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Robust Auto-Intelligent Sliding Accuracy for High Sensitive Surgical Joints

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Abstract

The use of robots in medical applications has increased considerably in the last decade. Today, there are robots being used in complex surgeries such as those of the brain, eye, heart, and hip. Complex surgeries have complex requirements, such as high precision, reliability over multiple and long procedures, ease of use for physicians and other personnel, and a demonstrated advantage, to the patient, of using a robot. Furthermore, all new technologies in the medical area have to undergo strict regulatory clearance procedures, which may include clinical trials, as outlined by various government regulatory agencies. Variable Structure controller is a powerful nonlinear robust controller under condition of partly uncertain dynamic parameters of system. This controller is used to control of highly nonlinear systems especially for surgical joints. Limitation of robustness in uncertain dynamic parameter is the main drawback in pure Variable Structure controller. This challenge in pure Variable Structure controller and intelligent Variable Structure controller is reduced by using sliding surface auto-tuning. Artificial intelligence theory is used to reduce the system's limitation. In this research, PI fuzzy sliding surface tuning Variable Structure controller is introduced. To eliminate the uncertain limitation, 49 rules Mamdani inference system is design and supervised the Variable Structure methodology. This method is based on resolve the on line sliding surface slope as well as improve the output performance by tuning the sliding surface slope coefficient. The sliding surface gain ($\boldsymbol{\lambda}$) of this controller is adjusted online depending on the last values of error (e) and integral of error ($\sum e$) by sliding surface slope updating factor (α). Fuzzy-based tuning controller is stable controller, which does not need to limits the dynamic model of surgical joints.

Keywords: *medical application, surgical robots, variable structure controller, sliding surface slope, intelligent methodology, PI fuzzy logic theory, online tuning*

1. Introduction

The use of robots in medical applications has increased considerably in the last decade. Today, there are robots being used in complex surgeries such as those of the brain, eye, heart, and hip. By one survey, 2285medical robots were estimated to be in use at the end of 2002, and that number is expected to rise to over 8000 medical robots by 2006. It is also estimated that medical robots may, in the end, have the largest market value among all types of robots. Complex surgeries have complex requirements, such as high precision, reliability over multiple and long procedures, ease of use for physicians and other personnel, and a demonstrated advantage, to the patient, of using a robot. Furthermore, all new technologies in the medical area have to undergo strict regulatory clearance procedures, which may include clinical trials, as outlined by various government regulatory agencies. In the U.S., the Food and Drug Administration (FDA) has jurisdiction over medical devices. As more and more devices get through the regulatory procedures, there will be more and more robots in the medical world. Before one can consider the usage of robots in medical applications, it is important to understand that medical applications have unique requirements, different from general, or “traditional,” robot design. Some of the design issues and associated advantages are described below [1-4]:

- **High precision**: Modern robots are demonstrated to be highly precise. The precision range depends on the robot and the application, of course, but it is generally accepted that for a given application, a robot can be designed to meet or exceed the precision requirements of the application. A typical industrial robot has repeatability specifications measured in tenths of a millimeter. A representative ratio of motion in robotic assisted surgery is that a 1 cm movement of a doctor’s hand translates to a 0.1 cm movement of the robotic tool.

- **Heavy payloads**: Modern robots can carry heavy payloads over large workspaces, at high speeds, with high precision. Industrial robots are available with payload capacity of a few ounces to over 1000 lb.

- **Workspace**: Medical robot workspace requirements tend to be significantly larger than industrial needs because of patient related factors, such as uncertainty in patient location during the procedure and safety requirements. There is an obvious overriding need to avoid any hazard to the patient, physician, and other medical personnel; this drives an exclusionary zone around the patient, doctor, and other equipment that may be attached to the patient. Thanks to the advances driven by industrial applications, the workspace of most available robots is significant and can be utilized for medical applications.

- **High Speed**: Most new robots have been designed and optimized for industrial automation, enabling them to move at high speeds with high precision. The majority of medical applications do not require robots to move at high speeds as these robots are working on a patient. Reassurance, comfort, and safety dictate the robot’s speed in medical applications.

- **Reliability**: Industrial robots are designed to work round the clock without stopping; their medical counterparts work only a few hours a day. The nature of medical applications is that most of the time is taken up by other parts of the surgery, such as operating room preparation, patient preparation, and postoperative procedures. The robots actually perform surgeries for only a limited time, around 10% of surgery time. The resulting reliability numbers for medical work are excellent, leading to very limited downtime.

- **Tedium**: Most of the medical applications where robots are sought involve repetitive tasks over a very long period of time. Some surgeries last for many hours, during which the operators are required to repeat tasks hundreds or thousands of times. Obviously, robots do not have any problems with tedium.

- **High Quality**: Robotic assisted surgery can help a wide variety of doctors perform complex surgeries with the same high quality previously achieved only by some accomplished surgeons. Additionally, most medical procedures cannot tolerate any degradation in quality due to trembling or unsteadiness of hands. Robotic systems in the operating room can compensate for imperfections in the user due to age, fatigue, or other factors, without degrading the quality of care administered to the patient.

- **Computer control**: Robotic surgery is able to capitalize on available diagnostic data to calculate an optimized approach to treatment. Most modern systems use fusion of multiple imaging modalities such as CT, PET, and MRI.

