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Robust Auto-Intelligent Sliding Accuracy for High Sensitive Surgical Joints

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Abstract

The objective of this paper is to design and coordinate controllers that will enhance transient stability of three dimensions motor subject to large disturbances. Two specific classes of controllers have been investigated, the first one is a type of disturbance signals added to the excitation systems of the generating units. To address a wide range of operating conditions, a nonlinear control design technique, called highly nonlinear computed torque control, is used. While these two types of controllers improve the dynamic performance significantly, a coordination of these controllers is even more promising. Results show that the proposed control technique provides better stability than conventional computed torque fixed gain controllers.

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

1. Introduction

The past two decades have seen the incorporation of robotics into medicine. From a manufacturing perspective, robots have been used in pharmaceuticals, preparing medications. But on more novel levels, robots have been used in service roles, surgery, and prosthetics. The first HelpMate robot went to work in a Danbury hospital in 1988, navigating the hospital wards, delivering supplies and medications, as needed by hospital staff. The capability of high-precision operation in manufacturing settings gave the medical industry high hopes that robots could be used to assist in surgery. Not only are robots capable of much higher precision than a human, they are not susceptible to human factors, such as trembling and sneezing, that are undesirable in the surgery room. In 1990, Robodoc was developed by Dr. William Bargar, an orthopedist, and the late Howard Paul, a veterinarian, of Integrated Surgical Systems, Inc., in conjunction with the University of California at Davis. The device was used to perform a hip replacement on a dog in 1990 and on the first human in 1992, receiving U.S. Food and Drug Administration (FDA) approval soon thereafter. The essence of the procedure is that traditional hip replacements required a surgeon to dig a channel down the patient's femur to allow the replacement hip to be attached, where it is cemented in place. The cement often breaks down over time, requiring a new hip replacement in 10 or 15 years for many patients. Robodoc allows the surgeon to machine a precise channel down the femur, allowing for a tight-fit between replacement hip and femur. No cement is required, allowing the bone to graft itself onto the bone, creating a much stronger and more permanent joint. Another advantage to robots in medicine is the ability to perform surgery with very small incisions, which results in minimal scar tissue, and dramatically reduced recovery times. The popularity of

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these minimally invasive surgical (MIS) procedures has enabled the incorporation of robots in endoscopic surgeries. Endoscopy involves the feeding of a tiny fiber optic camera through a small incision in the patient. The camera allows the surgeon to operate with surgical instruments, also inserted through small incisions, avoiding the trauma of large, open cuts. Endoscopic surgery in the abdominal area is referred to as laparoscopy, which has been used since the late 1980's for surgery on the gall bladder and female organs, among others. Thorascopic surgery is endoscopic surgery inside the chest cavity—lungs, esophagus, and thoracic artery. Robotic surgical systems allow doctors to sit at a console, maneuvering the camera and surgical instruments by moving joysticks, similar to those used in video games. This same remote robotic surgery has been extended to heart surgery as well. In addition to the precision and minimized incisions, the robotic systems have an advantage over the traditional endoscopic procedure in that the robotic surgery is very intuitive. Doctors trained in endoscopic surgery must learn to move in the opposite direction of the image transmitted by the camera, while the robotic systems directly mimic the doctor's movements. As of 2001, the FDA had cleared two robotic endoscopic systems to perform both laparoscopic and thoracoscopic surgeries—the da Vinci Surgical System and the ZEUS Robotic Surgical System. Another medical arena that has shown recent success is prosthetics. Robotic limbs have been developed to replicate natural human movement and return functionality to amputees. One such example is a bionic arm that was developed at the Princess Margaret Rose Hospital in Edinburgh, Scotland, by a team of bioengineers, headed by managing director David Gow. Conjuring up images of the popular 1970's television show "The Six Million Dollar Man," this robotic prosthesis, known as the Edinburgh Modular Arm System (EMAS), was created to replace the right arm from the shoulder down for Campbell Aird, a man whose arm was amputated after finding out he had cancer. The bionic arm was equipped with a motorized shoulder, rotating wrist, movable fingers, and artificial skin. With only several isolated glitches, the EMAS was considered a success, so much so that Aird had taken up a hobby of flying. Another medical frontier in robotics is that of robo-therapy. Research at NASA's Jet Propulsion Laboratory (JPL) and the University of California at Los Angeles (UCLA) has focused on using robots to assist in retraining the central nervous system in paralyzed patients. The therapy originated in Germany, where researchers retrained patients through a very manually intensive process, requiring four or more therapists. The new device would take the place of the manual effort of the therapists with one therapist controlling the robot via hand movements inside a set of gloves equipped with sensors [1-10].

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 [11-12].

- **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.

