A New Estimate Sliding Mode Fuzzy Controller for Robotic Manipulator

Farzin Piltan SSP.ROBOTIC@yahoo.com
Industrial Electrical and Electronic Engineering SanatkadeheSabze Pasargad. CO (S.S.P. Co), NO:16 ,PO.Code 71347-66773, Fourth floor Dena Apr , Seven Tir Ave , Shiraz , Iran

Farid Aghayari *SSP.ROBOTIC@yahoo.com*
Industrial Electrical and Electronic Engineering SanatkadeheSabze Pasargad. CO (S.S.P. Co), NO:16 ,PO.Code 71347-66773, Fourth floor Dena Apr , Seven Tir Ave , Shiraz , Iran

Mohammad Reza Rashidian *SSP.ROBOTIC@yahoo.com*
Industrial Electrical and Electronic Engineering SanatkadeheSabze Pasargad. CO (S.S.P. Co), NO:16 ,PO.Code 71347-66773, Fourth floor Dena Apr , Seven Tir Ave , Shiraz , Iran

Mohammad Shamsodini *SSP.ROBOTIC@yahoo.com*
Industrial Electrical and Electronic Engineering SanatkadeheSabze Pasargad. CO (S.S.P. Co), NO:16 ,PO.Code 71347-66773, Fourth floor Dena Apr , Seven Tir Ave , Shiraz , Iran

Abstract

One of the most active research areas in field of robotics is control of robot manipulator because this system has highly nonlinear dynamic parameters and most of dynamic parameters are unknown so design an acceptable controller is the main goal in this work. To solve this challenge position new estimation sliding mode fuzzy controller is introduced and applied to robot manipulator. This controller can solve to most important challenge in classical sliding mode controller in presence of highly uncertainty, namely; chattering phenomenon based on fuzzy estimator and online tuning and equivalent nonlinear dynamic based on estimation. Proposed method has acceptable performance in presence of uncertainty (e.g., overshoot=0%, rise time=0.8 s, steady state error = 1e-9 and RMS error=0.0001632).

Keywords: Sliding Mode Controller, Fuzzy Logic Methodology, Estimation, Sliding Mode Fuzzy Methodology, Robotic Manipulator.

1. INTRODUCTION, BACKGROUND and MOTIVATION

A robot is a machine that can be programmed to perform a variety of tasks it is divided into three main groups: Robot manipulator, Mobile robot and Hybrid robot, which Robot Manipulator is a set of rigid links interconnected by joints; it is divided into two main groups: open-chain manipulators and closed-chain robot manipulators. A serial link robot is a sequence of joints and links which begins with a base frame and ends with an end-effector. This type of robot manipulators, comparing with the load capacitance is more weightily because each link must be supported the weights of all next links and actuators between the present link and end-effector[6]. Serial robot manipulators have been used in automotive industry, medical application, and also in research laboratories. PUMA 560 robot manipulator is a 6 DOF serial robot manipulator. It has many applications in industrial and academic. From the control point of view, robot manipulator is divided into two main subparts: Kinematics and Dynamics. Robot manipulator kinematics is essential part to calculate the relationship between rigid bodies and end-effector without any forces. Study of this part is fundamental to design a controller with acceptable performance, in real situations and practical applications. Dynamic is the study of motion with regard to forces. Dynamic modeling is important for control, mechanical design, and simulation. Dynamic parameters are used to describe the behavior of systems, the relationship between displacement, velocity and acceleration to forces acting on robot manipulator [1-2].

Some of robot manipulators which work in industrial processes are controlled by linear PID controllers, but while system works with various parameters and hard nonlinearities this technique is very tricky and it has some limitations such as working near the system operating point. Nonlinear control methodology can deal with nonlinear equations in the dynamics of robotic manipulators. Conventional nonlinear control methodology cannot provide good robustness for controlling robot manipulators. The control system designer is often unsure of the exact value of the robot manipulator dynamic parameters which describe the behavior of robot manipulator. Sliding mode controller is an influential nonlinear controller to certain and uncertain systems which it is based on nonlinear Lyapunov formulation and computes the required arm torques using the nonlinear feedback control law. Sliding mode control theory for control of robot manipulator was first proposed in 1978 by Young to solve the set point problem ($\dot{q}_d = 0$) by discontinuous method in the following form;

$$\tau_{(q,t)} = \begin{cases} \tau_i^{+}(q,t) & if\ S_i > 0 \\ \tau_i^{-}(q,t) & if\ S_i < 0 \end{cases} \tag{1}$$

where S_i is sliding surface (switching surface), $i = 1, 2, \ldots\ldots, n$ for *n*-DOF robot manipulator, $\tau_i(q,t)$ is the i^{th} torque of joint. Sliding mode controller is divided into two main sub controllers: discontinues controller(τ_{dis}) and equivalent controller(τ_{eq}). Discontinues controller causes an acceptable tracking performance at the expense of very fast switching. In the theory of infinity fast switching can provide a good tracking performance but it also can provide some problems (e.g., system instability and chattering phenomenon). After going toward the sliding surface by discontinues term, equivalent term help to the system dynamics match to the sliding surface[1, 6]. When all dynamic and physical parameters are known or limitation unknown the controller works superbly and output responses are good quality ; practically a large amount of systems have unlimited or highly uncertainties and sliding mode controller with estimator methodology reduce this kind of limitation. 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. 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]. 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]. Wang et al. [5] 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.

