Design Novel Lookup Table Changed Auto Tuning FSMC: Applied to Robot 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

Mohammad Ali Dialame   *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

Abbas Zare   S*SP.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

Ali Badri   *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

Refer to this paper, design lookup table changed adaptive fuzzy sliding mode controller with minimum rule base and good response in presence of structure and unstructured uncertainty is presented. However sliding mode controller is one of the robust nonlinear controllers but when this controller is applied to robot manipulator with highly nonlinear and uncertain dynamic function; caused to be challenged in control. Sliding mode controller in presence of uncertainty has two most important drawbacks; chattering and nonlinear equivalent part which proposed method is solved these challenges with look up table change methodology. This method is based on self tuning methodology therefore artificial intelligence (e.g., fuzzy logic method) is played important role to design proposed method. This controller has acceptable performance in presence of uncertainty (e.g., overshoot=0%, rise time=0.8 s, steady state error = 1e-9 and RMS error=0.00017).

Keywords: Sliding Mode Controller, Fuzzy Logic Methodology, Fuzzy Sliding Mode Controller, Adaptive Methodology, Fuzzy Lookup Table Changed Sliding Mode Controller.

1. INTRODUCTION, BACKGROUND and MOTIVATION

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].

Farzin Piltan, M.A. Dialame, A. Zare & A. Badri

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 system dynamic parameters have large variations, and when the system has hard nonlinearities [1-3]. 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 [4-5]. 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). Sliding mode control methodology was first proposed in the 1950 [1-3]. This controller has been analyzed by many researchers in recent years. Many papers about the main theory of SMC are proposed such as references [1-44]. This controller now a day's used in wide range areas such as in robotics, in process control, in aerospace applications, and in power converters. 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 used in wide range area but, pure sliding mode controller has following disadvantages. Firstly, chattering problem; which can caused the high frequency oscillation of the controllers output. Secondly, sensitive; this controller is very sensitive to the noise when the input signals very close to the zero. Last but not the least, equivalent dynamic formulation; calculate the equivalent control formulation is difficult because it is depending on the nonlinear dynamic equation [6-9]. Many papers were presented to solve above problems such as references [21-44].

After the invention of fuzzy logic theory in 1965 by Zadeh [10], this theory was used in wide range area. 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. Fuzzy logic control systems, do not use complex mathematically models of plant for analysis. This method is free of some model-based techniques that used in classical controllers. It must be noted that application of fuzzy logic is not limited only to modeling of nonlinear systems [11-15, 20, 36] but also this method can help engineers to design easier controller. However pure FLC works in many engineering applications but, it cannot guarantee two most important challenges in control, namely, stability and acceptable performance [10-15].

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 so called fuzzy sliding mode controller [23, 25-27] and the other researchers applied sliding mode methodology in fuzzy logic controller (SMFC) to improve the stability of systems [29, 32-35].

Adaptive control used in systems whose dynamic parameters are varying and need to be training on line. In general states adaptive control classified in two main groups: traditional adaptive method and fuzzy adaptive method, that traditional adaptive method need to have some information about dynamic plant and some dynamic parameters must be known but fuzzy adaptive method can training the variation of parameters by expert knowledge. Adaptive fuzzy inference system provide a good knowledge tools for adjust a complex uncertain nonlinear system with changing dynamics to have an acceptable performance [37-44]. 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 [23-44].

In this research we will highlight a new auto adjust sliding surface slope 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 pure 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]:

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

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

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

Where B(q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques, and G(q) is the vector of gravity force. The dynamic terms in equation (2) are only manipulator position. This is a decoupled system with simple second order linear differential dynamics. In other words, the component $\ddot{q}$ influences, with a double integrator relationship, only the joint variableq_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [3, 16-28]:

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

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]:

$$e(t) = q_d(t) - q_a(t) \tag{4}$$

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]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \tag{5}$$

Where u is the vector of control input, $x^{(n)}$ is the nth derivation of$x$, $x = [x,\dot{x},\ddot{x},...,x^{(n-1)}]^T$ 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; $x_d = [x_d,\dot{x}_d,\ddot{x}_d,...,x_d^{(n-1)}]^T$, and have an acceptable error which is given by:

$$\tilde{x} = x - x_d = [\tilde{x},...,\tilde{x}^{(n-1)}]^T \tag{6}$$

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

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\,\tilde{x} = 0 \tag{7}$$

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

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\left(\int_0^t \tilde{x}\,dt\right) = 0 \tag{8}$$

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 $s(x,t)$.

