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Methodologies of Chattering Attenuation in Sliding Mode Controller

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Abstract

Uncertain or complicated systems are difficult to control. Modeling the system uncertainties is an especial topics in most of engineering field. On the other hand, since system has uncertainty, design stable and robust controller is crucial importance in control engineering. To solve this challenge nonlinear control technique is the best choice.

Sliding mode control is one important type of robust control. Model imprecision may come from actual uncertainty about the plant or from a purposeful simplification of the system's dynamics. Modeling inaccuracies can cause strong adverse effects on the control design of nonlinear systems. For the class of systems to which it applies, sliding mode controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision. However, sliding mode controller is a robust and stable controller but it has an important challenge called, chattering phenomenon. This research focuses on the comparative between three methods to eliminate/reduce the chattering.

***Keywords**: variable structure controller, sliding surface slope, chattering phenomenon, boundary layer methodology, PD parallel chattering attenuation, intelligent chattering elimination*

1. Introduction

Actuators are indispensable for all robots to provide the forces, torques, and mechanical motions to move the joints, limbs, or body. Actuators are generally electric, pneumatic, or hydraulic. Today's mechanical systems have such criteria for actuators as high power density, high power to weight ratio, rapid response, accurate and repeatable control, low cost, cleanliness and high efficiency. An important area of robotics technology is concerned with the development of manipulators that can replace human beings in the execution of specific tasks. This makes such qualities as light weight, high power, and fast, accurate response even more important for actuators. The three dimensions (3D) actuator, which possesses many of these advantages, is therefore considered an excellent candidate for robotic applications. However, the inherent nonlinearities, time-varying parameters, and high sensitivity to payload of 3D actuator make it a challenge for the accurate force and position control of manipulators employing these actuators.

This research investigates sliding mode, fuzzy, and derivative control techniques for control of robotic systems actuated by 3D joint. Sliding mode control is a powerful robust control method widely used in variable structure systems, with the feature of strong insensitivities to system uncertainties and nonlinearities. Sliding mode control (SMC)

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has the ability to tackle the parametric and modeling uncertainties of nonlinear systems. The robustness to system uncertainties makes it an ideal candidate for the control of systems containing 3D joint. In this research, a sliding mode controller is designed to force the end effector of a two-joint planar manipulator to track a spatial reference trajectory. This proposed sliding mode controller makes the planar manipulator relatively insensitive to parameter fluctuations [1-7].

"Chattering" is a natural byproduct of the sliding mode approach. It is caused by the control switches when the system state crosses a sliding surface. Chattering is undesirable because it increases control effort and excites high-frequency modes of the system. To reduce chattering, a boundary layer is usually introduced around the sliding surface. However, the introduction of this boundary layer causes increased tracking error. To decrease tracking error while reducing chattering, the parallel linear control and control bandwidth in the sliding surface are adjusted according to the variance of tracking error. To reduce or eliminate the chattering, various papers have been reported by many researchers which classified into two main methods:

- boundary layer saturation method
- artificial intelligence based method

The boundary layer saturation method is used to reduce or eliminate the high frequency oscillation in conventional sliding mode controller. However this method can solve the challenge of chattering phenomenon but it has two main challenges; increase the error and reduces the speed of response. Slotine and Sastry design conventional switching sliding mode controller for nonlinear system in presence of uncertainty and external disturbance. To rectify the chattering phenomenon, the saturation continuous control is introduced [11]. Slotine is presented sliding mode controller for nonlinear system [12]. According to [12] he solved the chattering challenges based on linear boundary layer method to improve the industry applications. Figure 1 shows the linear saturation boundary layer function.

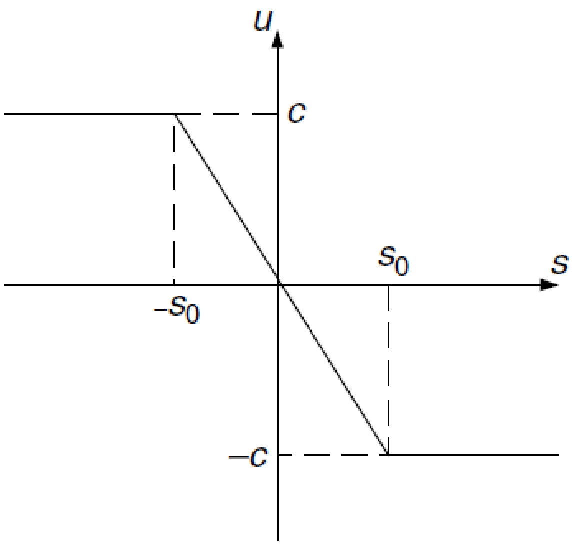

Figure 1. Linear Saturation Boundary Layer Functions [3]

Fuzzy logic is one of the techniques of soft computing. Since it utilizes vagueness in natural language and characterizes system behavior by using human knowledge and experience, suboptimality and impreciseness can be accommodated, even when providing adequate control. Fuzzy logic uses rules and membership functions to approximate nonlinear functions to any desired degree of precision, which makes it possible to provide quick, simple and sufficiently accurate control for complicated real-world systems. Fuzzy logic, using natural language to describe system behavior, provides a simple and effective way to tune control bandwidth. Accordingly, a so-called fuzzy sliding mode controller (FSMC) is designed for the 3D-joint robot manipulator. To eliminate the chattering the second method is intelligent fuzzy logic method. To reduce the challenge of chattering as well as reduce the error Palm [13] design nonlinear intelligent saturation boundary layer function instead of linear saturation boundary method. According to Palm [13] design, the fuzzy controller has been had two inputs, seven linguistic variables and has 49 rule bases. This method can solve the challenge of chattering as well as error but design this type of controller is difficult and tune the fuzzy logic gain updating factors are very the main challenges in this theory. Figure 2 shows the nonlinear artificial intelligence sliding mode controller based on fuzzy logic methodology.

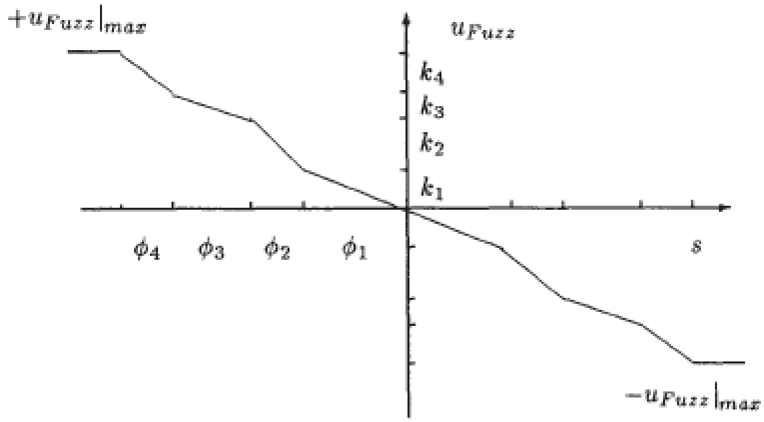

Figure 2. Nonlinear Fuzzy Saturation Boundary Layer Functions [13]

The third method to reduce/eliminate the chattering is parallel linear control method. Switching function is caused to chattering but it is one of the main parts to design robust and high speed sliding mode controller. In sliding mode controller, sliding surface slope (λ) is the second factor to control the chattering, as a result the main task in the first objective is reduce or eliminate the chattering in sliding mode controller based on design parallel linear control methodology and discontinuous part. Sliding mode controller and linear control methodologies are robust based on Lyapunov theory, therefore; Lyapunov stability is proved in proposed chattering free sliding mode controller based on switching theory [14-29].

In this research, three methods to reduce/eliminate the chattering are compared for 3D joint which used in robot manipulator. The boundary layer method, intelligent method and PD parallel method are these three methodologies to eliminate the chattering. This paper is organized as follows; Section 2, are served as an introduction to the dynamic formulation of 3D joints and sliding mode controller. Part 3, introduces and describes the methodology. Section 4 presents the simulation results and discussion of this algorithm and the final section is describing the conclusion.

2. Theory

A. *Dynamic of Surgical Joints:*

Dynamic modeling of spherical motors is used to describe the behavior of spherical motor such as linear or nonlinear dynamic behavior, design of model based controller such as pure sliding mode controller which design this controller is based on nonlinear dynamic equations, and for simulation. The dynamic modeling describes the relationship between motion, velocity, and accelerations to force/torque or current/voltage and also it can be used to describe the particular dynamic effects (*e.g.*, inertia, coriolios, centrifugal, and the other parameters) to behavior of system. Spherical motor has nonlinear and uncertain dynamic parameters 3 degrees of freedom (DOF) motor [20-26].

The equation of a spherical motor governed by the following equation:

$$\boldsymbol{H}(\boldsymbol{q})\begin{bmatrix}\ddot{\boldsymbol{\alpha}}\\ \ddot{\boldsymbol{\beta}}\\ \ddot{\boldsymbol{\gamma}}\end{bmatrix}+\mathbf{B}(\boldsymbol{q})\begin{bmatrix}\dot{\boldsymbol{\alpha}}\dot{\boldsymbol{\beta}}\\ \dot{\boldsymbol{\alpha}}\dot{\boldsymbol{\gamma}}\\ \dot{\boldsymbol{\beta}}\dot{\boldsymbol{\gamma}}\end{bmatrix}+\boldsymbol{C}(\boldsymbol{q})\begin{bmatrix}\dot{\boldsymbol{\alpha}}^{2}\\ \dot{\boldsymbol{\beta}}^{2}\\ \dot{\boldsymbol{\gamma}}^{2}\end{bmatrix}=\begin{bmatrix}\boldsymbol{\tau}_{x}\\ \boldsymbol{\tau}_{y}\\ \boldsymbol{\tau}_{z}\end{bmatrix} \quad \textbf{(1)}$$

Where τ is actuation torque, H (q) is a symmetric and positive define inertia matrix, B(q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques.

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 variableq_i, independently of the motion of the other parts. Therefore, the angular acceleration is found as to be [19-20]:

$$\ddot{\boldsymbol{q}}=\boldsymbol{H}^{-1}(\boldsymbol{q}).\{\boldsymbol{\tau}-\{\boldsymbol{B}+\boldsymbol{C}\}\} \quad \textbf{(2)}$$

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

Study of spherical motor is classified into two main groups: kinematics and dynamics. Calculate the relationship between rigid bodies and final part without any forces is called Kinematics. Study of this part is pivotal to design with an acceptable performance controller, and in real situations and practical applications. As expected the study of kinematics is divided into two main parts: forward and inverse kinematics. Forward kinematics has been used to find the position and orientation of task frame when angles of joints are known. Inverse kinematics has been used to find possible joints variable (angles) when all position and orientation of task frame be active.