Application of fuzzy logic to automatic control was first reported in [10], where, based on Zadeh's proposition, Mamdani buit a controller for a steam engine and boiler combination by synthesizing a set of linguistic expressions in the form of IF-THEN rules as follows: IF (system state) THEN (control action), which will be referred to as "Mamdani controller' hereafter. In Mamdani's controller the knowledge of the system state (the IF part) and the set of actions (the THEN part) are obtained from the experienced human operators [11]. Fuzzy control has gradually been recognized as the most significant and fruitful application for fuzzy logic. In the past three decades, more diversified application domains for fuzzy logic controllers have been created, which range from water cleaning process, home appliances such as air conditioning systems and online recognition of handwritten symbols [10-15, 20, 36].

However sliding mode controller has an acceptable performance but when system has unlimited uncertainty it cannot guarantee the best output performance so fuzzy logic method with applied system estimation improve the output response. Many dynamic systems to be controlled have unknown or varying uncertain parameters. For instance, robot manipulators may carry large objects with unknown inertial parameters. Generally, the basic objective of control estimation is to maintain performance of the closed-loop system in the presence of uncertainty (e.g., variation in parameters of a robot manipulator). The above objective can be achieved by estimating the uncertain parameters (or equivalently, the corresponding controller parameters) on-line, and based on the measured system signals. The estimated parameters are used in the computation of the control input. An adaptive system can thus be regarded as a control system with on-line parameter estimation [3, 16-29]. In conventional nonlinear adaptive controllers, the controller attempts to learn the uncertain parameters of particular structured dynamics, and can achieve fine control and compensate for the structure uncertainties and bounded disturbances. On the other hand, adaptive control techniques are restricted to the parameterization of known functional dependency but of unknown Constance. Consequently, these factors affect the existing nonlinear adaptive controllers in cases with a poorly known dynamic model or when the fast real-time control is required. Adaptive control methodologies and their applications to the robot manipulators have widely been studied and discussed in the following references [4-5, 16-45].

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

2. ROBOT MANIPULATOR DYNAMICS, PROBLEM STATEMENTS and SLIDING MODE CONTROLLER FORMULATION

Robot Manipulator Dynamic Formulation: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 3, 16-28, 30, 38-40]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \quad \textbf{(2)}$$

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:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \quad \textbf{(3)}$$

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 (3) 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 variable q_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [3, 16-28]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\} \quad (4)$$

Sliding Mode Control: This technique is very attractive from a control point of view. The central idea of sliding mode control (SMC) is based on nonlinear dynamic equivalent. It has assumed that the desired motion trajectory for the manipulator $q_d(t)$, as determined, by a path planner. Defines the tracking error as [4-9, 18, 21, 31-44]:

$$e(t) = q_d(t) - q_a(t) \quad (5)$$

Where e(t) is error of the plant, $q_d(t)$ is desired input variable, that in our system is desired displacement, $q_a(t)$ is actual displacement. Consider a nonlinear single input dynamic system of the form [6]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \quad (6)$$

Where u is the vector of control input, $x^{(n)}$ is the n^{th} derivation of x, $x = [x, \dot{x}, \ddot{x}, \dots, x^{(n-1)}]^T$ is the state vector, $f(x)$ is unknown or uncertainty, and $b(x)$ is of known *sign* function. The control problem is truck to the desired state; $x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d^{(n-1)}]^T$, and have an acceptable error which is given by:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \quad (7)$$

A time-varying sliding surface $s(x,t)$ is given by the following equation:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\tilde{x} = 0 \quad (8)$$

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

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\left(\int_0^t \tilde{x}\,dt\right) = 0 \quad (9)$$

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

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)| \quad (10)$$

where ζ is positive constant.

$$\textbf{If } S(0)>0 \rightarrow \frac{d}{dt}S(t) \le -\zeta \quad (11)$$

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

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt}S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \quad (12)$$

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

$$0 - S(0) \le -\eta(t_{reach}) \rightarrow t_{reach} \le \frac{S(0)}{\zeta} \quad (13)$$

and

$$if\, S(0) < 0 \rightarrow 0 - S(0) \le -\eta(t_{reach}) \rightarrow S(0) \le -\zeta(t_{reach}) \rightarrow t_{reach} \le \frac{|S(0)|}{\eta} \quad (14)$$

Equation (14) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \quad \textbf{(15)}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda) \quad \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \quad \textbf{(16)}$$

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

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \quad \textbf{(17)}$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \ \rightarrow \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \quad \textbf{(18)}$$

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

$$\hat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \quad \textbf{(19)}$$

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

$$U_{dis} = \hat{U} - K(\vec{x}, t) \cdot \mathrm{sgn}(s) \quad \textbf{(20)}$$

where the switching function $\mathrm{sgn}(S)$ is defined as

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \quad \textbf{(21)}$$

and the $K(\vec{x}, t)$ is the positive constant. Suppose by (10) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) = \dot{S} \cdot S = \left[f - \hat{f} - K\mathrm{sgn}(s)\right] \cdot S = \left(f - \hat{f}\right) \cdot S - K|S| \quad \textbf{(22)}$$

and if the equation (14) instead of (13) the sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x}\, dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \quad \textbf{(23)}$$

in this method the approximation of U is computed as

$$\hat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \quad \textbf{(24)}$$

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

$$\tau = \tau_{eq} + \tau_{dis} \quad \textbf{(25)}$$

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

$$\tau_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \quad \textbf{(26)}$$

Where [15-44]

$$\tau_{eq} = \begin{bmatrix} \tau_{eq1} \\ \tau_{eq2} \\ \tau_{eq3} \\ \tau_{eq4} \\ \tau_{eq5} \\ \tau_{eq6} \end{bmatrix}, M^{-1} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}^{-1}$$

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

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

and τ_{dis} is computed as;

$$\tau_{dis} = K \cdot \mathrm{sgn}(S) \qquad \textbf{(27)}$$

where

$$\tau_{dis} = \begin{bmatrix} \tau_{dis1} \\ \tau_{dis2} \\ \tau_{dis3} \\ \tau_{dis4} \\ \tau_{dis5} \\ \tau_{dis6} \end{bmatrix}, K = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \end{bmatrix}, (S) = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} \; and \;\; S = \lambda e + \dot{e}$$

The result scheme is shown in Figure 1.