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)| \tag{9}$$

where ζ is positive constant.

$$\textbf{If } \ S(0)>0 \rightarrow \frac{d}{dt}S(t) \le -\zeta \tag{10}$$

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

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt} S(t) \leq -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \leq -\zeta(t_{reach} - 0) \tag{11}$$

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

$$0 - S(0) \leq -\eta(t_{reach}) \rightarrow t_{reach} \leq \frac{S(0)}{\zeta} \tag{12}$$

and

$$if\ S(0) < 0 \rightarrow 0 - S(0) \leq -\eta(t_{reach}) \rightarrow S(0) \leq -\zeta(t_{reach}) \rightarrow t_{reach} \leq \frac{|S(0)|}{\eta} \tag{13}$$

Equation (13) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \tag{14}$$

suppose S is defined as

$$s(x, t) = (\frac{d}{dt} + \lambda)\ \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{15}$$

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

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

suppose the second order system is defined as;

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

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

$$\hat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \tag{18}$$

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

$$U_{dis} = \hat{U} - K(\vec{x}, t) \cdot sgn(s) \tag{19}$$

where the switching function sgn(S) is defined as

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{20}$$

and the $K(\vec{x}, t)$ is the positive constant. Suppose by (9) the following equation can be written as,

$$\frac{1}{2} \frac{d}{dt} s^2(x, t) = \dot{S} \cdot S = [f - \hat{f} - Ksgn(s)] \cdot S = (f - \hat{f}) \cdot S - K|S| \tag{21}$$

and if the equation (13) instead of (12) the sliding surface can be calculated as

$$s(x, t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x}\,dt \right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{22}$$

in this method the approximation of U is computed as

$$\hat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{23}$$

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

$$\tau = \tau_{eq} + \tau_{dis} \tag{24}$$

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

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

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;

$$\tau_{dis} = K \cdot \text{sgn}(S) \tag{26}$$

where

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

The result scheme is shown in Figure 1.

Problem Statement: Even though, SMC is used in wide range areas but, pure SMC has the chattering phenomenon disadvantages to reduce or eliminate the chattering this paper focuses on applied fuzzy logic methodology in sliding mode controller with minimum rule base after that sliding surface slope which has play important role in remove the chattering is auto adjusted.

Proof of Stability in Pure Sliding Mode Controller: 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

$$\tau = M(q)\ddot{q} + V(q, \dot{q})\dot{q} + G(q) \tag{27}$$

the lyapunov formulation can be written as follows,

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

the derivation of V can be determined as,

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

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

$$M\dot{S} = -VS + M\dot{S} + VS + G - \tau \tag{30}$$
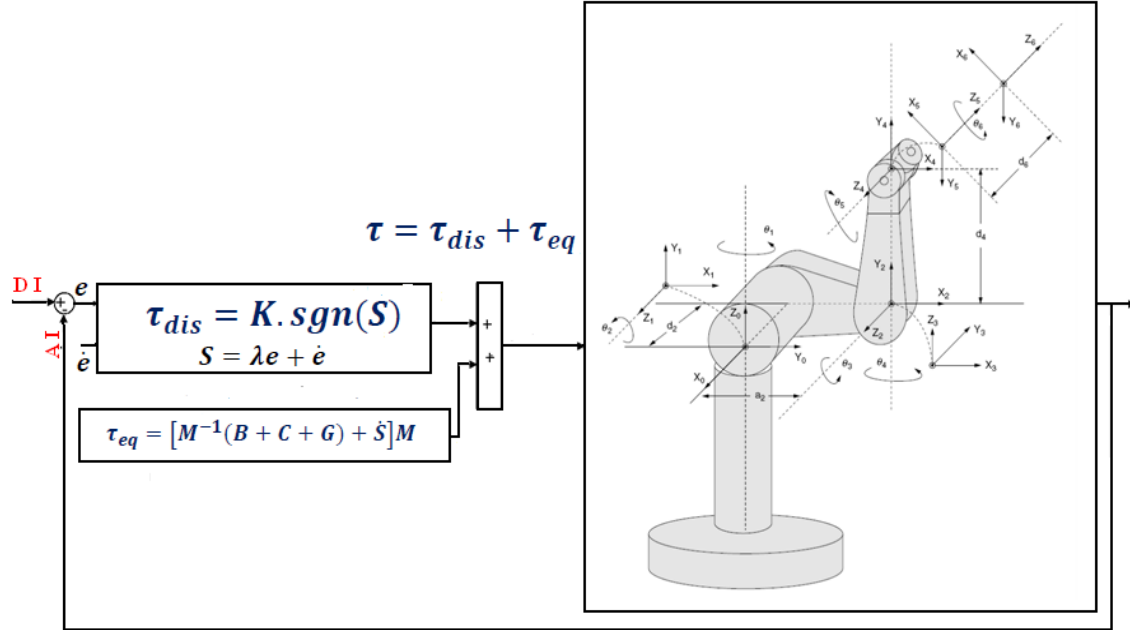
it is assumed that
$$S^T(\dot{M} - 2V)S = 0 \tag{31}$$