In medical robot, precision is the main goal. Precision machines vary widely in their design and application but follow several common principles. Machines are generally not accurate by accident but because of the effort taken in design throughout the process. Determinism is a proven machine design philosophy that guides engineers in these developments. Error motions and imperfections in the components used to build precision machines have different effects on the overall performance depending on their location in the system. Some errors are relatively inconsequential; other errors heavily influence the overall performance. One class of errors occurs when an angular error is multiplied by a lever arm into a linear error. These errors, referred to as Abbe errors, should be minimized in all precision machine designs. Applying forces to a machine strains the mechanical elements. These dimensional changes may affect the accuracy of the measurements. Machines should, therefore, be designed such that the load-bearing elements are as separate as possible from the elements used for metrology. Machines are all made of interconnected elements, and the method of connecting these elements affects both the precision of the design and the ease with which it can be analyzed. Exact constraint designs are based on having contact at the minimum number of points necessary to constrain the required degrees-of-freedom of the free part. Elastic-averaging is the opposite and relies on contact over so many points that errors are averaged down to a low level. Problematic designs are those that occur somewhere in the middle of the two extremes. Finally, some often-neglected elements of a precision machine design include cable management, the environment that the system will operate in, analysis of heat generation and flow, and maintenance. To improve the precision, controller design has the main role. Controller is a device which can sense information from linear or nonlinear system (*e.g.*, surgical joints) to improve the systems performance [11-19]. 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.

Computed torque controller (CTC) is an effective nonlinear control methodology for highly nonlinear robot manipulator. The principles of this type of controller are based on feedback linearization and compute the required arm torques. Computed torque controller works based on behavior (dynamic formulation) of robot manipulator which caused to works very well when all dynamic and physical parameters are known. In uncertain dynamic parameters when the robot manipulator has variation computed torque controller has challenges [20]. In most of industrial applications, dynamic parameters of serial links robot manipulators have uncertain parameters or indefinite payload consequently design nonlinear conventional controllers based on dynamic formulation of robot manipulator (*e.g.*, computed torque controller) are the vital challenge. In recent years, much research has been done in the area of computed torque controller for nonlinear systems which has been reported in papers and textbooks [21-26]. Jahed, *et al.*, [14] design fuzzy compensator computed torque controller to compensate the nonlinear part in conventional computed torque controller. In this research fuzzy logic method is applied to pure computed torque controller to increase the result performance. Based on above discussion, the performance of fuzzy computed torque controller increase in presence of uncertainty and external disturbances. Vivas and Mosquera [15] research about comparative study between predictive functional controller and computed torque controller in uncertain environment. Based on this research, in presence of uncertainty predictive strategy gives better result as a performance however these two methods have about the same performance in certain environment. Proportional-Derivative plus gravity is one of the important part of computed torque controller. This type of computed torque controller is used in many applications especially in uncertain systems to eliminate the effect of Gravity. An intelligent base PD plus gravity have been presented for highly nonlinear second order system. This type of controller is applied to highly nonlinear continuum robot manipulator. To reduce or eliminate the challenge of uncertain dynamic parameters switching methodology is applied to fuzzy PD plus gravity controller [16].design adaptive fuzzy computed torque controller is introduce by Chen, *et al.*, [17]. In this research authors design two type adaptive computed torque controller, feed forward and feed-back fuzzy compensator adaptive methodology. Based on this research comparative results exhibit that the two types of adaptive control schemes are effective in improving control performances in terms of modeling uncertainties and external disturbances.

The main goal in this paper is to design a SISO fuzzy highly nonlinear computed torque controller for surgical joints. This method is easy to design and implement to have acceptable safety repose. Surgical joints have 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 computed torque 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:

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

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:

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

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:

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

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;

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

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;

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

So (R_n^0) is given by

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

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

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

B. Computed Torque Control:

Computed torque controller (CTC) is one of the effective nonlinear control methodologies for second order nonlinear system (e.g., robot manipulator). Computed torque controller works based on behavior (dynamic formulation) of system, which caused to works very well when all dynamic and physical parameters are known. In uncertain dynamic parameters when the system has variation computed torque controller has challenges[14]. In this type of controller, if the desired position trajectory for the manipulator defined as $\boldsymbol{q_d(t)}$, and the actual position trajectory defined as $\boldsymbol{q_a(t)}$, the tracking error calculated by;

$$\boldsymbol{e(t) = q_d(t) - q_a(t)} \tag{9}$$

If state space equation is defined by [1, 7];

$$\dot{x} = Ax + BU \tag{10}$$

According to the Brunousky canonical form $\boldsymbol{U}$ is the nonlinearity term and defined by [1, 7];

$$U = \ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{A}^{-1}(\boldsymbol{q}).\{\boldsymbol{N}(\boldsymbol{q}.\dot{\boldsymbol{q}}) - \boldsymbol{\tau}\} \tag{11}$$

$$\dot{\boldsymbol{x}} = \begin{bmatrix} \mathbf{0} & \boldsymbol{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \boldsymbol{x} + \begin{bmatrix} \mathbf{0} \\ \boldsymbol{I} \end{bmatrix} \boldsymbol{U} \tag{12}$$

According to $\boldsymbol{x} = [\boldsymbol{e}^{\boldsymbol{T}}\ \dot{\boldsymbol{e}}^{\boldsymbol{T}}]^{\boldsymbol{T}}$

$$\frac{\boldsymbol{d}}{\boldsymbol{dt}} \begin{bmatrix} \boldsymbol{e} \\ \dot{\boldsymbol{e}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \boldsymbol{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{e} \\ \dot{\boldsymbol{e}} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \boldsymbol{I} \end{bmatrix} \boldsymbol{U} \tag{13}$$

The requirement torque calculated by;

$$\boldsymbol{\tau} = \boldsymbol{A}(\boldsymbol{q})(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{U}) + \boldsymbol{N}(\dot{\boldsymbol{q}}, \boldsymbol{q}) \tag{14}$$