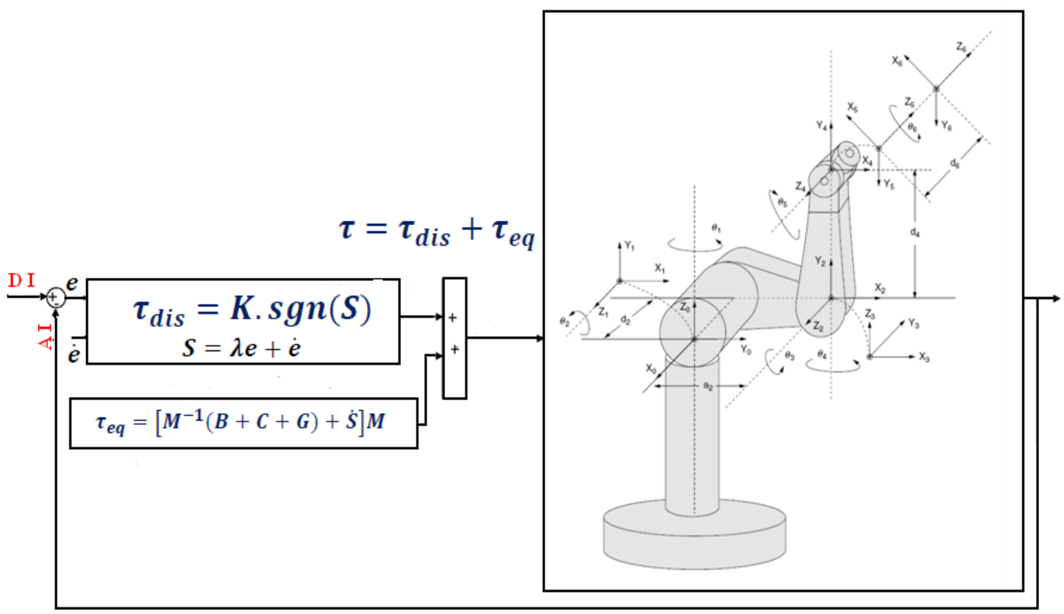

FIGURE 1: Block diagram of Sliding Mode Controller (SMC)

Problem Statement: Even though, SMC is used in wide range areas but, pure SMC has the following disadvantages; namely; chattering phenomenon and nonlinear equivalent dynamic formulation in presence of structure and unstructured uncertain system. Proposed method focuses on substitution fuzzy logic system applied to main controller (SMC) to compensate the uncertainty in nonlinear dynamic equation to implement easily.

Proof of Stability: The proof of Lyapunov function can be determined by the following equations. The dynamic formulation of robot manipulate can be written by the following equation

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \qquad \textbf{(28)}$$

the lyapunov formulation can be written as follows,

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

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2} S^T . \dot{M} . S + S^T \ M\dot{S} \tag{30}$$

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

$$M\dot{S} = -VS + M\dot{S} + VS + G - \tau \tag{31}$$

it is assumed that

$$S^T \left(\dot{M} - 2V \right) S = 0 \tag{32}$$

by substituting (31) in (30)

$$\dot{V} = \frac{1}{2} S^T \dot{M} S - S^T VS + S^T \left(M\dot{S} + VS + G - \tau \right) = S^T \left(M\dot{S} + VS + G - \tau \right) \tag{33}$$

suppose the control input is written as follows

$$\hat{\tau} = \widehat{\tau_{eq}} + \widehat{\tau_{dis}} = \left[\widehat{M^{-1}} \left(\hat{V} + \hat{G} \right) + \dot{S} \right] \hat{M} + K . sgn(S) + K_v S \tag{34}$$

by replacing the equation (34) in (33)

$$\dot{V} = S^T (M\dot{S} + VS + G - \hat{M}\dot{S} - \hat{V}S - \hat{G} - K_v S - K sgn(S) = S^T \left(\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K \right. \tag{35}$$

it is obvious that

$$\left| \tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K_v S \right| \le \left| \tilde{M}\dot{S} \right| + \left| \tilde{V}S \right| + \left| \tilde{G} \right| + \left| K_v S \right| \tag{36}$$

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

$$K_u = \left[\left| \tilde{M}\dot{S} \right| + \left| VS \right| + \left| G \right| + \left| K_v S \right| + \eta \right]_i , i = 1, 2, 3, 4, \ldots \tag{37}$$

the equation (32) can be written as

$$K_u \ge \left| \left[\tilde{M}\dot{S} + VS + G - K_v S \right]_i \right| + \eta_i \tag{38}$$

therefore, it can be shown that

$$\dot{V} \le - \sum_{i=1}^{n} \eta_i \left| S_i \right| \tag{39}$$

Consequently the equation (39) guaranties the stability of the Lyapunov equation.

3. METHODOLOGY: DESIGN A NEW STIMATE SLIDING MODE FUZZY CONTROLLER

First Step, Design Sliding Mode Fuzzy Controller: In recent years, artificial intelligence theory has been used in robotic systems. Neural network, fuzzy logic, and neuro-fuzzy are combined with nonlinear methods and used in nonlinear, time variant, and uncertainty plant (e.g., robot manipulator). This controller can be used to control of nonlinear, uncertain, and noisy systems. This method is free of some model-based techniques that used in classical controllers. 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. Besides applying 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 soft computing control method. The fuzzy inference mechanism provides a mechanism for referring the rule base in fuzzy set. There are two most commonly method that can be used in fuzzy logic controllers, namely, Mamdani method and Sugeno method, which Mamdani built one of the first fuzzy controller to control of system engine and Michio Sugeno suggested to use a singleton as a membership function of the rule consequent. The Mamdani fuzzy inference method has four steps, namely, fuzzification, rule evaluation, aggregation of the rule outputs and defuzzification. Sugeno method is very similar to Mamdani method but Sugeno changed the consequent rule base that he used the mathematical function of the input rule base instead of fuzzy set [15-44].