The main target in forward kinematics is calculating the following function:

$$\boldsymbol{\Psi}(\boldsymbol{X},\boldsymbol{q})=\mathbf{0} \quad \textbf{(3)}$$

Where $\Psi(.)\in R^{n}$ is a nonlinear vector function, $X=[X_1,X_2,\dots\dots,X_l]^T$ is the vector of task space variables which generally task frame has three task space variables, three orientation, $q=[q_1,q_2,\dots.,q_n]^T$ is a vector of angles or displacement, and finally n is the number of actuated joints. The Denavit-Hartenberg (D-H) convention is a method of drawing spherical motor free body diagrams. Denvit-Hartenberg (D-H) convention study is necessary to calculate forward kinematics in this motor.

A systematic Forward Kinematics solution is the main target of this part. The first step to compute Forward Kinematics (F.K) is finding the standard D-H parameters. The following steps show the systematic derivation of the standard D-H parameters.

1. Locate the spherical motor
2. Label joints
3. Determine joint rotation (θ)
4. Setup base coordinate frames.
5. Setup joints coordinate frames.
6. Determineα_i, thatα_i, link twist, is the angle between Z_i and Z_{i+1} about an X_i.
7. Determine d_i and a_i , that a_i, link length, is the distance between Z_i and Z_{i+1} along X_i. d_i, offset, is the distance between X_{i-1} and X_i along Z_i axis.
8. Fill up the D-H parameters table. The second step to compute Forward kinematics is finding the rotation matrix (R_n^0). The rotation matrix from$\{F_i\}$ to $\{F_{i-1}\}$ is given by the following equation;

$$\boldsymbol{R}_{i}^{i-1}=\boldsymbol{U}_{i(\boldsymbol{\theta}_i)}\boldsymbol{V}_{i(\boldsymbol{\alpha}_i)} \quad \textbf{(4)}$$

Where $U_{i(\theta_i)}$ is given by the following equation;

$$\boldsymbol{U_{i(\theta_i)}} = \begin{bmatrix} \boldsymbol{cos(\theta_i)} & \boldsymbol{-sin(\theta_i)} & \boldsymbol{0} \\ \boldsymbol{sin(\theta_i)} & \boldsymbol{cos(\theta_i)} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix} \quad \textbf{(5)}$$

and $V_{i(\alpha_i)}$ is given by the following equation;

$$\boldsymbol{V_{i(\theta_i)}} = \begin{bmatrix} \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{cos(\alpha_i)} & \boldsymbol{-sin(\alpha_i)} \\ \boldsymbol{0} & \boldsymbol{sin(\alpha_i)} & \boldsymbol{cos(\alpha_i)} \end{bmatrix} \quad \textbf{(6)}$$

So (R_n^0) is given by

$$\boldsymbol{R_n^0 = (U_1V_1)(U_2V_2)\ldots\ldots\ldots(U_nV_n)} \quad \textbf{(7)}$$

The final step to compute the forward kinematics is calculate the transformation ${}_n^0T$ by the following formulation [3]

$$\boldsymbol{{}_n^0T = {}_1^0T.\,{}_2^1T.\,{}_3^2T\ldots\ldots.\,{}_n^{n-1}T} = \begin{bmatrix} \boldsymbol{R_n^0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{1} \end{bmatrix} \quad \textbf{(8)}$$

B. Sliding Mode Controller:

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 control theory for control of robot manipulator was first proposed in 1978 by Young to solve the set point problem ($\dot{\boldsymbol{q}}_{\boldsymbol{d}} = \boldsymbol{0}$) by discontinuous method in the following form;

$$\boldsymbol{\tau_{(q,t)}} = \begin{cases} \boldsymbol{\tau_i^+(q,t)} & \boldsymbol{if\ S_i} > 0 \\ \boldsymbol{\tau_i^-(q,t)} & \boldsymbol{if\ S_i} < 0 \end{cases} \quad \textbf{(9)}$$

where $\boldsymbol{S_i}$ is sliding surface (switching surface), $\boldsymbol{i = 1, 2, \ldots\ldots, n}$ for *n*-DOF robot manipulator, $\boldsymbol{\tau_i(q,t)}$ is the $\boldsymbol{i^{th}}$ torque of joint. Sliding mode controller is divided into two main sub controllers: discontinues controller($\boldsymbol{\tau_{dis}}$) and equivalent controller($\boldsymbol{\tau_{eq}}$).

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 [20-29].

Chattering phenomenon (Figure 3) 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].

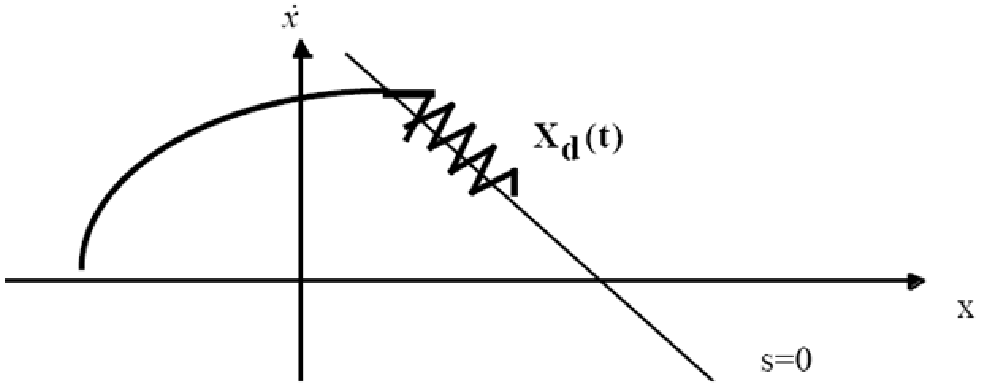

Figure 3. Chattering as a Result of Imperfect Control Switching [1]

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]:

$$\boldsymbol{x^{(n)} = f(\vec{x}) + b(\vec{x})u} \qquad \textbf{(10)}$$

Where u is the vector of control input, $\boldsymbol{x^{(n)}}$ is the $\boldsymbol{n^{th}}$ derivation of $\boldsymbol{x}$, $\boldsymbol{x = [x, \dot{x}, \ddot{x}, \dots, x^{(n-1)}]^T}$ is the state vector, $\boldsymbol{f(x)}$ is unknown or uncertainty, and $\boldsymbol{b(x)}$ is of known *sign* function. The main goal to design this controller is train to the desired state; $\boldsymbol{x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d{}^{(n-1)}]^T}$, and trucking error vector is defined by [6]:

$$\boldsymbol{\widetilde{x} = x - x_d = [\widetilde{x}, \dots, \widetilde{x}^{(n-1)}]^T} \qquad \textbf{(11)}$$

A time-varying sliding surface $\boldsymbol{s(x,t)}$ in the state space $\boldsymbol{R^n}$ is given by [6-9]:

$$\boldsymbol{s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\, \widetilde{x} = 0} \qquad \textbf{(12)}$$

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

$$\boldsymbol{s(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \left(\int_0^t \widetilde{x}\, dt\right) = 0} \qquad \textbf{(13)}$$

The main target in this methodology is kept the sliding surface slope $\boldsymbol{s(x,t)}$ near to the zero. Therefore, one of the common strategies is to find input $\boldsymbol{U}$ outside of $\boldsymbol{s(x,t)}$ [10-20].

$$\boldsymbol{\frac{1}{2}\frac{d}{dt} s^2(x,t) \le -\zeta |s(x,t)|} \qquad \textbf{(14)}$$

where ζ is positive constant.

$$\text{If } \mathbf{S(0)} > 0 \rightarrow \frac{\mathbf{d}}{\mathbf{dt}}\mathbf{S(t)} \le -\boldsymbol{\zeta} \qquad \textbf{(15)}$$

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

$$\boldsymbol{\int_{t=0}^{t=t_{reach}} \frac{d}{dt} S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0)} \qquad \textbf{(16)}$$

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

$$\boldsymbol{0 - S(0) \le -\eta(t_{reach}) \rightarrow t_{reach} \le \frac{S(0)}{\zeta}} \qquad \textbf{(17)}$$

And

$$\boldsymbol{if\ S(0)} < 0 \rightarrow 0 - S(\mathbf{0}) \le \boldsymbol{-\eta(t_{reach}) \rightarrow S(0) \le -\zeta(t_{reach}) \rightarrow t_{reach} \le \frac{|S(0)|}{\eta}} \ \textbf{(18)}$$

Equation (2.41) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$\boldsymbol{if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0} \qquad \textbf{(19)}$$

suppose S is defined as

$$\boldsymbol{s(x,t) = (\frac{d}{dt} + \lambda)\quad \widetilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d)} \qquad \textbf{(20)}$$

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

$$\dot{\boldsymbol{S}} = (\ddot{\mathbf{x}} - \ddot{\mathbf{x}}_{\mathbf{d}}) + \boldsymbol{\lambda}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) \quad \textbf{(21)}$$

suppose the second order system is defined as;

$$\ddot{\boldsymbol{x}} = \boldsymbol{f} + \boldsymbol{u} \ \rightarrow \dot{\boldsymbol{S}} = \boldsymbol{f} + \boldsymbol{U} - \ddot{\boldsymbol{x}}_{\boldsymbol{d}} + \boldsymbol{\lambda}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) \quad \textbf{(22)}$$

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

$$\widehat{\boldsymbol{U}} = -\widehat{\boldsymbol{f}} + \ddot{\boldsymbol{x}}_{\boldsymbol{d}} - \boldsymbol{\lambda}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) \quad \textbf{(23)}$$

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

$$\boldsymbol{U}_{\boldsymbol{dis}} = \widehat{\boldsymbol{U}} - \boldsymbol{K}(\vec{\boldsymbol{x}}, \boldsymbol{t}) \cdot \mathbf{sgn}(\boldsymbol{s}) \quad \textbf{(24)}$$

where the switching function $\mathbf{sgn}(\mathbf{S})$ is defined as [11- 16]

$$\boldsymbol{sgn}(\boldsymbol{s}) = \begin{cases} \mathbf{1} & \boldsymbol{s} > 0 \\ -\mathbf{1} & \boldsymbol{s} < 0 \\ \mathbf{0} & \boldsymbol{s} = \mathbf{0} \end{cases} \quad \textbf{(25)}$$

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

$$\frac{\mathbf{1}}{\mathbf{2}}\frac{\boldsymbol{d}}{\boldsymbol{dt}}\boldsymbol{s}^{\mathbf{2}}(\boldsymbol{x}, \boldsymbol{t}) = \dot{\mathbf{S}} \cdot \mathbf{S} = \left[\boldsymbol{f} - \widehat{\boldsymbol{f}} - \boldsymbol{K}\mathbf{sgn}(\boldsymbol{s})\right] \cdot \boldsymbol{S} = \left(\boldsymbol{f} - \widehat{\boldsymbol{f}}\right) \cdot \boldsymbol{S} - \boldsymbol{K}|\boldsymbol{S}| \quad \textbf{(26)}$$