- **Remote operation**: Finally, because robots are typically controlled by computers and/or remote electrical signals, the option exists to remotely operate the units over large distances through direct data links, or even over the internet (telerobotics). People have recognized many of these obvious advantages; therefore, we have seen a considerable increase in usage of robots in medical applications in recent times. As these advantages are general and apply to many medical procedures, the authors believe that it is just a matter of time before more robots are employed in automating a variety of procedures, ultimately increasing the quality while reducing the cost of medical care in the future.

Using robots in medical applications presents a unique set of challenges. The following part briefly discusses the design issues that should be considered in many medical applications [5-9].

- **Safety**: Safety of patients and users is the ultimate concern when using robotics in medical applications. In the industrial world, safety is addressed, most typically, by ensuring that humans are not present in the robot's workspace. Considerable precautions are taken so that no one inadvertently enters the workspace of a working robot, and if someone does enter the area, the robot is automatically stopped. In the case of a medical application, by definition, a human being (the patient) needs to be in the workspace. Moreover, the physician and other medical personnel generally need to be in the workspace as well to attend to other needs of the patient and the surgery. A robotic system, therefore, has to be designed so that it is safe for the patient, physician, and other personnel in the room while it is effectively operating on the patient.

- **Uncertainty of position**: Most medical applications have a higher level of uncertainty in the position of the target (patient) than their industrial counterparts do. In a typical industrial application, one can expect the work piece to be aligned and mounted precisely in the same location and orientation. In a typical surgery, the patient and the specific organ that needs to undergo surgery cannot practically be located in the same location and orientation. Furthermore, various steps in the procedure will likely have to be modified and adapted based on the patient's condition.

- **Fail-safe**: It is required that the medical robotic system operates in a fail-safe mode. By fail-safe, one means that if and when any component fails, the system reaches a safe state, thus minimizing chance for injury or death to the patient or other personnel.

- **Power/System Failure**: The system needs to be designed in such away that in case of a power/system failure, the physician can move the robot away to keep the patient safe and be able to attend to the patient.

- **Record Keeping**: All records related to an operation need to be kept and protected for future use. This issue has become more acute in recent times with current U.S. and international regulations regarding patient data privacy. The opposing needs of the system are to maintain confidentiality, while ensuring that the patient on the table matches the program in the robotic system.

- **Regulatory Issues**: All design, development, and production activity needs to be done in a controlled fashion following the appropriate regulatory guidelines. The issues outlined above are in addition to the technical issues one has to deal with for any product design. It is obvious that these additional requirements add a significant cost in terms of time and resources to successfully design, develop, and deploy a product in the field.

Figure 1 shows the type of surgical robot. In this figure the workspace joint is multi degrees of freedom.

Figure 1. Surgical Robot and Multi Degrees of Freedom Joints

A spherical joint, often abbreviated as “S”, is a lower pair formed by contact of two congruent spherical surfaces. Once again, one is an internal surface, and the other is an external surface. A spherical joint permits rotation about any line through the center of the sphere. Thus, it permits independent rotation about axes in up to three different directions and has three degrees of freedom. A spherical joint is easily replaced by a kinematically equivalent compound joint consisting of three revolutes that have concurrent axes. They do not need to be successively orthogonal, but often they are implemented that way. The arrangement is, in general, kinematically equivalent to a spherical joint, but it does exhibit a singularity when the revolute joint axes become coplanar. This is as compared to the native spherical joint that never has such a singularity. Likewise, if a spherical joint is modeled in simulation as three revolutes, computational difficulties again can arise from the necessary inclusion of massless virtual links having zero length. It is nonlinear and uncertain dynamic parameters. A nonlinear robust controller design is major subject in this work.

Controller is a device which can sense information from linear or nonlinear system (*e.g.*, surgical joints) to improve the systems performance [3]. The main targets in designing control systems are stability, good disturbance rejection, and small tracking error[5]. Several joints are controlled by linear methodologies (*e.g.*, Proportional-Derivative (PD) controller, Proportional- Integral (PI) controller or Proportional- Integral-Derivative (PID) controller), but joint works with various situations and have uncertainty in dynamic models this technique has limitations. From the control point of view, uncertainty is divided into two main groups: uncertainty in unstructured inputs (*e.g.*, noise, disturbance) and uncertainty in structure dynamics (*e.g.*, parameter variations). In some applications surgical joints are used in an unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design nonlinear robust controller with an acceptable performance (*e.g.*, minimum error, good trajectory, disturbance rejection). Sliding mode controller is an influential nonlinear controller to certain and uncertain systems which it is based on system's dynamic model.

Sliding mode controller is a powerful nonlinear robust controller under condition of partly uncertain dynamic parameters of system [7]. This controller is used to control of highly nonlinear systems. High frequency oscillation, nonlinear equivalent dynamic formulation in uncertain dynamic parameter and robustness are three main drawbacks in pure sliding mode controller [20]. Pure and intelligent sliding mode controller have difficulty in handling unstructured model uncertainties (robustness). It is possible to solve this problem by combining sliding mode controller and PI-fuzzy-based tuning. This method is based on resolve the on line sliding surface gain (λ) as well as improve the output performance by tuning the sliding surface slope updating factor (α). Fuzzy-based tuning error-based fuzzy sliding mode controller is stable model-free controller which does not need to limits the dynamic model of joints and eliminate the chattering phenomenon without to use the boundary layer saturation function.