Fuzzification: Fuzzification is used to determine the membership degrees for antecedent part when x and y have crisp values. The first step in fuzzification is determine inputs and outputs which, it has one input (U_T) and one output (U_{fuzzy}). The input is S which measures the summation of discontinuous and equivalent part in main controller. 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. 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 (U_T) 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 in to 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 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) and it is quantized in to thirteen levels represented by: -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6.

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 the fuzzy rules in this controller is [36];

$$\textbf{F.R}^1\textbf{: } \textit{IF } U_T \textit{ is NB, THEN } U_{fuzzy} \textit{ is LL.} \quad \textbf{(40)}$$

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 sliding mode controller. This part is used AND/OR fuzzy operation in antecedent part which AND operation is used.

Aggregation of the Rule Output (Fuzzy Inference): There are several methodologies in aggregation of the rule outputs that can be used in fuzzy logic controllers, namely, Max-Min aggregation, Sum-Min aggregation, Max-bounded product, Max-drastic product, Max-bounded sum, Max-algebraic sum and Min-max. Two most common methods that used in fuzzy logic controllers are Max-min aggregation and Sum-min aggregation. Max-Min aggregation is used to this work which the calculation is defined as follows;

$$\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U) = max\left\{min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]\right\} \quad \textbf{(41)}$$

Deffuzzification: The last step to design fuzzy inference in our sliding mode fuzzy 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. There are several methodologies in defuzzification of the rule outputs that can be used in fuzzy logic controllers but two most common defuzzification methods are: Center of gravity method (COG) and Center of area (COA) method. In this design the Center of gravity method (COG) is used and calculated by the following equation [36];

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \mu_u(x_k, y_k, U_i)} \quad \textbf{(42)}$$

This table has 7 cells, and used to describe the dynamics behavior of sliding mode fuzzy controller.

U_T	NB	NM	NS	Z	PS	PM	PB
U_{fuzzy}	LL	ML	SL	Z	SR	MR	LR

TABLE 1: Rule table

Figure 2 is shown the sliding mode fuzzy estimator controller based on fuzzy logic controller and minimum rule base.

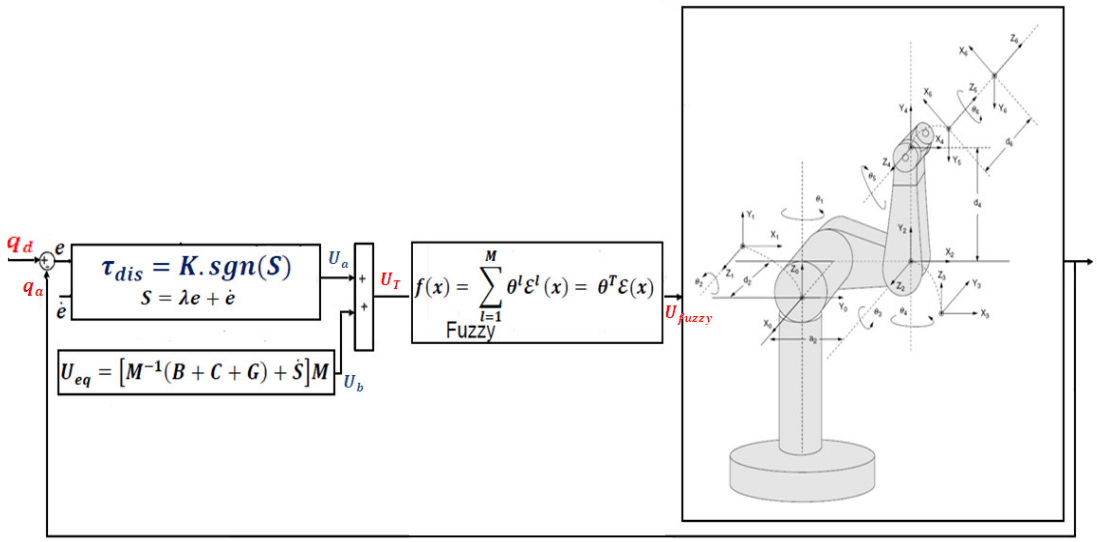

FIGURE2: Block Diagram of sliding mode Fuzzy estimator Controller with Minimum Rule Base

Second step; design sliding mode fuzzy estimator and applied an input fuzzy logic methodology to online tuning: All conventional controller have common difficulty, they need to find and estimate several nonlinear parameters. Tuning sliding mode fuzzy method can tune duration nonlinear parameters automatically the scale parameters using artificial intelligence method. To keep the structure of the controller as simple as possible and to avoid heavy computation, in this design one input Mamdani fuzzy supervisor tuner is selected. In this method the tuneable controller tunes the nonlinear uncertainty and removes the chattering in opt to applied fuzzy logic method to previous fuzzy logic estimator. However pure inverse sliding mode controller has satisfactory performance in a limit uncertainty but tune the performance of this controller in highly nonlinear and uncertain parameters (e.g., robot manipulator) is a difficult work which proposed methodology can solve above challenge by applied two fuzzy methodology; the first one for estimation and the second one for online tuning. The lyapunov candidate formulation for our design is defined by:

$$V = \frac{1}{2} S^T M S + \frac{1}{2} \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi^T . \phi_j \quad \textbf{(43)}$$