The sliding surface can be calculated as

$$\boldsymbol{s}(\boldsymbol{x}, \boldsymbol{t}) = (\frac{\boldsymbol{d}}{\boldsymbol{dt}} + \boldsymbol{\lambda})^{\mathbf{2}} \ \left(\int_{\mathbf{0}}^{\boldsymbol{t}} \widetilde{\boldsymbol{x}} \, \boldsymbol{dt}\right) = (\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) + \mathbf{2}\boldsymbol{\lambda}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) - \boldsymbol{\lambda}^{\mathbf{2}}(\mathbf{x} - \mathbf{x}_{\mathbf{d}}) \quad \textbf{(27)}$$

in this method the approximation of $\boldsymbol{U}$ is computed as [6]

$$\widehat{\boldsymbol{U}} = -\widehat{\boldsymbol{f}} + \ddot{\boldsymbol{x}}_{\boldsymbol{d}} - \mathbf{2}\boldsymbol{\lambda}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_{\mathbf{d}}) + \boldsymbol{\lambda}^{\mathbf{2}}(\mathbf{x} - \mathbf{x}_{\mathbf{d}}) \quad \textbf{(28)}$$

Based on above discussion, the sliding mode control law for a multi degrees of freedom robot manipulator is written as [12-18]:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{\boldsymbol{eq}} + \boldsymbol{\tau}_{\boldsymbol{dis}} \quad \textbf{(29)}$$

where, the model-based component $\boldsymbol{\tau}_{\boldsymbol{eq}}$ is the nominal dynamics of systems and $\boldsymbol{\tau}_{\boldsymbol{eq}}$ can be calculate as follows [1]:

$$\boldsymbol{\tau}_{\boldsymbol{eq}} = \left[\boldsymbol{M}^{-\mathbf{1}}(\boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G}) + \dot{\boldsymbol{S}}\right]\boldsymbol{M} \quad \textbf{(30)}$$

and $\boldsymbol{\tau}_{\boldsymbol{dis}}$ is computed as [1];

$$\boldsymbol{\tau}_{\boldsymbol{dis}} = \boldsymbol{K} \cdot \mathbf{sgn}(\boldsymbol{S}) \quad \textbf{(31)}$$

The control output can be written as;

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{\boldsymbol{eq}} + \boldsymbol{K}.\,\mathbf{sgn}(\boldsymbol{S}) \quad \textbf{(32)}$$

The sliding mode control of system is calculated as;

$$\boldsymbol{\tau} = \left[\boldsymbol{M}^{-\mathbf{1}}(\boldsymbol{B} + \boldsymbol{C} + \boldsymbol{G}) + \dot{\boldsymbol{S}}\right]\boldsymbol{M} + \boldsymbol{K} \cdot \mathbf{sgn}(\boldsymbol{S}) \quad \textbf{(33)}$$

where $S = \lambda e + \dot{e}$ in PD-SMC and $S = \lambda e + \dot{e} + (\frac{\lambda}{2})^2 \sum e$ in PID-SMC.

3. Methodology

In this research chattering attenuation based on three methods are compared.

Chattering Attenuation Using Boundary Layer Method: According to the literature to attenuate the chattering challenge, linear boundary layer method based on saturation function is introduced. In this method the researcher introduced saturation function in the sliding mode control law instead of the switching (sign) function. The saturation (linear) method with small neighborhood of the switching surface is calculated as

$$\boldsymbol{B}(\boldsymbol{t}) = \{\boldsymbol{x}, |\boldsymbol{S}(\boldsymbol{t})| \le \emptyset\}; \emptyset > 0 \quad \textbf{(34)}$$

where $\emptyset$ is the boundary layer thickness.

$$\boldsymbol{U} = \boldsymbol{K}(\vec{\boldsymbol{x}}, \boldsymbol{t}) \cdot \mathbf{Sat}\left({\boldsymbol{S}}/{\emptyset}\right) \quad \textbf{(35)}$$

While saturation function formulation ($\mathbf{Sat}\left({\mathbf{S}}/{\emptyset}\right)$ **)** is as follows

$$\mathbf{sat}\left({}^{S}/_{\emptyset}\right)=\begin{cases}\mathbf{1} & ({}^{S}/_{\emptyset}>1)\\ -\mathbf{1} & \left({}^{S}/_{\emptyset}<-1\right)\\ {}^{S}/_{\emptyset} & (-\mathbf{1}<{}^{S}/_{\emptyset}<1)\end{cases} \quad \textbf{(36)}$$

Considering the above points, to reduce chattering phenomenon in sliding mode controller based on saturation function, the following formulation is used

$$\boldsymbol{\tau}=\boldsymbol{\tau_{eq}}+\boldsymbol{\tau_{sat}} \quad \textbf{(37)}$$

and $\boldsymbol{\tau_{eq}}$ can be calculate as follows:

$$\boldsymbol{\tau_{eq}}=\left[\boldsymbol{A^{-1}(B+C+G)+\dot{S}}\right]\boldsymbol{A} \quad \textbf{(38)}$$

and $\boldsymbol{\tau_{sat}}$ is computed as

$$\boldsymbol{\tau_{sat}}=\boldsymbol{K}\cdot\mathbf{sat}\left({}^{S}/_{\emptyset}\right) \quad \textbf{(39)}$$

The linear chattering free sliding mode control is calculated as;

$$\boldsymbol{\tau}=\left[\boldsymbol{M^{-1}(B+C+G)+\dot{S}}\right]\boldsymbol{M}+\boldsymbol{K}\cdot\mathbf{sat}\left({}^{S}/_{\emptyset}\right) \quad \textbf{(40)}$$

According to above discussion the chattering phenomenon may be eliminated by linear boundary layer method but there is no theoretical Lyapunov stability proof for using this control law.

Chattering Attenuation Using a Parallel Linear Method: To reduce the chattering in presence of switching functions; linear controller is added to discontinuous part of sliding mode controller. Linear controller is type of stable controller as well as conventional sliding mode controller. In proposed methodology PD, PI or PID linear controller is used in parallel with discontinuous part to reduce the role of sliding surface slope as a main coefficient. The formulation of new chattering free sliding mode controller for robot manipulator is;

$$\boldsymbol{\tau}=\boldsymbol{\tau_{eq}}+\boldsymbol{\tau_{dis-new}} \quad \textbf{(41)}$$

$\boldsymbol{\tau_{eq}}$ is equivalent term of sliding mode controller and this term is related to the nonlinear dynamic formulation of joint. The new switching discontinuous part is introduced by $\boldsymbol{\tau_{dis-new}}$ and this item is the important factor to resistance and robust in this controller. In PD sliding surface, the change of sliding surface calculated as;

$$\boldsymbol{S_{PD}}=\boldsymbol{\lambda e}+\boldsymbol{\dot{e}}\rightarrow\boldsymbol{\dot{S}_{PD}}=\boldsymbol{\lambda\dot{e}}+\boldsymbol{\ddot{e}} \quad \textbf{(42)}$$

The discontinuous switching term ($\boldsymbol{\tau_{dis}}$) is computed as

$$\boldsymbol{\tau_{dis-new}}=\boldsymbol{K_a}\cdot\mathbf{sgn}(\boldsymbol{S})+\boldsymbol{K_b}.\boldsymbol{S} \quad \textbf{(43)}$$

$$\boldsymbol{\tau_{dis-PD-new}}=\boldsymbol{K_a}\cdot\mathbf{sgn}(\boldsymbol{\lambda e}+\boldsymbol{\dot{e}})+\boldsymbol{K_b}\cdot(\boldsymbol{\lambda e}+\boldsymbol{\dot{e}}) \quad \textbf{(44)}$$

$$\boldsymbol{\tau_{dis-PI-new}}=\boldsymbol{K_a}\cdot\mathbf{sgn}\left(\boldsymbol{\lambda e}+(\tfrac{\lambda}{2})^{2}\textstyle\sum\boldsymbol{e}\right)+\boldsymbol{K_b}\cdot\left(\boldsymbol{\lambda e}+(\tfrac{\lambda}{2})^{2}\textstyle\sum\boldsymbol{e}\right) \quad \textbf{(45)}$$

$$\boldsymbol{\tau_{dis-PID-new}}=\boldsymbol{K_a}\cdot\mathbf{sgn}\left(\boldsymbol{\lambda e}+\boldsymbol{\dot{e}}+(\tfrac{\lambda}{2})^{2}\textstyle\sum\boldsymbol{e}\right)+\boldsymbol{K_b}\cdot\left(\boldsymbol{\lambda e}+\boldsymbol{\dot{e}}+(\tfrac{\lambda}{2})^{2}\textstyle\sum\boldsymbol{e}\right) \quad \textbf{(46)}$$

$$\boldsymbol{\tau}=\boldsymbol{\tau_{eq}}+\boldsymbol{K_a}.\mathbf{sgn}(\boldsymbol{S})++\boldsymbol{K_b}.\boldsymbol{S}=\left[\boldsymbol{A^{-1}(q)}\times(\boldsymbol{N(q,\dot{q})})+\boldsymbol{\dot{S}}\right]\times\boldsymbol{A(q)}+\boldsymbol{K_a}.\mathbf{sgn}(\boldsymbol{S})+\boldsymbol{K_b}.\boldsymbol{S} \quad \textbf{(47)}$$

The formulation of PD-SMC is;

$$\boldsymbol{\tau_{PD-SMC-new}}=\boldsymbol{K_a}\cdot\mathbf{sgn}(\boldsymbol{\lambda e}+\boldsymbol{\dot{e}})+\boldsymbol{K_b}\cdot(\boldsymbol{\lambda e}+\boldsymbol{\dot{e}})+\left[\boldsymbol{A^{-1}(q)}\times(\boldsymbol{N(q,\dot{q})})+\boldsymbol{\dot{S}}\right]\times\boldsymbol{A(q)} \quad \textbf{(48)}$$

$$\boldsymbol{A(q)\ddot{q}}+\boldsymbol{V(q,\dot{q})\dot{q}}+\boldsymbol{G(q)}=\boldsymbol{\hat{A}\ddot{q}_r}+\boldsymbol{\hat{V}\dot{q}_r}+\boldsymbol{\hat{G}}+\boldsymbol{K_a}\,\boldsymbol{sgn(S)}+\boldsymbol{K_b}.\boldsymbol{S} \quad \textbf{(49)}$$

Where $\boldsymbol{\hat{A}},\boldsymbol{\hat{V}}\ \boldsymbol{and}\ \boldsymbol{\hat{G}}$ are the estimation of $\boldsymbol{A(q)},\boldsymbol{V(q,\dot{q})}\ and\ \boldsymbol{G(q)}$ and in this formulation $\boldsymbol{K_a}=\left[\boldsymbol{K_{a1}},\boldsymbol{K_{a2}},\boldsymbol{K_{a3}}\right]$ and $\boldsymbol{K_b}=\left[\boldsymbol{K_{b1}},\boldsymbol{K_{b2}},\boldsymbol{K_{b3}}\right]$