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

by substituting (30) in (29)
$$\dot{V} = \frac{1}{2}S^T \dot{M}S - S^T VS + S^T(MS + VS + G - \tau) = S^T(M\dot{S} + VS + G - \tau) \tag{32}$$

suppose the control input is written as follows
$$\hat{\tau} = \hat{\tau}_{eq} + \widehat{\tau}_{dis} = [\overline{M}^{-1}(V + \hat{G}) + \dot{S}]\hat{M} + K.sgn(S) + K_v S \tag{33}$$

by replacing the equation (33) in (32)
$$\dot{V} = S^T(M\dot{S} + VS + G - \dot{M}S - \dot{V}S - \hat{G} - K_v S - Ksgn(S) = S^T\left(\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K\right) \tag{34}$$

it is obvious that
$$\left|\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K_v S\right| \le \left|\tilde{M}\dot{S}\right| + \left|\tilde{V}S\right| + \left|\tilde{G}\right| + \left|K_v S\right| \tag{35}$$

the Lemma equation in robot manipulator system can be written as follows
$$K_u = \left[\left|\tilde{M}\dot{S}\right| + |VS| + |G| + |K_v S| + \eta\right]_i , i = 1, 2, 3, 4, \dots \tag{36}$$

the equation (31) can be written as
$$K_u \ge \left|\left[\tilde{M}\dot{S} + VS + G - K_v S\right]_i\right| + \eta_i \tag{37}$$

therefore, it can be shown that
$$\dot{V} \le -\sum_{i=1}^{n} \eta_i |S_i| \tag{38}$$

Consequently the equation (38) guaranties the stability of the Lyapunov equation.

Improve the Chattering: To remove the chattering boundary layer method; in boundary layer method is used [32-44]. This method is based on the replace discontinuous method by saturation (linear) method with small neighborhood of the switching surface.

$$H(t) = \{x, |S(t)| \leq \emptyset\}; \emptyset > 0 \tag{39}$$

Where $\emptyset$ is the boundary layer thickness. Therefore the saturation function $Sat(S/\emptyset)$ is added to the control law as

$$\tau_{sat} = K(\vec{x}, t) \cdot Sat\left(S/\emptyset\right) \tag{40}$$

Where $Sat\left(S/\emptyset\right)$ can be defined as

$$\text{sat}\left(S/\emptyset\right) = \begin{cases} 1 & (S/\emptyset > 1) \\ -1 & \left(S/\emptyset < 1\right) \\ S/\emptyset & (-1 < S/\emptyset < 1) \end{cases} \tag{41}$$

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

$$\tau = \tau_{eq} + \tau_{sat} \tag{42}$$

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

$$\tau_{eq} = [M^{-1}(B + C + G) + S]M \tag{43}$$

and τ_{sat} is computed as;

$$\tau_{sat} = K \cdot \text{sat}\left(S/\emptyset\right) \tag{44}$$

By replace the formulation (44) in (42) the control output can be written as;

$$\tau = \tau_{eq} + K.\text{sat}\left(S/\emptyset\right) = \begin{cases} \tau_{eq} + K.\text{sgn}(S) & ,|S| \geq \emptyset \\ \tau_{eq} + K.S/\emptyset & ,|S| < \emptyset \end{cases} \tag{45}$$