Where γ_{sj} is positive coefficient, $\phi = \theta^* - \theta;\ \theta^*\ is\ minimum\ error\ \&\ \theta\ is\ adjustable\ parameter$

Since $\dot{M} - 2V$ is skew-symetric matrix, we can get

$$S^T M \dot{S} + \frac{1}{2} S^T \dot{M} S = S^T (M\dot{S} + VS) \quad \textbf{(44)}$$

From following two functions:

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \tag{45}$$

And

$$\tau = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \tag{46}$$

We can get:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \tag{47}$$

Since; $\dot{q}_r = \dot{q} - S$ & $\ddot{q}_r = \ddot{q} - \dot{S}$ then

$$M\dot{S} + (V + A)S = \Delta f - K \tag{48}$$

$$M\dot{S} = \Delta f - K - VS - AS$$

The derivative of V defined by;

$$\dot{V} = S^T M\dot{S} + \frac{1}{2}S^T \dot{M}S + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j \tag{49}$$

$$\dot{V} = S^T(M\dot{S} + VS) + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j$$

$$\dot{V} = S^T(\Delta f - K - VS - AS + VS) + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j$$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - K_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j$$

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M}\theta_j^l[\mu_A(S_j)]}{\sum_{l=1}^{M}[\mu_A(S_j)]} = \theta_j^T\zeta_j(S_j) \tag{50}$$

Where $\zeta_j(S_j) = [\zeta_j^1(S_j), \zeta_j^2(S_j), \zeta_j^3(S_j), \ldots\ldots, \zeta_j^M(S_j)]^T$ and $\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)}$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - \theta^T\zeta(S_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j \tag{51}$$

Based on $\phi = \theta^* - \theta \rightarrow \theta = \theta^* - \phi$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - \theta^{*T}\zeta(S_j) + \phi^T\zeta(S_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j \tag{52}$$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - (\theta^*)^T\zeta(S_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi_j^T[\gamma_{sj}.S_j.\zeta_j(S_j) + \dot{\phi}_j])$$

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

$$\dot{V} = \sum_{j=1}^{m} [S_j \Delta f_j - ((\theta_j^*)^T \zeta_j(S_j))] - S^T A S \quad (53)$$

If the minimum error can be defined by

$$e_{mj} = \Delta f_j - ((\theta_j^*)^T \zeta_j(S_j)) \quad (54)$$

$\dot{V}$ is intended as follows

$$\dot{V} = \sum_{j=1}^{m} [S_j e_{mj}] - S^T A S \quad (55)$$

$$\le \sum_{j=1}^{m} |S_j||e_{mj}| - S^T A S$$

$$= \sum_{j=1}^{m} |S_j||e_{mj}| - a_j S_j^{\,2}$$

$$= \sum_{j=1}^{m} |S_j|(|e_{mj}| - a_j S_j)$$

For continuous function $g(x)$, and suppose $\varepsilon > 0$ it is defined the fuzzy logic system in form of $Sup_{x \in U} |f(x) - g(x)| < \varepsilon$

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

$if \quad a_j = \alpha \quad that \quad \alpha|S_j| > e_{mj} \; (S_j \neq 0) \quad then \quad \dot{V} < 0 \; for \; (S_j \neq 0)$

Figure 3 is shown the block diagram of proposed fuzzy online applied to sliding mode fuzzy estimator controller.

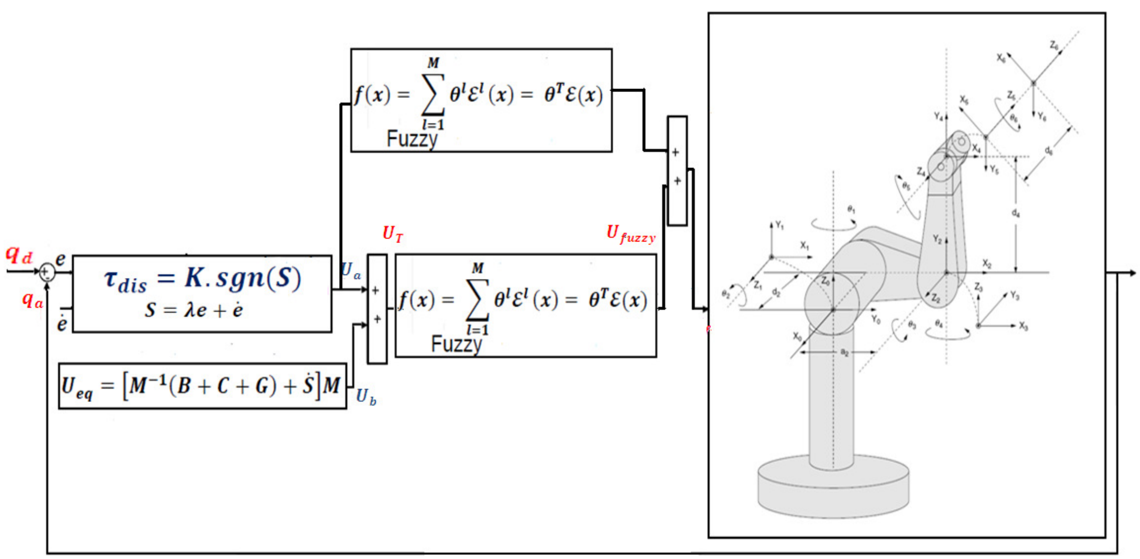

FIGURE 3: Design fuzzy online sliding mode fuzzy estimator controller

4 SIMULATION RESULTS

Pure sliding mode controller (SMC) and fuzzy online sliding mode fuzzy estimator controller (ASMFC) are implemented in Matlab/Simulink environment. Tracking performance and disturbance rejection is compared.

