

Design Minimum Rule-Base Fuzzy Inference Nonlinear Controller for Second Order Nonlinear System

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Abstract—This research is focused on proposed minimum rule base PID computed torque algorithms with application to continuum robot manipulator. The stability of the closed-loop system is proved mathematically based on the Lyapunov method. Classical Computed Torque Controller (CTC) is robust to control model partly uncertainties and external disturbances. This controller is one of the significant nonlinear methodologies; according to the nonlinear dynamic formulation. One of the main targets in this research is increase the robustness based on the artificial intelligence methodology. Classical computed torque control has difficulty in handling unstructured model uncertainties. One can overcome this problem by combining a computed torque controller and artificial intelligence (e.g. fuzzy logic). To approximate a time-varying nonlinear dynamic system, a fuzzy system requires a large amount of fuzzy rule base. This large number of fuzzy rules will cause a high computation load. To reduce the number of rule base this research is focused on the PD like fuzzy plus integral methodology. This method is applied to continuum robot manipulator to have the best performance.

Index Terms— Fuzzy Inference System, Computed Torque Controller, PD Like Fuzzy Theory, Continuum Robot Manipulator

I. INTRODUCTION AND BACKGROUND

The first person who used the word robot was Karel Capek in 1920 in his satirical play, R.U.R (Rossum's Universal Robots). The first person who used the word robotics was the famous author, Issac Asimov along with three fundamental rules. Following World War II, the first industrial robot manipulator have been installation at General Motors in 1962 for the automation. In 1978 the PUMA (Programmable Universal Machine for Assembly) and in 1979 the SCARA (Selective Compliance Assembly Robot Arm) were introduced and they were quickly used in research laboratories and industries. According to the MSN Learning & Research, "700000 robots were in the industrial world in 1995 and over 500000 were used in Japan, about 120000 in Western Europe, and 60000 in the United States [1- 6]." Research

about mechanical parts and control methodologies in robotic system is shown; the mechanical design, type of actuators, and type of systems drive play important roles to have the best performance controller. More over types of kinematics chain, i.e., serial Vs. parallel manipulators, and types of connection between link and joint actuators, i.e., highly geared systems Vs. direct-drive systems are played important roles to select and design the best acceptable performance controllers [7-11]. A serial link continuum robot is a sequence of joints and links which begins with a base frame and ends with an end-effector. This type of robot manipulators, comparing with the load capacitance is more weightily because each link must be supported the weights of all next links and actuators between the present link and end-effector [12-18]. Serial continuum robot manipulators have been used in medical application, and also in research laboratories. One of the most important classifications in controlling the robot manipulator is how the links have connected to the actuators. This classification divides into two main groups: highly geared (e.g., 200 to 1) and direct drive (e.g., 1 to 1). High gear ratios reduce the nonlinear coupling dynamic parameters in robot manipulator. In this case, each joint is modeled the same as SISO systems. In high gear robot manipulators which generally are used in industry, the couplings are modeled as a disturbance for SISO systems. Direct drive increases the coupling of nonlinear dynamic parameters of robot manipulators. This effect should be considered in the design of control systems. As a result some control and robotic researchers' works on nonlinear robust controller design [19-24]. Although most of continuum robot manipulator is high gear but this research focuses on design MIMO controller.

In modern usage, the word of control has many meanings, this word is usually taken to mean regulate, direct or command. The word feedback plays a vital role in the advance engineering and science. The conceptual frame work in Feed-back theory has developed only since world war II. In the twentieth century, there was a rapid growth in the application of feedback controllers in process industries. According to Ogata, to do the first significant work in three-term or PID controllers which Nicholas Minorsky worked on it by automatic controllers in 1922. In 1934, Stefen Black was invention of the feedback amplifiers to develop the negative feedback amplifier [25-40]. Negative feedback invited

