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Intelligent Precision Improvement on Robot Assisted Minimally Invasive Direct Coronary Artery Bypass

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Abstract

Robot-assisted MIDCAB and Endoscopic coronary artery bypass (TECAB) operations are being performed with the DaVinci system. In this paper, we propose an adaptive feedback linearization control scheme (AFC) for continuous-time,multiple input-multipleoutput (MIMO) linear time-varying uncertain robotic system. The AFC consists of a fuzzy controller with adaptivemechanism to reconstruct the system states using the trackingerror and to make the state error reach the equilibrium point ina finite time period quickly. The sliding surface is first employedto represent the state error to reach the equilibrium point ina finite time period using adaptive theory. Then, a fuzzy controller usingsliding surface is developed to achieve the feedback linearization control performanceand the state tracking errors performance quickly. The reachingmode of the uncertain system using the proposed fuzzy sliding surface adaptive feedback linearization controller is guaranteed.Moreover,thechatteringaround the slidingsurface for the proposedcontrolcan bereduced.This method has an acceptable accuracy regarding to three nonlinear method; sliding surface technique, fuzzy logic and feedback linearization method. Therefore it can guarantee the performance of multi degrees of freedom joint in robot-assisted MIDCAB.

***Keywords**: Robot-assisted MIDCAB, Endoscopic coronary artery bypass (TECAB), Multi-degrees of freedom joints, computed torque control, fuzzy logic theory, spherical motor, robustness, stability*

1. Introduction and Background

Minimally Invasive Direct Coronary Artery Bypass (MIDCAB) is a surgical treatment for coronary heart disease that is a less invasive method of coronary artery bypass surgery (CABG). MIDCAB gains surgical access to the heart with a smaller incision than other types of CABG. Robotic surgery is used to reject the human error in by-pass surgery to improve the surgery performance. In these types of robots multi degrees of freedom joints has a main role.

Multi-degrees-of-freedom (DOF) actuators are wide used in a number of Industries. Currently, a significant number of the existing robotic actuators that can realize multi-DOF motion are constructed using gear and linkages to connect several single-DOF motors in series and/or parallel. Not only do such actuators tend to be large in size and mass, but they also have a decreased positioning accuracy due to mechanical deformation, friction and backlash of the gears and linkages. A number of these systems also exhibit singularities in their workspaces, which makes it virtually impossible to obtain uniform, high-speed, and high-precision motion. For high precession trajectory planning and control, it is necessary to replace the actuator system made up of several single-DOF motors connected in series and/or parallel with a single multi-DOF actuator. The need for such systems has motivated years of research in the development of unusual, yet high

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performance actuators that have the potential to realize multi-DOF motion in a single joint. One such actuator is the spherical motor. Compared to conventional robotic manipulators that offer the same motion capabilities, the spherical motor possesses several advantages. Not only can the motor combine 3-DOF motion in a single joint, it has a large range of motion with no singularities in its workspace. The spherical motor is much simpler and more compact in design than most multiple single-axis robotic manipulators. The motor is also relatively easy to manufacture. The spherical motor have potential contributions to a wide range of applications such as coordinate measuring, object tracking, material handling, automated assembling, welding, and laser cutting. All these applications require high precision motion and fast dynamic response, which the spherical motor is capable of delivering. Previous research efforts on the spherical motor have demonstrated most of these features. These, however, come with a number of challenges. The spherical motor exhibits coupled, nonlinear and very complex dynamics. The design and implementation of feedback controllers for the motor are complicated by these dynamics. The orientation-varying torque generated by the spherical motor further complicates the controller design. Some of these challenges have been the focus of previous and ongoing research [1-7]. High accuracy position control of multi degrees of freedom joints is the main challenge in this research in this research. According to the control theory, systems' controls are divided into two main groups: linear control theory and nonlinear control theory. However linear controller is used to control of linear and nonlinear systems but it cannot guarantee the stability and robust especially in uncertain condition. To solve this challenge nonlinear control theory is recommended. In nonlinear control theory, the dynamic formulation is nonlinear and can reduce the coupling effect between each joint in multi degrees of freedom joints. Nonlinear control theoriesare divided into two main groups: conventional nonlinear control theory and soft computing control theory. The most important conventional nonlinear controllers are; Sliding mode controller, Feedback linearization controller, Backstepping controller and Lyapunov based controller. In this research the main control theory is feedback linearization controller and sliding surface technique is used to online tuning. Soft computing nonlinear control theories are work based on intelligent theory and fuzzy logic theory, neural network, neuro fuzzy, and algorithm genetic are the main soft computing control technique. In this research fuzzy logic theory used as an adaptive modify sliding surface [8-11].