Figure 2 shows the chattering free sliding mode control for robot manipulator. By (45) and (43) the sliding mode control of PUMA 560 robot manipulator is calculated as;

$$\tau = [M^{-1}(B + C + G) + S]M + K \cdot \text{sat}\left(S/\emptyset\right) \tag{46}$$
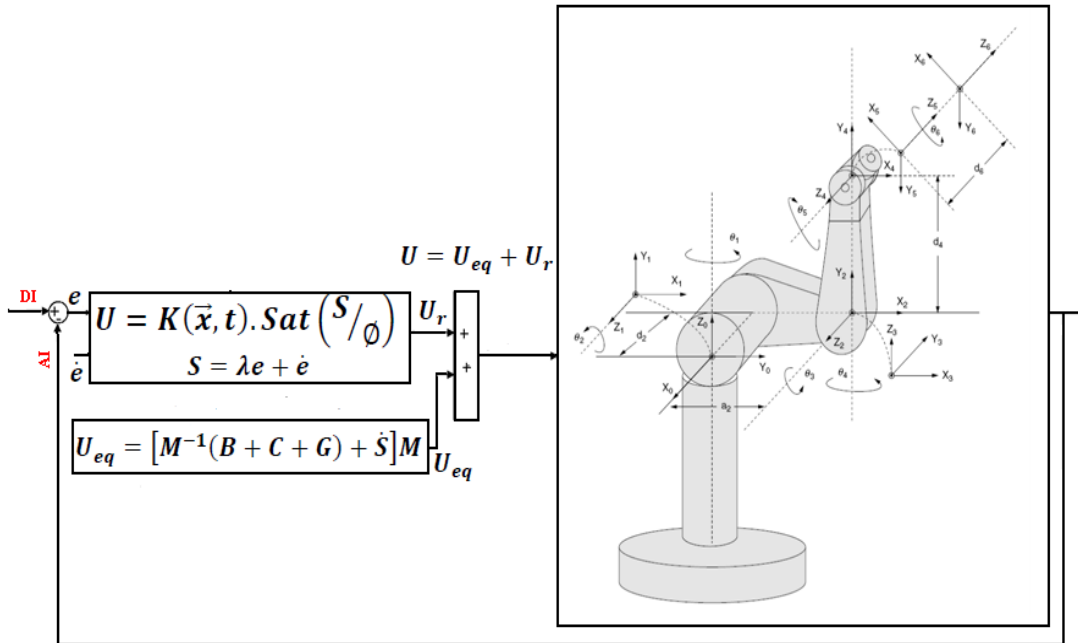
FIGURE 2: Block diagram of chattering free Sliding Mode Controller (SMC)

Second Step, Design Sliding Mode Fuzzy Controller: As shown in Figure 1, sliding mode controller divided into two main parts: equivalent controller, based on dynamics formulation of robot manipulators and sliding surface saturation part based on saturation continuous function to reduce the chattering. Boundary layer method (saturation function) is used to reduce the chattering. Reduce or eliminate the chattering regarding to reduce the error is play important role in this research therefore boundary layer method is used beside the equivalent part to solve the chattering problem besides reduce the error.

Combinations of fuzzy logic systems with sliding mode method have been proposed by several researchers. SMFC is fuzzy controller based on sliding mode method for easy implementation, stability, and robustness. Control rules for SMFC can be described as:

$$\textbf{IF } \textbf{ S is<ling.var> THEN U is<ling.var>} \tag{47}$$

Table 1 is shown the fuzzy rule table for SMFC, respectively:

S	NB	NM	NS	Z	PS	PM	PB
T	NB	NM	NS	Z	PS	PM	PB

TABLE 1: Rule table (SMFC)