communications engineer Harold Black in 1928 and it occurs when the output is subtracted from the input. Automatic control has played an important role in advance science and engineering and its extreme importance in many industrial applications, i.e., aerospace, mechanical engineering and robotic systems. The first significant work in automatic control was James Watt's centrifugal governor for the speed control in motor engine in eighteenth century[41-48]. There are several methods for controlling a robot manipulator, which all of them follow two common goals, namely, hardware/software implementation and acceptable performance. However, the mechanical design of robot manipulator is very important to select the best controller but in general two types schemes can be presented, namely, a joint space control schemes and an operation space control schemes[49-59]. Joint space and operational space control are closed loop controllers which they have been used to provide robustness and rejection of disturbance effect. The main target in joint space controller is to design a feedback controller which the actual motion ($q_a(t)$) and desired motion ($q_d(t)$) as closely as possible. This control problem is classified into two main groups. Firstly, transformation the desired motion $X_d(t)$ to joint variable $q_d(t)$ by inverse kinematics of robot manipulators[34-59]. This control include simple PD control, PID control, inverse dynamic control, Lyapunov-based control, and passivity based control that explained them in the following section. The main target in operational space controller is to design a feedback controller to allow the actual end-effector motion $X_a(t)$ to track the desired endeffector motion $X_d(t)$. This control methodology requires a greater algorithmic complexity and the inverse kinematics used in the feedback control loop. Direct measurement of operational space variables are very expensive that caused to limitation used of this controller in industrial robot manipulators[55-59]. One of the simplest ways to analysis control of multiple DOF robot manipulators are analyzed each joint separately such as SISO systems and design an independent joint controller for each joint. In this controller, inputs only depends on the velocity and displacement of the corresponding joint and the other parameters between joints such as coupling presented by disturbance input. Joint space controller has many advantages such as one type controllers design for all joints with the same formulation, low cost hardware, and simple structure.

A nonlinear methodology is used for nonlinear uncertain systems (e.g., robot manipulators) to have an acceptable performance. These controllers divided into six groups, namely, feedback linearization (computed-torque control), passivity-based control, sliding mode control (variable structure control), artificial intelligence control, lyapunov-based control and adaptive control[1-20]. Computed torque controller (CTC) is a powerful nonlinear controller which it widely used in control of continuum robot manipulator. It is based on feedback linearization and computes the required arm torques by the nonlinear feedback control law. This controller works

very well when all dynamic and physical parameters are known but when the system has variation in dynamic parameters, the controller has no acceptable performance[14]. In practice, most of physical systems (e.g., continuum robot manipulators) parameters are unknown or time variant, therefore, computed torque like controller used to compensate dynamic equation of robot manipulator[15-23]. When all dynamic and physical parameters are known, computed torque controller works fantastically; practically a large amount of systems have uncertainties, therefore fuzzy inference methodology is one of the best case to solve this challenge.

In recent years, artificial intelligence theory has been used in sliding mode control systems. Neural network, fuzzy logic, and neuro-fuzzy are synergically combined with nonlinear classical controller and used in nonlinear, time variant, and uncertainty plant (e.g., robot manipulator). Fuzzy logic controller (FLC) is one of the most important applications of fuzzy logic theory. This controller can be used to control nonlinear, uncertain, and noisy systems. This method is free of some model-based techniques as in classical controllers. As mentioned that fuzzy logic application is not only limited to the modelling of nonlinear systems [31-36]but also this method can help engineers to design easier controller. Control robot arm manipulators using classical controllers are based on manipulator dynamic model. These controllers often have many problems for modelling. Conventional controllers require accurate information of dynamic model of robot manipulator, but these models are multi-input, multi-output and non-linear and calculate accurate model can be very difficult. When the system model is unknown or when it is known but complicated, it is difficult or impossible to use classical mathematics to process this model[32]. The main reasons to use fuzzy logic technology are able to give approximate recommended solution for unclear and complicated systems to easy understanding and flexible. Fuzzy logic provides a method which is able to model a controller for nonlinear plant with a set of IF-THEN rules, or it can identify the control actions and describe them by using fuzzy rules. It should be mentioned that application of fuzzy logic is not limited to a system that's difficult for modeling, but it can be used in clear systems that have complicated mathematics models because most of the time it can be shortened in design but there is no high quality design just sometimes we can find design with high quality. Besides using fuzzy logic in the main controller of a control loop, it can be used to design adaptive control, tuning parameters, working in a parallel with the classical and non classical control method [32-39]. The applications of artificial intelligence such as neural networks and fuzzy logic in modelling and control are significantly growing especially in recent years. For instance, the applications of artificial intelligence, neural networks and fuzzy logic, on robot arm control have reported in [40-59].

