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Design Sliding Mode Controller of with Parallel Fuzzy Inference System Compensator to Control of Robot Manipulator

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Article Info	ABSTRACT
	Sliding mode controller (SMC) is a significant nonlinear controller under condition of partly uncertain dynamic parameters of system. This controller is used to control of highly nonlinear systems especially for robot manipulators, because this controller is a robust and stable. 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. The nonlinear equivalent dynamic formulation problem and chattering phenomenon in uncertain system can be solved by using artificial intelligence theorem. However fuzzy logic controller is used to control complicated nonlinear dynamic systems, but it cannot guarantee stability and robustness. In this research parallel fuzzy logic theory is used to compensate the system dynamic uncertainty.

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1. INTRODUCTION

In modern usage, the word of control has many meanings, this word is usually taken to mean regulate, direct or command. The word feedback plays a vital role in the advance engineering and science. The conceptual frame work in Feed-back theory has developed only since world war II. In the twentieth century, there was a rapid growth in the application of feedback controllers in process industries. According to Ogata, to do the first significant work in three-term or PID controllers which Nicholas Minorsky worked on it by automatic controllers in 1922. In 1934, Stefen Black was invention of the feedback amplifiers to develop the negative feedback amplifier [3]. Negative feedback invited communications engineer Harold Black in 1928 and it occurs when the output is subtracted from the input. Automatic control has played an important role in advance science and engineering and its extreme importance in many industrial applications, i.e., aerospace, mechanical engineering and robotic systems. The first significant work in automatic control was James Watt's centrifugal governor for the speed control in motor engine in eighteenth century [2]. There are several methods for controlling a robot manipulator, which all of them follow two common goals, namely, hardware/software implementation and acceptable performance. However, the mechanical design of robot manipulator is very important to select the best controller but in general two types schemes can be presented, namely, a joint space control schemes and an operation space control schemes [1]. Joint space and operational space control are closed loop controllers which they have been used to provide robustness and rejection of disturbance effect. The main target in joint space controller is design a feedback controller that allows the actual motion ($q_a(t)$) tracking of the desired motion ($q_d(t)$). This control problem is classified into two main groups. Firstly, transformation the desired motion $X_d(t)$ to joint variable

$q_d(t)$ by inverse kinematics of robot manipulators [6]. The main target in operational space controller is to design a feedback controller to allow the actual end-effector motion $X_a(t)$ to track the desired endeffector motion $X_d(t)$. This control methodology requires a greater algorithmic complexity and the inverse kinematics used in the feedback control loop. Direct measurement of operational space variables are very expensive that caused to limitation used of this controller in industrial robot manipulators [6]. One of the simplest ways to analysis control of multiple DOF robot manipulators are analyzed each joint separately such as SISO systems and design an independent joint controller for each joint. In this methodology, the coupling effects between the joints are modeled as disturbance inputs. To make this controller, the inputs are modeled as: total velocity/displacement and disturbance. Design a controller with the same formulation and different coefficient, low cost hardware and simple structure controller are some of most important independent-joint space controller advantages. Nonlinear controllers divided into six groups, namely, feedback linearization (computed-torque control), passivity-based control, sliding mode control (variable structure control), artificial intelligence control, Lyapunov-based control and adaptive control [1], [6], [14].