Since $\boldsymbol{\dot{q}_d}=\boldsymbol{\dot{q}}-\boldsymbol{S}$ and $\boldsymbol{\ddot{q}_d}=\boldsymbol{\ddot{q}}-\boldsymbol{\dot{S}}$

$$\boldsymbol{A\dot{S}}+(\boldsymbol{V}+\boldsymbol{K_b})\boldsymbol{S}=\Delta\boldsymbol{f}-\boldsymbol{K_a}\,\boldsymbol{sgn(S)} \quad \textbf{(50)}$$

Where $\Delta\boldsymbol{f}=\Delta\boldsymbol{A\ddot{q}}+\Delta\boldsymbol{V\dot{q}}+\Delta\boldsymbol{G}$ and $\Delta\boldsymbol{A}=\boldsymbol{\hat{A}}-\boldsymbol{A},\Delta\boldsymbol{V}=\boldsymbol{\hat{V}}-\boldsymbol{V}\ \boldsymbol{and}\ \Delta\boldsymbol{G}=\boldsymbol{\hat{G}}-\boldsymbol{G}$

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

$$\boldsymbol{A\dot{S}}=-\boldsymbol{VS}+\boldsymbol{A\dot{S}}+\boldsymbol{VS}+\boldsymbol{G}-\boldsymbol{\tau} \quad \textbf{(51)}$$

Assuming that it can be expressed by the following equation:

$$\boldsymbol{S^T\big(\dot{A}-2V\big)S=0} \tag{52}$$

If the Lyaponuv function is written by;

$$\boldsymbol{V=\frac{1}{2}S^T A(q)S} \tag{53}$$

We can written the derivative of Lyapunov functions as;

$$\begin{aligned}\boldsymbol{\dot{V}} &= \boldsymbol{S^T A\dot{S}+\frac{1}{2}S^T\,\dot{A}S} \\ &= \boldsymbol{S^T\big(A\dot{S}+VS\big)} \\ &= \boldsymbol{S^T[-k_{ab}S+\Delta f-k_a sgn(S)]} \\ &= \textstyle\sum_{i=1}^{6}\boldsymbol{(S_i[\Delta f_i-k_{ai}sgn(S_i)])-S^T k_b S}.\end{aligned} \tag{54}$$

and

$$\boldsymbol{\dot{V}=\frac{1}{2}S^T\dot{A}S-S^T VS+S^T\big(A\dot{S}+VS+G-\tau\big)=S^T\big(A\dot{S}+VS+G-\tau\big)} \tag{55}$$

$$\boldsymbol{\hat{\tau}=\widehat{\tau_{eq}}+\widehat{\tau_{dis}}=\big[\widehat{A^{-1}}\big(\widehat{V}+\widehat{G}\big)+\dot{S}\big]\widehat{A}+K_a\,sgn(S)+K_b.S} \tag{56}$$

$$\boldsymbol{\dot{V}=S^T(A\dot{S}+VS+G-\widehat{A}\dot{S}-\widehat{V}S-\widehat{G}-K_a\,sgn(S)-K_b.S=S^T\big(\widetilde{A}\dot{S}+\widetilde{V}S+\widetilde{G}-Ksgn(S)-K_b.S\big)} \tag{57}$$

For $k_{ai}\geq\ |\Delta f_i|$ we always get $S_i[\boldsymbol{\Delta f_i-k_{ai}sgn(S_i)}]\leq \boldsymbol{0}$ and we can write:

$$\boldsymbol{\dot{V}=}\ \textstyle\sum_{i=1}^{6}\boldsymbol{(S_i[\Delta f_i-k_{ai}sgn(S_i)])-S^T k_{bi}S\leq -S^T k_{bi}S}<0 \qquad (\boldsymbol{S\neq 0}) \tag{58}$$

Chattering Attenuation Using Fuzzy Logic Method: Supposed that U is the universe of discourse and x is the element of U, therefore, a crisp set can be defined as a set which consists of different elements (x) will all or no membership in a set. A fuzzy set is a set that each element has a membership grade, therefore it can be written by the following definition;

$$\boldsymbol{A=\{x,\mu_A(x)|x\in X\};A\in U} \tag{59}$$

Where an element of universe of discourse is x, μ_A is the membership function (MF) of fuzzy set. The membership function $(\mu_A(x))$ of fuzzy set A must have a value between zero and one. If the membership function $\mu_A(x)$ value equal to zero or one, this set change to a crisp set but if it has a value between zero and one, it is a fuzzy set. Defining membership function for fuzzy sets has divided into two main groups; namely; numerical and functional method, which in numerical method each number has different degrees of membership function and functional method used standard functions in fuzzy sets. The membership function which is often used in practical applications includes triangular form, trapezoidal form, bell-shaped form, and Gaussian form. A Trapezoidal membership function of fuzzy set is defined by the following equation

$$\boldsymbol{\mu_{F(x)}}=\begin{cases}\boldsymbol{0} & ,\ x<a \\ \boldsymbol{\frac{x-a}{b-a}}, & a\leq x<b \\ \boldsymbol{\frac{d-x}{d-c}}, & c\leq x<d \\ \boldsymbol{0} & ,\ x>d\end{cases} \tag{60}$$

A Triangular membership function of fuzzy set is defined by the following equation

$$\boldsymbol{\mu_{F(x)}}=\begin{cases}\boldsymbol{0} & ,\ x<a \\ \boldsymbol{\frac{x-a}{b-a}}, & a\leq x<b \\ \boldsymbol{\frac{c-x}{c-b}}, & b\leq x\leq c \\ \boldsymbol{0} & ,\ x>c\end{cases} \tag{61}$$

A Gaussian membership function of fuzzy set is defined by

$$\boldsymbol{\mu_{F(x)}=e^{\frac{-(x-c_F)^2}{w}}} \tag{62}$$

and a Bell-shaped membership function of fuzzy set is defined by

$$\boldsymbol{\mu_{F(x)}=\frac{1}{1+(x-c_F)^2}} \tag{63}$$

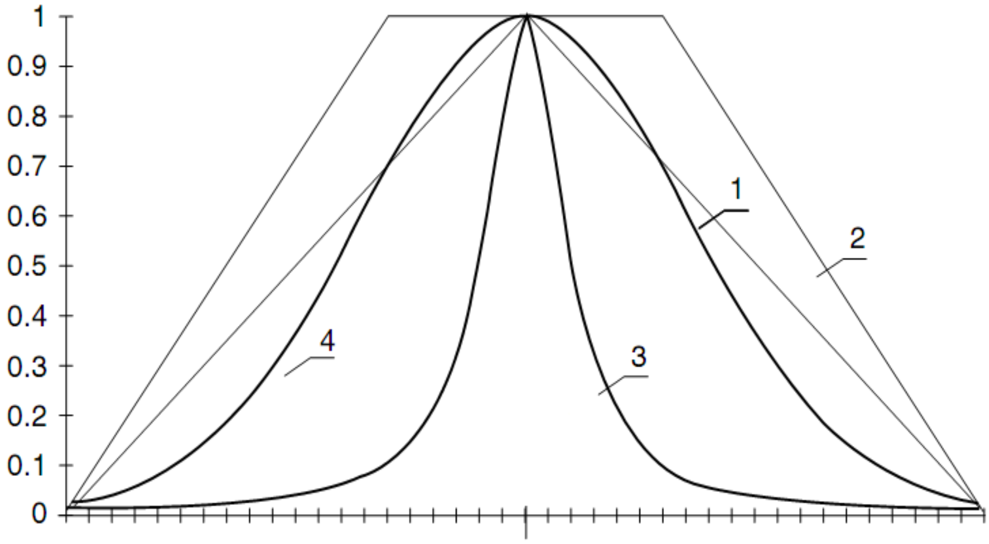

Figure 4. Most Important Membership Functions in Fuzzy Set: 1-Trianglar, 2-Trapezoidal, 3-Gaussian, 4-Bell-shaped

Figure 4 shows the typical shapes of membership functions in a fuzzy set.

The union of two fuzzy set A and B ($S - norm$) is a new fuzzy set which the new membership function is given by

$$\boldsymbol{S(a,b) = \mu_{A\cup B(u)} = \max\{\mu_{A(u)}, \mu_{B(u)}\}}, \qquad \forall \boldsymbol{u} \in \boldsymbol{U} \tag{64}$$

The intersection of two fuzzy set A and B ($T - norm$) is a new fuzzy set which the new membership function is given by

$$\boldsymbol{T(a,b) = \mu_{A\cap B(u)} = \min\{\mu_{A(u)}, \mu_{B(u)}\} = \mu_{A(u)} \cdot \mu_{B(u)}} \tag{65}$$

$$= \boldsymbol{\max(0,\ \mu_{A(u)} + \mu_{B(u)} - 1)} = \begin{cases} \boldsymbol{\mu_{A(u)}} & ,\ if\, \boldsymbol{\mu_{B(u)} = 1} \\ \boldsymbol{\mu_{B(u)}} & ,\ if\, \boldsymbol{\mu_{A(u)} = 1} \\ \boldsymbol{0} & ,\ \boldsymbol{if\, \mu_{B(u)}, \mu_{A(u)}} < 1 \end{cases}$$

In fuzzy set the min operation can resolve the statement $A\ AND\ B$ and can be shown by $min(A,B)$ operation. Using the same reason, the $A\ OR\ B$ operation can be replace by max operation in fuzzy set and at last the $NOT\ A$ operation can be replace by $1 - A$ operation in fuzzy set. The algebraic $product$ of two fuzzy set A and B is the multiplication of the membership functions which is given by the following equation

$$\boldsymbol{\mu_{A.B(u)} = \mu_{A(u)} \cdot \mu_{B(u)}} \tag{66}$$

The algebraic Sum of two fuzzy sets A and B is given by the following equation

$$\boldsymbol{\mu_{A\hat{+}B(u)} = \mu_{A(u)} \cdot \mu_{B(u)} - \mu_{A(u)} \cdot \mu_{B(u)}} \tag{67}$$

Linguistic variable can open a wide area to use of fuzzy logic theory in many applications (*e.g.*, control and system identification). In a natural artificial language all numbers replaced by words or sentences. In Figure 5 the linguistic variable is torque and the linguistic values are Low,$Medium$ and $High$.

$If - then$ Rule statements are used to formulate the condition statements in fuzzy logic. A single fuzzy $If - then$ rule can be written by

$$\boldsymbol{If\ x\ is\ A\ Then\ y\ is\ B} \tag{68}$$

where A and B are the Linguistic values that can be defined by fuzzy set, the $If - part$ of the part of "$x\ is\ A$" is called the antecedent part and the $then - part$ of the part of "$y\ is\ B$" is called the Consequent or Conclusion part. The antecedent of a fuzzy if-then rule can have multiple parts, which the following rules shows the multiple antecedent rules:

$$if\ e\ is\ NB\ and\ \dot{e}\ is\ ML\ then\ T\ is\ LL \tag{69}$$

where e is error, $\dot{e}$ is change of error, NB is Negative Big, ML is Medium Left, T is torque and LL is Large Left.

