varepsilon_j^1(s_j), \varepsilon_j^2(s_j), \dots, \varepsilon_j^M(s_j)\right]^T , \tag{41}$$

$$\varepsilon_j^l(s_j) = \frac{\sum_{l=1}^{M} \mu_{A_j^l}(s_j)}{\sum_{l=1}^{M} \left[\mu_{A_j^l}(s_j)\right]} \tag{42}$$

The membership function $\mu_{A_j^l}(s_j)$ is a Gaussian membership function defined in bellows:

$$\mu_{A_j^l}(s_j) = \exp\left[-\left(\frac{s_j - \alpha_j^l}{\delta_j^l}\right)^2\right] \quad (j = 1, \dots, m). \tag{43}$$

The Lyapunov function candidate is given by

$$V = \frac{1}{2} s^T M s + \frac{1}{2} \sum_{j=1}^{m} \frac{1}{\gamma_{sj}} \emptyset_j^T \emptyset_j \tag{44}$$

Where $\phi_j = \theta_j^* - \theta_j$. The derivative of V is

$$\dot{V} = s^T M\dot{s} + \frac{1}{2}s^T \dot{M} s + \sum_{j=1}^{m} \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j^1 \tag{45}$$

Since $\dot{M} - 2C_1$ is a skew-symmetric matrix, we can get $s^T M\dot{s} + \frac{1}{2}s^T \dot{M} s = s^T(M\dot{s} + C_1 s)$. From (2) and (36), we get

$$\tau = M(q)\ddot{q} + c(q,\dot{q})\dot{q} + G(q) = M^{\wedge}\ddot{q}_r + C_1^{\wedge}\dot{q}_r + G^{\wedge} - As - K \tag{46}$$

Since $\dot{q}_r = \dot{q} - s$ and $\ddot{q}_r = \ddot{q} - \dot{s}$ in (44) and (45), we get

$$M\dot{s} + (C_1 + A)s = \Delta F - K \tag{47}$$

Where $\Delta F = \Delta M \ddot{q}_r + \Delta C_1 \dot{q}_r + \Delta G$, $\Delta M = M^{\wedge} - M$, $\Delta C_1 = C_1^{\wedge} - C_1$ and $G = G^{\wedge} - G$. then $\dot{V}$ becomes

$$\begin{aligned}
\dot{V} &= s^T(M\dot{s} + C_1 s) + \sum_{j=1}^{m} \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j^1 \\
&= -s^T(-As + \Delta f - K) + \sum_{j=1}^{m} \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j^1 \\
&= \sum_{j=1}^{m} [s_j(\Delta f_j - K_j)] - s^T As + \sum_{j=1}^{m} \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j^1 \\
&= \sum_{j=1}^{m} [s_j(\Delta f_j - \theta_j^T \varepsilon_j(s_j))] - s^T As + \sum_{j=1}^{m} \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j^1 \\
&= \sum_{j=1}^{m} (s_j [\Delta f_j - (\theta_j^*)\varepsilon_j(s_j) + \phi_j^T \varepsilon_j(s_j)]) - s^T As + \sum_{j=1}^{m} \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j^1 \\
&= \sum_{j=1}^{m} (s_j [\Delta f_j - (\theta_j^*)\varepsilon_j(s_j)]) - s^T As + \sum_{j=1}^{m} \left(\frac{1}{\gamma_{sj}} \phi_j^T [\gamma_{sj} s_j \varepsilon_j(s_j) + \dot{\phi}_j]\right)
\end{aligned}$$

We choose the adaptation law $\dot{\theta}_j = \gamma_{sj} s_j \varepsilon_j(s_j)$. Since $\dot{\phi}_j = -\dot{\theta}_j = -\gamma_{sj} s_j \varepsilon_j(s_j)$, $\dot{V}$ becomes

$$\dot{V} = \sum_{j=1}^{m} \left(s_j \left[\Delta f_j - (\theta_j^*)^T \varepsilon_j(s_j)\right]\right) - s^T As \tag{48}$$