One of the most important nonlinear safety controllers is feedback linearization methodology which is used in nonlinear certain systems. This methodology is used in wide range areas such as control access process, aerospace applications and in robotics. Even though, this methodology is used in wide range areas but pure feedback linearization method has an important drawbacks beside uncertain system and in presence of external disturbance. To solve uncertainty challenges in feedback linearization methodology different researchers have different methodology such as artificial intelligence. In this research, sliding surface theory is used to improve the robustness in feedback linearization theory. Sliding surface theory is part of sliding mode controller. Sliding mode controller (SMC) is a significant nonlinear controller under condition of partly uncertain dynamic parameters of system. This controller is used to control of highly nonlinear systems especially for robot manipulators, because this controller is a robust and stable. This controller has two main parts: sliding surface and equivalent part. However, this controller is more robust than feedback linearization method but it has an important drawback (chattering). Sliding surface part has high-speed response in uncertain condition. To improve sliding surface technique fuzzy logic theory is introduced. Although the fuzzy-logic control is not a new technique, its application in this current research is considered to be novel since it aimed for an automated dynamic-less response rather than for the traditional objective of uncertainties compensation[12-13]. The intelligent tracking control using the fuzzy-logic technique provides a cost-and-time efficient control implementation due to the automated dynamic-less input. This in turn would further inspire multi-uncertainties testing for 3-D motor [11-16].

In this research, the new technique of computed torque controller is recommended, namely, sliding surface-fuzzy computed torque controller. To modify the response of this controller, on-line tuning fuzzy sliding surfacetechnique is recommended.

This paper is organized as follows; section 2, is served as an introduction to the dynamic of spherical motor, sliding mode controller, fuzzy logic theory and feedback linearization method. Part 3 focuses on the design proposed methodology. Section 4 presents the simulation results and discussion of this algorithm applied to a spherical motor and the final section describe the conclusion.

2. Theory and Background

Dynamic and Kinematics Formulation of Spherical Motor: 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[1-10]. Spherical motor is nonlinear and uncertain dynamic parameters and it is 3 degrees of freedom (DOF) electrical motor.

The equation of a spherical motor governed by the following equation [1-10]:

$$\boldsymbol{H}(\boldsymbol{q})\begin{bmatrix}\ddot{\alpha}\\ \ddot{\beta}\\ \ddot{\gamma}\end{bmatrix}+\mathbf{B}(\boldsymbol{q})\begin{bmatrix}\dot{\alpha}\dot{\beta}\\ \dot{\alpha}\dot{\gamma}\\ \dot{\beta}\dot{\gamma}\end{bmatrix}+\boldsymbol{C}(\boldsymbol{q})\begin{bmatrix}\dot{\alpha}^2\\ \dot{\beta}^2\\ \dot{\gamma}^2\end{bmatrix}=\begin{bmatrix}\tau_x\\ \tau_y\\ \tau_z\end{bmatrix} \tag{1}$$

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 variableq_i, independently of the motion of the other parts. Therefore, the angular acceleration is found as to be [1-11]:

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

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 [1].

According to the forward kinematics formulation;

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

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}.
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;

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

Where $U_{i(\theta_i)}$ is given by the following equation [1-11];

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

and$\mathrm{V}_{\mathrm{i}(\alpha_\mathrm{i})}$ is given by the following equation [1-11];

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

So (R_n^0) is given by [8]

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

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

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

Feedback Linearization Control Technique: Computed torque controller (CTC) is a powerful nonlinear controller which it widely used in control of robot manipulator. It is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. This controller works very well when all dynamic and physical parameters are known. In practical application, most of physical systems (e.g., robot manipulators) parameters are unknown or time variant, therefore, computed torque like controller used to compensate dynamic equation of robot manipulator[16]. The central idea of Computed torque controller (CTC) is feedback linearization so, originally this algorithm is called feedback linearization controller. It has assumed that the desired motion trajectory for the manipulator$\boldsymbol{q_d(t)}$, as determined, by a path planner. Defines the tracking error as:

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

Where $e(t)$ is error of the plant, $q_d(t)$ is desired input variable, that in our system is desired displacement, $q_a(t)$ is actual displacement. If an alternative linear state-space equation in the form $\dot{x} = Ax + BU$ can be defined as

$$\dot{\boldsymbol{x}} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \boldsymbol{x} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{I} \end{bmatrix} \boldsymbol{U} \tag{10}$$