Sliding mode controller (SMC) is a powerful nonlinear controller which has been analyzed by many researchers especially in recent years. This theory was first proposed in the early 1950 by Emelyanov and several co-workers and has been extensively developed since then with the invention of high speed control devices [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], [17]-[20]. 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. Conversely in this theory good trajectory following is based on fast switching, fast switching is caused to have system instability and chattering phenomenon. Fine tuning the sliding surface slope is based on nonlinear equivalent part [1], [6]. However, this controller is used in many applications but, pure sliding mode controller has two most important challenges: chattering phenomenon and nonlinear equivalent dynamic formulation in uncertain parameters [20]. Chattering phenomenoncan causes some problems such as saturation and heats the mechanical parts of robot manipulators or drivers. To reduce or eliminate the chattering, various papers have been reported by many researchers which classified into two most important methods: boundary layer saturation method and estimated uncertainties method [1]. In boundary layer saturation method, the basic idea is the discontinuous method replacement by saturation (linear) method with small neighborhood of the switching surface. This replacement caused to increase the error performance against with the considerable chattering reduction. Slotine and Sastry have introduced boundary layer method instead of discontinuous method to reduce the chattering [21]. Slotine has presented sliding mode with boundary layer to improve the industry application [22]. Palm has presented a fuzzy method to nonlinear approximation instead of linear approximation inside the boundary layer to improve the chattering and control the result performance [23]. Moreover, Weng and Yu improved the previous method by using a new method in fuzzy nonlinear approximation inside the boundary layer and adaptive method [24]. As mentioned [24] sliding mode fuzzy controller (SMFC) is fuzzy controller based on sliding mode technique to most exceptional stability and robustness. Sliding mode fuzzy controller has the two most important advantages: reduce the number of fuzzy rule base and increase robustness and stability. Conversely sliding mode fuzzy controller has the above advantages, define the sliding surface slope coefficient very carefully is the main disadvantage of this controller. Estimated uncertainty method used in term of uncertainty estimator to compensation of the system uncertainties. It has been used to solve the chattering phenomenon and also nonlinear equivalent dynamic. If estimator has an acceptable performance to compensate the uncertainties, the chattering is reduced. Research on estimated uncertainty to reduce the chattering is significantly growing as their applications such as industrial automation and robot manipulator. For instance, the applications of artificial intelligence, neural networks and fuzzy logic on estimated uncertainty method have been reported in [25]-[28]. Wu et al. [30] have proposed a simple fuzzy estimator controller beside the discontinuous and equivalent control terms to reduce the chattering. Their design had three main parts i.e. equivalent, discontinuous and fuzzy estimator tuning part which has reduced the chattering very well. Elmali et al. [27] and Li and Xu [29] have addressed sliding mode control with perturbation estimation method (SMCPE) to reduce the classical sliding mode chattering. This method was tested for the tracking control of the first two links of a SCARA type HITACHI robot. In this technique, digital controller is used to increase the system's response quality. However this controller's response is very fast and robust but it has chattering phenomenon.

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 uncertain 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 techniques as in model-based controllers. As mentioned that fuzzy logic application is not only limited to the modelling of nonlinear systems [31]-[36]

but also this method can help engineers to design a model-free controller. Control robot arm manipulators using model-based 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 most of time these models are MIMO, nonlinear and partly uncertain therefore calculate accurate dynamic model is complicated [32]. The main reasons to use fuzzy logic methodology are able to give approximate recommended solution for uncertain and also certain complicated systems to easy understanding and flexible. Fuzzy logic provides a method to design a model-free controller for nonlinear plant with a set of IF-THEN rules [32].

Based on mechanical and control methodologies research in robotic system, mechanical design, type of actuators and type of systems drive play important roles to have the best performance controller. This section has focused on the robot manipulator mechanical classification. Types of kinematics chain, i.e., serial Vs. parallel manipulators, and types of connection between link and join actuators, i.e., highly geared systems Vs. direct-drive systems are presented in the following sections because these topics played important roles to select and design the best acceptable performance controllers [1], [6], [14]. 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 capacity is more weightily because each link must be supported the weights of all next links and actuators between the present link and end-effector [1], [6]. Serial robot manipulators have been used in automotive industry, medical application, and also in research laboratories [1], [6]. In contrast, parallel robot manipulators design according to close loop which base frame is connected to the end-effector frame with two or more kinematic chains [6]. In the other words, a parallel link robot has two or more branches with some joints and links, which support the load in parallel. Parallel robot have been used in many applications such as expensive flight simulator, medical robotics (I.e., high accuracy, high repeatability, high precision robot surgery), and machinery tools [1]. Parallel links robot manipulators have higher accuracy and faster than serial links robot manipulators but the work space limitation in serial links robot manipulator is lower than parallel links robot manipulator. From control point of view, the coupling between different kinematic chains can generate the uncertainty problems which cause difficult controller design of parallel robot manipulator [1], [6]. One of the most important classifications in controlling the robot manipulator is how the links have connected to the actuators. This classification divides into two main groups: highly geared (e.g., 200 to 1) and direct drive (e.g., 1 to 1) [1]. High gear ratios reduce the nonlinear coupling dynamic parameters in robot manipulator. In this case, each joint is modeled the same as SISO systems. In high gear robot manipulators which generally are used in industry, the couplings are modeled as a disturbance for SISO systems [14]. Direct drive increases the coupling of nonlinear dynamic parameters of robot manipulators. This effect should be considered in the design of control systems. As a result some control and robotic researchers' works on nonlinear robust controller design [2].