This paper is organized as follows; second part focuses on the modeling dynamic formulation based on Lagrange methodology, fuzzy logic methodology and computed

torque methodology. Third part is focused on the methodology which can be used to reduce the error, increase the performance quality and increase the robustness and stability. Simulation result and discussion is illustrated in forth part which based on trajectory following and disturbance rejection. The last part focuses on the conclusion and compare between this method and the other ones.

II. THEORY

DESIGN PID CONTROLLER: Design of a linear methodology to control of flexible robot manipulator was very straight forward. Since there was an output from the

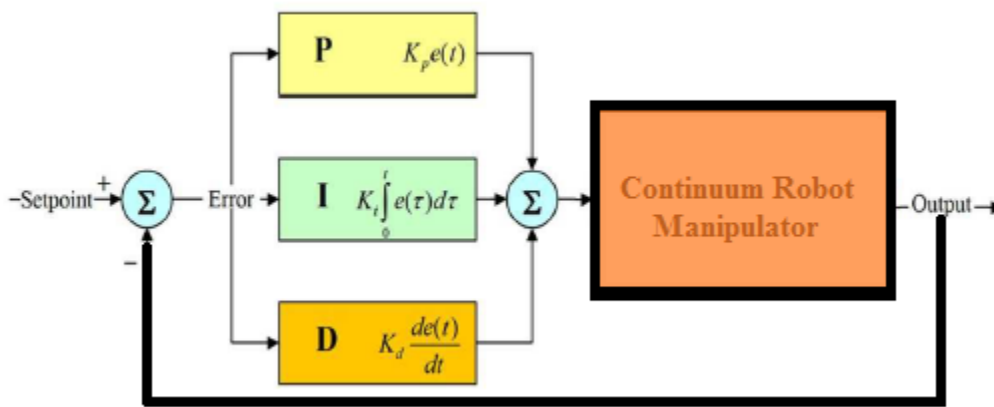


Fig. 1. Block diagram of linear PID method

The model-free control strategy is based on the assumption that the joints of the manipulators are all independent and the system can be decoupled into a group of single-axis control systems [18-23]. Therefore, the kinematic control method always results in a group of individual controllers, each for an active joint of the manipulator. With the independent joint assumption, no a priori knowledge of robot manipulator dynamics is needed in the kinematic controller design, so the complex computation of its dynamics can be avoided and the controller design can be greatly simplified. This is suitable for real-time control applications when powerful processors, which can execute complex algorithms rapidly, are not accessible. However, since joints coupling is neglected, control performance degrades as operating speed increases and a manipulator controlled in this way is only appropriate for relatively slow motion [34-37]. The fast motion requirement results in even higher dynamic coupling between the various robot joints, which cannot be compensated for by a standard robot controller such as PID [36], and hence model-based control becomes the alternative.

COMPUTED TORQUE CONTROL: The central idea of Computed torque controller (CTC) is feedback linearization method therefore, originally this algorithm is called feedback linearization controller. It has assumed that the desired motion trajectory for the

torque model, this means that there would be two inputs into the PID controller. Similarly, the outputs of the controller result from the two control inputs of the torque signal. In a typical PID method, the controller corrects the error between the desired input value and the measured value. Since the actual position is the measured signal. Figure 1 is shown linear PID methodology, applied to flexible robot manipulator [26-34].

$$e(t) = \theta_a(t) - \theta_d(t) \quad (1)$$

$$U_{PID} = K_{p_a} e + K_{v_a} \dot{e} + K_I \int e \quad (2)$$

manipulator $q_d(t)$, as determined, by a path planner. Defines the tracking error as [23-37]:

$$e(t) = q_d(t) - q_a(t) \quad (3)$$

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

$$\dot{x} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ I \end{bmatrix} u \quad (4)$$

With $U = -D^{-1}(q) \cdot N(q, \dot{q}) + D^{-1}(q) \cdot \tau$ and this is known as the Brunousky canonical form. By equation (3) and (4) the Brunousky canonical form can be written in terms of the state $x = [e^T \ \dot{e}^T]^T$ as [11-34]:

$$\frac{d}{dt} \begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} u \quad (5)$$