The main goal in this paper is to design a SISO PI-fuzzy adaptive variable structure controller for surgical joints. This method is easy to design and implement to have acceptable safety repose. Surgical joints has nonlinear dynamic and uncertain parameters consequently; following objective have been pursuit in the mentioned research: To develop a safety trajectory result in a position adaptive variable structure method against uncertainties. This paper is organized as follows; Section 2, is served as an introduction to the dynamic formulation of surgical joints, introduction to nonlinear robust variable structure controller and fuzzy inference engine and its application to control and estimate dynamic uncertainty of surgical joint. 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 [10-15].
The equation of a spherical motor governed by the following equation:

$$\boldsymbol{H}(\boldsymbol{q})\begin{bmatrix}\ddot{\boldsymbol{\alpha}}\\ \ddot{\boldsymbol{\beta}}\\ \ddot{\boldsymbol{\gamma}}\end{bmatrix}+\mathbf{B}(\boldsymbol{q})\begin{bmatrix}\dot{\boldsymbol{\alpha}}\dot{\boldsymbol{\beta}}\\ \dot{\boldsymbol{\alpha}}\dot{\boldsymbol{\gamma}}\\ \dot{\boldsymbol{\beta}}\dot{\boldsymbol{\gamma}}\end{bmatrix}+\boldsymbol{C}(\boldsymbol{q})\begin{bmatrix}\dot{\boldsymbol{\alpha}}^2\\ \dot{\boldsymbol{\beta}}^2\\ \dot{\boldsymbol{\gamma}}^2\end{bmatrix}=\begin{bmatrix}\boldsymbol{\tau}_x\\ \boldsymbol{\tau}_y\\ \boldsymbol{\tau}_z\end{bmatrix} \tag{1}$$

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 variable q_i , independently of the motion of the other parts. Therefore, the angular acceleration is found as to be:

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

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:

$$\boldsymbol{\Psi}(\boldsymbol{X}, \boldsymbol{q}) = \boldsymbol{0} \tag{3}$$

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;

$$\boldsymbol{R_i^{i-1}} = \boldsymbol{U_{i(\theta_i)}} \boldsymbol{V_{i(\alpha_i)}} \tag{4}$$

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

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

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

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

So (R_n^0) is given by

$$\boldsymbol{R_n^0} = (\boldsymbol{U_1 V_1})(\boldsymbol{U_2 V_2}) \dots \dots \dots (\boldsymbol{U_n V_n}) \tag{7}$$

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

$$\boldsymbol{{}_n^0T} = \boldsymbol{{}_1^0T}.\boldsymbol{{}_2^1T}.\boldsymbol{{}_3^2T} \dots \dots .\boldsymbol{{}_n^{n-1}T} = \begin{bmatrix} \boldsymbol{R_n^0} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{bmatrix} \tag{8}$$

B. Adaptive Control Methodology:

In various dynamic parameters systems that need to be training on-line adaptive control methodology is used. Adaptive control methodology can be classified into two main groups, namely, traditional adaptive method and fuzzy adaptive method [24]. Fuzzy adaptive method is used in systems which want to training parameters by expert knowledge. Traditional adaptive method is used in systems which some dynamic parameters are known. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, adaptive method is applied to artificial sliding mode controller. Hsu *et al.*, [16] have presented traditional adaptive fuzzy sliding mode control which can update fuzzy rules to compensate nonlinear parameters and guarantee the stability robot manipulator controller. Hsueh e*t al.*, [13] have presented traditional self tuning sliding mode controller which can resolve the chattering problem without using saturation function.

For nonlinear dynamic systems (*e.g.*, robot manipulators) with various parameters, adaptive control technique can train the dynamic parameter to have an acceptable controller performance. Calculate several scale factors are common challenge in pure sliding mode controller and fuzzy logic controller, as a result it is used to adjust and tune coefficient.

Adaptive fuzzy sliding mode controller is used to many applications. This controller is based on online tuning the parameters and caused to improve the trajectory [12, 17-19]. The adaptive sliding mode controller is used to estimate the unknown dynamic parameters and external disturbances. For instance, the applications of adaptive fuzzy sliding mode controller to control the robot manipulators have been reported in [10-11, 15]. Generally, adaptive fuzzy sliding mode control of robot manipulator is classified into two main groups' *i.e.*, multi-input multi-output (MIMO) and single-input single-output (SISO) fuzzy systems.

Yoo and Ham [20] have proposed a MIMO fuzzy system to help the compensation and estimation the torque coupling. In $\boldsymbol{n-DOF}$ robot manipulator with $\boldsymbol{k}$ membership function for each input variable, the number of fuzzy rules for each joint is equal to $\boldsymbol{3k^{2n}}$ that causes to high computation load and also this controller has chattering. This method can only tune the consequence part of the fuzzy rules. Guo and Woo [22] have proposed a SISO fuzzy controller to compensate the switching terms. The number of fuzzy rules is reduced $(\boldsymbol{K_2})$ with regard to reduce the chattering. Lin and Hsu [23] have proposed a methodology to tuning consequence and premise part of fuzzy rules to reduce the chattering based on tuning the membership function. In this method the number of fuzzy rules equal to $\boldsymbol{K_2}$ with low computational load but chattering is expected. Shahnazi *et al.*, have proposed a SISO PI direct adaptive fuzzy sliding mode controller based on Lin and

Hsu algorithm to reduce or eliminate chattering with $\boldsymbol{K_2}$ fuzzy rules numbers. The bounds of PI controller and the parameters are online adjusted by low adaption computation and tune the membership function [14]. Medhafer *et al.*, [21] have proposed an indirect adaptive fuzzy sliding mode controller to control robot manipulator. This MIMO algorithm, applies to partly estimate the nonlinear dynamic parameters.