With $U = -H^{-1}(q).N(q,\dot{q}) + H^{-1}(q).\tau$ and this is known as the Brunousky canonical form. By equation (9) and (10) the Brunousky canonical form can be written in terms of the state $x = [e^T \dot{e}^T]^T$ as [1]:

$$\frac{\boldsymbol{d}}{\boldsymbol{dt}} \begin{bmatrix} \boldsymbol{e} \\ \dot{\boldsymbol{e}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{e} \\ \dot{\boldsymbol{e}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{I} \end{bmatrix} \boldsymbol{U} \tag{11}$$

With

$$\boldsymbol{U} = \ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{H^{-1}(q)}.\{\boldsymbol{N(q.\dot{q}) - \tau}\} \tag{12}$$

Then compute the required arm torques using inverse of equation (12), is;

$$\boldsymbol{\tau = H(q)(\ddot{q}_d - U) + N(\dot{q}, q)} \tag{13}$$

This is a nonlinear feedback control law that guarantees tracking of desired trajectory. Selecting proportional-plus-derivative (PD) feedback for U(t) results in the PD-computed torque controller [16];

$$\boldsymbol{\tau = H(q)\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) + N(q, \dot{q})} \tag{14}$$

and the resulting linear error dynamics are

$$\boldsymbol{\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) = 0} \tag{15}$$

Sliding Mode Controller: Sliding mode controller (SMC) is a powerful nonlinear controller which has been analyzed by many researchers especially in recent years. 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. Sliding mode control theory for control of robot manipulator used to solve the set point problem ($\boldsymbol{\dot{q}_d = 0}$) by discontinuous method (sliding surface) in the following form [12-14];

$$\boldsymbol{\tau_{(q,t)}} = \begin{cases} \boldsymbol{\tau_i^+(q,t) if S_i} > 0 \\ \boldsymbol{\tau_i^-(q,t) if S_i} < 0 \end{cases} \tag{16}$$

where$\boldsymbol{S_i}$ is sliding surface (switching surface), $\boldsymbol{i = 1, 2, \ldots\ldots, n}$ for n-DOF robot manipulator, $\boldsymbol{\tau_i(q,t)}$ is the $\boldsymbol{i^{th}}$ torque of joint. Sliding mode controller is divided into two main sub controllers: discontinues controller($\boldsymbol{\tau_{dis}}$) / sliding surface part and equivalent controller($\boldsymbol{\tau_{eq}}$). Discontinues controller/sliding surface technique causes an acceptable tracking performance at the expense of very fast switching. However this part of theory can improve the stability and robustness but caused to high frequency oscillations. High frequency oscillation can causes some problems such as saturation and heat the mechanical parts of robot manipulators or drivers.A time-varying sliding surface $s(x,t)$ in the state space $R^n$is given by [15]:

$$\boldsymbol{s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\tilde{x} = 0} \tag{17}$$

where λ is the positive constant. The main target in this methodology is kept the sliding surface slope $\boldsymbol{s(x,t)}$ near to the zero. Therefore, one of the common strategies is to find input $\boldsymbol{U}$ outside of $(\boldsymbol{x,t})$**.**

$$\boldsymbol{\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)|} \tag{18}$$

whereζ is positive constant.

$$\text{If}\ \ \mathbf{S(0)>0} \rightarrow \frac{\mathbf{d}}{\mathbf{dt}}\mathbf{S(t)} \le -\boldsymbol{\zeta} \tag{19}$$

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

$$\boldsymbol{\int_{t=0}^{t=t_{reach}} \frac{d}{dt}S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S\,(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0)} \tag{20}$$

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

$$\boldsymbol{0 - S(0) \le -\eta(t_{reach}) \rightarrow t_{reach} \le \frac{S(0)}{\zeta}} \tag{21}$$

and

$$\boldsymbol{ifS(0)} < 0 \rightarrow 0 - S(\boldsymbol{0}) \le \boldsymbol{-\eta(t_{reach}) \rightarrow S(0) \le -\zeta(t_{reach}) \rightarrow t_{reach} \le \frac{|S(0)|}{\eta}} \tag{22}$$

Equation (21) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$since the trajectories are outside of $S(t)$.

$$\boldsymbol{ifS_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0} \tag{23}$$

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

$$\boldsymbol{U_{dis} = \hat{U} - K(\vec{x},t) \cdot \mathbf{sgn}(s)} \tag{24}$$

where the switching function $\mathbf{sgn}(\mathbf{S})$ is defined as

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

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

Fuzzy Logic Theory: 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;

$$\boldsymbol{A} = \{\boldsymbol{x}, \boldsymbol{\mu_A}(\boldsymbol{x}) | \boldsymbol{x} \in \boldsymbol{X}\}; \boldsymbol{A} \in \boldsymbol{U} \quad \mathbf{(26)}$$

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.