Normal combinations of fuzzy logic methodology (FLM) and sliding mode (SMC) are to apply these two controllers at the same time [17], while FLM compensates the control error, SMC reduces the remain error of fuzzy inference system such that the final tracking error is asymptotically stable [18]. The chattering is eliminating, because SMC and FLM work parallel. In this paper, the asymptotic stability of SMC control with parallel fuzzy logic compensation is proposed (SMC+FLM). The fuzzy inference system is used to approximate the nonlinear plant. A dead one algorithm is applied for the fuzzy control. After the regulation error enter converges to the dead-zone, a super-twisting second-order sliding-mode is used to guarantee finite time convergence of the whole control (FLM+SMC). By means of a Lyapunov approach, we prove that this type of control can ensure finite time convergence and less chattering than SMC [33-39].

This paper is organized as follows; second part focuses on the modeling dynamic formulation based on Lagrange methodology, fuzzy logic methodology and sliding mode controller to have a robust control. Third part is focused on the methodology which can be used to reduce the error, increase the performance quality and increase the robustness and stability. Simulation result and discussion is illustrated in forth part which based on trajectory following and disturbance rejection. The last part focuses on the conclusion and compare between this method and the other ones.

2. THEOREM
2.1. Dynamic Formulation of IC Engine's Fuel Ratio
The equation of a multi degrees of freedom (DOF) robot manipulator is calculated by the following equation [6]:

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

Where τ is $n \times 1$ vector of actuation torque, M (q) is $n \times n$ symmetric and positive define inertia matrix, $N(q, \dot{q})$ is the vector of nonlinearity term, and q is $n \times 1$ position vector. In equation 2.8 if vector of nonlinearity term derive as Centrifugal, Coriolis and Gravity terms, as a result robot manipulator dynamic equation can also be written as [80]:

$$N(q, \dot{q}) = V(q, \dot{q}) + G(q) \tag{2}$$
$$V(q, \dot{q}) = B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 \tag{3}$$
$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \tag{4}$$

Where, $B(q)$ is matrix of coriolis torques, $C(q)$ is matrix of centrifugal torque, $[\dot{q}\,\dot{q}]$ is vector of joint velocity that it can give by: $[\dot{q}_1.\dot{q}_2, \dot{q}_1.\dot{q}_3, \ldots, \dot{q}_1.\dot{q}_n, \dot{q}_2.\dot{q}_3, \ldots]^T$, and $[\dot{q}]^2$ is vector, that it can given by: $[\dot{q}_1{}^2, \dot{q}_2{}^2, \dot{q}_3{}^2, \ldots]^T$.

In robot manipulator dynamic part the inputs are torques and the outputs are actual displacements, as a result in (2.11) it can be written as [1], [6], [80-81];

$$\ddot{q} = M^{-1}(q).\{\tau - N(q, \dot{q})\} \tag{5}$$

To implementation Equation (5) the first step is implement the kinetic energy matrix (M) parameters by used of Lagrange's formulation. The second step is implementing the Coriolis and Centrifugal matrix which they can calculate by partial derivatives of kinetic energy. The last step to implement the dynamic equation of robot manipulator is to find the gravity vector by performing the summation of Lagrange's formulation.

The kinetic energy equation (M) is a $n \times n$ symmetric matrix that can be calculated by the following equation:

$$M(\theta) = m_1 J_{v1}^T J_{v1} + J_{\omega 1}^{TC1} I_1 J_{\omega 1} + m_2 J_{v2}^T J_{v2} + J_{\omega 2}^{TC2} I_2 J_{\omega 2} + m_3 J_{v3}^T J_{v3} + J_{\omega 3}^{TC3} I_3 J_{\omega 3} + \tag{6}$$
$$m_4 J_{v4}^T J_{v4} + J_{\omega 4}^{TC4} I_4 J_{\omega 4} + m_5 J_{v5}^T J_{v5} + J_{\omega 5}^{TC5} I_5 J_{\omega 5} + m_6 J_{v6}^T J_{v6} + J_{\omega 6}^{TC6} I_6 J_{\omega 6}$$

As mentioned above the kinetic energy matrix in n DOF is a $n \times n$ matrix that can be calculated by the following matrix [1], [6]:

$$M(q) = \begin{bmatrix} M_{11} & M_{12} & \ldots & \ldots & \ldots & M_{1n} \\ M_{21} & \ldots & \ldots & \ldots & \ldots & M_{2n} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ M_{n.1} & \ldots & \ldots & \ldots & \ldots & M_{n.n} \end{bmatrix} \tag{7}$$