C. Fuzzy Inference Engine:

This section provides a review about foundation of fuzzy logic based on [12-13]. 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;

$$\boldsymbol{A = \{x, \mu_A(x) | x \in X\}; A \in U} \tag{9}$$

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

$$\boldsymbol{\mu_{F(x)}} = \begin{cases} \boldsymbol{0}, & x < a \\ \dfrac{\boldsymbol{x-a}}{\boldsymbol{b-a}}, & a \le x < b \\ \dfrac{\boldsymbol{d-x}}{\boldsymbol{d-c}}, & c \le x < d \\ \boldsymbol{0}, & x > d \end{cases} \tag{10}$$

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

$$\boldsymbol{\mu_{F(x)}} = \begin{cases} \boldsymbol{0}, & x < a \\ \dfrac{\boldsymbol{x-a}}{\boldsymbol{b-a}}, & a \le x < b \\ \dfrac{\boldsymbol{c-x}}{\boldsymbol{c-b}}, & b \le x \le c \\ \boldsymbol{0}, & x > c \end{cases} \tag{11}$$

A Gaussian membership function of fuzzy set is defined by

$$\boldsymbol{\mu_{F(x)} = e^{\frac{-(x-c_F)^2}{W}}} \tag{12}$$

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

$$\boldsymbol{\mu_{F(x)} = \frac{1}{1+(x-c_F)^2}} \tag{13}$$

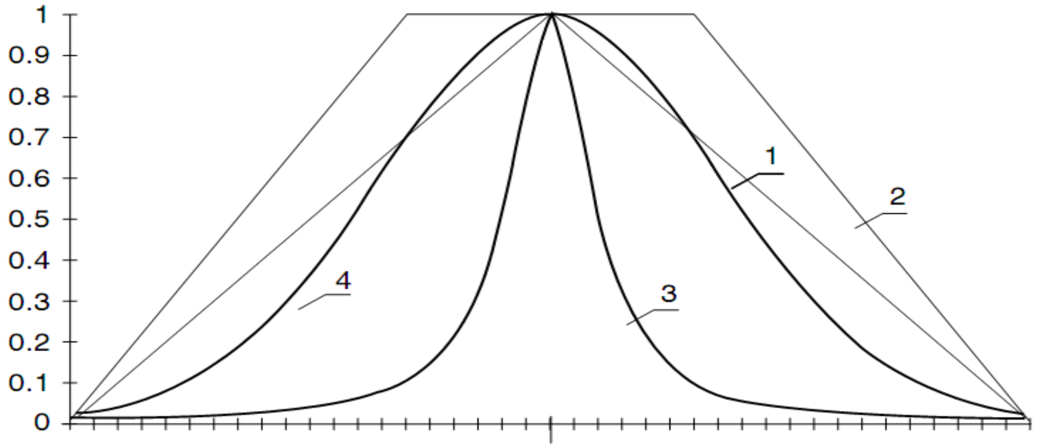

Figure 2. Most Important Membership Functions in Fuzzy Set: 1-Trianglar, 2-Trapezoidal, 3-Gaussian, 4-Bell-shaped

Figure 2 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

$$\boldsymbol{S(a,b)} = \boldsymbol{\mu_{A\cup B(u)}} = \mathbf{max}\{\boldsymbol{\mu_{A(u)}}, \boldsymbol{\mu_{B(u)}}\}, \qquad \forall \boldsymbol{u} \in \boldsymbol{U} \tag{14}$$

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

$$\begin{aligned}\boldsymbol{T(a,b)} &= \boldsymbol{\mu_{A\cap B(u)}} = \mathbf{min}\{\boldsymbol{\mu_{A(u)}}, \boldsymbol{\mu_{B(u)}}\} = \boldsymbol{\mu_{A(u)}}\cdot\boldsymbol{\mu_{B(u)}} \\ &= \mathbf{max}(\mathbf{0},\ \boldsymbol{\mu_{A(u)}} + \boldsymbol{\mu_{B(u)}} - \mathbf{1}) = \begin{cases}\boldsymbol{\mu_{A(u)}} & ,\ if\,\boldsymbol{\mu_{B(u)}} = \mathbf{1} \\ \boldsymbol{\mu_{B(u)}} & ,\ if\,\boldsymbol{\mu_{A(u)}} = \mathbf{1} \\ \mathbf{0} & ,\ \boldsymbol{if\,\mu_{B(u)}}, \boldsymbol{\mu_{A(u)}} < 1\end{cases}\end{aligned} \tag{15}$$

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

$$\boldsymbol{\mu_{A.B(u)}} = \boldsymbol{\mu_{A(u)}}\cdot\boldsymbol{\mu_{B(u)}} \tag{16}$$

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

$$\boldsymbol{\mu_{A\hat{+}B(u)}} = \boldsymbol{\mu_{A(u)}}\cdot\boldsymbol{\mu_{B(u)}} - \boldsymbol{\mu_{A(u)}}\cdot\boldsymbol{\mu_{B(u)}} \tag{17}$$

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 3 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

$$If\ x\ is\ A\ Then\ y\ is\ B \tag{18}$$

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:

$$if\ e\ is\ NB\ and\ \dot{e}\ is\ ML\ then\ T\ is\ LL \tag{19}$$

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.