With

$$U = \ddot{q}_d + D^{-1}(q) \cdot \{N(q, \dot{q}) - \tau\} \quad (6)$$

Then compute the required arm torques using inverse of equation (6), is;

$$\tau = D(q)(\ddot{q}_d - U) + N(\dot{q}, q) \tag{7}$$

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 [8-10];

$$\tau = D(q)(\ddot{q}_d + K_v \dot{e} + K_p e) + N(q, \dot{q}) \tag{8}$$

and the resulting linear error dynamics are

$$(\ddot{q}_d + K_v \dot{e} + K_p e) = 0 \tag{9}$$

According to the linear system theory, convergence of the tracking error to zero is guaranteed [6]. Where K_p and K_v are the controller gains.

FUZZY LOGIC THEORY: Zadeh introduced fuzzy sets in 1965. After 40 years, fuzzy systems have been widely used in different fields, especially on control problems. Fuzzy systems transfer expert knowledge to mathematical models. Fuzzy systems used fuzzy logic to estimate dynamics of our systems. Fuzzy controllers including fuzzy if-then rules are used to control our systems. However the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of:

- Input fuzzification (binary-to-fuzzy[B/F]conversion)
- Fuzzy rule base (knowledge base)
- Inference engine
- Output defuzzification (fuzzy-to-binary [F/B] conversion)[30-40].

Conventional control methods use mathematical models to controls systems. Fuzzy control methods replace the mathematical models with fuzzy if then-rules and fuzzy membership function to controls systems. Both fuzzy and conventional control methods are designed to meet system requirements of stability and convergence. When mathematical models are unknown or partially unknown, fuzzy control models can used fuzzy systems to estimate the unknown models. This is called the model-free approach [31, 35]. Conventional control models can use adaptive control methods to achieve the model-free approach. When system dynamics become more complex, nonlinear systems are difficult to handle by conventional control methods. Fuzzy systems can approximate arbitrary nonlinear systems. In practical problems, systems can be controlled perfectly by expert. Experts provide linguistic description about systems. Conventional control methods cannot design controllers combined with linguistic information. When linguistic information is important for designing controllers, we need to design fuzzy controllers for our systems. Fuzzy control methods are easy to understand for designers. The design process of fuzzy controllers can be simplified with

simple mathematical models. We define fuzzy systems as two different types. The first type of fuzzy systems is given by

$$f(x) = \sum_{l=1}^M \theta^l \varepsilon^l(x) = \theta^T \varepsilon(x) \tag{10}$$

Where $\theta = (\theta^1, \dots, \theta^M)^T$, $\varepsilon(x) = (\varepsilon^1(x), \dots, \varepsilon^M(x))^T$, and $\varepsilon^l(x) = \frac{\mu_{A_i^l}(x_i)}{\sum_{l=1}^M \mu_{A_i^l}(x_i)}$. $\theta^1, \dots, \theta^M$ are adjustable parameters in (10). $\mu_{A_1^1}(x_1), \dots, \mu_{A_n^m}(x_n)$ are given membership functions whose parameters will not change over time.

The second type of fuzzy systems is given by

$$f(x) = \frac{\sum_{l=1}^M \theta^l \left[\prod_{i=1}^n \exp\left(-\left(\frac{x_i - \alpha_i^l}{\delta_i^l}\right)^2\right) \right]}{\sum_{l=1}^M \left[\prod_{i=1}^n \exp\left(-\left(\frac{x_i - \alpha_i^l}{\delta_i^l}\right)^2\right) \right]} \tag{11}$$

Where θ^l , α_i^l and δ_i^l are all adjustable parameters.

From the universal approximation theorem, we know that we can find a fuzzy system to estimate any continuous function. For the first type of fuzzy systems, we can only adjust θ^l in (10). We define $f^\wedge(x|\theta)$ as the approximator of the real function $f(x)$.

$$f^\wedge(x|\theta) = \theta^T \varepsilon(x) \tag{12}$$

We define θ^* as the values for the minimum error:

$$\theta^* = \arg \min_{\theta \in \Omega} \left[\sup_{x \in U} |f^\wedge(x|\theta) - g(x)| \right] \tag{13}$$

Where Ω is a constraint set for θ . For specific x , $\sup_{x \in U} |f^\wedge(x|\theta^*) - f(x)|$ is the minimum approximation error we can get.