The formulation of PD computed torque controller is [1, 7, 14, and 16];

$$\boldsymbol{\tau} = \boldsymbol{A}(\boldsymbol{q})\left(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{K}_{\boldsymbol{v}}\dot{\boldsymbol{e}} + \boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{e}\right) + \boldsymbol{N}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \tag{15}$$

The PI computed torque controller formulation is;

$$\boldsymbol{\tau} = \boldsymbol{A}(\boldsymbol{q})\left(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{e} + \boldsymbol{K}_{\boldsymbol{i}}\sum \boldsymbol{e}\right) + \boldsymbol{N}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \tag{16}$$

The PID computed torque controller formulation is;

$$\boldsymbol{\tau} = \boldsymbol{A}(\boldsymbol{q})\left(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{e} + \boldsymbol{K}_{\boldsymbol{v}}\dot{\boldsymbol{e}} + \boldsymbol{K}_{\boldsymbol{i}}\sum \boldsymbol{e}\right) + \boldsymbol{N}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \tag{17}$$

Where $\boldsymbol{K}_{\boldsymbol{p}}$, $\boldsymbol{K}_{\boldsymbol{v}}$ and $\boldsymbol{K}_{\boldsymbol{i}}$ are the controller gain coefficients. This type of controller has two main important parts; partly linear part and nonlinear term of dynamic equivalent part.

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;

$$\boldsymbol{A} = \{\boldsymbol{x}, \boldsymbol{\mu}_{\boldsymbol{A}}(\boldsymbol{x}) | \boldsymbol{x} \in \boldsymbol{X}\}; \boldsymbol{A} \in \boldsymbol{U} \tag{18}$$

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

$$\mu_{F(x)} = \begin{cases} \mathbf{0}, & x < a \\ \dfrac{\boldsymbol{x-a}}{\boldsymbol{b-a}}, & a \le x < b \\ \dfrac{\boldsymbol{d-x}}{\boldsymbol{d-c}}, & c \le x < d \\ \mathbf{0}, & x > d \end{cases} \tag{19}$$

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

$$\mu_{F(x)} = \begin{cases} \mathbf{0}, & x < a \\ \dfrac{\boldsymbol{x-a}}{\boldsymbol{b-a}}, & a \le x < b \\ \dfrac{\boldsymbol{c-x}}{\boldsymbol{c-b}}, & b \le x \le c \\ \mathbf{0}, & x > c \end{cases} \tag{20}$$

A Gaussian membership function of fuzzy set is defined by

$$\boldsymbol{\mu_{F(x)} = e^{\frac{-(x-c_F)^2}{W}}} \tag{21}$$

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

$$\boldsymbol{\mu_{F(x)} = \frac{1}{1+(x-c_F)^2}} \tag{22}$$

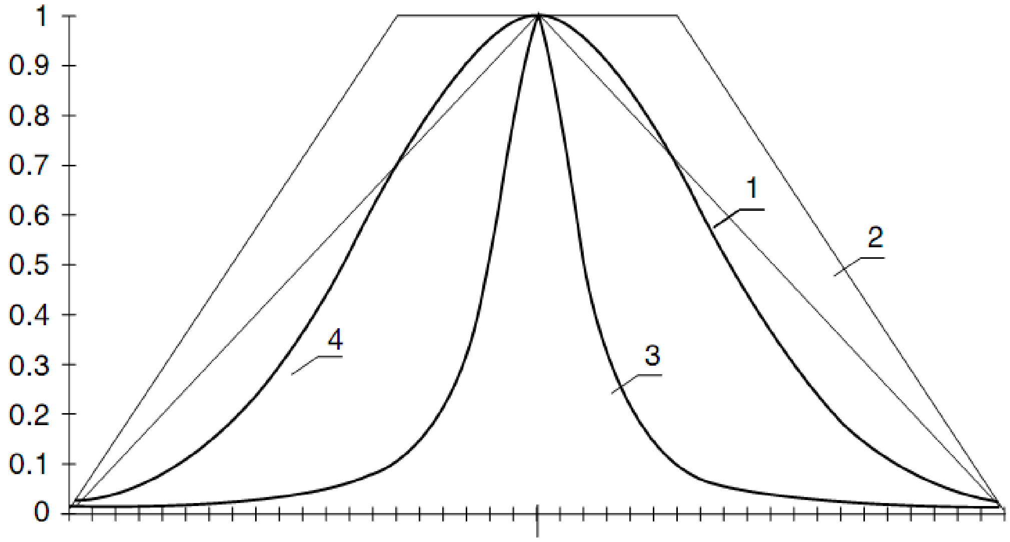

Figure 1. Most Important Membership Functions in Fuzzy Set: 1-Trianglar, 2-Trapezoidal, 3-Gaussian, 4-Bell-shaped

Figure 1 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

$$\boldsymbol{S(a,b) = \mu_{A\cup B(u)} = \max\{\mu_{A(u)}, \mu_{B(u)}\}}, \qquad \forall \boldsymbol{u} \in \boldsymbol{U} \tag{23}$$