We define the minimum approximation error as

$$\omega_j = \Delta f_j - (\theta_j^*)^T \varepsilon_j(s_j) \tag{49}$$

Then $\dot{V}$ change to

$$\begin{aligned}
\dot{V} &= \sum_{j=1}^{m} s_j \omega_j - s^T As \\
&\le \sum_{j=1}^{m} |s_j||\omega_j| - s^T As \\
&= \sum_{j=1}^{m} (|s_j||\omega_j| - a_j s_j^2) \\
&= \sum_{j=1}^{m} \left(|s_j|(|\omega_j| - a_j|s_j|)\right)
\end{aligned} \tag{50}$$

According to Universal Approximation theorem in sliding mode algorithm, the minimum approximation error ω_j is as small as possible. We can simply pick a_j to make $a_j|s_j| > |\omega_j|$ $(s_j \ne 0)$. Then we get $\dot{V} < 0$ for $s \ne 0$.

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

$$\theta^* = \arg\min \left[Sup_{x \in U} \left| \sum_{l=1}^{M} \theta^T \zeta(x) - U_{equ} \right|\right] \tag{51}$$

Where $\theta^*$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.

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l [\mu_A(S_j)]}{\sum_{l=1}^{M} [\mu_A(S_j)]} = \theta_j^T \zeta_j(S_j) \tag{52}$$

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

$$\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)} \tag{53}$$

where the γ_{sj} is the positive constant.

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

$$[M^{-1}(B + C + G) + \dot{S}]M = \sum_{l=1}^{M} \theta^T \zeta(x) - \lambda S - K \tag{54}$$

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

$$U = U_{eq_{fuzzy}} + U_r \tag{55}$$

Where $U_{eq_{fuzzy}} = [M^{-1}(B + C + G) + \dot{S}]M + \sum_{l=1}^{M} \theta^T \zeta(x) + K$

Figure 4 is shown the proposed fuzzy sliding mode controller.

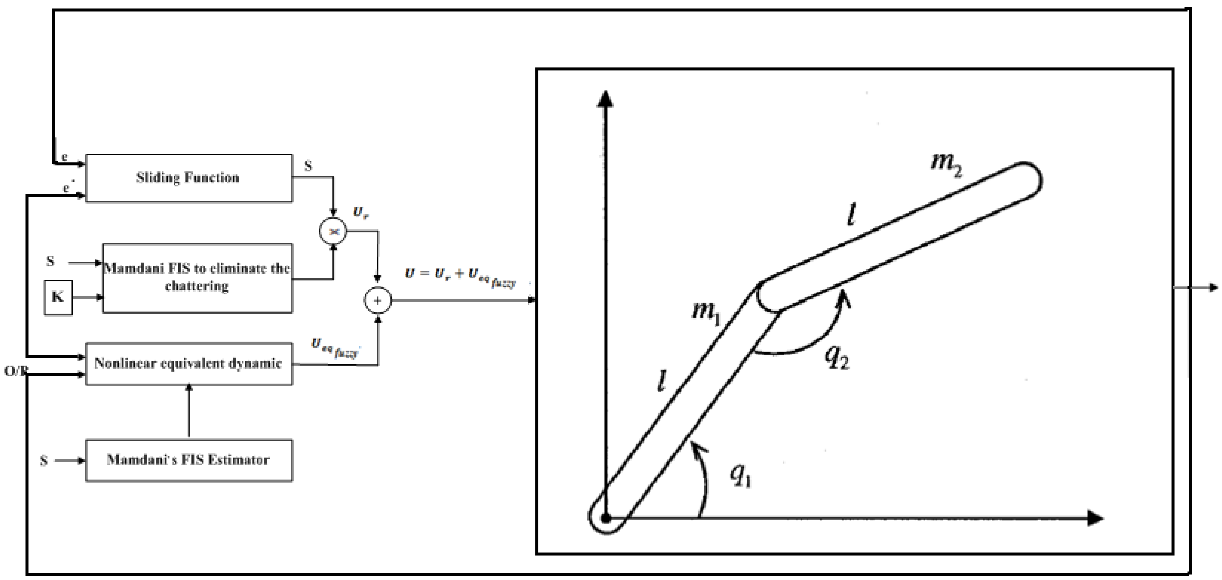

FIGURE 4: Proposed fuzzy estimator sliding mode algorithm: applied to robot manipulator

Figure 5 is shown the fuzzy instead of saturation function.

