Design PID-Like Fuzzy Controller With Minimum Rule Base and Mathematical Proposed On-line Tunable Gain: Applied to Robot Manipulator

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Abstract

In this study, an on-line tunable gain model free PID-like fuzzy controller (GTFLC) is designed for three degrees of freedom (3DOF) robot manipulator to rich the best performance. Fuzzy logic controller is studied because of its model free and high performance. Today, robot manipulators are used in unknown and unstructured environment and caused to provide sophisticated systems, therefore strong mathematical tools are used in new control methodologies to design adaptive nonlinear robust controller with acceptable performance (e.g., minimum error, good trajectory, disturbance rejection). The strategies of control robot manipulator are classified into two main groups: classical and non-classical methods, however non linear classical theories have been applied successfully in many applications, but they also have some limitation. One of the most important nonlinear non classical robust controller that can used in uncertainty nonlinear systems, are fuzzy logic controller. This paper is focuses on applied mathematical tunable gain method in robust non classical method to reduce the fuzzy logic controller limitations. Therefore on-line tunable PID like fuzzy logic controller will be presented in this paper.

Keywords: Tunable Gain, Robot Manipulator, Fuzzy Logic Controller, Classical Control, Non-Classical Control, on-line Tunable Gain.

1. INTRODUCTION

Controller design is the main part in robotic manipulator as well as the major objectives stability and robustness. Consequently to improve the system's performance lots of researchers are about control systems [2].

Some of robot manipulators which work in industrial processes are controlled by linear PID controllers, but design linear controller for robotic manipulators is extremely difficult because they are nonlinear, uncertainty, multi input multi output (MIMO) and time variant [1, 3]. To eliminate the above problems control researchers applied PID methods in nonlinear robust controller (e.g., fuzzy logic controller).

After the invention of fuzzy logic theory in 1965, this theory was used in wide range applications that fuzzy logic controller (FLC) is one of the most important applications in fuzzy logic theory because the controller has been used for nonlinear and uncertain (e.g., robot manipulator) systems controlling. However pure FLC works in many areas but calculation and tune the PID coefficient most of time is challenge [4-7, 15-24].

On-line tuning control is used in systems with various dynamic parameters and need to be training on line. Combined on-line tuneable gain method for artificial controllers can solve the uncertainty challenge in uncertain nonlinear systems [8, 15-24].

This paper is organized as follows: In section 2, main subject of modelling three degrees of freedom robot manipulator formulation are presented. Detail of fuzzy logic controllers with on-line tuneable gain is presented in section 3. In section 4, the simulation result is presented and finally in section 5, the conclusion is presented.

2. ROBOT MANIPULATOR DYNAMIC FORMULATION

The equation of an *n-DOF* robot manipulator governed by the following equation [1, 3, 15-24]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \quad \textbf{(1)}$$

Where τ is actuation torque, M (q) is a symmetric and positive define inertia matrix, $N(q,\dot{q})$ is the vector of nonlinearity term. This robot manipulator dynamic equation can also be written in a following form:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \quad \textbf{(2)}$$

Where B(q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques, and G(q) is the vector of gravity force. The dynamic terms in equation (2) are only manipulator position. 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 joint variable q_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [3, 15-24]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\} \quad \textbf{(3)}$$

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

3. PID LIKE FUZZY INFERENCE SYSTEM WITH ON-LINE TUNABLE GAIN

In recent years, artificial intelligence theory has been used in robotic systems. Neural network, fuzzy logic, and neuro-fuzzy are combined with tuneable methods and used in nonlinear, time variant, and uncertainty plant (e.g., robot manipulator). After the invention of fuzzy logic theory in 1965 by Zadeh [4], this theory was used in wide range area. Fuzzy logic controller (FLC) is one of the most important applications of fuzzy logic theory. This controller can be used to control of nonlinear, uncertain, and noisy systems. This method is free of some model-based techniques that used in classical controllers. It should be mentioned that fuzzy logic application is not only limited to the modelling of nonlinear systems [5-9] but also this method can help engineers to design easier controller.

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. 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 [5, 15-18].

3.1 Fuzzy Inference System

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) [5, 15-18].

The basic structure of a fuzzy controller is shown in Figure 1.