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

$$\boldsymbol{T(a,b)=\mu_{A\cap B(u)}=\min\{\mu_{A(u)},\mu_{B(u)}\}=\mu_{A(u)}\cdot\mu_{B(u)}} \tag{24}$$
$$=\boldsymbol{\max(0,\ \mu_{A(u)}+\mu_{B(u)}-1)}=\begin{cases}\boldsymbol{\mu_{A(u)}} & ,\ if\,\boldsymbol{\mu_{B(u)}=1}\\ \boldsymbol{\mu_{B(u)}} & ,\ if\,\boldsymbol{\mu_{A(u)}=1}\\ \boldsymbol{0} & ,\ \boldsymbol{if\mu_{B(u)},\mu_{A(u)}}<1\end{cases}$$

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

$$\boldsymbol{\mu_{A.B(u)}=\mu_{A(u)}\cdot\mu_{B(u)}} \tag{25}$$

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

$$\boldsymbol{\mu_{A\hat{+}B(u)}=\mu_{A(u)}\cdot\mu_{B(u)}-\ \mu_{A(u)}\cdot\mu_{B(u)}} \tag{26}$$

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 2 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

$$\boldsymbol{If\ x\ is\ A\ Then\ y\ is\ B} \tag{27}$$

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:

$$\boldsymbol{if\ e\ is\ NB\ and\ \dot{e}\ is\ ML\ then\ T\ is\ LL} \tag{28}$$

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.

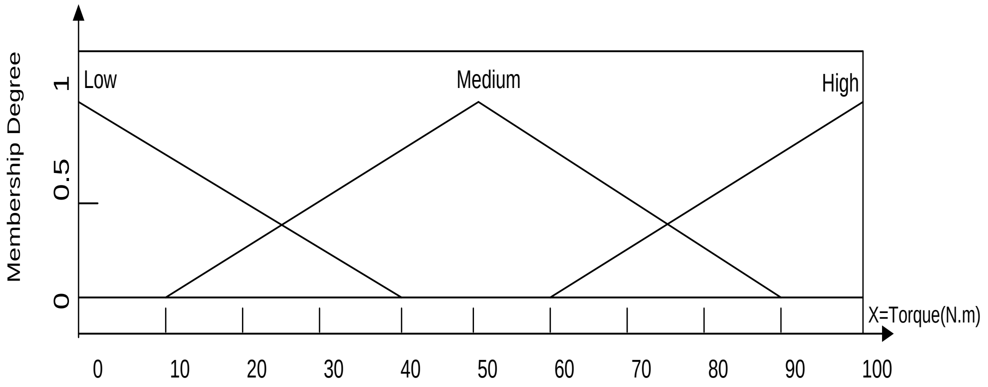

Figure 2. Linguistic Variable and Linguistic Value

$If - then$ 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 3 shows the main three parts in $If - then$ rules.

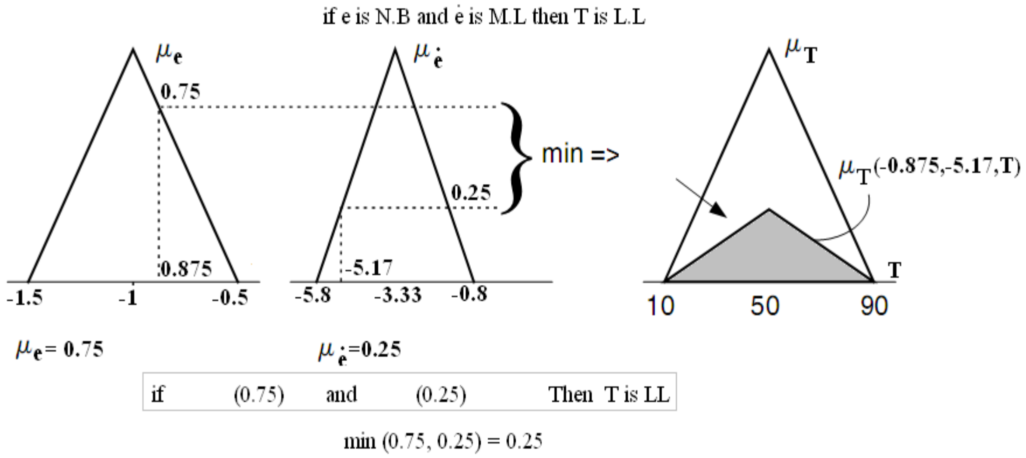

Figure 3. Main Three Parts in IF-THEN Rules in Fuzzy Set

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

$$\begin{array}{llll} \boldsymbol{Mamdani} & \boldsymbol{F.R^1: if} & \boldsymbol{x\ is\ A\ and\ y\ is\ B} & \boldsymbol{then} \quad \boldsymbol{z\ is\ C} \\ \boldsymbol{Sugeno} & \boldsymbol{F.R^1: if} & \boldsymbol{x\ is\ A\ and\ y\ is\ B} & \boldsymbol{then} \quad \boldsymbol{f(x,y) is\ C} \end{array} \quad \textbf{(29)}$$

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

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\bigcup_{i=1}^{r} FR^i}(x_k, y_k, U) = \max\left\{\min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]\right\}} \tag{30}$$

The Sum-min aggregation defined as below

$$\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\bigcup_{i=1}^{r} FR^i}(x_k, y_k, U) = \sum \min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)\right]} \tag{31}$$

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

$$\boldsymbol{COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}} \tag{32}$$

and COA method used the following equation to calculate the defuzzification

$$\boldsymbol{COA(x_k, y_k) = \frac{\sum_i U_i \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \mu_U \cdot (x_k, y_k, U_i)}} \tag{33}$$

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 [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.