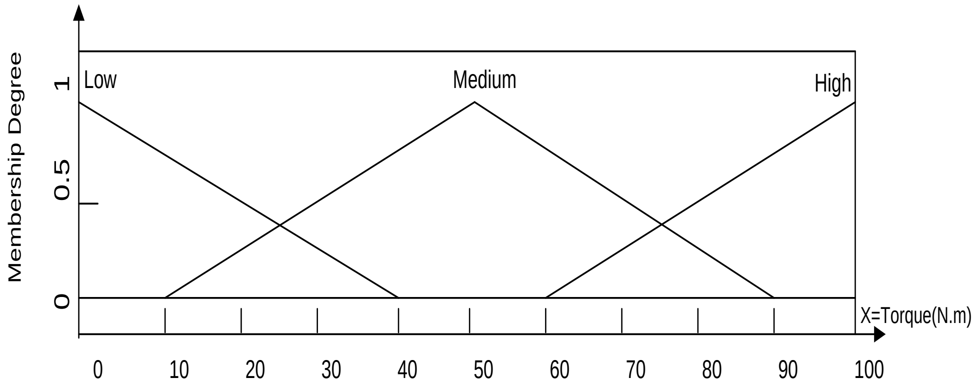

Figure 5. Linguistic Variable and Linguistic Value

$If - then$ rules have three parts, namely, fuzzify inputs, apply fuzzy operator and apply implication method which in fuzzify inputs the fuzzy statements in the antecedent replaced by the degree of membership, apply fuzzy operator used when the antecedent has multiple parts and replaced by single number between 0 to 1, this part is a degree of support for the fuzzy rule, and apply implication method used in consequent of fuzzy rule to replaced by the degree of membership. Figure 6 shows the main three parts in $If - then$ rules.

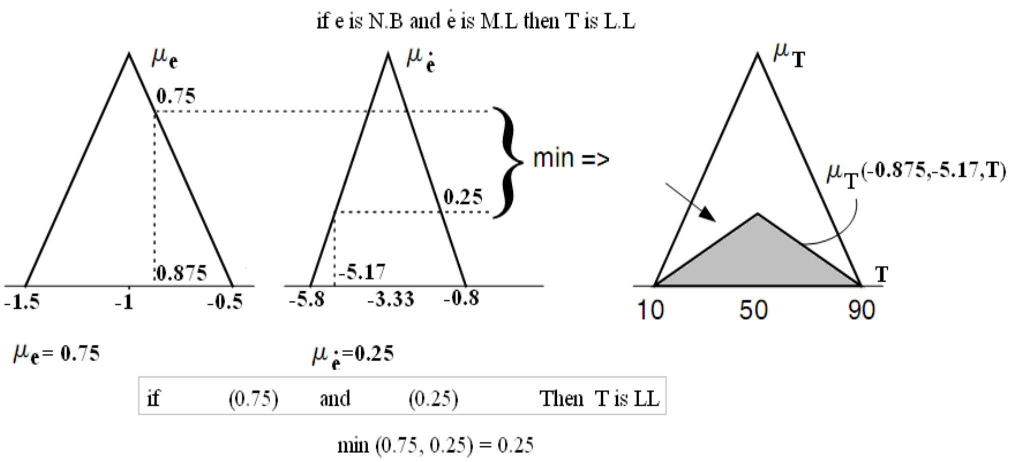

Figure 6. Main Three Parts in IF-THEN Rules in Fuzzy Set

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 controllers 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 use a singleton as a membership function of the rule consequent part. The following definition shows the Mamdani and Sugeno fuzzy rule base

$$\boldsymbol{Mamdani \quad F.R^1: if \quad x\ is\ A\ and\ y\ is\ B \quad then \quad z\ is\ C}$$

$$\boldsymbol{Sugeno} \quad \boldsymbol{F.R^1: if} \quad \boldsymbol{x\ is\ A\ and\ y\ is\ B} \quad \boldsymbol{then} \quad \boldsymbol{f(x,y) is\ C} \quad \mathbf{(70)}$$

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. Two most common methods that used in fuzzy logic controllers are Max-min aggregation and Sum-min aggregation. Max-min aggregation defined as below

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\bigcup_{i=1}^{r} FR^i}(x_k, y_k, U) = \max\left\{\min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]\right\}} \quad \mathbf{(71)}$$

The Sum-min aggregation defined as below

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\bigcup_{i=1}^{r} FR^i}(x_k, y_k, U) = \sum \min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]} \quad \mathbf{(72)}$$

where r is the number of fuzzy rules activated by x_k and y_k and also $\mu_{\bigcup_{i=1}^{r} FR^i}(x_k, y_k, U)$ is a fuzzy interpretation of $i-th$ rule. 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, which COG method used the following equation to calculate the defuzzification

$$\boldsymbol{COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}} \quad \mathbf{(73)}$$

and COA method used the following equation to calculate the defuzzification

$$\boldsymbol{COA(x_k, y_k) = \frac{\sum_i U_i \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \mu_U \cdot (x_k, y_k, U_i)}} \quad \mathbf{(74)}$$

Where $COG(x_k, y_k)$ and $COA(x_k, y_k)$ illustrates the crisp value of defuzzification output, $U_i \in U$ is discrete element of an output of the fuzzy set, $\mu_U.(x_k, y_k, U_i)$ is the fuzzy set membership function, and r is the number of fuzzy rules.

Based on foundation of fuzzy logic methodology; fuzzy logic controller has played important rule to design nonlinear controller for nonlinear and uncertain systems. However, the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of;

- Input fuzzification (binary-to-fuzzy[B/F]conversion)
- Fuzzy rule base (knowledge base)
- Inference engine
- Output defuzzification (fuzzy-to-binary [F/B] conversion).

Fuzzification is used to change the crisp set into fuzzy set. Knowledge base is used to rule evaluation and determine the membership degree and if all fuzzy inputs activated by the known input values. Fuzzy inference engine is used to transferring the rule base into fuzzy set by Mamdani's or Sugeno method based on aggregation of the rules output. Deffuzification is the last part to calculate the fuzzy inference system.

Fuzzy logic theory is used to estimate the system's chattering. This type of controller is free of mathematical dynamic parameters of plant. However fuzzy logic controller used in many applications, but pure fuzzy logic controller have problems in pre sense of uncertainty condition (robust) and pre-define the inputs/outputs gain updating factors. To solve the chattering challenge especially in uncertain system, sliding mode fuzzy controller is recommended. The formulation of PD-SMC is;

$$\boldsymbol{\tau_{PD-SMC} = K_a \cdot \mathrm{sgn}(\lambda e + \dot{e}) + \left[A^{-1}(q) \times (N(q, \dot{q})) + \dot{S}\right] \times A(q)} \quad \mathbf{(75)}$$

That $\boldsymbol{\tau_{eq}}$ is;

$$\boldsymbol{\tau_{eq} = \left[\widehat{A}^{-1}(q) \times (\widehat{N}(q, \dot{q})) + \dot{S}\right] \times \widehat{A}(q)} \quad \mathbf{(76)}$$

When system works in uncertainty, the nonlinearity term of robot manipulator is not equal to equivalent term of sliding mode controller and the amplitude of chattering can be increase. To solve this challenge in this research PD like fuzzy logic controller is recommended as follows;

$$\boldsymbol{\tau_{PD-SMC} = K_a \cdot \mathrm{sgn}(\lambda e + \dot{e}) + U_{PD-fuzzy}} \tag{77}$$

PD like fuzzy logic controller has two inputs, Proportional (P), and Derivative (D) if each input defined by N linguistic variables has $N \times N$linguistic variables. According to fuzzy logic methodology definition;

$$\boldsymbol{U_{fuzzy} = \left(\sum_{l=1}^{M} \theta^T\, \zeta(x)\right)_{e,\sum e,\dot{e}}} \tag{78}$$

where $\boldsymbol{\theta^T}$ is gain updating factor and $\boldsymbol{\zeta(x)}$ is defined by;

$$\boldsymbol{\zeta(x) = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)}} \tag{79}$$

And the $\boldsymbol{\mu(x_i)}$ parameter is membership function.

Fuzzy logic controller (FLC) is one of the most important applications of fuzzy logic theory. This controller can be used to control of nonlinear, uncertain, and noisy systems. However the application of fuzzy logic controller is really wide, all types of fuzzy logic controllers consists of the following parts;

- Choosing inputs
- Scaling inputs
- Input fuzzification (binary-to-fuzzy[B/F] conversion)
- Fuzzy rule base (knowledge base)
- Inference engine
- Output defuzzification (fuzzy-to-binary[F/B] conversion)
- Scaling output

Define the Inputs and Control Variables: In most of industrial controllers error and the functional of error are used as inputs to design controller. According to design the PD-like fuzzy controller, error and change of error are used to define as controllers' inputs. Therefore the antecedent part of rule base is comprised of two parts. In this part fuzzy controller's inputs are error (e) and change of error $(\dot{e})$ and the fuzzy controller output is PD fuzzy output $\left(U_{PD-fuzzy}\right)$.

Scaling inputs/outputs: in fuzzy logic controller to define membership function, scaling the universe of discourse for all parts of rule base (consequent and antecedent part) is very important. The role of a right choice of scaling factors is obviously shown by the fact that if your choice is bad, the actual operating area of the inputs/outputs will be transformed into a saturation or narrow situation. Input scaling factors have played important role to basic sensitivity of the controller with respect to the optimal choice of the operating areas of the input signals moreover when the scale output is scaled, the gain updating factor of the controller is scaled which it is caused to modify the stability and oscillation tendency. Because of its strong impact on stability and reduce the oscillation, this factor is important factor to design fuzzy controller. In this research the scaling factor for error is $[-0.1\ to\ 0.1]$ and divided into eleven levels as follows:

$e = \{-0.1, -0.08, -0.06, -0.04, -0.02, 0, 0.02, 0.04, 0.06, 0.08, 0.1\}$ and the scaling factor of change of error is $[-1\ to\ 1]$ and divided into eleven levels as follows:

$\dot{e} = \{-1, -0.8, -0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6, 0.8, 1\}$ and at last the scaling factor of PD fuzzy output are between $[-1.5\ to\ 1.5]$.

Input Fuzzification (Binary-to-Fuzzy [B/F] Conversion):

This part is divided into three main parts;

- Linguistic variables
- Scaling factor (normalization factor)
- Inputs membership function

In this research a linguistic variable is defined by;

- Symbolic name of inputs/outputs variables: $error, change\ of\ error$ and $PD\ fuzzy\ output$.
- Set of linguistic values that for error can take on: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB). The linguistic values for change of error are: Negative (N), Zero (Z) and Positive (P) and the linguistic variables for PD fuzzy output are: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB).
- Scaling factor as actual physical domain over which the meaning of the linguistic value, based on experience knowledge this range for error is $[-0.1\ to\ 0.1]$, for change of error is $[-1\ to\ 1]$ and finally for PD fuzzy output is$[\ -1.5\ to\ 1.5]$.