The Coriolis matrix (B) is a $n \times \frac{n(n-1)}{2}$ matrix which calculated as follows:

$$B(q) = \begin{bmatrix} b_{112} & b_{113} & \ldots & b_{11n} & b_{123} & \ldots & b_{12n} & \ldots & \ldots & b_{1.n-1.n} \\ b_{212} & \ldots & \ldots & b_{21n} & b_{223} & \ldots & \ldots & \ldots & \ldots & b_{2.n-1.n} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ b_{n.1.2} & \ldots & \ldots & b_{n.1.n} & \ldots & \ldots & \ldots & \ldots & \ldots & b_{n.n-1.n} \end{bmatrix} \tag{8}$$

And the Centrifugal matrix (C) is a $n \times n$ matrix;

$$C(q) = \begin{bmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nn} \end{bmatrix} \tag{9}$$

And last the Gravity vector (G) is a $n \times 1$ vector;

$$G(q) = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_n \end{bmatrix} \tag{10}$$

2.2. Sliding Mode Controller

Design a robust controller for robot manipulator is essential because robot manipulator has highly nonlinear dynamic parameters. In this section formulations of sliding mode controller for robot manipulator is presented based on [1], [6]. Consider a nonlinear single input dynamic system is defined by [6]:

$$\mathbf{x}^{(n)} = \mathbf{f}(\vec{\mathbf{x}}) + \mathbf{b}(\vec{\mathbf{x}})\mathbf{u} \tag{11}$$

Where u is the vector of control input, $x^{(n)}$ is the nth 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 main goal to design this controller is train to the desired state; $x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d^{(n-1)}]^T$, and trucking error vector is defined by [6]:

$$\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x_d} = [\tilde{\mathbf{x}}, \dots, \tilde{\mathbf{x}}^{(n-1)}]^T \tag{12}$$

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

$$\mathbf{s}(\mathbf{x}, \mathbf{t}) = (\frac{\mathbf{d}}{\mathbf{dt}} + \lambda)^{\mathbf{n-1}} \, \tilde{\mathbf{x}} = \mathbf{0} \tag{13}$$

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

$$\mathbf{s}(\mathbf{x}, \mathbf{t}) = (\frac{\mathbf{d}}{\mathbf{dt}} + \lambda)^{\mathbf{n-1}} \left(\int_{\mathbf{0}}^{\mathbf{t}} \tilde{\mathbf{x}} \, \mathbf{dt} \right) = \mathbf{0} \tag{14}$$

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 $s(x, t)$ [6].

$$\frac{\mathbf{1}}{\mathbf{2}} \frac{\mathbf{d}}{\mathbf{dt}} \mathbf{s}^2(\mathbf{x}, \mathbf{t}) \le -\zeta|\mathbf{s}(\mathbf{x}, \mathbf{t})| \tag{15}$$

Where ζ is positive constant.

$$\text{If } \mathbf{S(0)}{>}0 \rightarrow \frac{\mathbf{d}}{\mathbf{dt}} \mathbf{S(t)} \le -\zeta \tag{16}$$

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

$$\int_{\mathbf{t=0}}^{\mathbf{t=t_{reach}}} \frac{\mathbf{d}}{\mathbf{dt}} \mathbf{S(t)} \le - \int_{\mathbf{t=0}}^{\mathbf{t=t_{reach}}} \mathbf{\eta} \rightarrow \mathbf{S}\,(\mathbf{t_{reach}}) - \mathbf{S(0)} \le -\zeta(\mathbf{t_{reach}} - \mathbf{0}) \tag{17}$$

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

$$\mathbf{0} - \mathbf{S(0)} \le -\mathbf{\eta}(\mathbf{t_{reach}}) \rightarrow \mathbf{t_{reach}} \le \frac{\mathbf{S(0)}}{\mathbf{\zeta}} \tag{18}$$

And

$$\text{if } \mathbf{S(0)} < \mathbf{0} \rightarrow \mathbf{0} - \mathbf{S(0)} \le -\mathbf{\eta}(\mathbf{t_{reach}}) \rightarrow \mathbf{S(0)} \le -\zeta(\mathbf{t_{reach}}) \rightarrow \mathbf{t_{reach}} \le \frac{|\mathbf{S(0)}|}{\mathbf{\eta}} \tag{19}$$

Equation (19) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$\text{if } S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \tag{20}$$