3. Methodology

Computed torque controller (CTC) is an influential nonlinear controller to certain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. When all dynamic and physical parameters are known computed torque controller works superbly; practically a large amount of systems have uncertainties and researchers should solve this challenge. To solve this challenge, nonlinear dynamic free equations and fuzzy logic theory are introduced. If the conventional CTC is:

$$\boldsymbol{\tau = A(q)\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) + N(q,\dot{q})} \tag{34}$$

To improve the robustness nonlinear formulation used in linear part

$$\boldsymbol{U = \frac{S^2 + K_1.S + K_2}{K_3.S + K_4}} \tag{35}$$

$$\boldsymbol{\tau = A(q)\left(\ddot{q}_d + \frac{S^2 + K_1.S + K_2}{K_3.S + K_4}\right) + N(q,\dot{q})} \tag{36}$$

These changes in CTC caused improve stability and robustness. To show this controller is stable and achieves zero steady state error, the Lyapunov function is introduced;

$$V = \frac{1}{2}\,[\dot{q}^T\,A(q)\dot{q} + \,e^T\,K_1 S] = \\ \frac{1}{2}\,\frac{d}{dt}\,[\dot{q}^T\,A\dot{q}] = \dot{q}\,\tau \tag{37}$$

If the conversation energy is written by the following form:

$$\frac{1}{2}\,\frac{d}{dt}\,[\dot{q}^T\,A\dot{q}] = \dot{q}\,\tau$$

Where $(\boldsymbol{\dot{q}\,\tau})$ shows the power inputs from actuator and $\boldsymbol{\frac{1}{2}\,\frac{d}{dt}\,[\dot{q}^T\,A\dot{q}]}$ is the derivative of the robot kinematic energy.

$$\dot{V} = \,\dot{q}^T[\,\tau + K_1 S] \tag{38}$$

Based on $\boldsymbol{\tau = A(q)\left(\ddot{q}_d + \frac{S^2+K_1.S+K_2}{K_3.S+K_4}\right)}$**,** we can write:

$$\dot{V} = \,\dot{q}^T\,K_1\dot{q}\;\le 0 \tag{39}$$

If $\boldsymbol{\dot{V} = 0}$, we have

$$\dot{q} = 0\;\rightarrow \ddot{q} = 0\;\rightarrow\;\ddot{q} = A^{-1}K_1 S\;\rightarrow S = 0 \tag{40}$$

In this state, the actual trajectories converge to the desired state.

To solve the challenge of dynamic base controller, fuzzy logic algorithm is introduced. In this controller; PD-Mamdani's fuzzy inference system has considered with totally 25 rules.

$$\boldsymbol{\hat{\tau} = \tau_{eq_{fuzzy}} + \tau_{cont}} \tag{41}$$

Based on fuzzy logic methodology

$$\boldsymbol{f(x) = U_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x)} \tag{42}$$

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

$$\boldsymbol{\zeta(x) = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)}} \tag{43}$$

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

$$\boldsymbol{\tau_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = N(q, \dot{q})} \tag{44}$$

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.

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:

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

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

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

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:

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

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

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:

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

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

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

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

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

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

e $\dot{e}$	***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.

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

Table 2. Lookup Table in PD Like Fuzzy Logic Controller

e → $\dot{e}$ ↓	***-0.1***	***-0.08***	***-0.06***	***-0.04***	***-0.02***	***0***	***0.02***	***0.04***	***0.06***	***0.08***	***1***
-1	1.34	1.32	1.31	1.3	1.28	1.25	1.04	0.88	0.62	0.291	0
0.8	1.33	1.32	1.31	1.2	1.27	1.24	1.03	0.877	0.61	0.291	0
-0.6	1.31	1.12	0.923	0.888	0.635	0.619	0.464	0.222	0.1	-0.11	-0.3
-0.4	1.31	1.05	0.88	0.695	0.441	0.3	0.109	-0.074	-0.223	-0.8	-0.62
-0.2	1.28	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	1.28	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, two types of controller are compared, namely; computed torque controller and proposed (intelligent highly nonlinear computed torque) controller. These three types of controller are tested in certain and uncertain situation.

Comparison of the Tracking Data and Information: the accuracy of data tracking for conventional computed torque controller and proposed controller are compared in this section. According to Figure 4, conventional CTC has the better rise time in data tracking. Regarding to Figure 4, both controller have about the same accuracy. In error point of view, proposed control technique is better than computed torque controller.