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.

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

$$\boldsymbol{IfxisAThenyisB} \quad \mathbf{(27)}$$

where$A$ and B are the Linguistic values that can be defined by fuzzy set, the $If - part$ of the part of *"$xisA$"* is called the antecedent part and the $then - part$ of the part of *"$yisB$"* 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 [12-15]:

$$\boldsymbol{ifeisNBand\dot{e}isMLthenTisLL} \quad \mathbf{(28)}$$

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. $If - then$ 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. 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. MichioSugenouse a singleton as a membership function of the rule consequent part. The following definition shows the Mamdani and Sugeno fuzzy rule base

$$\begin{gathered} \boldsymbol{MamdaniF.R^1: ifxisAandyisBthenzisC} \\ \boldsymbol{SugenoF.R^1: ifxisAandyisBthenf(x,y)isC} \end{gathered} \tag{29}$$

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 [14-16]

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

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

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

andCOA 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. However, the application area for fuzzy control is 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).

3. Methodology

Conventional feedback linearization controller (FC) is a type of nonlinear, stable, and reliable controller. However, this type of controller is worked in many applications but there are two main issues limiting:robustness and on-line tuning.

To solve the first challenge (robustness), sliding surface technique is recommended in this research.The main challenge to design sliding surface technique based on switching function is high frequency oscillation, which caused to heating and oscillation in mechanical part of system. However switching function is caused to chattering and oscillation but it is the main part to design robust controller. According to defined stability based on Lyaponuv functions, feedback linearization and sliding surface technique are type of stable methods.

In this challenge select the desired sliding surface and $\boldsymbol{sign}$function play a vital role to system performance. In this state, the derivative of sliding surface can help to decoupled and linearized closed-loop system dynamics that one expects in computed torque control. Linearization and decoupling by this technique can be obtained in spite of the quality of the system dynamic model, in contrast to feedback linearization control that requires the exact dynamic model of a system. As a result, uncertainties are estimated by discontinuous feedback control but it can cause to high frequency oscillation. To improve the robustness in feedback linearization technique; robust sliding surface technique is added to feedback linearization controller. Robust sliding surface technique is type of stable controller as well as conventional feedback linearization controller. In this methodology robust PD sliding surfacetechnique is used in parallel with feedback linearization controller to improve the robustness. The formulation of robustfeedback linearization controller is;

$$\boldsymbol{\tau = H(q)\big(\ddot{q}_d + K_v \dot{e} + K_p e\big) + N(q,\dot{q}) + U_{slidingsurface}} \tag{34}$$

The sliding surface part is introduced by $\boldsymbol{\tau_{slidingsurface}}$ and this item is very important to improve the resistance and robustness. The sliding surface calculated as;

$$\boldsymbol{U_{slidingsurface} = K \cdot \mathbf{sgn}(\lambda e + \dot{e})} \tag{35}$$

Assuming that it can be expressed by the following equation:

$$\boldsymbol{S^T\big(\dot{H} - 2N\big)S = 0} \tag{36}$$

and

$$\boldsymbol{\dot{V} = \frac{1}{2} S^T \dot{H} S - S^T N S + S^T(NS - \tau) = S^T\big(H\dot{S} + NS - \tau\big)} \tag{37}$$

$$\boldsymbol{\begin{aligned}\hat{\tau} &= H(q)\big(\ddot{q}_d + K_v \dot{e} + K_p e\big) + N(q,\dot{q}) + U_{slidingsurface} \\ &= \big[H(q)\big(\ddot{q}_d + K_v \dot{e} + K_p e\big)\big] + K.sgn(S)\end{aligned}} \tag{38}$$

$$\dot{V} = S^T(H\dot{S} + NS - \hat{H}\dot{S} - \hat{N}S - Ksgn(S) = S^T\left(\tilde{H}\dot{S} + \tilde{N}S - Ksgn(S)\right) \quad (39)$$

$$\left|\tilde{H}\dot{S} + \tilde{N}S\right| \leq \left|\tilde{H}\dot{S}\right| + \left|\tilde{N}S\right| \quad (40)$$

and

$$K_u = \left[\left|\tilde{H}\dot{S}\right| + |NS| + \eta\right]_i, i = 1, 2, 3, 4, \dots \quad (41)$$