Suppose S is defined as:

$$s(x, t) = (\frac{d}{dt} + \lambda) \quad \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{21}$$

The derivation of S, namely, $\dot{S}$ can be calculated as the following;
$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{22}$$

Suppose the second order system is defined as;

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

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

$$\widehat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \tag{24}$$

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

$$U_{dis} = \widehat{U} - K(\vec{x}, t) \cdot sgn(s) \tag{25}$$

where the switching function $sgn(S)$ is defined as [1, 6]:

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{26}$$

and the $K(\vec{x}, t)$ is the positive constant. Suppose by (2.37) the following equation can be written as,
$$\frac{1}{2}\frac{d}{dt}s^2(x, t) = \dot{S} \cdot S = [f - \hat{f} - Ksgn(s)] \cdot S = (f - \hat{f}) \cdot S - K|S| \tag{27}$$

And if the Equation (19) instead of (18) the sliding surface can be calculated as:

$$s(x, t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x} \, dt \right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{28}$$

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

$$\widehat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{29}$$

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

$$\tau = \tau_{eq} + \tau_{dis} \tag{30}$$

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

$$\tau_{eq} = [M^{-1}(B + C + G) + \dot{S}]M \tag{31}$$

And τ_{dis} is computed as [1];

$$\tau_{dis} = K \cdot sgn(S) \tag{32}$$

By replace the formulation (2.54) in (2.52) the control output can be written as;

$$\tau = \tau_{eq} + K.\, sgn(S) \tag{33}$$

Figure 1 shows the position classical sliding mode control for PUMA 560 robot manipulator. By Equation (33) and (31) the sliding mode control of PUMA 560 robot manipulator is calculated as;

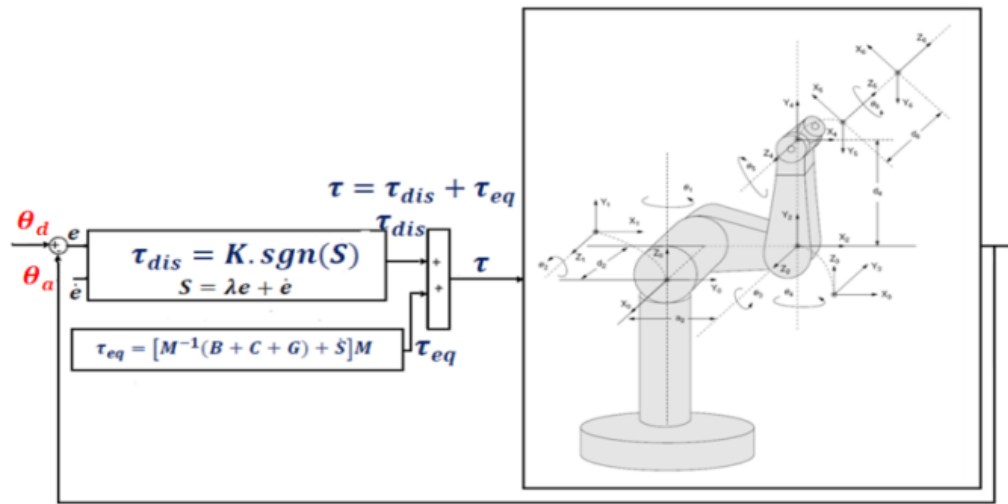$$\tau = \left[M^{-1}(B + C + G) + \dot{S}\right]M + K \cdot sgn(S) \tag{34}$$

Figure 1. Block diagram of pure sliding mode controller with switching function

2.3. Fuzzy Logic Technique

Based on foundation of fuzzy logic methodology; fuzzy logic management has played important rule to design nonlinear management for nonlinear and uncertain systems [16]. However the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of;
Input fuzzification (binary-to-fuzzy [B/F] conversion)

Fuzzy rule base (knowledge base), Inference engine and Output defuzzification (fuzzy-to-binary [F/B] conversion). Figure 2 shows the fuzzy controller part. The fuzzy inference engine offers a mechanism for transferring the rule base in fuzzy set which it is divided into two most important methods, namely, Mamdani method and Sugeno method. Mamdani method is one of the common fuzzy inference systems and he designed one of the first fuzzy managements to control of system engine. Mamdani's fuzzy inference system is divided into four major steps: fuzzification, rule evaluation, aggregation of the rule outputs and defuzzification. Michio Sugeno uses a singleton as a membership function of the rule consequent part. The following definition shows the Mamdani and Sugeno fuzzy rule base [22]-[33]

$$if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ C \quad 'mamdani'$$
$$if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ f(x,y)'sugeno'$$