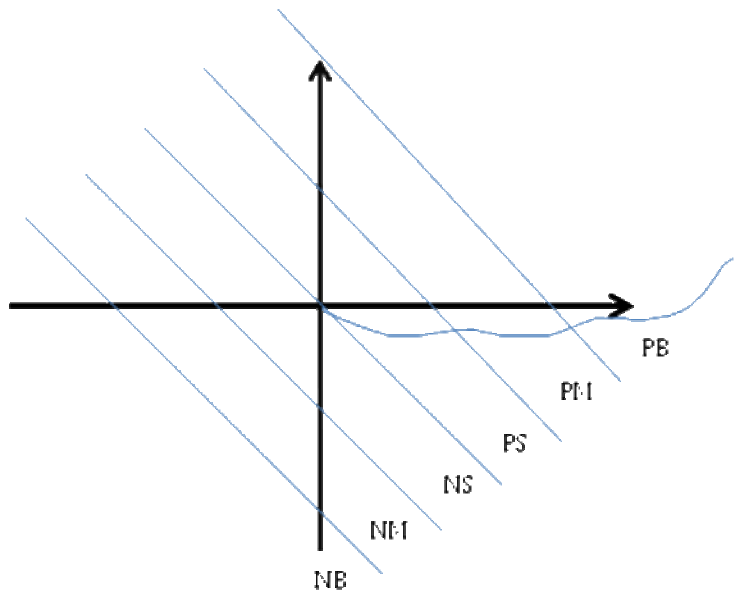

FIGURE 5: Nonlinear fuzzy inference system applied to linear saturation function

Parts three is focused on PSO algorithm and tune the coefficient of sliding function. Particle Swarm Optimization (PSO) is one of the evolutionary optimization algorithms in the branch of swarm intelligence developed by Eberhart and Kennedy in 1995[4]. This algorithm was inspired by the social movement behavior of the birds in the flock searching for food. Compared to the other evolutionary algorithms, the main excellences of this algorithm are: Simple concept, easy to implement, robustness in tuning parameters, minimum storage space and both global and local exploration capabilities. These birds in a flock are symbolically described as particles. These particles are supposed to a swarm "flying" through the problem space. Each particle has a position and a velocity. Any particle's position in the problem space has one solution for the problem. When a particle transfers from one place to another, a different problem solution is generated. Cost function evaluated the solution in order to provide the fitness value of a particle. "Best location" of each particle which has experienced up to now, is recorded in their memory, in order to determine the best fitness value. Particles of a swarm transmit the best location with each other to adapt their own location according to this best location to find the global minimum point. For every generation, the new location is computed by adding the particle's current velocity to its location. PSO is initialized with a random population of solutions in N-dimensional problem space, the $\boldsymbol{i}_{th}$ particle changes and updates its position and velocity according to the following formula:

$$\boldsymbol{V_{id} = w \times (V_{id} + C_1 \times rand_1 * (P_{id} - X_{id}) + C_2 \times rand_2 \times (P_{gd} - X_{id}))} \quad \textbf{(56)}$$