A block diagram for sliding mode fuzzy controller is shown in Figure 3.
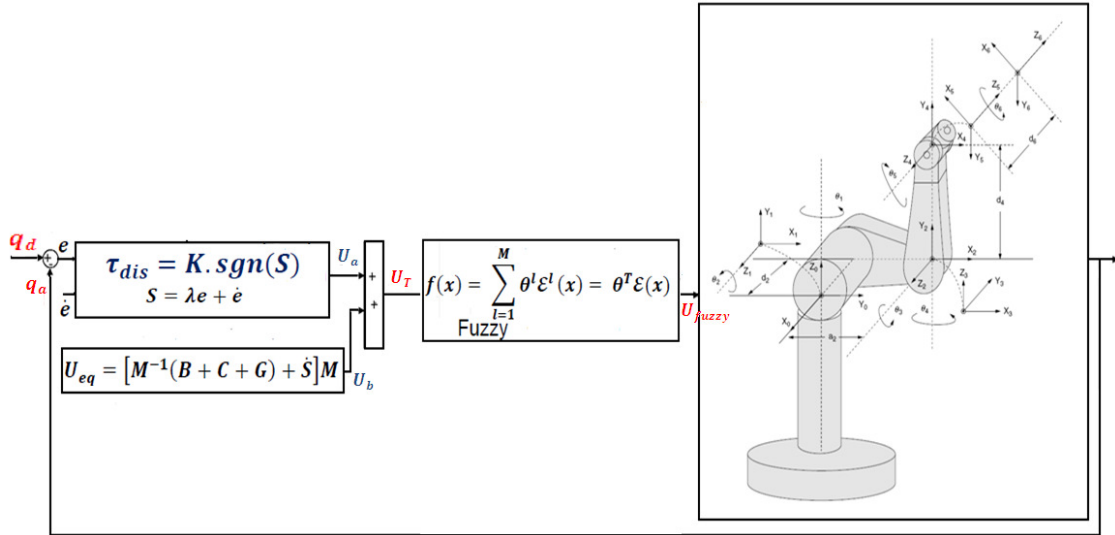
FIGURE3: Block Diagram of sliding mode Fuzzy Controller with Minimum Rule Base

It is basic that the system performance is sensitive to the sliding surface slope λ for sliding mode fuzzy controller. For instance, if large value of λ are chosen the response is very fast but the system is very unstable and conversely, if small value of λ considered the response of system is very slow but the system is very stable. Therefore, calculate the optimum value of λ for a system is one of the most important challenging works. SMFC has two most important advantages i.e. the number of rule base is smaller and Increase the robustness and stability.
In this method the control output can be calculated by

$$U_T = U_{dis} + U_{eq} \tag{48}$$

Where U_{eq} the nominal compensation is term and U_{dis} is the output of sliding function [9].

Third Step; Auto Tuning Sliding Surface Slope: All conventional controller have common difficulty, they need to find and estimate several nonlinear parameters. Tuning sliding surface slope can tune by mathematical automatically the scale parameters using mathematical model free method. To keep the structure of the controller as simple as possible and to avoid heavy computation, in this design model free mathematical supervisor tuner is selected. For nonlinear, uncertain, and time-variant plants (e.g., robot manipulators) adaptive method can be used to self adjusting the surface slope and gain updating factors. Research on adaptive sliding mode fuzzy controller is significantly growing, for instance, the different ASMFC have been reported in [5]; [10-12]. It is a basic fact that the system performance in SMFC is sensitive to sliding surface slope, λ. Thus, determination of an optimum λ value for a system is an important problem. If the system parameters are unknown or uncertain, the problem becomes more highlighted. This problem may be solved by adjusting the surface slope and boundary layer thickness of the sliding mode controller continuously in real-time. To keep the structure of the controller as simple as possible and to avoid heavy computation, a new supervisor tuner based on updated by a new coefficient factor km is presented. In this method the supervisor part tunes the output scaling factors using gain online updating factors. The inputs of the supervisor term are error and change of error $(e, \dot{e})$ and the output of this controller is U, which it can be used to tune sliding surface slope, λ.

$$k_n = e^2 - \frac{(r_v - r_{vmin})^3}{1 + |e|} + r_{vmin} \tag{49}$$

$$r_v = \frac{(de(k) - de(k-1))}{de(.)} = \frac{\ddot{e}(t)}{\dot{e}(.)} \tag{50}$$

$$de(.) = \begin{cases} de(k); & if\ de(k) \geq de(k-1) \\ de(k-1) & if\ de(k) < de(k-1) \end{cases}$$

$$S_{new} = \lambda_{new} \times e_{new} + \dot{e}_{new}$$

$$e_{new} = e \times \lambda_{new}$$

$$\lambda_{new} = \lambda \times K_n$$

In this way, the performance of the system is improved with respect to the SMFC controller.
In this method the tunable part tunes the sliding surface slope. However pure 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 adaptive. The lyapunov candidate formulation for our design is defined by:

$$V = \frac{1}{2}S^T M S + \frac{1}{2}\sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{51}$$

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

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

$$S^T M\dot{S} + \frac{1}{2}S^T \dot{M}S = S^T(M\dot{S} + VS) \tag{52}$$

From following two functions:

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \tag{53}$$

And

$$\tau = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \tag{54}$$

We can get:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \tag{55}$$

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

$$M\dot{S} + (V + A)S = \Delta f - K \tag{56}$$

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

The derivative of V defined by;

$$\dot{V} = S^T M\dot{S} + \frac{1}{2}S^T \dot{M}S + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{57}$$

$$\dot{V} = S^T(M\dot{S} + VS) + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{58}$$

$$\dot{V} = S^T(\Delta f - K - VS - AS + VS) + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{59}$$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - K_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{60}$$

suppose K_n is defined as follows

$$k_n = e^2 - \frac{(r_v - r_{vmin})^3}{1 + |e|} + r_{vmin} \tag{61}$$

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

$$V = \sum_{j=1}^{M} [S_j(\Delta f_j - (\theta^*)^T \zeta(S_j)k_n] - S^T AS + \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi_j^T [\gamma_{sj}, S_j, \zeta_j(S_j) + \phi_j]) \qquad (62)$$

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 V can be considered by

$$V = \sum_{j=1}^{m} [S_j \Delta f_j - ((\theta_j^*)^T \zeta_j(S_j)k_n)] - S^T AS \qquad (63)$$

If the minimum error can be defined by

$$e_{mj} = \Delta f_j - ((\theta_j^*)^T \zeta_j(S_j)) \qquad (64)$$

V is intended as follows

$$\begin{aligned} \dot{V} &= \sum_{j=1}^{m} [S_j e_{mj}] - S^T AS \\ &\leq \sum_{j=1}^{m} |S_j| |e_{mj}| - S^T AS \\ &= \sum_{j=1}^{m} |S_j| |e_{mj}| - a_j S_j^2 \\ &= \sum_{j=1}^{m} |S_j| (|e_{mj}| - a_j S_j) \end{aligned} \qquad (65)$$

For continuous function $g(x)$, and suppose $\varepsilon > 0$ it is defined mathematical model free in form of

$$Sup_{x \in U} |f(x) - g(x)| < \varepsilon \qquad (66)$$

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

$$if \ a_j = a \quad that \quad a|S_j| > e_{mj} \ (S_j \neq 0) \quad then \ \dot{V} < 0 \ for \ (S_j \neq 0) \qquad (67)$$

3.   SIMULATION RESULTS

Classical sliding mode control (SMC) and adaptive sliding mode fuzzy control (ASMFC) are implemented in Matlab/Simulink environment. In theses controllers changing updating factor performance, tracking performance, error, and robustness are compared.

Changing Sliding Surface Slope performance: For various value of sliding surface slope (λ) in SMC and ASMFC the trajectory performances have shown in Figures 4 and 5.
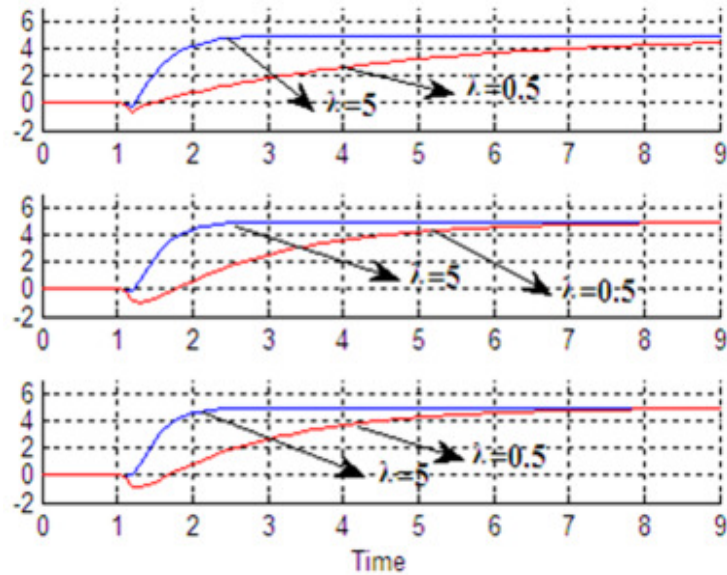
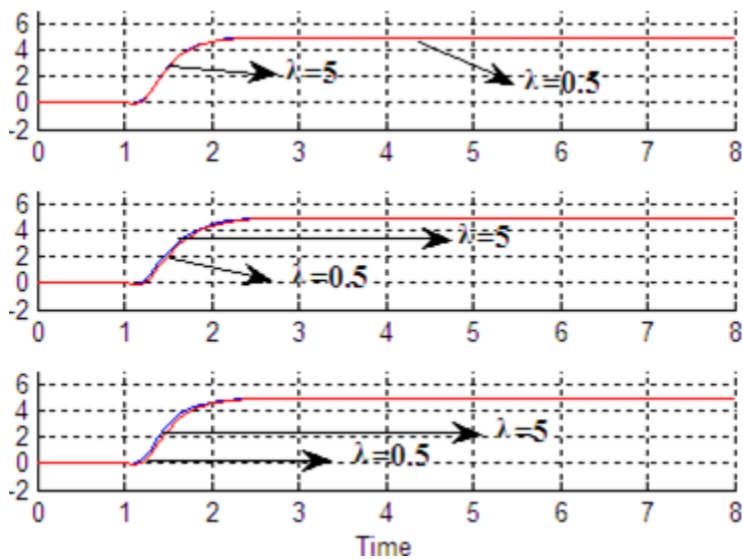**FIGURE 4:** Sliding surface slope in SMC: applied to 3DOF's robot manipulator