When x and y have crisp values fuzzification calculates the membership degrees for antecedent part. Rule evaluation focuses on fuzzy operation (AND/OR) in the antecedent of the fuzzy rules. The aggregation is used to calculate the output fuzzy set and several methodologies can be used in fuzzy logic controller aggregation, namely, Max-Min aggregation, Sum-Min aggregation, Max-bounded product, Max-drastic product, Max-bounded sum, Max-algebraic sum and Min-max. Defuzzification is the last step in the fuzzy inference system which it is used to transform fuzzy set to crisp set. Consequently defuzzification's input is the aggregate output and the defuzzification's output is a crisp number. Centre of gravity method (COG) and Centre of area method (COA) are two most common defuzzification methods.
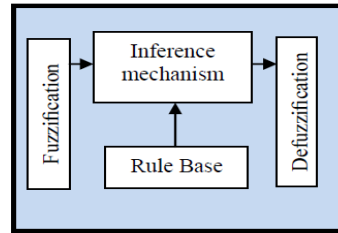
Figure 2. Fuzzy Controller Part

3.   METHODOLOGY

Sliding mode controller (SMC) is an important nonlinear controller in a partly uncertain dynamic system's parameters. This controller is used in several applications such as in robotics, process control, aerospace and power electronics. Sliding mode controller is used to control of nonlinear dynamic systems particularly for robot manipulators, because it has a suitable control performance and it is a robust and stable. Conversely pure sliding mode controller is a high-quality nonlinear controller; it has two important problems; chattering phenomenon and nonlinear equivalent dynamic formulation in uncertain dynamic parameter. To reduce the chattering phenomenon and equivalent dynamic problems, this research is focused on applied parallel fuzzy logic theorem in sliding mode controller as a compensator. Fuzzy logic theory is used in parallel with sliding mode controller to compensate the limited uncertainty in system's dynamic. In this method fuzzy logic theorem is applied to sliding mode controller to remove the nonlinear uncertainty part which it is based on nonlinear dynamic formulation. To achieve this goal, the dynamic equivalent part of pure sliding mode controller is modeled by Mamdani's performance/error-based fuzzy logic methodology. Another researcher's method is based on applied fuzzy logic theorem in sliding mode controller to design a fuzzy model-based controller. This technique was employed to obtain the desired control behavior with a number of information about dynamic model of system and a fuzzy switching control was applied to reinforce system performance. Reduce or eliminate the chattering phenomenon and reduce the error are played important role, therefore switching method is used beside the artificial intelligence part to solve the chattering problem with respect to reduce the error. Equivalent part of sliding mode controller is based on nonlinear dynamic formulations of robot manipulator. Robot manipulator's dynamic formulations are highly nonlinear and some of parameters are unknown therefore design a controller based on dynamic formulation is complicated. To solve this challenge parallel fuzzy logic methodology is applied to sliding mode controller. In this method fuzzy logic method is used to compensate some dynamic formulation that they are used in equivalent part. To solve the challenge of sliding mode controller based on nonlinear dynamic formulation this research is focused on compensate the nonlinear equivalent formulation by parallel fuzzy logic controller. In this method; dynamic nonlinear equivalent part is modelled by performance/error-based fuzzy logic controller. In this method; error based Mamdani's fuzzy inference system has considered with two inputs, one output and totally 49 rules.   Figure 3 shows error-based parallel fuzzy plus sliding mode controller.
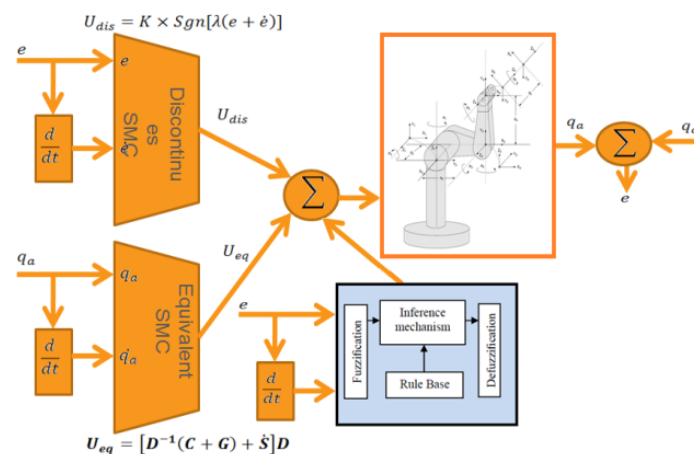