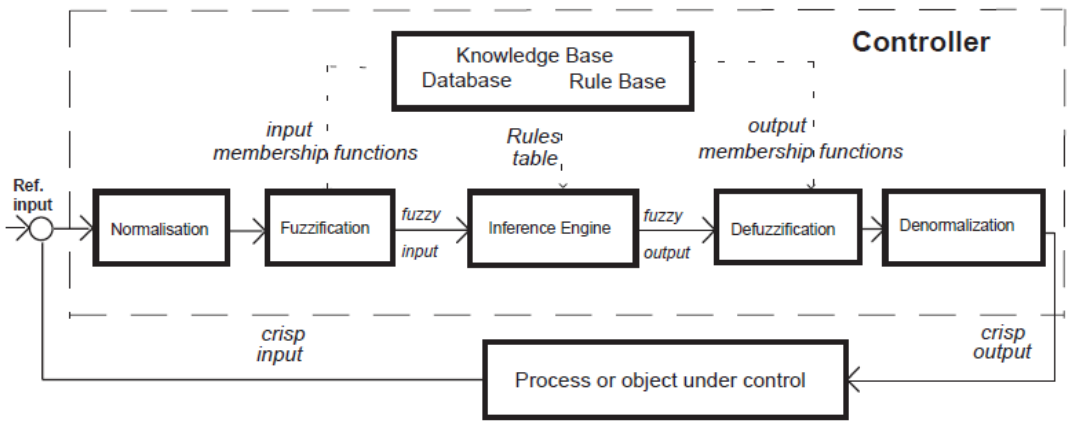

FIGURE 1: Block diagram of a fuzzy controller with details.

3.2. PID Fuzzy Logic Controller

A PID fuzzy controller is a controller which takes error, integral of error and derivative of error as inputs. Fuzzy controller with three inputs is difficult to implementation, because it needs large number of rules, in this state the number of rules increases with an increase the number of inputs or fuzzy membership functions [10-12]. In the PID FLC, if each input has 7 linguistic variables, then $7 \times 7 \times 7 = 343$ rules will be needed. The proposed PID FLC is constructed as a parallel structure of a PD FLC and PI FLC (Figure 2), and the output of the PID FLC is formed by adding the output of two fuzzy control blocks. This work will reduce the number of rules needed to $7 \times 7 + 7 \times 7 = 98$ rules only.

As a summary the design of PID like fuzzy logic controller based on Mamdani's fuzzy inference method has four steps , namely, fuzzification, fuzzy rule base and rule evaluation, aggregation of the rule output (fuzzy inference system), and deffuzzification [15-18].

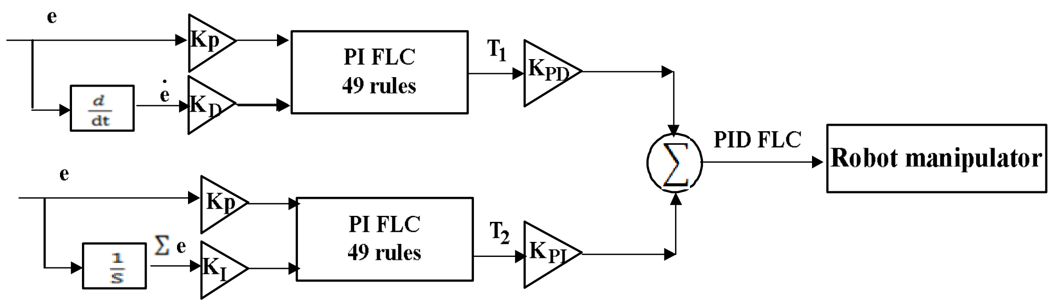

FIGURE 2: Proposed PID controller with minimum rule base

Fuzzification: the first step in fuzzification is determine inputs and outputs which, it has two inputs ($e, \dot{e}$) or $(e, \sum e)$ and one output (τ_{1fuzzy} or τ_{2fuzzy}). The inputs are error (e) which measures the difference between desired and actual output position, the change of error ($\dot{e}$) which measures the difference between desired and actual velocity and the summation of error $(\sum e)$ which measured the difference between desired and actual summation of error. The second step is chosen an appropriate membership function for inputs and output which, for simplicity in implementation and also to have an acceptable performance the researcher is selected the triangular membership function that it is shown in Figure 3. The third step is chosen the correct labels for each fuzzy set which, in this research namely as 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 in to 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, the linguistic variables for summation of error ($\sum e$) 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 in to 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 and the linguistic variables to find the output are; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR), Large Right (LR) and it is quantized in to thirteen levels represented by: -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6.