And finally

$$K_u \geq \left|\left[\tilde{H}\dot{S} + NS\right]_i\right| + \eta_i \quad (42)$$

Resulting, the following formulation guaranties the stability and robustness of the robust sliding surface feed-back linearization method.

$$\dot{V} \leq -\sum_{i=1}^{n} \eta_i \, |S_i| \quad (43)$$

Equivalent part of controller is used to eliminate the decoupling and nonlinear term of dynamic parameters of each link. However, equivalent part is very essential to reliability but it can to have challenges in uncertain condition. To solve this challenge adaptive on-line tuning methodology is recommended. Regarding to this design it has two important coefficients: sliding surface slope which is important to robustness and PD coefficients in feedback linearization method. This design focuses on the design on-line tuning for sliding surface slope.

$$\tau_{new} = H(q)\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) + N(q, \dot{q}) + U_{New-slidingsurface} \quad (44)$$

$$U_{slidingsurface-new} = K \cdot \mathbf{sgn}(\lambda_{new} e + \dot{e}) \quad (45)$$

$$\lambda_{new} = \lambda \times \alpha_{on-linefuzzy} \quad (46)$$

$$\alpha_{fuzzy} = (\textstyle\sum_{l=1}^{M} \theta^T \, \zeta(x))_{e,\dot{e}} \quad (47)$$

$$(\tau_{new}) = H(q)(\ddot{q}_d + K_v\dot{e} + K_p e) + N(q, \dot{q}) + K \cdot \mathbf{sgn}\left([\lambda \times (\textstyle\sum_{l=1}^{M} \theta^T \, \zeta(x))_{e,\dot{e}}]e + \dot{e}\right)] \quad (48)$$

To design α_{fuzzy}, error has seven linguisticvariables namely; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB) and change of error has three linguistic variables; Negative (N), Zero (Z) and Positive (P).Therefore, rule table has 21 states.

4. RESULT AND DISCUSSION

Robust sliding surface feedback linearization controller and adaptive robust sliding surface feedback linearization controller are tested to accuracy checking.

Precision checking: the first table (Table 1) shows the comparison between on-line and off-line tuning in certain and uncertain condition. Regarding to control theory, however robust sliding surface technique modify the performance of feedback linearization control but it is limit robust. To improve the robustness in robust sliding surface feedback linearization control online tuning is recommended in this research.

Table 1. Precision Checking

Disturbance	Error	Robust sliding surface FC	Proposed Method
$\tau_d = 0\%$		0.0001	0.0002
$\tau_d = 25\%$		0.12	0.00022

Regarding to Table 1, in certain condition, both of methodology have the same error response but in uncertainty, off-line tuning cannot guarantee the precision. In presence of uncertainty, proposed method has an acceptable disturbance rejection.

Trajectory follow: Figure 1 shows the trajectory following performance in proposed method and sliding surface feedback linearization control. According to this figure and Table 1, these two methods have the same performance. In certain condition, these two methods are stable and robust so it can guarantee an acceptable performance.