Figure 3. Block diagram of fuzzy inference system + pure sliding mode controller with switching function

For both sliding mode controller and parallel fuzzy inference system plus sliding mode controller applications the system performance is sensitive to the sliding surface slope coefficient(λ). For instance, if large value of λ is chosen the response is very fast the system is unstable and conversely, if small value of λ is considered the response of system is very slow but system is stable. Therefore to have a good response, compute the best value sliding surface slope coefficient is very important. In parallel fuzzy inference system compensator of sliding mode controller the PD-sliding surface is defined as follows:

$$S = \dot{e} + \lambda_1 e \tag{35}$$

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

$$\dot{S} = \ddot{q}_d + \lambda_1 \dot{e} \tag{36}$$

Based on Figure 3, the parallel fuzzy error-based compensator of sliding mode controller's output is written;

$$\hat{\tau} = \tau_{eq_{fuzzy}} + \tau_{SMC} \tag{37}$$

Based on fuzzy logic methodology:

$$f(x) = U_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) \tag{38}$$

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

$$\zeta(x) = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)} \tag{39}$$

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

$$\tau_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = [(B + C + G)] \tag{40}$$

As mentioned in Figure 3, design an error-based parallel fuzzycompensate of equivalent part based on Mamdani's fuzzy inference method has four steps, namely, fuzzification, fuzzy rule base and rule evaluation, aggregation of the rule output (fuzzy inference system) and defuzzification.

Fuzzification: the first step in fuzzification is determine inputs and outputs which, it has two inputs $(e, \dot{e})$ and one output (τ_{fuzzy}). The inputs are error (e) which measures the difference between desired and actual output position, and the change of error ($\dot{e}$) which measures the difference between desired and actual velocity and output is fuzzy equivalent torque. The second step is chosen an appropriate membership function for inputs and output which, to simplicity in implementation because it is a linear function with regard to acceptable performance triangular membership function is selected in this research as shown in Figure 3. The third step is chosen the correct labels for each fuzzy set which, in this research namely as linguistic variable. Based on experience knowledge the linguistic variables for error (e) are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and based on literature [40] and experience knowledge it is quantized into thirteen levels represented by: -1, -0.83, -0.66, -0.5, -0.33, -0.16, 0, 0.16, 0.33, 0.5, 0.66, 0.83, 1 the linguistic variables for change of error ($\dot{e}$) are; Fast Left (FL), Medium Left (ML), Slow Left (SL),Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR), and it is quantized in to thirteen levels represented by: -6, -5, -0.4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, and the linguistic variables 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: -85, -70.8, -56.7, -42.5, -28.3, -14.2, 0, 14.2, 28.3, 42.5, 56.7, 70.8, 85.

Fuzzy rule base and rule evaluation: the first step in rule base and evaluation is to 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 parallel fuzzy plus 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. 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): based onfuzzy methodology, Max-Min aggregation is used in this work.

Table 1. Modified Fuzzy rule base table

$\dot{e}$ \\ e	FL	ML	SL	Z	SR	MR	FR
NB	LL	LL	LL	ML	SL	SL	Z
NM	LL	ML	ML	ML	SL	Z	SR
NS	LL	ML	SL	SL	Z	SR	MR
Z	LL	ML	SL	Z	SR	MR	LR
PS	ML	SL	Z	SR	SR	MR	LR
PM	SL	Z	SR	MR	MR	MR	LR
PB	Z	SR	SR	MR	LR	LR	LR

(Decrease the overshoot $\dot{e}$ — Decrease the rise time e)

Defuzzification: The last step to design fuzzy inference in our parallel fuzzy compensator plus sliding mode 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. Based on fuzzy methodology Center of gravity method (COG) is used in this research. Table 2 shows the lookup table in parallel fuzzy compensator sliding mode controller which is computed by COG defuzzification method. Table 2 has 169 cells to shows the error-based fuzzy compensate of equivalent part behavior.