Tracking Performances: From the simulation for first, second and third trajectory without any disturbance, it was seen that SMC and ASMFC have the about the same performance because this system is worked on certain environment and in sliding mode controller also is a robust nonlinear controller with acceptable performance. Figure 4 shows tracking performance without any disturbance for SMC and ASMFC.

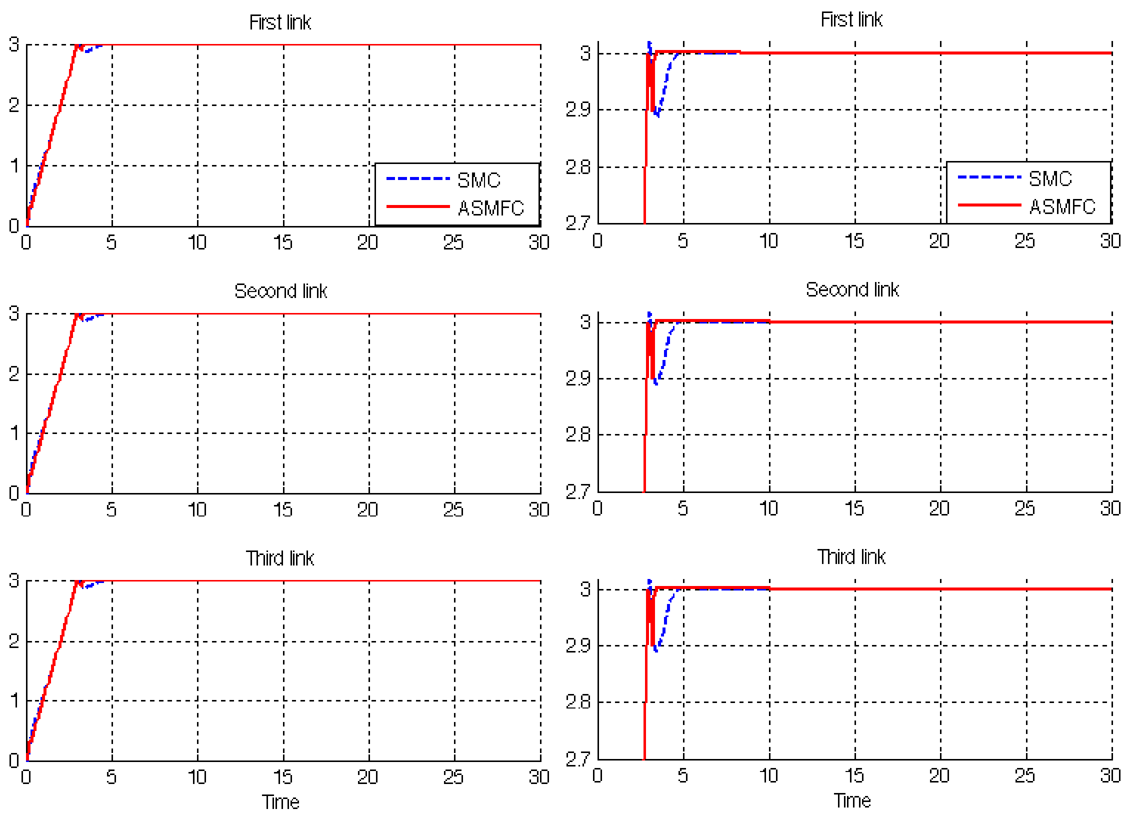

FIGURE 4: SMC Vs. ASMFC: applied to 3DOF's robot manipulator

By comparing trajectory response trajectory without disturbance in SMC and ASMFC, it is found that the SMFC's overshoot **(0%)** is lower than IDC's **(3.3%)** and the rise time in both of controllers are the same.

Disturbance Rejection: Figure 5 has shown the power disturbance elimination in SMC and ASMFC. The main targets in these controllers are disturbance rejection as well as the remove the chattering phenomenon. A band limited white noise with predefined of 40% the power of input signal is applied to the SMC and SMFC. It found fairly fluctuations in SMC trajectory responses.