We used the first type of fuzzy systems (10) to estimate the nonlinear system (15) the fuzzy formulation can be write as below;

$$f(x|\theta) = \frac{\theta^T \varepsilon(x)}{\sum_{l=1}^n \theta^l [\mu_{A^l}(x)]} = \frac{\sum_{l=1}^n \theta^l [\mu_{A^l}(x)]}{\sum_{l=1}^n [\mu_{A^l}(x)]} \tag{14}$$

Where $\theta^1, \dots, \theta^n$ are adjusted by an adaptation law. The adaptation law is designed to minimize the parameter errors of $\theta - \theta^*$.

DYNAMIC FORMULATION OF CONTINUUM ROBOT:

The Continuum section analytical model developed here consists of three modules stacked together in series. In general, the model will be a more precise replication of

the behavior of a continuum arm with a greater of modules included in series. However, we will show that three modules effectively represent the dynamic behavior of the hardware, so more complex models are not motivated. Thus, the constant curvature bend exhibited by the section is incorporated inherently within the model. The model resulting from the application of Lagrange's equations of motion obtained for this system can be represented in the form

$$F_{coeff} \underline{\tau} = D(\underline{q}) \underline{\ddot{q}} + C(\underline{q}) \underline{\dot{q}} + G(\underline{q}) \quad (15)$$

where τ is a vector of input forces and q is a vector of generalized co-ordinates. The force coefficient matrix

$$F_{coeff} = \begin{bmatrix} 1 & 1 & \cos(\theta_1) & \cos(\theta_1) & \cos(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \\ 0 & 0 & 1 & 1 & \cos(\theta_2) & \cos(\theta_2) \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 1/2 & -1/2 & 1/2 & -1/2 & 1/2 + s_2 \sin(\theta_2) & -1/2 + s_2 \sin(\theta_2) \\ 0 & 0 & 1/2 & -1/2 & 1/2 & -1/2 \\ 0 & 0 & 0 & 0 & 1/2 & -1/2 \end{bmatrix} \quad (16)$$

$$D(\underline{q}) = \begin{bmatrix} m_1 + m_2 + m_3 & m_2 \cos(\theta_1) + m_3 \cos(\theta_1) & m_3 \cos(\theta_1 + \theta_2) & -m_2 s_2 \sin(\theta_1) - m_3 s_2 \sin(\theta_1) - m_3 s_3 \sin(\theta_1 + \theta_2) & 0 & 0 \\ m_2 \cos(\theta_1) + m_3 \cos(\theta_1) & m_2 + m_3 & m_3 \cos(\theta_2) & -m_3 s_3 \sin(\theta_2) & -m_3 s_3 \sin(\theta_2) & 0 \\ m_3 \cos(\theta_1 + \theta_2) & m_3 \cos(\theta_2) & m_3 & m_3 s_3 \sin(\theta_2) & 0 & 0 \\ -m_2 s_2 \sin(\theta_1) - m_3 s_2 \sin(\theta_1) - m_3 s_3 \sin(\theta_1 + \theta_2) & -m_3 s_3 \sin(\theta_2) & m_3 s_2 \sin(\theta_2) & m_2 s_2^2 + I_1 + I_2 + I_3 + m_3 s_2^2 + m_3 s_3^2 + 2m_3 s_3 \cos(\theta_2) s_2 & I_2 + m_3 s_3^2 + I_3 + m_3 s_3 \cos(\theta_2) s_2 & I_3 \\ -m_3 s_3 \sin(\theta_1 + \theta_2) & -m_3 s_3 \sin(\theta_2) & 0 & I_2 + m_3 s_3^2 + I_3 + m_3 s_3 \cos(\theta_2) s_2 I & I_2 + m_3 s_3^2 + I_3 & I_3 \\ 0 & 0 & 0 & I_3 & I_3 & I_3 \end{bmatrix} \quad (17)$$