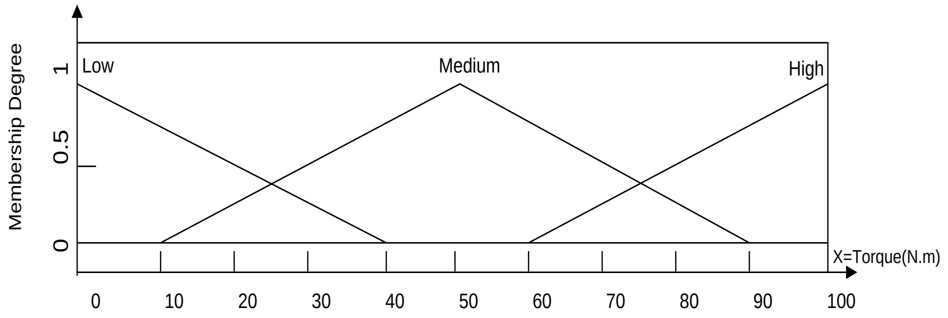

Figure 3. Linguistic Variable and Linguistic Value

$If - then$ 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 4 shows the main three parts in $If - then$ rules.

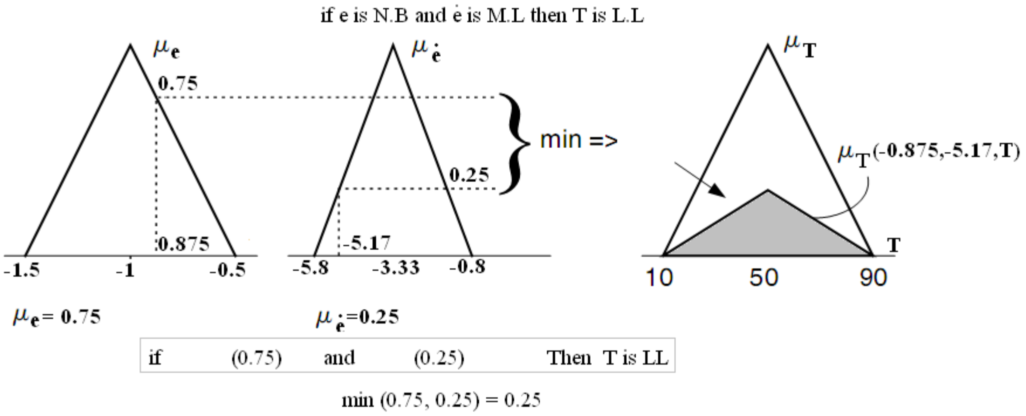

Figure 4. Main Three Parts in IF-THEN Rules in Fuzzy Set

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

$$\begin{array}{lllll} \boldsymbol{Mamdani} & \boldsymbol{F.R^1: if} & \boldsymbol{x\ is\ A\ and\ y\ is\ B} & \boldsymbol{then} & \boldsymbol{z\ is\ C} \\ \boldsymbol{Sugeno} & \boldsymbol{F.R^1: if} & \boldsymbol{x\ is\ A\ and\ y\ is\ B} & \boldsymbol{then} & \boldsymbol{f(x,y) is\ C} \end{array} \tag{20}$$

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

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U) = \max\left\{\min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]\right\}} \tag{21}$$

The Sum-min aggregation defined as below

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U) = \sum \min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]} \tag{22}$$

where r is the number of fuzzy rules activated by x_k and y_k and also $\mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U)$ 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

$$\boldsymbol{COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}} \tag{23}$$

and COA method used the following equation to calculate the defuzzification

$$COA(x_k, y_k) = \frac{\sum_i U_i \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \mu_U \cdot (x_k, y_k, U_i)} \tag{24}$$

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, $\mu_U \cdot (x_k, y_k, U_i)$ 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 [53]. 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.

D. Conventional 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 ($\dot{q}_d = 0$) by discontinuous method in the following form;

$$\tau_{(q,t)} = \begin{cases} \tau_i^+(q,t) & if\ S_i > 0 \\ \tau_i^-(q,t) & if\ S_i < 0 \end{cases} \tag{25}$$

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

Discontinues controller causes an acceptable tracking performance at the expense of very fast switching. 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
- nonlinear equivalent dynamic formulation in uncertain parameters[20].

Chattering phenomenon (Figure 6) can causes some problems such as saturation and heats the mechanical parts of robots 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].

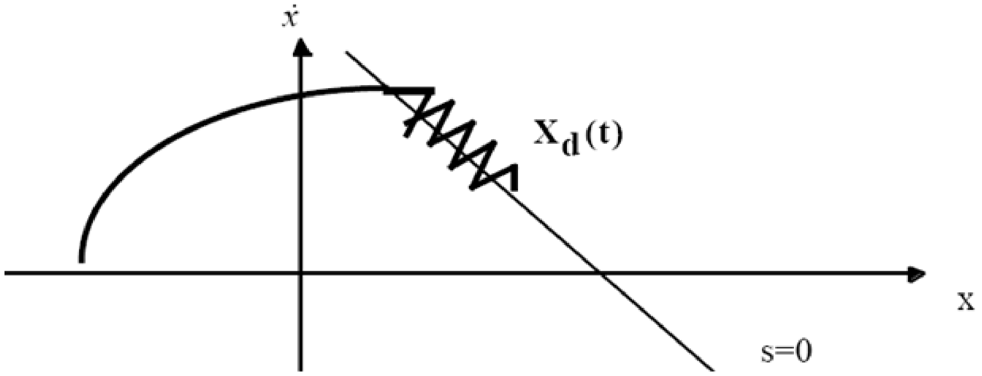

Figure 6. Chattering as a Result of Imperfect Control Switching [1]

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 [13-15]. Wu *et al.*, [25] 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.*, [26]and Li and Xu [11] 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.