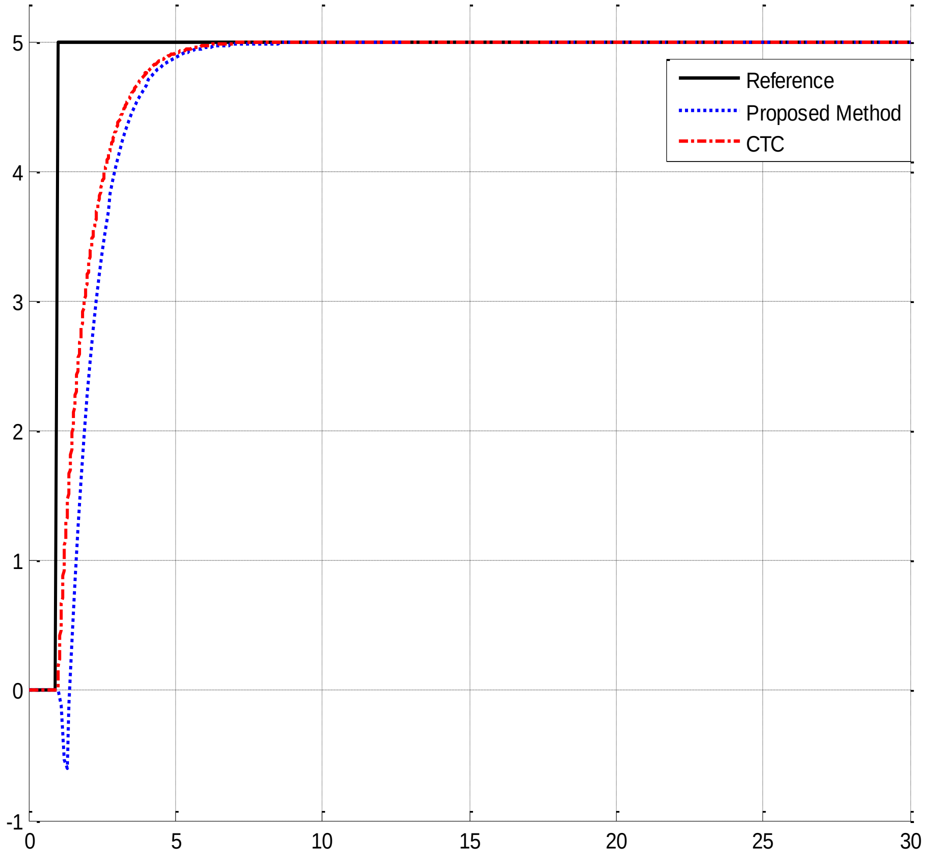

Figure 4. Tracking Data: Proposed Method and CTC

Comparison the Actuation Torque(τ_i): the control input, forces the three dimensions joint to track the desired trajectories. Figure 5 shows the torque performance in conventional sliding computed torque controller and proposed controller. According to the following graph, computed torque controller has fluctuation in torque energy. In the control forces, smaller amplitude means less energy. According to Figure 5, the amplitude of the control forces in CTC controller is much larger than proposed method. Therefore, proposed methods require less energy than the CTC controller.

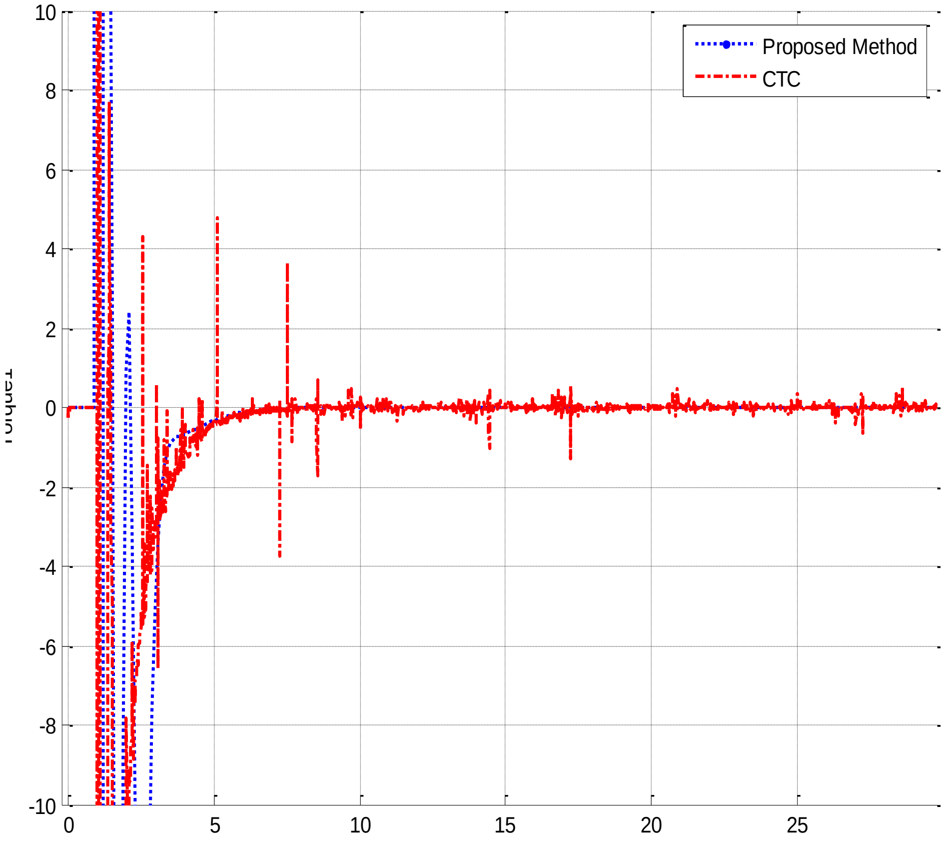

Figure 5. Torque Performance: Conventional CTC and Proposed Method

Robustness: the power of disturbance rejection is very important to robust checking in any controllers. In this section trajectory accuracy, and torque performances are test under uncertainty condition. To test the disturbance rejection band limited white noise with 30% amplitude is applied to conventional computed torque controller and proposed method. In Figures 6 and 7, data accuracy and torque performance are shown. According to the following graph, however proposed controller increase the rise-time in presence of uncertainty but it is more robust than computed torque controller. Computed torque controller has very much fluctuations in presence of external disturbance.