$$C(\underline{q}) = \begin{bmatrix} c_{11} + c_{21} & -2m_2 \sin(\theta_1) \dot{\theta}_1 - 2m_3 \sin(\theta_1) \dot{\theta}_1 & -2m_3 \sin(\theta_1 + \theta_2) (\dot{\theta}_1 + \dot{\theta}_2) & -m_2 s_2 \cos(\theta_1) (\dot{\theta}_1) + (1/2)(c_{11} + c_{21}) - m_3 s_2 \cos(\theta_1) (\dot{\theta}_1) - m_3 s_3 \cos(\theta_1 + \theta_2) (\dot{\theta}_1) & -m_3 s_3 \sin(\theta_1 + \theta_2) & 0 \\ 0 & c_{12} + c_{22} & -2m_3 \sin(\theta_2) (\dot{\theta}_1 + \dot{\theta}_2) & -m_3 s_3 (\dot{\theta}_1) + (1/2)(c_{12} + c_{22}) - m_3 s_2 (\dot{\theta}_1) - m_3 s_3 \cos(\theta_2) (\dot{\theta}_1) & -2m_3 s_3 \cos(\theta_2) (\dot{\theta}_1) & 0 \\ 0 & 2m_3 \sin(\theta_2) (\dot{\theta}_1) & c_{13} + c_{23} & -m_3 s_3 s_2 \cos(\theta_2) (\dot{\theta}_1) - m_3 s_3 (\dot{\theta}_1) & -2m_3 s_3 (\dot{\theta}_1) - m_3 s_3 (\dot{\theta}_2) & (1/2)(c_{13} + c_{23}) \\ (1/2)(c_{11} + c_{21}) & 2m_3 s_3 \cos(\theta_2) (\dot{\theta}_1) - 2m_3 s_2 (\dot{\theta}_1) + 2m_2 s_2 (\dot{\theta}_1) & 2m_3 s_3 (\dot{\theta}_1 + \dot{\theta}_2) - 2m_3 s_2 \cos(\theta_2) (\dot{\theta}_1 + \dot{\theta}_2) & 2m_3 s_3 s_2 \sin(\theta_2) (\dot{\theta}_2) + (1/4)(c_{11} + c_{21}) & m_3 s_3 s_2 \sin(\theta_2) (\dot{\theta}_2) & 0 \\ 0 & (1/2)(c_{12} + c_{22}) + 2m_3 s_3 \cos(\theta_2) (\dot{\theta}_1) & 2m_3 s_3 (\dot{\theta}_1 + \dot{\theta}_2) & m_3 s_3 s_2 \sin(\theta_2) (\dot{\theta}_1) & (1/4)(c_{12} + c_{22}) & 0 \\ 0 & 0 & (1/2)(c_{13} - c_{23}) & 0 & 0 & (1/4)(c_{13} + c_{23}) \end{bmatrix} \quad (18)$$

F_{coeff} transforms the input forces to the generalized forces and torques in the system. The inertia matrix, D is composed of four block matrices. The block matrices that correspond to pure linear accelerations and pure angular accelerations in the system (on the top left and on the bottom right) are symmetric. The matrix C contains coefficients of the first order derivatives of the generalized co-ordinates. Since the system is nonlinear, many elements of C contain first order derivatives of the generalized co-ordinates. The remaining terms in the dynamic equations resulting from gravitational potential energies and spring energies are collected in the matrix G . The coefficient matrices of the dynamic equations are given below,

$$G(q) = \begin{bmatrix} -m_1g - m_2g + k_{11}(s_1 + (1/2)\theta_1 - s_{01}) + k_{21}(s_1 - (1/2)\theta_1 - s_{01}) - m_3g \\ -m_2g\cos(\theta_1) + k_{12}(s_2 + (1/2)\theta_2 - s_{02}) + k_{22}(s_2 - (1/2)\theta_2 - s_{02}) - m_3g\cos(\theta_1) \\ -m_3g\cos(\theta_1 + \theta_2) + k_{13}(s_3 + (1/2)\theta_3 - s_{03}) + k_{23}(s_3 - (1/2)\theta_3 - s_{03}) \\ m_2s_2g\sin(\theta_1) + m_3s_3g\sin(\theta_1 + \theta_2) + m_3s_2g\sin(\theta_1) + k_{11}(s_1 + (1/2)\theta_1 - s_{01})(1/2) \\ + k_{21}(s_1 - (1/2)\theta_1 - s_{01})(-1/2) \\ m_3s_3g\sin(\theta_1 + \theta_2) + k_{12}(s_2 + (1/2)\theta_2 - s_{02})(1/2) + k_{22}(s_2 - (1/2)\theta_2 - s_{02})(-1/2) \\ k_{13}(s_3 + (1/2)\theta_3 - s_{03})(1/2) + k_{23}(s_3 - (1/2)\theta_3 - s_{03})(-1/2) \end{bmatrix} \quad (19)$$