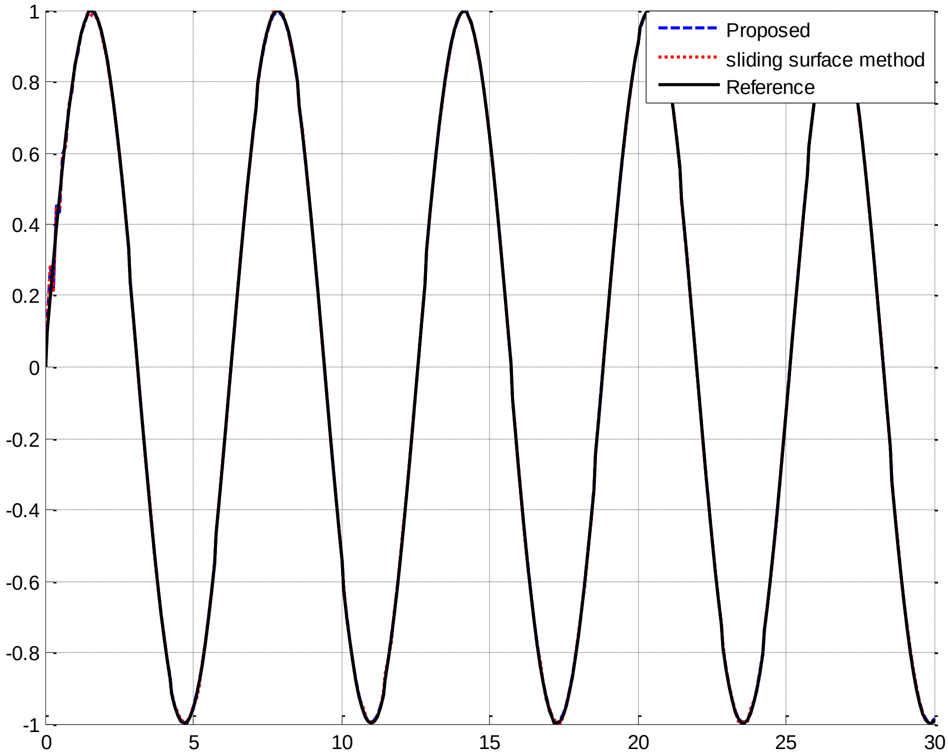

Figure1. Trajectory follows: Fuzzy Hype-plane variable CTC vs. CTC

Disturbance rejection: Figure 2 shows the power disturbance elimination in proposed method and sliding surface feedback linearization controller. Regarding to the following figure online tuning is more powerful than sliding surface FC. However sliding surface

FC is more robust than pure FC but it has fluctuation in presence of uncertainty and external disturbance.

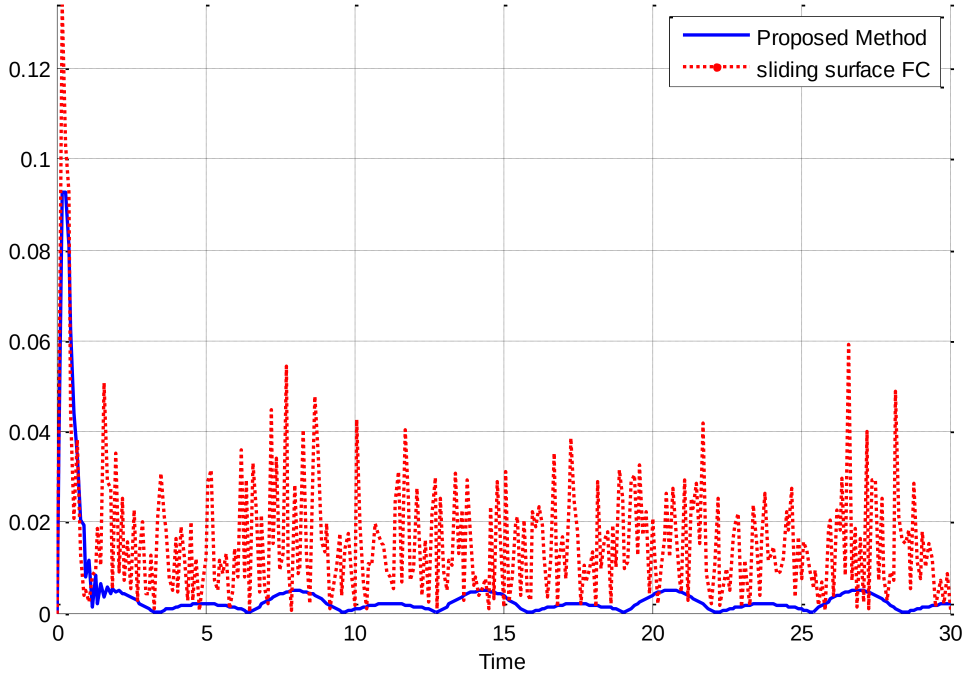

Figure2.Power of Disturbance Rejection: Proposed Method and Sliding Surface Feedback Linearization Control

5. Conclusion

In this research,an adaptive robust sliding surface feedback linearization control is proposed in order to design a high performance robust controller in presence of structure and unstructured uncertainties to control of industrial medical robot. Regarding to this research, feed-back linearization controller has two drawbacks: robustness and on-line tuning. To improve the robustness, switching sliding surface slope is recommended. However, this method could improve the limitation robustness but it has many challenges in presence of higher order uncertainties. Regarding to result when we have 25% disturbance we can see fluctuation in robust sliding surface feedback linearization controller. To improve this challenge on-line tuning sliding surface slope is recommended. The approach improves performance by using the advantages of fuzzy logic theory and adaptive methodology. The proposed controller attenuates the effect of model uncertainties from both structure and unstructured uncertainties.

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- Education unit
- Research and Development unit

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