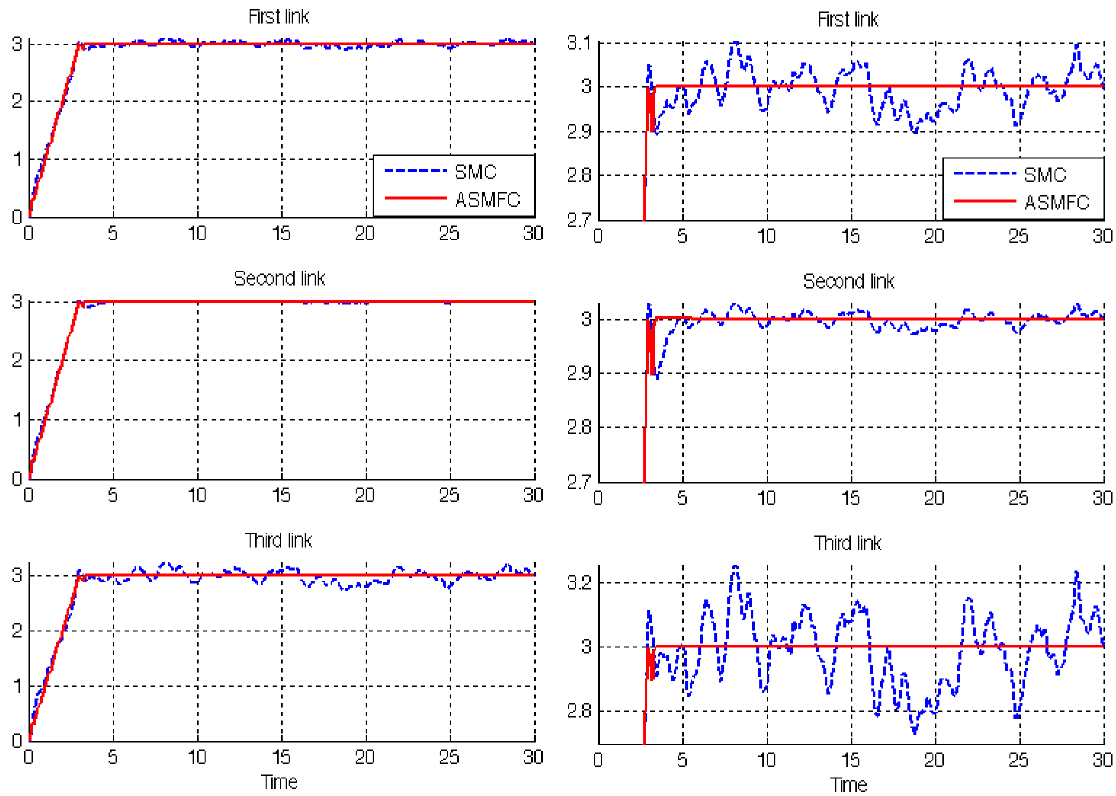

FIGURE 5: SMC Vs. ASMFC in presence of uncertainty: applied to robot manipulator.

Among above graph relating to trajectory following with external disturbance, SMC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the ASMFC's overshoot **(0%)** is lower than SMC's **(12%)**, although both of them have about the same rise time**.**

5 CONCLUSIONS

Refer to the research, a position online tuning sliding mode fuzzy estimator controller (ASMFC) design and application to robot manipulator has proposed. This research is based on sliding mode controller which eliminate the chattering phenomenon based on nonlinear fuzzy logic method and estimator block, eliminate the uncertainty unknown nonlinearity part based on applied online tuning fuzzy logic methodology in SMFC and reduce the uncertainty challenge based on fuzzy logic methodology and estimate via fuzzy estimator method. As a result proposed method has superior performance in presence of structure and unstructured uncertainty (e.g., overshoot=0%, rise time=0.8 s, steady state error = 1e-9 and RMS error=0.0001632) and eliminate the chattering.

REFERENCES

[1] Thomas R. Kurfess, Robotics and Automation Handbook: CRC press, 2005.

[2] Bruno Siciliano and Oussama Khatib, Handbook of Robotics: Springer, 2007.

[3] Slotine J. J. E., and W. Li., Applied nonlinear control: Prentice-Hall Inc, 1991.

[4] Piltan Farzin, et al., "Artificial Chattering Free on-line Fuzzy Sliding Mode Algorithm for Uncertain System: Applied in Robot Manipulator," International Journal of Engineering, 5 (5):220-238, 2011.

[5] L.X.Wang, "stable adaptive fuzzy control of nonlinear systems", IEEE transactions on fuzzy systems, 1(2): 146-154, 1993.

[6] Frank L.Lewis, Robot dynamics and control, in robot Handbook: CRC press, 1999.

[7] Piltan, F., et al., "Evolutionary Design on-line Sliding Fuzzy Gain Scheduling Sliding Mode Algorithm: Applied to Internal Combustion Engine," International journal of Engineering Science and Technology , 3 (10): 7301-7308, 2011.

[8] Soltani Samira and Piltan, F. "Design artificial control based on computed torque like controller with tunable gain," World Applied Science Journal, 14 (9): 1306-1312, 2011.

[9] Piltan, F., et al., "Designing on-line Tunable Gain Fuzzy Sliding Mode Controller using Sliding Mode Fuzzy Algorithm: Applied to Internal Combustion Engine," World Applied Sciences Journal , 14 (9): 1299-1305, 2011.

[10] Lotfi A. Zadeh" Toward a theory of fuzzy information granulation and its centrality in human easoning and fuzzy logic" Fuzzy Sets and Systems 90 (1997) 111-127

[11] Reznik L., Fuzzy Controllers, First edition: BH NewNes, 1997.

[12] Zhou, J., Coiffet, P," Fuzzy Control of Robots," Proceedings IEEE International Conference on Fuzzy Systems, pp: 1357 – 1364, 1992.

[13] Banerjee, S., Peng Yung Woo, "Fuzzy logic control of robot manipulator," Proceedings Second IEEE Conference on Control Applications, pp: 87 – 88, 1993.

[14] Akbarzadeh-T A. R., K.Kumbla, E. Tunstel, M. Jamshidi. ,"Soft Computing for autonomous Robotic Systems," IEEE International Conference on Systems, Man and Cybernatics, pp: 5252-5258, 2000.

[15] Lee C.C.," Fuzzy logic in control systems: Fuzzy logic controller-Part 1," IEEE International Conference on Systems, Man and Cybernetics, 20(2), P.P: 404-418, 1990.

[16] F. Piltan*, et al.*, "Artificial Control of Nonlinear Second Order Systems Based on AFGSMC," Australian Journal of Basic and Applied Sciences, 5(6*)*, pp. 509-522, 2011.

[17] Piltan, F., et al., "Design sliding mode controller for robot manipulator with artificial tunable gain," Canaidian Journal of pure and applied science, 5 (2): 1573-1579, 2011.

[18] Piltan, F., et al., "Design Artificial Nonlinear Robust Controller Based on CTLC and FSMC with Tunable Gain," International Journal of Robotic and Automation, 2 (3): 205-220, 2011.

[19] Piltan, F., et al., "Design of FPGA based sliding mode controller for robot manipulator," International Journal of Robotic and Automation, 2 (3): 183-204, 2011.