FIGURE 5: Sliding surface slope in ASMFC: applied to 3DOF's robot manipulator

Figures 4 and 5 are shown trajectory performance with different sliding surface slope; it is seen that AFSMC has the better performance in comparison with classical SMC.

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 6 shows tracking performance without any disturbance for SMC and ASMFC.
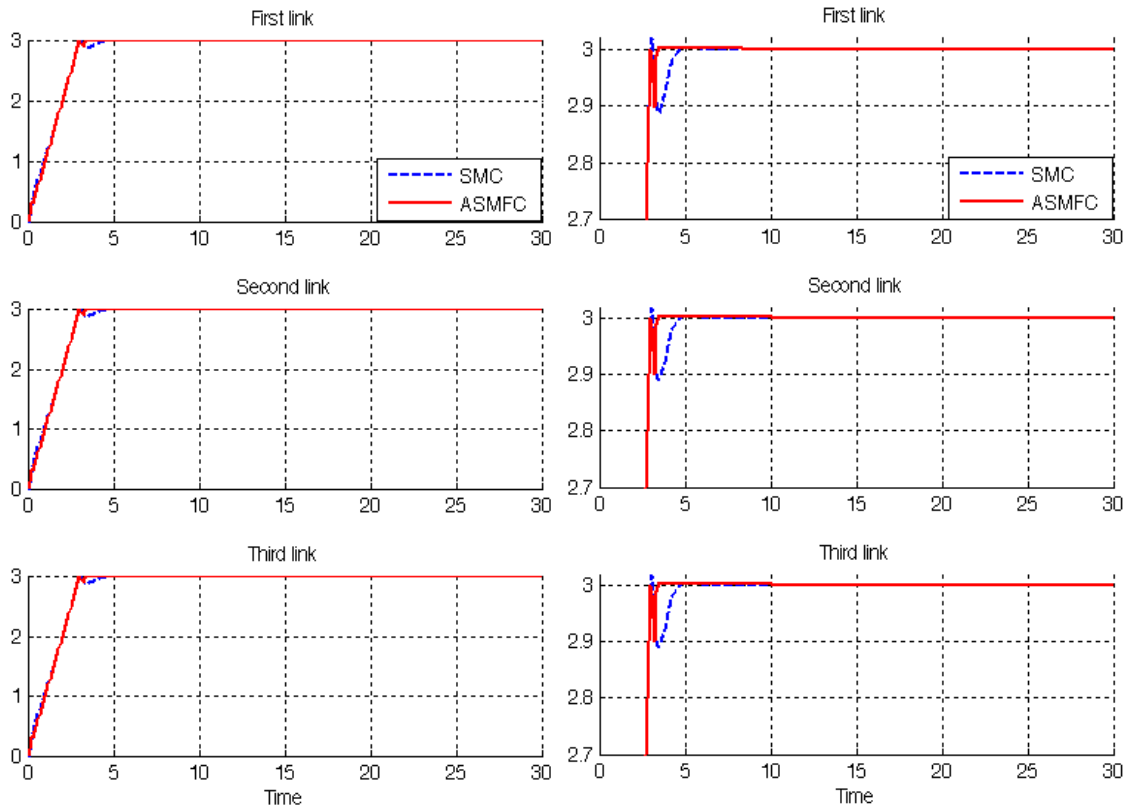
FIGURE 6: SMC Vs. ASMFC: applied to 3DOF's robot manipulator

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 **(3.33%)** and the rise time in both of controllers are the same.