Table 2. τ_{fuzzy} performance: lookup table in parallel fuzzy compensate of sliding mode controller by COG

e \\ $\dot{e}$	Membership Function (τ_{fuzzy})												
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-1	-85	-84.8	-84.8	-84	-82.1	-81	-79	-71	-68	-65	-62	-60	-54
-0.83	-84.8	-84	-82	-80	-78	-77	-74	-70	-64	-60	-56	-54	-47
-0.66	-78	-73	-70	-68	-64	-61	-60	-57	-55	-50	-47	-40	-38
-0.5	-70	-60	-58	-51	-42	-38	-34	-33	-31	-29	-28.4	-28.1	-28
-0.33	-50	-48	-45	-40	-38	-34	-32	-30	-28	-26	-25	-21	-20
-0.16	-30	-25	-21	-18	-16	-14	-10	-9	-8	-7	-6.8	-6	-5
0	-10	-8	-6	-1	2	3	6	7	8	10	12	15	17
0.16	15	18	21	22	23	25	27	28	29	30	30.5	30.8	31
0.33	29	29.8	31	33	34	34.6	35	35.2	36	37	38	39	42
0.5	40	41	42	43	45	45	46	46.3	46.8	47	48	51	52
0.66	48	49	50	52	53	55	56	57	58	59	60	61	63
0.83	60	61	62	63	64	66	67	68	68.5	69	70	70.8	71
1	66	68.7	68.9	70	72	74	75	77	78	79	81	83	84

4. RESULTS

In this section, we use a benchmark model, robot manipulator, to evaluate our control algorithms. We compare the following managements: classical PD controller, PD fuzzy controller and parallel fuzzy inference compensator plus sliding mode controller which is proposed in this paper. The simulation was implemented in MATLAB/SIMULINK environment.

Close loop response of robot manipulator trajectory planning: Figure 4 illustrates the tracking performance in three types of controllers.
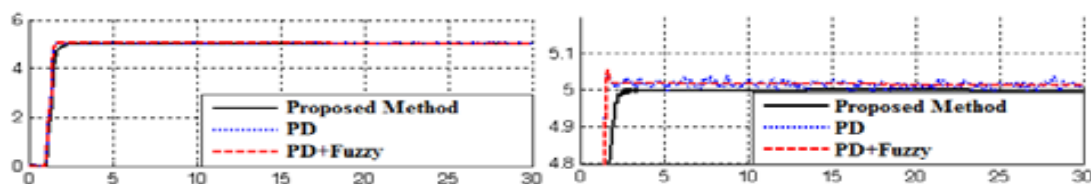

Figure 4. Linear PD, PD+FLC and Proposed method trajectory following without disturbance

Based on Figure 4; pure PD controller has oscillation in all links, because robot is a highly nonlinear system and control of this system by linear method is very difficult. Based on above graph, however PD+FUZZY controller is a nonlinear methodology but it has difficulty to control this plant because it is a model free controller.

Close loop response of trajectory planning in presence of disturbance: Figure 5 demonstrates the power disturbance elimination in three types of controller in presence of disturbance for robot. The disturbance rejection is used to test the robustness comparisons of these three methodologies.
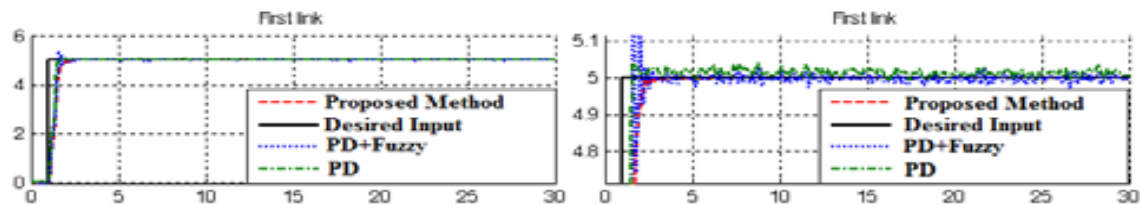

Figure 5. Linear PD, PD+FLC and Proposed method trajectory following with disturbance

Based on Figure 5; by comparison with the PD and PD+FLC, proposed methodology is more stable and robust and our method doesn't have any chattering and oscillation.

5. CONCLUSION

The main contributions of this paper iscompensate the nonlinear model base controller by nonlinear artificial intelligence model-free compensator. The structure of sliding mode controller with parallel fuzzy inference compensator is new. We propose parallel structure and chattering free compensator: parallel compensation, and chattering free method. The key technique is dead-zone, such that fuzzy inference compensator and sliding mode control can be switched automatically. The stability analysis of parallel fuzzy compensator plus sliding mode controller is test via Lyapunov methodology. The benefits of the proposed method; the chattering effects of parallel fuzzy inference compensator plus sliding mode controller, the slow convergence of the fuzzy and the chattering problem of sliding mode method are avoided effectively.

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