According to experience knowledge in this research, triangular membership function is selected for inputs and output. Figures 7 to 9 show the fuzzification part for PD like fuzzy controller system, this controller has two inputs (error and change of error) and one output (PD fuzzy output), the first input (error) is described with seven linguistic values; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB) and it is quantized into eleven levels as follows: $e = \{-0.1, -0.08, -0.06, -0.04, -0.02, 0, 0.02, 0.04, 0.06, 0.08, 0.1\}$, the second input (change of error) is described with three linguistic values; Negative (N), Zero (Z) and Positive (P) and it is quantized into eleven levels as: $\dot{e} = \{-1, -0.8, -0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6, 0.8, 1\}$ and the output (PD fuzzy output) is described with seven linguistic values; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB) and triangular membership functions are used for inputs and output.

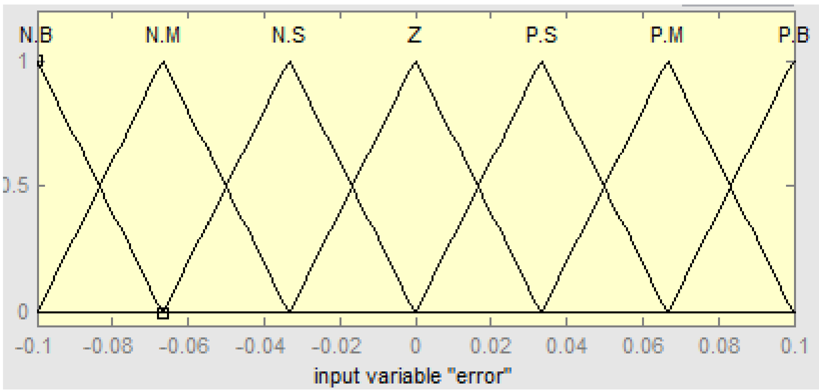

Figure 7. Membership Function, Scaling and Linguistic Variables for Error

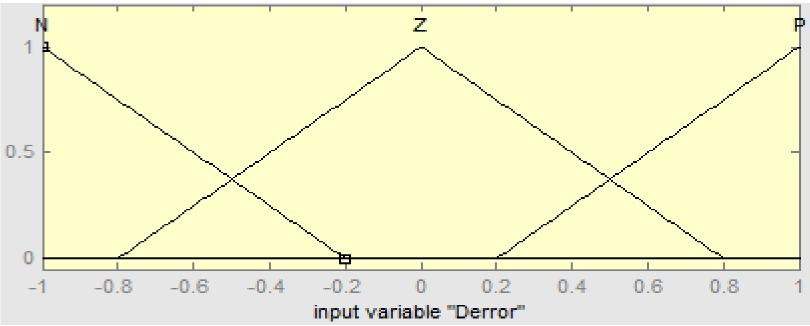

Figure 8. Membership Function, Scaling and Linguistic Variables for Change of Error

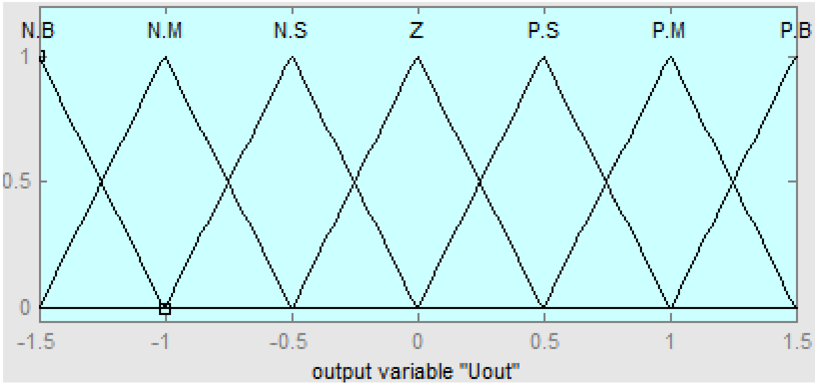

Figure 9. Membership Function, Scaling and Linguistic Variables for PD Fuzzy Output

Fuzzy rule Base: the role of the rules in fuzzy logic controller is extremely significant and the main approaches and source of fuzzy logic controller rules are;

- Expert experience and knowledge base
- Learning based on operators' control action
- Identification of fuzzy model system under control action
- The application of learning technique

According to above, the main approach comes from an expert knowledge of system because any fuzzy controller is expert system to solve the control problem. According to fuzzification the error has seven linguistic variables, the change of error has three linguistic variables and the PD fuzzy output has seven linguistic variables. Therefore PD like fuzzy controller has 21 rule-bases in five parts as follows:

Part 1:

$\boldsymbol{FR^1: IF\ e\ is\ PS\ and\ \dot{e}\ is\ Z\ then\ U_{PD}\ is\ NS}$
$\boldsymbol{FR^2: IF\ e\ is\ Z\ and\ \dot{e}\ is\ Z\ then\ U_{PD}\ is\ Z}$
$\boldsymbol{FR^3: IF\ e\ is\ NS\ and\ \dot{e}\ is\ Z\ then\ U_{PD}\ is\ PS}$

According to first three rule-base error is positive or negative small or zero and change of error is zero. In this case the system's output ($\boldsymbol{U_{PD}}$) has close deviation around the desired level. Therefore these three rules are related to steady state system's output behavior. In this case if error is positive small to estimate it, the controllers output needs to change the direction with the same power.

Part 2:

$\boldsymbol{FR^4: IF\ e\ is\ PB\ and\ \dot{e}\ is\ N\ then\ U_{PD}\ is\ Z}$
$\boldsymbol{FR^5: IF\ e\ is\ PM\ and\ \dot{e}\ is\ N\ then\ U_{PD}\ is\ PS}$

In this part the error is Positive Big or medium, therefore based on error formulation ($\boldsymbol{e = q_d - q_a}$) the desired input is considerably above the actual input. In this time the rate of error is negative, it means that actual input is moving towards to the desired input and caused to reduce the error towards to zero. The control action should to tune the rate of reduce the error. For example when error is Positive Big and change of error is Negative, no control action is recommended because the actual input will be estimate by the speed of change of error due to the desired input.

Part 3:

$\boldsymbol{FR^6: IF\ e\ is\ PS\ and\ \dot{e}\ is\ N\ then\ U_{PD}\ is\ PM}$
$\boldsymbol{FR^7: IF\ e\ is\ Z\ and\ \dot{e}\ is\ N\ then\ U_{PD}\ is\ PB}$
$\boldsymbol{FR^8: IF\ e\ is\ NS\ and\ \dot{e}\ is\ N\ then\ U_{PD}\ is\ PB}$

FR^9: $IF\ e\ is\ NM\ and\ \dot{e}\ is\ N\ then\ U_{PD}\ is\ PB$
FR^{10}: $IF\ e\ is\ NB\ and\ \dot{e}\ is\ N\ then\ U_{PD}\ is\ PB$

In this part the actual input is near the desired input (e(t) is Positive Small, Zero or Negative Small) or the actual input is drastically above it (e(t) is Negative Medium or Negative Big) and at this time the rate of error is negative, it means the rate of actual input is greater than desired input and caused to actual input moving away from desired input. In this time, the role of controller is to reverse this trend and caused actual input start to moving toward to the desired input. According to part 3 rule bases the trend of error will be reduces.

Part 4:

FR^{11}: $IF\ e\ is\ NM\ and\ \dot{e}\ is\ P\ then\ U_{PD}\ is\ NS$
FR^{12}: $IF\ e\ is\ NB\ and\ \dot{e}\ is\ P\ then\ U_{PD}\ is\ Z$
FR^{13}: $IF\ e\ is\ NM\ and\ \dot{e}\ is\ Z\ then\ U_{PD}\ is\ PM$
FR^{14}: $IF\ e\ is\ NB\ and\ \dot{e}\ is\ Z\ then\ U_{PD}\ is\ PB$

For this group the actual input is drastically below the desired input (e(t) is Negative Medium or Negative Big) and at this time the rate of error is Positive or Zero, it means the rate of actual input is lower than desired input and caused to actual input moving toward to desired input. In this time, the role of controller is to speed control to reduce the error.

Part 5:

FR^{15}: $IF\ e\ is\ NS\ and\ \dot{e}\ is\ P\ then\ U_{PD}\ is\ NM$
FR^{16}: $IF\ e\ is\ Z\ and\ \dot{e}\ is\ P\ then\ U_{PD}\ is\ NB$
FR^{17}: $IF\ e\ is\ PS\ and\ \dot{e}\ is\ P\ then\ U_{PD}\ is\ NB$
FR^{18}: $IF\ e\ is\ PM\ and\ \dot{e}\ is\ P\ then\ U_{PD}\ is\ NB$
FR^{19}: $IF\ e\ is\ PB\ and\ \dot{e}\ is\ P\ then\ U_{PD}\ is\ NB$
FR^{20}: $IF\ e\ is\ PM\ and\ \dot{e}\ is\ Z\ then\ U_{PD}\ is\ NM$
FR^{21}: $IF\ e\ is\ PB\ and\ \dot{e}\ is\ Z\ then\ U_{PD}\ is\ NB$

This part is very similar to part 3. In this group, the actual input is near the desired input (e(t) is Negative Small, Zero or Positive Small) or the actual input is drastically below it (e(t) is Positive Medium or Positive Big) and at this time the rate of error is positive or Zero, it means the rate of actual input is lower than desired input and caused to actual input moving away from desired input. In this time, the role of controller is to reverse this trend and caused actual input start to moving toward to the desired input.

The PD like fuzzy rule table shows in Table 1.

Table 1. Rule Table in PD Like Fuzzy Logic Controller

$\dot{e}$ \ e	***PB***	***PM***	***PS***	***Z***	***NS***	***NM***	***NB***
P	NB	NB	NB	NB	NM	NS	Z
Z	NB	NM	NS	Z	PS	PM	PB
N	Z	PS	PM	PB	PB	PB	PB

Inference Engine (Fuzzy Rule Processing): The fuzzy inference engine recommends a fuzzy method to transfer the fuzzy rule base to fuzzy set. Mamdani and Sugeno methods are two main techniques of fuzzy rule processing. In this research Mamdani fuzzy inference engine is used as fuzzy rule processing. To inference analysis, two following rule bases are defined as bellows:

$$F.R^1{:}\, if\ e\ is\ NM \quad and \quad \dot{e}\ is\ N \quad then \quad U\ is\ PB$$
$$F.R^2{:}\, if\ e\ is\ NB \quad and \quad \dot{e}\ is\ N \quad then \quad U\ is\ PB$$

If two positions are selected to this analyze: $e = -0.06664$ and $\dot{e} = -0.6$ and according to Figures 3.10 to 3.12, all three membership degree are: $e_{(NM)} = 1$, for $\dot{e}_{(N)} = 0.5$ and $e_{(NB)} = 0$.