Where $\boldsymbol{X_{id}}$ is calculated by

$$\boldsymbol{X_{id} = X_{id} + V_{id}} \quad \textbf{(57)}$$

Where $\boldsymbol{V_{id}}$ is the inertia weight implies the speed of the particle moving along the dimensions in a problem space. $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ are acceleration parameters, called the cognitive and social parameters; $\boldsymbol{rand_1}$ and $\boldsymbol{rand_2}$ are functions that create random values in the range of (0, 1). $\boldsymbol{X_{id}}$ is the particle's current location; $\boldsymbol{P_{id}}$ (personal best) is the location of the particle experienced its personal best fitness value; $\boldsymbol{P_{gd}}$ (global best) is the location of the particle experienced the highest best fitness value in entire population; ***d*** is the number of dimensions of the problem space; . ***W*** is the momentum part of the particle or constriction coefficient [5] and it is calculated based on the following equation;

$$\boldsymbol{W = 2 / (2 - \varphi - \sqrt{\varphi^2 - 4\varphi})} \quad \textbf{(58)}$$

$$\varphi = C_1 + C_2 \quad , \quad \varphi > 4 \tag{59}$$

Equation 56 needs each particle to record its location X_{id}, its velocity V_{id}, its personal best fitness value P_{id}, and the whole population's best fitness value P_{gd}. On the basis of following equation the best fitness value X_i is updated at each generation, where the sign $f(.)$ represents the cost function; $X_i(.)$ indicated the best fitness values; and t denotes the generation step.

$$X_i(t+1) = \begin{cases} X_i(t) & f(P_d(t+1)) \le X_i(t) \\ f(P_d(t+1)) & f(P_d(t+1)) > X_i(t) \end{cases} \tag{60}$$

In PSO, the knowledge of each particle will not be substituted until the particle meets a new position vector with a higher competence value than the currently recorded value in its memory [6]. External disturbances influence on tracking trajectory, error rate and torque which result in chattering. But the values are not such a great values and these oscillations are in all physical systems. So, the sliding mode controller can reject perturbations and external disturbances if these parameters adjust properly. So the methodology which is applied in this paper in order to select the best values for these deterministic coefficients to accomplish high performance control is the particle swarm optimization algorithm. This algorithm tunes the gains and determines the appropriate values for these parameters in harmony with the system which was introduced in rear part.

4. RESULTS

Sliding mode controller (PD-SMC) and PSO SISO Lyapunov based fuzzy estimator sliding mode (PSO-FSMC) algorithms were tested to desired response trajectory. In this research the first and second joints are moved from home to final position without and with external disturbance. The simulation was implemented in Matlab/Simulink environments. Trajectory performance, torque performance and disturbance rejection 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. This type of noise is used to external disturbance in continuous and hybrid systems.

Tracking performances: From the simulation for first and second trajectory without any disturbance with sinus trajectory, it was seen that both of controllers almost have the same performance, because these controllers are adjusted and worked on certain environment. Figure 6 is shown tracking performance in certain system and without external disturbance these two controllers.