III. METHODOLOGY

The design of PD fuzzy plus integral computed torque controller to control the continuum robot manipulator was very straight forward. PID like fuzzy controller has superior performance according to increase the number of rule base. PD like fuzzy controller is faster than PID like fuzzy, but it has some challenges such as steady state error and overshoot. To reduce the steady state error and overshoot in presence the number of rule base PD like fuzzy plus integral (I) is applied to powerful nonlinear computed torque controller. PID is a linear controller, referring to the three terms operating on the error signal to produce a control signal.

$$e(t) = \theta_d(t) - \theta_a(t) \quad (20)$$

$$U_{PD} = K_p e + K_v \dot{e} \quad (21)$$

$$U_{PD+I} = (U_{PD}) + K_I \int e \quad (22)$$

Based on pure computed torque controller;

$$\tau_{CTC} = D(q)(\ddot{q}_d + K_p e + K_v \dot{e}) + N(q, \dot{q}) \quad (23)$$

When all dynamic and physical parameters are known, baseline CTC works fantastically. According to the linear system theory, convergence of the tracking error to zero is guaranteed. Where K_p and K_v are the controller gains. Computed torque controller has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining computed torque controller and (PD plus I) fuzzy-based tuning method which this method can helps to reduce the error in presence of model base controller and reduce the number of rule base, according to reduce the number of inputs. Based on above discussion, compute the best value of controller coefficient has played important role to improve system's tracking performance especially the system parameters are unknown or uncertain. This problem is solved by Gradient Descent Optimization (GDO) to adjust the coefficients. In this methodology, the system's performance is improved with respect to the trial and error method.

If $f(x|K)$ as the fuzzy inference system;

$$\hat{f}(x|K) = K^T \zeta(x) \quad (24)$$

If minimum error (K^*) is defined by;

$$K^* = \arg \min [(Sup | \hat{f}(x|K) - f(x))] \quad (25)$$

where K^T is adjusted by an optimization law and this law is designed to minimize the error's parameters of $K - K^*$. Fuzzy-based part is a main controller based on Mamdani's fuzzy logic methodology. This controller has two inputs namely; error (e) and change of error (\dot{e}) and an output namely; gain factor (α). As a summary design a PD+I fuzzy logic method has five steps:

- Determine inputs and outputs:** it has two inputs error and change of error (e, \dot{e}) and the output name's is controller coefficient factor (α).
- Find linguistic variable:** The linguistic variables for error(e) are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and it is quantized into thirteen levels represented by: -1, -0.83, -0.66, -0.5, -0.33, -0.16, 0, 0.16, 0.33, 0.5, 0.66, 0.83, 1, the linguistic variables for change of error(\dot{e}) are ;Fast Left (FL), Medium Left (ML), Slow Left (SL),Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR), and it is quantized in to thirteen levels represented by: -6, -5, -0.4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, and the linguistic variables for controller coefficient updating factor (α) are; Zero (ZE), Very Small (VS), Small (S), Small Big (SB), Medium Big (MB), Big (B), and Very Big (VB) and they are defined on [0.5,1] and quantized into thirteen levels respected by: 0.5, 0.5417, 0.583, 0.625, 0.667, 0.7087, 0.7503, 0.792, 0.834, 0.876, 0.917, 0.959, 1.
- Type of membership function:** In this research triangular membership function is selected because it has linear equation with regard to has a high-quality response.
- Design fuzzy rule table:** the rule base for controller coefficient updating factor of fuzzy-based tuning BLCTC is based on

$$\mathbf{FR}^1: \text{IF } e \text{ is NB and } \dot{e} \text{ is NB, THEN } \alpha \text{ is VB.} \quad (26)$$

The complete rule base for supervisory controller is shown in Table 1.