Disturbance Rejection
Figure 7 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.
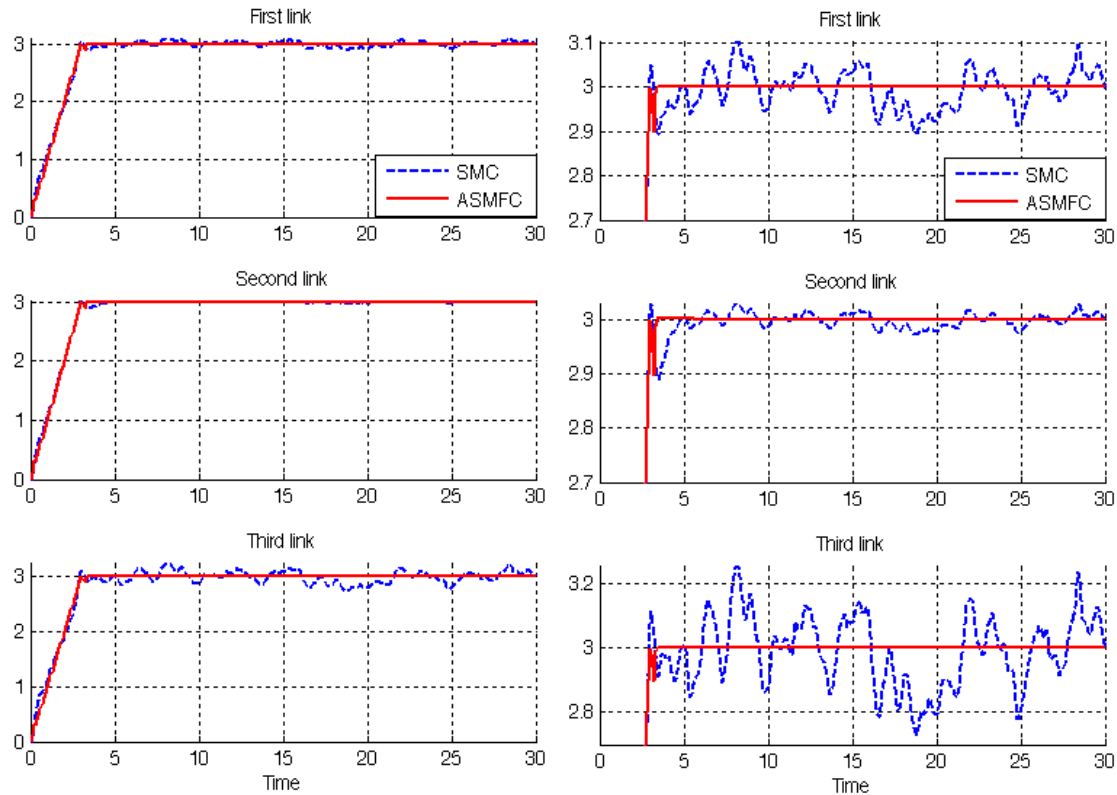
FIGURE 7: SMC Vs. ASMFC in presence of uncertainty: applied to robot manipulator.

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 **(12.4%)**, although both of them have about the same rise time**.**

4.   CONCLUSIONS

This research presents a design auto adjust sliding surface slope in sliding mode fuzzy controller (ASMFC) with improved in sliding mode controller which offers a model-free sliding mode controller. The sliding mode fuzzy controller is designed as 7 rules Mamdani's error-based to estimate the uncertainties in nonlinear equivalent part. To eliminate the chattering with regard to the uncertainty and external disturbance applied mathematical self tuning method to sliding mode fuzzy controller for adjusting the sliding surface slope coefficient (λ). In this research new λ is obtained by the previous λ multiple gains updating factor (K_n) which it also is based on error and change of error and also the second derivation of error. The proof of stability in this method is discussed. As a result auto adjust sliding surface slope in sliding mode fuzzy controller has superior performance in presence of structure and unstructured uncertainty (e.g., overshoot=0%, rise time=0.9 s, steady state error = 1e-7 and RMS error=0.00016) 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," Canadian 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.