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]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \tag{26}$$

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \tag{27}$$

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

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\, \tilde{x} = 0 \tag{28}$$

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

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \left(\int_0^t \tilde{x}\, dt \right) = 0 \tag{29}$$

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].

$$\frac{1}{2}\frac{d}{dt} s^2(x,t) \le -\zeta |s(x,t)| \tag{30}$$

where ζ is positive constant.

If $\mathbf{S(0)>0} \rightarrow \frac{d}{dt}\mathbf{S(t)} \leq -\zeta$ (31)

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

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt} S(t) \leq -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S\,(t_{reach}) - S(0) \leq -\zeta(t_{reach} - 0) \tag{32}$$

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

$$0 - S(0) \leq -\eta(t_{reach}) \rightarrow t_{reach} \leq \frac{S(0)}{\zeta} \tag{33}$$

and

$$if\ S(0) < 0 \rightarrow 0 - S(0) \leq -\eta(t_{reach}) \rightarrow S(0) \leq -\zeta(t_{reach}) \rightarrow t_{reach} \leq \frac{|S(0)|}{\eta} \tag{34}$$

$$if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \tag{35}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda) \quad \widetilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{36}$$

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

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{37}$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \ \rightarrow \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \tag{38}$$

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

$$\widehat{U} = -\widehat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \tag{39}$$

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

$$U_{dis} = \widehat{U} - K(\vec{x}, t) \cdot \mathrm{sgn}(s) \tag{40}$$

where the switching function $\mathbf{sgn}(\mathbf{S})$ is defined as [1, 6]

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{41}$$

and the $\boldsymbol{K}(\vec{x}, t)$ is the positive constant.

$$\frac{1}{2}\frac{d}{dt} s^2(x,t) = \dot{S} \cdot S = \left[f - \widehat{f} - K\mathrm{sgn}(s)\right] \cdot S = \left(f - \widehat{f}\right) \cdot S - K|S| \tag{42}$$

The sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \widetilde{x}\, dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{43}$$

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

$$\widehat{U} = -\widehat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{44}$$

$$\tau = \tau_{eq} + \tau_{dis} \tag{45}$$

$$\boldsymbol{\tau_{eq}} = \left[\boldsymbol{H^{-1}}(\boldsymbol{B}+\boldsymbol{C})+\dot{\boldsymbol{S}}\right]\boldsymbol{H} \tag{46}$$

$$\boldsymbol{\tau_{dis}} = \boldsymbol{K}\cdot \mathbf{sgn}(\boldsymbol{S}) \tag{47}$$

The control output can be written as;

$$\boldsymbol{\tau} = \boldsymbol{\tau_{eq}} + \boldsymbol{K}.\,\mathbf{sgn}(\boldsymbol{S}) \tag{48}$$

$$\boldsymbol{\tau} = \left[\boldsymbol{M^{-1}}(\boldsymbol{B}+\boldsymbol{C}+\boldsymbol{G})+\dot{\boldsymbol{S}}\right]\boldsymbol{M} + \boldsymbol{K}\cdot \mathbf{sgn}(\boldsymbol{S}) \tag{49}$$

3. Methodology

The first solution to design high performance controller is design the robust algorithm in order to reduce the uncertainty problems in a limit variation (*e.g.*, sliding mode controller). Conversely the first solution is used in many applications it has some limitations such as nonlinear dynamic part in controller.

The second solution is applied artificial intelligence method (*e.g.*, fuzzy logic) in conventional nonlinear method to reduce or eliminate the challenges. However the second solution is a superior to reduce or eliminate the dynamic nonlinear part with respect to have stability and fairly good robustness but it has a robust in a limit variation.

The third solution is design on-line controller (*e.g.*, intelligent tuning sliding surface slope controller). Adaptive (on-line) control is used in systems whose dynamic parameters are varying and need to be training on line. Sliding mode controller has difficulty in handling unstructured model uncertainties and this controller's performance is sensitive to sliding surface slope coefficient. It is possible to solve above challenge by combining intelligent tuning method and sliding mode.

Compute the best value of sliding surface slope coefficient has played important role to improve system's tracking performance. This problem is solved by tuning the surface slope coefficient ($\boldsymbol{\lambda}$) of the sliding mode controller continuously in real-time. To adjust the sliding surface slope coefficient we define $\hat{\boldsymbol{f}}(\boldsymbol{x}|\boldsymbol{\lambda})$ as the fuzzy based tuning.

$$\hat{f}(x|\lambda) = \boldsymbol{\lambda^T}\boldsymbol{\zeta}(\boldsymbol{x}) \tag{50}$$

$$\lambda^{*} = \boldsymbol{arg\ min}\ \left[\left(\boldsymbol{Sup}\left|\hat{f}(x|\lambda) - \boldsymbol{f}(\boldsymbol{x})\right)\right]\right. \tag{51}$$

where λ^T is adjusted by an adaption law and this law is designed to minimize the error's parameters of $\boldsymbol{\lambda}-\boldsymbol{\lambda}^{*}$. Fuzzy-based tuning part is a supervisory controller based on Mamdani's PI fuzzy logic methodology. This controller has two inputs namely; error (e) and integral of error ($\sum e$) and an output namely; gain updating factor(α). Design on-line tuning controller divided into the following steps:

1. **Inputs/outputs**: it has two inputs error and integral of error ($e, \sum e$) and the output name's is sliding surface slope updating factor (α).