5. **Defuzzification:** based on previous discussion COG method is used to defuzzification in this research.

Table 1. Fuzzy rule base for controller coefficients updating factor (α)

$e \backslash \dot{e}$	FL	ML	SL	Z	SR	MR	FR
NB	VB	VB	VB	B	SB	S	ZE
NM	VB	VB	B	B	MB	S	VS
NS	VB	MB	B	VB	VS	S	VS
Z	S	SB	MB	ZE	MB	SB	S
PS	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
PB	ZE	S	SB	B	VB	VB	VB

PD like fuzzy controller has 49 rule bases. The integral part caused to reduce the error and increase the stability.

$$U = \left[\frac{\sum_{l=1}^n \theta^l [\mu_{A^l}(x)]}{\sum_{l=1}^n [\mu_{A^l}(x)]} \right]_{PD} + K_I \sum e \quad (27)$$

$$\tau = D(q) (\ddot{q}_d + K_p e + K_v \dot{e}) + \left[\frac{\sum_{l=1}^n \theta^l [\mu_{A^l}(x)]}{\sum_{l=1}^n [\mu_{A^l}(x)]} \right]_{PD} + K_I \sum e \quad (28)$$

IV. RESULT AND DISCUSSION

PD like fuzzy computed torque controller (PD-FCTC) and PD+I like fuzzy computed torque controller (PD+I-FCTC) are implemented in MATLAB/SIMULINK environment. Tracking performance and disturbance rejection are compared.

Tracking performances: From the simulation systems trajectory without any disturbance, it was seen that both of controllers have the same performance, because these controllers are adjusted and worked on certain environment. Figure 2 shows the tracking performance in certain system and without external disturbance.

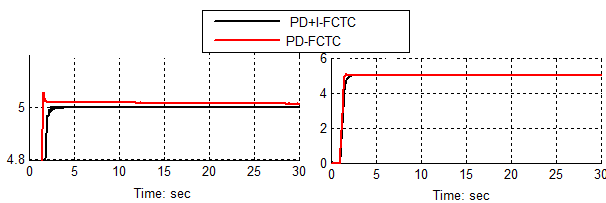


Fig. 2. PD-FCTC Vs. PD+I-FCTC

By comparing trajectory response in above graph it is found that the proposed method overshoot (0%) is lower than PD-FCTC (3.8%), although both of them have about the same steady state error.

Disturbance rejection: Figure 3 shows the power disturbance elimination in above controllers. One of the important targets in this research is the test of robustness as well as the other responses. A band limited white noise with predefined of 40% the power of input signal is applied to controllers. It found fairly fluctuations in PD-like fuzzy computed torque controller trajectory responses, but proposed method has better response.

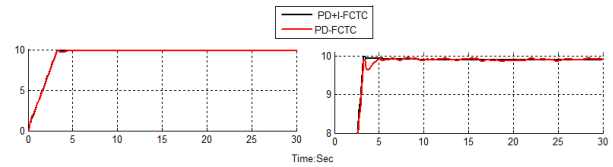


Fig. 3. PD-FCTC Vs. PD+I-FCTC in presence of uncertainty and external disturbance

Among above graph relating to trajectory following with external disturbance, PD like fuzzy computed torque control has fairly fluctuations.

V. CONCLUSION

PD plus integral like fuzzy computed torque control algorithm for robot manipulators is investigated in this paper. Proposed algorithm utilizes SISO fuzzy system to estimate the cross-coupling effects in robotic manipulator and gets ideal tracking accuracy. However, pure computed torque control and pure fuzzy logic methodology have challenges in presence of uncertainty, but proposed method could solve it. Proposed algorithm attenuated the external disturbance problem very well by substituting a integral fuzzy compensator. The number of fuzzy rules is also reduced by abandoning SISO PD fuzzy plus integral part. But we still need to predefine the premise part of the fuzzy rules based on methodology of optimization.

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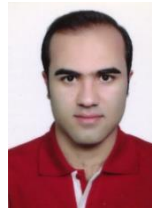
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