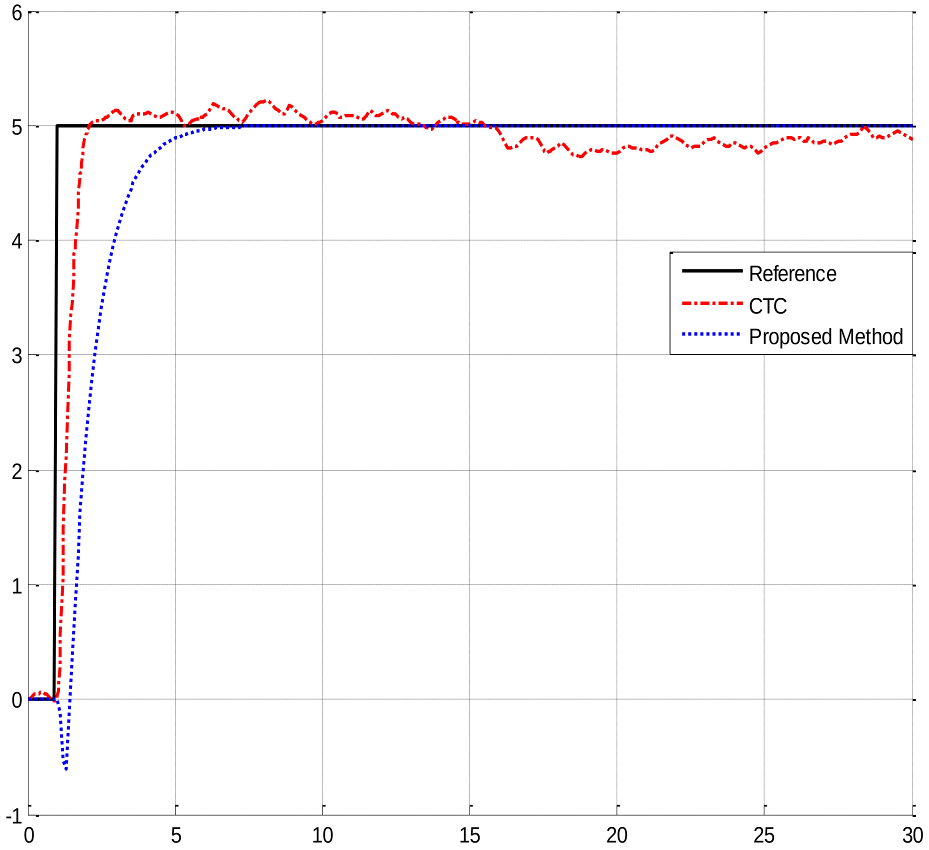

Figure 6. Tracking Data: Conventional CTC and Proposed Controller in Presence of Uncertainty

Figure 7 shows the torque performance in presence of uncertainty. According to above graph, however proposed controller has transient fluctuations but it is more stable than CTC in presence of uncertainties. After applied uncertainties the force amplitude in CTC is increased which will lead to high energy consumption.