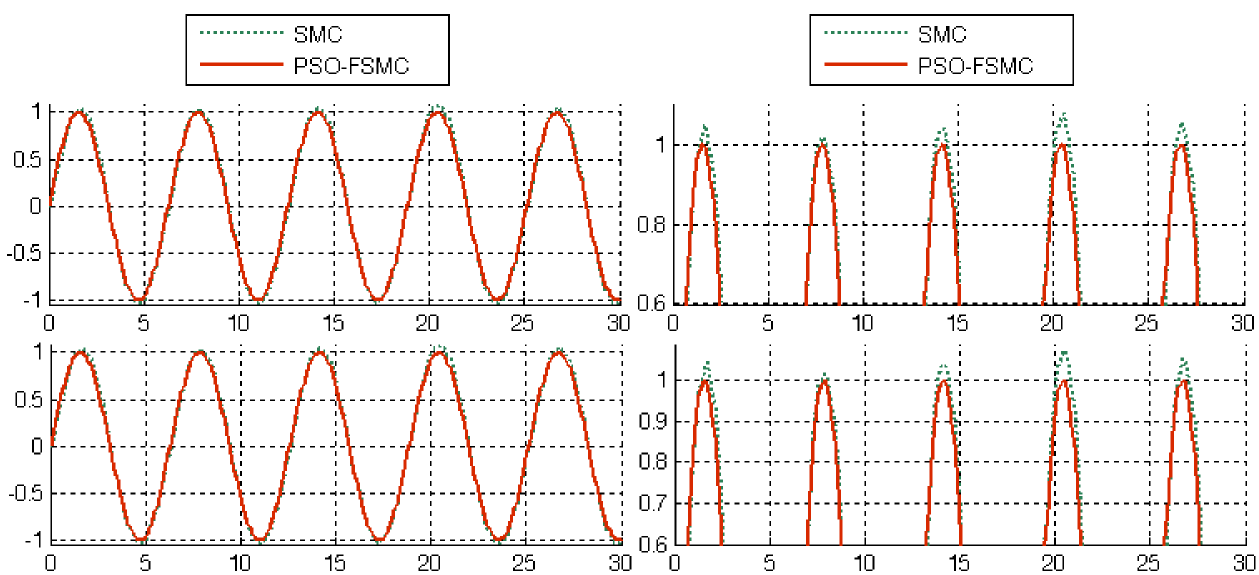

FIGURE 6: SMC Vs. PSO-FSMC: applied to 2-DOF serial robot manipulator

By comparing trajectory response in above graph it is found that the PSOFSMC undershoot **(0%)** is lower than SMC **(8.8%)**, although both of them have about the same overshoot.

Disturbance Rejection: Figure 7 has shown the power disturbance elimination in SMC and PSOFSMC. 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 trajectory responses.

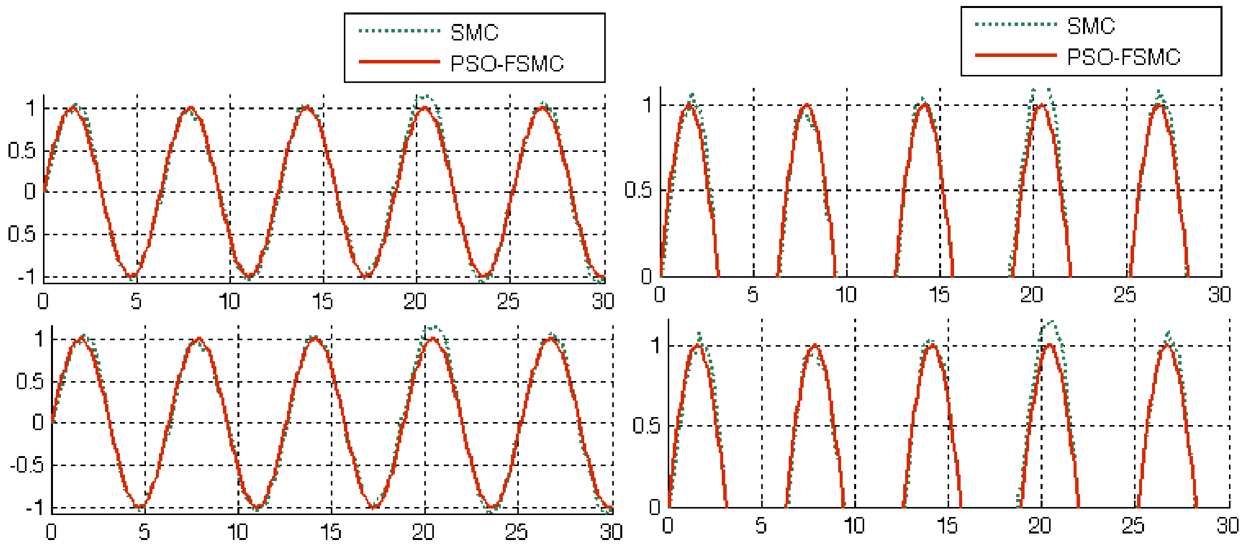

FIGURE 7: SMC Vs. PSO-FSMC with disturbance: applied to 2-DOF serial robot manipulator

Among above graph, relating to sinus trajectory following with external disturbance, pure SMC has slightly fluctuation. By comparing overshoot, rise time, and settling time; PSO SMC's overshoot **(0%)** is lower than SMC's **(11%)** and SMC's rise time **(0.66 sec)** is considerably the same as PSO SMC's **(0.61 sec)**.