2. **linguistic variable**: 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).

   the linguistic variables for integral of error ($\sum e$) are ;Fast Left (FL), Medium Left (ML), Slow Left (SL),Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR).

the linguistic variables for sliding surface slope updating factor (α) are; Zero (ZE), Very Small (VS), Small (S), Small Big (SB), Medium Big (MB), Big (B), and Very Big (VB).

3. **Membership function**: triangular membership function is used in this research.
4. **Fuzzy rule table**: the rule base for sliding surface slope updating is (Table 1):
5. **Defuzzification**: COG method is used to defuzzification:

Table 1. Fuzzy Rule Base for Sliding Surface Slope Updating Factor (α)

e \ ie	FL	ML	SL	Z	SR	MR	FR
NB	VB	VB	VB	B	SB	S	ZE
NM	VB	VB	B	B	MB	S	VS
NS	VB	MB	B	VB	VS	S	VS
Z	S	SB	MB	ZE	MB	SB	S
PS	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
PB	ZE	S	SB	B	VB	VB	VB

This controller consists of two parts: fuzzy logic controller and scaling factor. Fuzzy logic controller is a Mamdani's error base inference system which has error (e) and integral of error $(\sum e)$ as inputs and sliding surface slope updating factor (α) as output. Scaling factor $(k_\alpha \; and \; k_\beta)$ are used to limit error between $[\pm x]$ and integral of error between $[\pm y]$. To normalize the error and integral of error scaling factors are applied $(k_\alpha \; and \; k_\beta)$ to these variables:

$$\boldsymbol{e_n = k_\alpha \times e} \tag{52}$$

$$\boldsymbol{\sum e_n = k_\beta \times \sum e} \tag{53}$$

Finally, fuzzy-based tuning sliding mode controller for multi degrees of freedom actuator with application in surgical robot manipulator calculated by the following equation;

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \end{bmatrix} = \begin{bmatrix} \tau_{1eq} \\ \tau_{2eq} \\ \tau_{3eq} \end{bmatrix} + \begin{bmatrix} \lambda_1 \times \alpha_1 \\ \lambda_2 \times \alpha_2 \\ \lambda_3 \times \alpha_3 \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} sgn \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \tag{54}$$

4. Results

Pure sliding mode controller has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining sliding mode controller and fuzzy-based tuning in a single controller method. This method can improve the system's tracking performance by online tuning method. This method is based on resolve the on line sliding surface slope as well as improve the output performance by tuning the sliding surface slope coefficient. The sliding surface gain $(\boldsymbol{\lambda})$ of this controller is adjusted online depending on the last values of error and integral of error by sliding surface slope updating factor (α). Fuzzy-based tuning sliding mode controller is stable model-based.

Tracking performances: In sliding mode controller; controllers performance are depended on the gain updating factor (K) and sliding surface slope coefficient (λ). These two coefficients are computed by trial and error in PD-SMC. In fuzzy-based tuning sliding mode controller the sliding surface gain is adjusted online depending on the last values of error and integral of error by sliding surface slope updating factor (α). Figure 7 shows tracking performance in fuzzy-based tuning sliding mode controller (Adaptive SMC) and PD-SMC without disturbance for step trajectory.

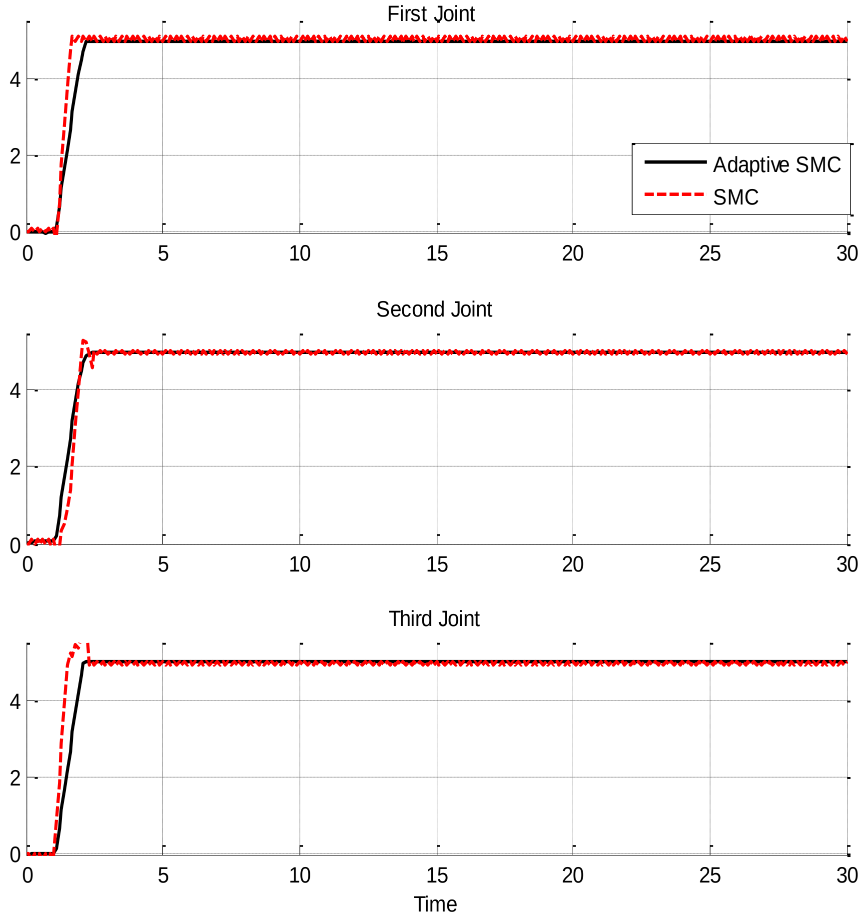

Figure 7. Tracking Performance, Fuzzy-Based Tuning Sliding Mode Controller (Adaptive SMC) and PD-SMC, without Disturbance

Based on Figure 7, the overshoot in Adaptive SMC's is 0% and in PD-SMC's is 1%, and rise time in Adaptive SMC's is 0.6 seconds and in PD-SMC's is 0.483 second. From the trajectory MATLAB simulation for Adaptive SMC and FSMC in certain system, these two controllers have acceptable performance.