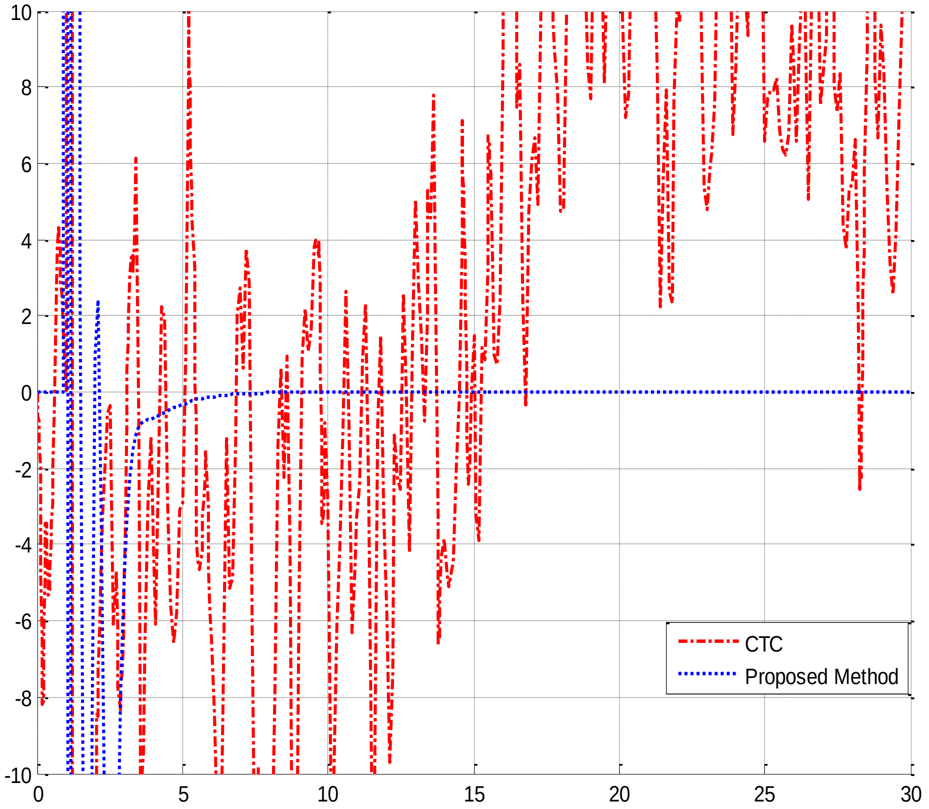

Figure 7. Torque Performance: Conventional CTC and Proposed Controller in Presence of Uncertainty

5. Conclusion

Refer to this research, a new intelligent highly nonlinear computed torque controller is proposed for three DOF joints with application to surgical robot manipulator. The main problem of the pure computed torque controller was stability and robustness in certain and uncertain systems, the second challenge was equivalent part. To solve these problems, intelligent nonlinear CTC is introduced. The nonlinear function is used to improve the stability and robust of CTC. The fuzzy logic theory improves the controller dynamic dependence and caused to improve the robustness as well stability and improve the flexibility. According to result, the systems performance improve and the performances are enough accurate for surgical joints.

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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.

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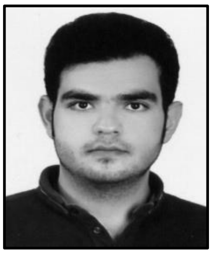
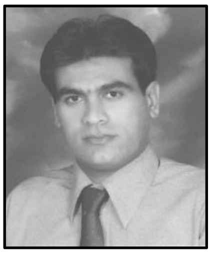


Mohammad Hadi Mazloom, He is currently research assistant at Institute of Advanced Science and Technology, Research Center, IRAN SSP. He is research assistant of team (8 researchers) to design a Micro-electronic Based nonlinear controller for first order delay system since Jan, 2015 to now, research student (21 researchers) to design high precision and fast dynamic controller for multi-degrees of freedom actuator since 2014 to date, and published 3 journal papers since 2014 to date. His current research interests are nonlinear control, artificial control system, Microelectronic Device, and HDL design.

Farzin Piltan, He is an outstanding scientist in the field of Electronics and Control engineering with expertise in the areas of nonlinear systems, robotics, and microelectronic control. Mr. Piltan is an advanced degree holder in his field. Currently, Mr. Piltan is the Head of Mechatronics, Intelligent System, and Robotics Laboratory at the Iranian Institute of Advanced Science and Technology (IRAN SSP). Mr. Piltan led several high impact projects involving more than 150 researchers from countries around the world including Iran, Finland, Italy, Germany, South Korea, Australia, and the United States. Mr. Piltan has authored or co-authored more than 140 papers in academic journals, conference papers and book chapters. His papers have been cited at least 3900 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. Moreover, Mr. Piltan has peer-reviewed at least 23 manuscripts for respected international journals in his field. Mr. Piltan will also serve as a technical committee member of the upcoming EECSI 2015 Conference in Indonesia. Mr. Piltan has served as an editorial board member or journal reviewer of several international journals in his field as follows: International Journal Of Control And Automation (IJCA), Australia, ISSN: 2005-4297, International Journal of Intelligent System and Applications (IJISA), Hong Kong, ISSN:2074-9058, IAES International Journal Of Robotics And Automation, Malaysia, ISSN:2089-4856, International Journal of Reconfigurable and Embedded Systems, Malaysia, ISSN:2089-4864.

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.



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.

Mohammad Reza Avazpour, He is currently research assistant at Institute of Advanced Science and Technology, Research Center, IRAN SSP. He is research assistant of team (8 researchers) to design a Micro-electronic Based nonlinear controller for first order delay system since Jan, 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, and published 3 journal papers since 2014 to date. His current research interests are nonlinear control, artificial control system, Microelectronic Device, and HDL design.

Hootan Ghiasi, He is currently research assistant at Institute of Advanced Science and Technology, Research Center, IRAN SSP. He is research assistant of team (8 researchers) to design a Micro-electronic Based nonlinear controller for first order delay system since Jan, 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, and published 3 journal papers since 2014 to date. His current research interests are nonlinear control, artificial control system, Microelectronic Device, and HDL Design.

Nasri Sulaiman, He is a Senior Lecturer in the Department Electrical and Electronic Engineering at the Universiti Purta Malaysia (UPM), which is one of the leading research universities in Malaysia. He is a supervisor and senior researcher at research and training center called, Iranian Institute of Advanced Science and technology (Iranssp) since 2012. He obtained his M.Sc. from the University of Southampton (UK), and Ph.D. in Microelectronics from the University of Edinburgh (UK). He has published more than 80 technical papers related to control and system engineering, including several co-authored papers with Mr. Piltan. He has been invited to present his research at numerous national and international conferences. He has supervised many graduate students at doctoral and masters level. He is an outstanding scientist in the field of Micro-Electronics.

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)