[20] Piltan Farzin, et al., "Design PID-Like Fuzzy Controller With Minimum Rule Base and Mathematical Proposed On-line Tunable Gain: Applied to Robot Manipulator," International Journal of Artificial intelligence and expert system, 2 (4):184-195, 2011.

[21] Farzin Piltan, A. R. Salehi and Nasri B Sulaiman.," Design artificial robust control of second order system based on adaptive fuzzy gain scheduling," world applied science journal (WASJ), 13 (5): 1085-1092, 2011.

[22] Piltan, F., et al., "Design On-Line Tunable Gain Artificial Nonlinear Controller ," Journal of Advances In Computer Research , 2 (4): 19-28, 2011.

[23] Piltan, F., et al., "Design Mathematical Tunable Gain PID-Like Sliding Mode Fuzzy Controller with Minimum Rule Base," International Journal of Robotic and Automation, 2 (3): 146-156, 2011.

[24] Piltan Farzin, et al., "Design of PC-based sliding mode controller and normalized sliding surface slope using PSO method for robot manipulator," International Journal of Robotics and Automation, 2 (4):245-260, 2011.

[25] Piltan, F., et al., "A Model Free Robust Sliding Surface Slope Adjustment in Sliding Mode Control for Robot Manipulator," World Applied Science Journal, 12 (12): 2330-2336, 2011.

[26] Piltan, F., et al., "Design Adaptive Fuzzy Robust Controllers for Robot Manipulator," World Applied Science Journal, 12 (12): 2317-2329, 2011.

[27] Piltan Farzin, et al., " Design Model Free Fuzzy Sliding Mode Control: Applied to Internal Combustion Engine," International Journal of Engineering, 5 (4):302-312, 2011.

[28] Piltan Farzin, et al., "Design of PC-based sliding mode controller and normalized sliding surface slope using PSO method for robot manipulator," International Journal of Robotics and Automation, 2 (4):245-260, 2011.

[29] Piltan, F., et al., "Design a New Sliding Mode Adaptive Hybrid Fuzzy Controller," Journal of Advanced Science & Engineering Research , 1 (1): 115-123, 2011.

[30] Piltan, F., et al., "Novel Sliding Mode Controller for robot manipulator using FPGA," Journal of Advanced Science & Engineering Research, 1 (1): 1-22, 2011.

[31] Piltan Farzin, et al., "Design of Model Free Adaptive Fuzzy Computed Torque Controller: Applied to Nonlinear Second Order System," International Journal of Robotics and Automation, 2 (4):232-244, 2011.

[32] Piltan Farzin, et al., "Control of IC Engine: Design a Novel MIMO Fuzzy Backstepping Adaptive Based Fuzzy Estimator Variable Structure Control ," International Journal of Robotics and Automation, 2 (5):357-370, 2011.

[33] Piltan, F., et al., "Adaptive MIMO Fuzzy Compensate Fuzzy Sliding Mode Algorithm: Applied to Second Order Nonlinear System," International Journal of Engineering, 5 (5): 249-263, 2011.

[34] Piltan, F., et al., "Novel Robot Manipulator Adaptive Artificial Control: Design a Novel SISO Adaptive Fuzzy Sliding Algorithm Inverse Dynamic Like Method," International Journal of Engineering, 5 (5): 264-279, 2011.

[35] Piltan Farzin, et al., "Position Control of Robot Manipulator: Design a Novel SISO Adaptive Sliding Mode Fuzzy PD Fuzzy Sliding Mode Control," International Journal of Artificial intelligence and Expert System, 2 (5):184-198, 2011.

[36] Piltan Farzin, et al., "Artificial Control of PUMA Robot Manipulator: A-Review of Fuzzy Inference Engine And Application to Classical Controller ," International Journal of Robotics and Automation, 2 (5):387-403, 2011.

[37] Piltan, F., et al., "Design Adaptive Fuzzy Inference Sliding Mode Algorithm: Applied to Robot Arm," International Journal of Robotics and Automation , 2 (5): 275-295, 2011.

[38] Piltan, F., et al., "Novel Artificial Control of Nonlinear Uncertain System: Design a Novel Modified PSO SISO Lyapunov Based Fuzzy Sliding Mode Algorithm ," International Journal of Robotics and Automation, 2 (5): 310-325, 2011.

[39] Piltan Farzin, et al., "Evolutionary Design of Mathematical tunable FPGA Based MIMO Fuzzy Estimator Sliding Mode Based Lyapunov Algorithm: Applied to Robot Manipulator," International Journal of Robotics and Automation, 2 (5):340-356, 2011.

[40] Piltan Farzin, et al., "Evolutionary Design of Backstepping Artificial Sliding Mode Based Position Algorithm: Applied to Robot Manipulator," International Journal of Engineering, 5 (5):239-248, 2011.

[41] Piltan, F., et al., "An Adaptive sliding surface slope adjustment in PD Sliding Mode Fuzzy Control for Robot Manipulator," International Journal of Control and Automation , 4 (3): 65-76, 2011.

[42] Piltan, F., et al., "Design PID-Like Fuzzy Controller with Minimum Rule base and Mathematical proposed On-line Tunable Gain: applied to Robot manipulator," International Journal of Artificial Intelligence and Expert System, 2 (5): 195-210, 2011.

[43] Piltan Farzin, et al., "Design and Implementation of Sliding Mode Algorithm: Applied to Robot Manipulator-A Review ," International Journal of Robotics and Automation, 2 (5):371-386, 2011.

[44] Piltan Farzin, et al., "Control of Robot Manipulator: Design a Novel Tuning MIMO Fuzzy Backstepping Adaptive Based Fuzzy Estimator Variable Structure Control ," International Journal of Control and Automation, 4 (4):25-36, 2011.