According to fuzzy rule base, the connection words is AND, the activation degrees is computed as

$$\mu_{FR_1} = \min[\mu_{e(NM)}(-0.06664), \mu_{\dot{e}(NB)}(-0.6)] = \min[1{,}0.5] = 0.5$$
$$\mu_{FR_2} = \min[\mu_{e(N.B)}(-0.06664), \mu_{\dot{e}(NS)}(-0.6)] = \min[0{,}0.5] = 0$$

The activation degrees of the consequent parts for $F.R^1$ and $F.R^2$ are computed as:

$$\mu_{FR_1}(-0.06664, -0.6, U) = \min[\mu_{FR_1}(-0.06664, -0.6), \mu_{U(PB)}] = \min[0.5, \mu_{U(PB)}]$$
$$\mu_{FR_2}(-0.06664, -0.6, U) = \min[\mu_{FR_2}(-0.06664, -0.6), \mu_{U(PB)}] = \min[0, \mu_{U(PB)}]$$

Fuzzy set $U_{PB(1)}$ and $U_{PB(2)}$ have three elements:

$$F.F^1(-0.06664, -0.6, U) = \{(0{,}1.002), (0.5{,}1.5), (0{,}1.998)\}$$
$$F.F^2(-0.06664, -0.6, U) = \{(0{,}1.002), (0{,}1.5), (0{,}1.998)\}$$

The aggregation degree is the aggregate two neighbouring fuzzy rules and makes a new consequent part. The Max-min aggregation is in above instance is;

$$\mu_{U_{12}}(-0.06664, -0.6, U) = \mu_{\bigcup_{i=1}^{2} FR^1}(-0.06664, -0.6, U)$$
$$= \max\{\mu_{FR}^1(-0.06664, -0.6, U)_{PB}\ ,\ \mu_{FR}^2(-0.06664, -0.6, U)_{PB}\ \}$$

$$AD_{12} = \{(0{,}1.002), (0.5{,}1.5), (0{,}1.998)\}$$

Defuzzification: defuzzification is the last step to design fuzzy logic controller and 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 types method to calculate the defuzzifications.

In this research COG method is used for defuzzification:

$$COG = [(0 \times 1.002) + (0.5 \times 1.251) + (0.5 \times 1.5) + (0.5 \times 1.749) + (0 \times 1.998)][0 + 0.5 + 0.5 + 0.5 + 0]^{-1} \quad = \frac{2.25}{1.5} = +1.5$$

Therefore the output PD-like fuzzy controller for two rule-bases is 1.5. Figure 10 shows the output rule base viewer in PD like fuzzy controller.

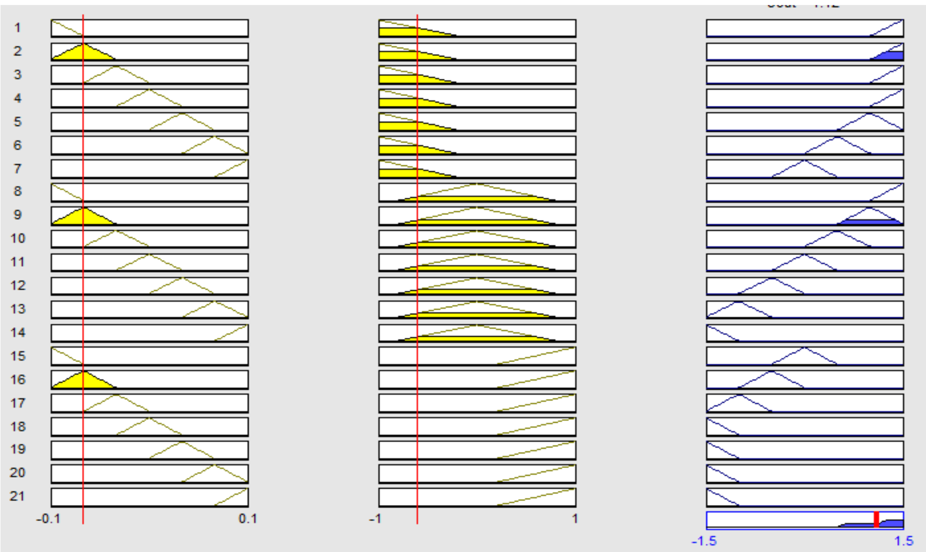

Figure 10. Rule Viewers in PD-Like Fuzzy Controller

According to design fuzzy logic controller, Figure 11 shows PD like fuzzy logic controller.

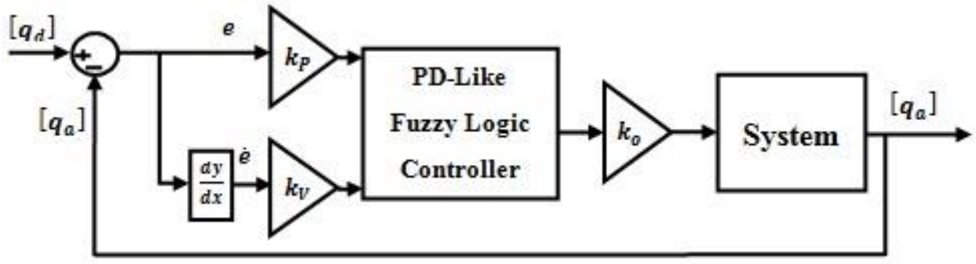

Figure 11. PD-Like Fuzzy Logic Controller

Table 2 shows the PD like fuzzy logic controller lookup Table.

Table 2. Lookup Table in PD Like Fuzzy Logic Controller

$e \rightarrow$ $\dot{e} \downarrow$	*-0.1*	*-0.08*	*-0.06*	*-0.04*	*-0.02*	*0*	*0.02*	*0.04*	*0.06*	*0.08*	*1*
-1	1.40	1.40	1.40	1.38	1.28	1.25	1.04	0.88	0.62	0.391	0
0.8	1.40	1.32	1.31	1.2	1.27	1.24	1.03	0.877	0.61	0.291	0
-0.6	1.40	1.12	0.923	0.888	0.635	0.619	0.464	0.222	0.1	-0.11	-0.3
-0.4	1.37	1.05	0.88	0.695	0.441	0.3	0.109	-0.074	-0.223	-0.8	-0.62
-0.2	1.37	1.04	0.877	0.622	0.291	0	-0.291	-0.623	-0.878	-1.04	-1.32
0	1.28	1.04	0.877	0.622	0.291	0	-0.291	-0.623	-0.9	-1.04	-1.32
0.2	1.20	1.04	0.877	0.622	0.291	0	-0.291	-0.623	-0.9	-1.04	-1.32
0.4	0.619	0.464	0.222	0.08	-0.11	-0.3	-0.441	-0.695	-0.9	-1.1	-1.34
0.6	0.298	0.109	-0.074	-0.222	-0.646	-0.619	-0.635	-0.89	-0.924	-1.33	-1.35
0.8	~0	-0.291	-0.622	-0.87	-1.04	-1.34	-1.32	-1.34	-1.33	-1..35	-1.37
1	0	-0.291	-0.63	-0.88	-1.04	-1.25	-1.32	-1.34	-1.35	-1.36	-1.38

4. Results

In this part conventional sliding mode controller, chattering attenuation boundary layer method, chattering attenuation intelligent method and chattering attenuation PD parallel method are compared for 3-D joint.

Comparison of the Tracking Data and Information: the trajectory following for conventional sliding mode controller, chattering attenuation boundary layer method, chattering attenuation intelligent method and chattering attenuation PD parallel method are compared in this section. According to Figure 12, traditional sliding mode controller has high frequency oscillation chattering. To chattering attenuation three methods are compare: chattering attenuation boundary layer method, chattering attenuation intelligent method and chattering attenuation PD parallel method. However boundary layer method can reduce the chattering but this method has two challenges: proof the stability and quality of performance. To solve these two challenges, parallel linear sliding mode controller and intelligent chattering attenuation sliding mode controller are used. Based on the following Figure, eliminating the sign function in sliding mode controller using saturation function caused to eliminate the chattering however, robustness of control and accuracy are lost. The trajectory following and chattering elimination is illustrated in Figure 12. According to Figure 12, fuzzy sliding mode controller is faster than parallel linear sliding mode controller and saturation sliding mode controller because the rise time in fuzzy like sliding mode controller is about 0.47 second, in parallel sliding mode controller is 0.55 second and in saturation sliding mode controller is 3.14 second. In error point of view, parallel linear SMC is better than intelligent sliding mode control and boundary layer SMC. However, boundary layer sliding mode controller can reduce the chattering but this method is caused to increase undershoot and error. According to Figure 12, intelligent sliding mode control and parallel linear sliding mode controller have accurate trajectory response and they can eliminate the chattering as well as reduce the error.

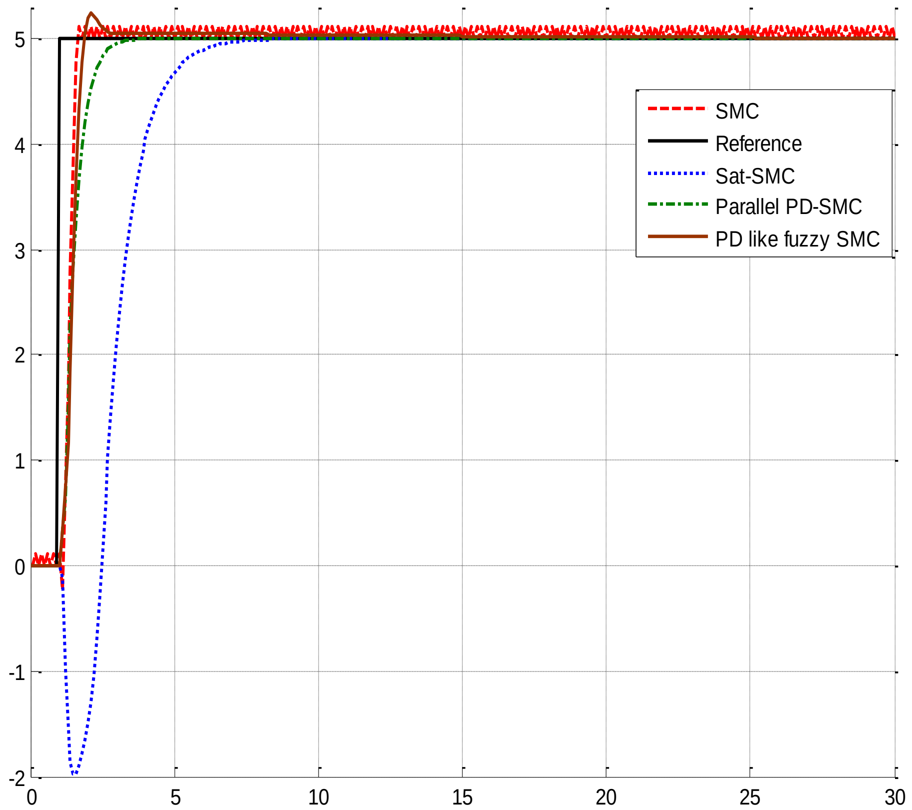

Figure 12. Chattering Attenuation: SMC, Saturation SMC, Fuzzy SMC and Parallel Linear SMC

Comparison the Disturbance Rejection: the power of disturbance rejection is very important to robust checking in any controllers. In this section trajectory accuracy is test under uncertainty condition. To test the disturbance rejection band limited white noise with 30% amplitude is applied to sliding mode controller, parallel linear sliding mode controller, boundary layer sliding mode controller and intelligent fuzzy sliding mode algorithm. In Figures 13, trajectory accuracy is shown. According to this graph, however intelligent fuzzy sliding mode controller has suitable steady state error in presence of uncertainty but it is robust than parallel linear sliding mode controller and more robust than boundary layer sliding mode controller. Boundary layer sliding mode controller has very much fluctuations in presence of external disturbance. In error point of view, intelligent sliding mode control is better than parallel linear SMC. Both intelligent sliding mode control and parallel linear SMC are better than boundary layer SMC in certain and uncertain condition. However, boundary layer sliding mode controller can reduce the chattering but this method is caused to increase undershoot and error. However, these three methodology can eliminate the chattering but they have challenges in presence of uncertainty and external disturbance.