Disturbance rejection: Figures 8 shows the power disturbance elimination in adaptive SMC and PD-SMC. The disturbance rejection is used to test the robustness comparisons of these two controllers for step trajectory. A band limited white noise with predefined of 40% the power of input signal value is applied to the step trajectory. It found fairly fluctuations in trajectory responses.

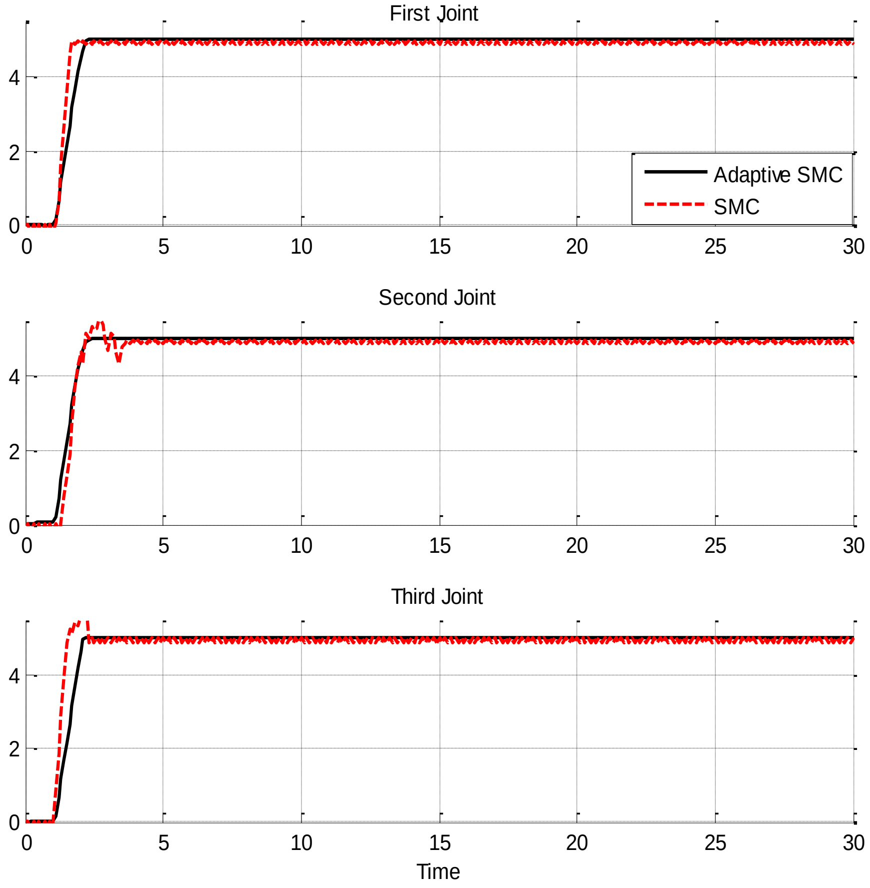

Figure 7. Power Disturbance Elimination in Adaptive SMC and PD-SMC

Based on Figure 7; by comparing step response trajectory with 40% disturbance of relative to the input signal amplitude in adaptive SMC, and PD-SMC, adaptive SMC's overshoot about (0%) is lower than PD-SMC's (**1%). PD-SMC's rise time (0.5 seconds)** is lower than adaptive SMC's **(0.65 second).** Besides the Steady State and RMS error in adaptive SMC, and PD-SMC, error performances in adaptive SMC **(Steady State error =1.08e-12 and RMS error=1.5e-12)** are bout lower than PD-SMC's **(Steady State error=1.6e-6 and RMS error=1.9e-6)**.

5. Conclusion

Refer to this research, a new PI adaptive fuzzy-based tuning sliding mode controller is proposed for three DOF joints with application to surgical robot manipulator. The first problem of the pure sliding mode controller with switching function was chattering phenomenon in certain and uncertain systems, the second challenge was equivalent part and finally the third one is robust limitation. To solve these problems, online tuning method is introduced. Sliding surface gain is adapted on-line by sliding surface slope updating factor. In pure sliding mode controller, the sliding surface gain is chosen by trial and error, which means pure sliding mode controller has to have a prior knowledge of the system uncertainty. If the knowledge is not available error performance and chattering phenomenon are go up. In fuzzy-based tuning sliding mode controller the sliding surface gain are updated on-line to compensate the system unstructured uncertainty. The stability and convergence of the fuzzy-based tuning sliding mode controller based on switching function is guarantee and proved by the Lyapunov method. The simulation results exhibit that the fuzzy-based tuning sliding mode controller works well in various situations. Based on theoretical and simulation results, fuzzy-based tuning sliding mode controller is a best solution to eliminate chattering phenomenon and solve the equivalent challenge in unlimited uncertainty.

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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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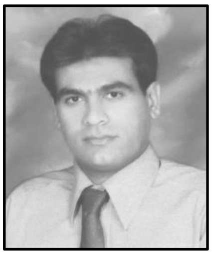

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