Chattering Phenomenon: Chattering is one of the most important challenges in sliding mode controller for this reason the major objectives in this research is eliminate the chattering in controller's output. Figure 8 has shown the power of boundary layer (saturation) method to reduce the chattering in SMC.

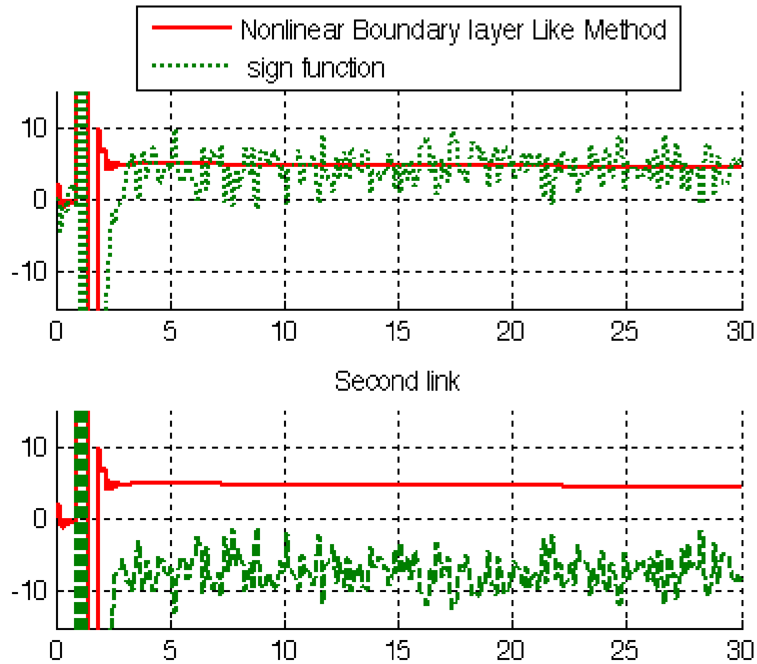

FIGURE 8: Sign Vs. Nonlinear boundary layer like method in PSO-FSMC: applied to 2-DOF serial robot manipulator

Figure 8 has indicated the power of chattering rejection in PSO-FSMC, with and without nonlinear boundary layer like method using fuzzy algorithm. Overall in this research with regard to the sinus response, PSO SMC has the steady chattering compared to the pure SMC in uncertain or/and external disturbance area with regard to nonlinear boundary layer like method using fuzzy inference system.

Error Calculation: Table 2 and Table 3are shown error performance in SMC and PSO-FSMC in presence of external disturbance. SMC has oscillation in tracking which causes chattering phenomenon.

TABLE 2: RMS Error Rate of Presented controllers

RMS Error Rate	SMC	PSO-FSMC
Without Noise	1e-3	0.9e-3
With Noise	0.012	0.00012

In these methods if integration absolute error (IAE) is defined by (61), table 2 is shown comparison between these two methods.

$$IAE = \int_0^{\infty} |e(t)|\, dt \qquad (61)$$

TABLE 3: Calculate IAE

Method	Traditional SMC	PSO-Fuzzy Estimator SMC
IAE	430	209.1

5. CONCLUSION

In this work, a SISO PSO fuzzy estimate sliding mode controller is design, analysis and applied to robot manipulator. This method focuses on design PSO-FSMC algorithm with the formulation derived in the Lyapunov sense. The stability of the closed-loop system is proved mathematically based on the Lyapunov method. The first objective in proposed method is removed the chattering which non linear boundary layer method using fuzzy inference system is used to solve this challenge. The second target in this work is compensate the model uncertainty by SISO fuzzy inference system, 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 K_1 which will result in a low computational load. In finally part PSO algorithm is used to off-line tuning and adjusted the sliding function and eliminates the chattering with minimum computational load. In this case the performance is improved by using the advantages of sliding mode algorithm, artificial intelligence compensate method and PSO 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.

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