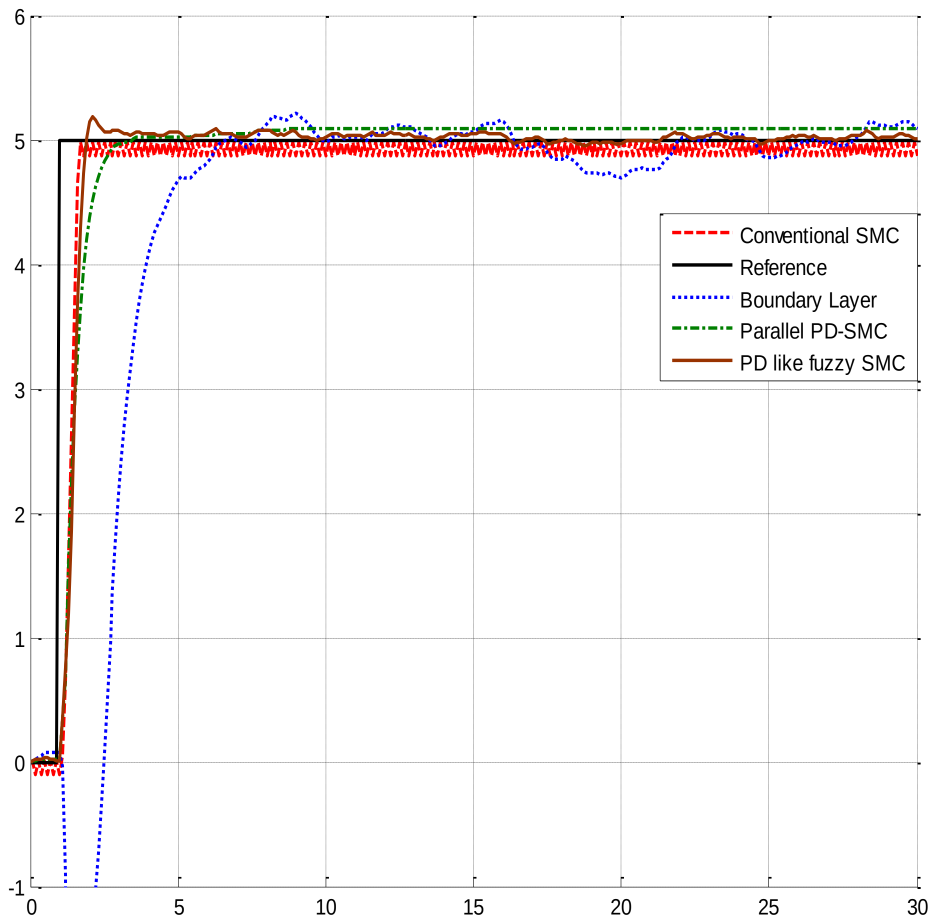

Figure 13. Chattering Attenuation: SMC, Saturation SMC, Fuzzy SMC and Parallel linear SMC in Presence of Uncertainty

5. CONCLUSION

This research is concerned with development of mathematical models and control methods investigation about a certain and uncertain type of three dimensions joint. Three dimension of joint is a novel type of actuator that closely mimics human skeletal muscles in size and power capabilities, which is considered for use in exoskeletons to be worn by humans for strength augmentation and for use as actuators in robotic systems. Since 3-D joints are nonlinear and time-varying, perfect knowledge of 3D joint characteristics i s impossible. Moreover, the inertial parameters of robot manipulators, which depend on the payload, are often unknown and changing. Therefore, precise dynamical models of robot manipulators actuated by 3D joints are usually unavailable.

Sliding mode is a well-known robust control approach due to its strong insensitivity to system parameters variation. The discontinuous switching control strategy of sliding mode is designed such that a constringency property dominates the closed-loop dynamics of the nonlinear system. In this way, it induces a stabilization on the sliding surface hence the desired tracking trajectories are obtained. This part of sliding mode controller caused chattering phenomenon. To attenuation of this challenge in sliding mode controller, three types methodology are introduced: boundary layer algorithm, parallel PD control and intelligent fuzzy PD controller. Regarding to results, parallel PD control and intelligent fuzzy PD controller are more suitable than boundary layer method for chattering attenuation in three dimensions joint. According to this research, intelligent method has minimum error in uncertain condition but it has some challenges in real time situations.

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Project Title: “Design High Precision and Fast Dynamic Controller For Multi-Degrees Of Freedom Actuator”

Iranian center of Advance Science and Technology (IRAN SSP) is one of the independent research centers specializing in research and training across of Control and Automation, Electrical and Electronic Engineering, and Mechatronics & Robotics in Iran. At IRAN SSP research center, we are united and energized by one mission to discover and develop innovative engineering methodology that solve the most important challenges in field of advance science and technology. The IRAN SSP Center is instead to fill a long-standing void in applied engineering by linking the training a development function one side and policy research on the other. This center divided into two main units:

- Education unit
- Research and Development unit

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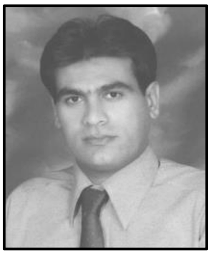

Amirzubir Sahamijoo, He is currently a senior research assistant at Institute of Advanced Science and Technology, Research Center, IRAN SSP. He is senior research assistant of team to Design Intelligent FPGA-Based Control Unit to Control of 4-DOF Medical Robot Manipulator since July, 2015 to now, research assistant of team (8 researchers) to design a Micro-electronic Based nonlinear controller for first order delay system since March, 2015 to now, research student (21 researchers) to design high precision and fast dynamic controller for multi-degrees of freedom actuator since 2014 to date, research student (9 researchers) to design Prevent the Risk of Lung Cancer Progression Based on Fuel Ratio Optimization since 2014 to date, and published 4 journal papers since 2014 to date. His current research interests are nonlinear control, artificial control system, Microelectronic Device, Internal Combustion Engine, and HDL design.

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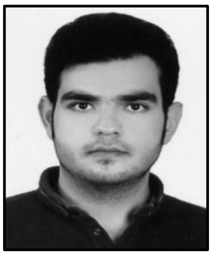
Mr. Piltan has acquired a formidable repertoire of knowledge and skills and established himself as one of the leading young scientists in his field. Specifically, he has accrued expertise in the design and implementation of intelligent controls in nonlinear systems. Mr. Piltan has employed his remarkable expertise in these areas to make outstanding contributions as detailed follows:Nonlinear control for industrial robot manipulator (2010-IRAN SSP), Intelligent Tuning The Rate Of Fuel Ratio In Internal Combustion Engine (2011-IRANSSP), Design High Precision and Fast Dynamic Controller For Multi-Degrees Of Freedom Actuator (2013-IRANSSP), Research on Full Digital Control for Nonlinear Systems (2011-IRANSSP), Micro-Electronic Based Intelligent Nonlinear Controller (2015-IRANSSP), Active Robot Controller for Dental Automation (2015-IRANSSP), Design a Micro-Electronic Based Nonlinear Controller for First Order Delay System (2015-IRANSSP).

The above original accomplishments clearly demonstrate that Mr. Piltan has performed original research and that he has gained a distinguished reputation as an outstanding scientist in the field of electronics and control engineering. Mr. Piltan has a tremendous and unique set of skills, knowledge and background for his current and future work. He possesses a rare combination of academic knowledge and practical skills that are highly valuable for his work. In 2011, he published 28 first author papers, which constitute about 30% of papers published by the Department of Electrical and Electronic Engineering at University Putra Malaysia. Additionally, his 28 papers represent about 6.25% and 4.13% of all control and system papers published in Malaysia and Iran, respectively, in 2011.



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Dr. Nasri Sulaiman advisor and supervisor of several high impact projects involving more than 150 researchers from countries around the world including Iran, Malaysia, Finland, Italy, Germany, South Korea, Australia, and the United States. Dr. Nasri Sulaiman has authored or co-authored more than 80 papers in academic journals, conference papers and book chapters. His papers have been cited at least 3000 times by independent and dependent researchers from around the world including Iran, Algeria, Pakistan, India, China, Malaysia, Egypt, Columbia, Canada, United Kingdom, Turkey, Taiwan, Japan, South Korea, Italy, France, Thailand, Brazil and more.

Dr. Nasri Sulaiman has employed his remarkable expertise in these areas to make outstanding contributions as detailed below:

- Design of a reconfigurable Fast Fourier Transform (FFT) Processor using multi-objective Genetic Algorithms **(2008-UPM)**
- Power consumption investigation in reconfigurable Fast Fourier Transform (FFT) processor **(2010-UPM)**
- Crest factor reduction And digital predistortion Implementation in Orthogonal frequency Division multiplexing (ofdm) systems (2011-UPM)
- High Performance Hardware Implementation of a Multi-Objective Genetic Algorithm, (RUGS), Grant amount RM42,000.00, September (2012-UPM)
- Nonlinear control for industrial robot manipulator (2010-IRAN SSP)
- Intelligent Tuning The Rate Of Fuel Ratio In Internal Combustion Engine (2011-IRANSSP)
- Design High Precision and Fast Dynamic Controller For Multi-Degrees Of Freedom Actuator (2013-IRANSSP)
- Research on Full Digital Control for Nonlinear Systems (2011-IRANSSP)
- Micro-Electronic Based Intelligent Nonlinear Controller (2015-IRANSSP)
- Active Robot Controller for Dental Automation (2015-IRANSSP)
- Design a Micro-Electronic Based Nonlinear Controller for First Order Delay System (2015-IRANSSP)