Fuzzy rule base and rule evaluation: the first step in rule base and evaluation is provide a least structured method to derive the fuzzy rule base which, expert experience and control engineering knowledge is used because this method is the least structure of the other one and the researcher derivation the fuzzy rule base from the knowledge of system operate and/or the classical controller. Design the rule base of fuzzy inference system can play important role to design the best performance of fuzzy sliding mode controller, that to calculate the fuzzy rule base the researcher is used to heuristic method which, it is based on the behavior of the control of robot manipulator suppose that two fuzzy rules in this controller are;

F.R^1: ***IF e is NB and $\dot{e}$ is FL, THEN τ is LL.*** **(4)**

F.R^2: ***IF e is PS and $\dot{e}$ is FL THEN τ is ML***

The complete rule base for this controller is shown in Table 1. Rule evaluation focuses on operation in the antecedent of the fuzzy rules in fuzzy sliding mode controller. This part is used AND/OR fuzzy operation in antecedent part which AND operation is used.

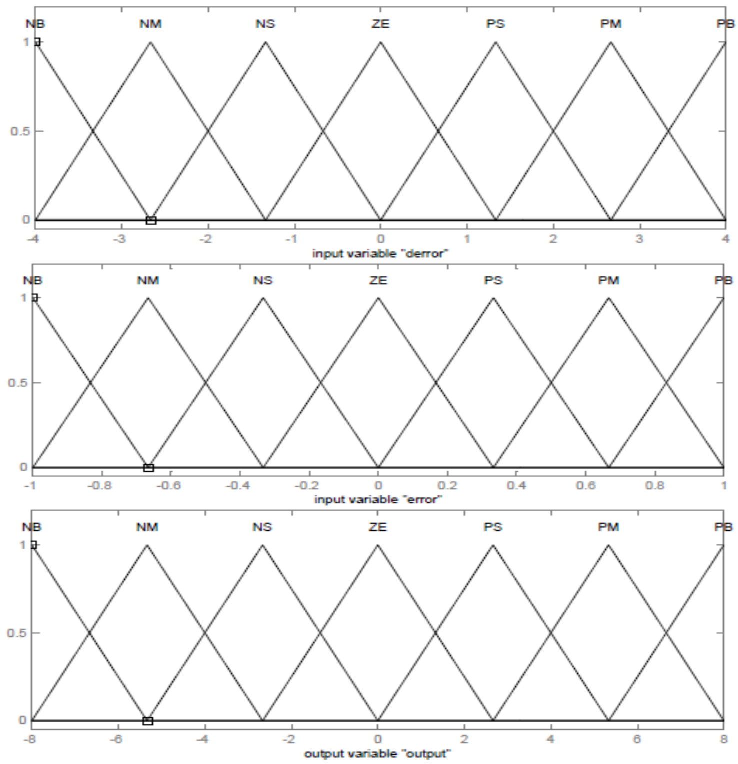

FIGURE 3: Membership function: a) error b) change of error c) output

Aggregation of the rule output (Fuzzy inference): Max-Min aggregation is used to this work which the calculation is defined as follows;

$$\mu_U(x_k,y_k,U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k,y_k,U) = max\left\{min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k,y_k),\mu_{p_m}(U)\right]\right\} \quad (5)$$

Deffuzzification: The last step to design fuzzy inference in our fuzzy sliding mode controller is defuzzification. This part is used to transform fuzzy set to crisp set, therefore the input for defuzzification is the aggregate output and the output of it is a crisp number. In this design the Center of gravity method (COG) is used and calculated by the following equation;

$$COG(x_k,y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \mu_u(x_k,y_k,U_i)}{\sum_i \sum_{j=1}^{r} \mu_u(x_k,y_k,U_i)} \quad (6)$$

$\dot{e}$ \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	PS	PS	PM	PB	PB	NB	ZE

TABLE 1: Modified fuzzy rule base table

This table has 49 cells, and used to describe the dynamics behavior of fuzzy controller.
Table 2 is shown the lookup table in fuzzy logic controller which is computed by COG deffuzzification method. These output values were obtained from trial and error after some manual adjustment to reach the best performance in fuzzy logic controller.

$\dot{e}$ → / e ↓	Membership Function												
	-1	**-0.83**	**-0.66**	**-0.5**	**-0.33**	**-0.16**	**0**	**0.16**	**0.33**	**0.5**	**0.66**	**0.83**	**1**
-1	-5.6	-5.4	-5	-4.8	-4.8	-4.7	-4.7	-4.6	-4.5	-4.4	-4.3	-4.3	-4.2
-0.83	-4.7	-4.5	-4.4	-4.3	-4.2	-4.1	-4	-3.9	-3.8	-3.8	-3.7	-3.6	-3.5
-0.66	-3.7	-3.6	-3.5	-3.2	-3	-3	-3	-2.9	-2.9	-2.8	-2.8	-2.7	-2.7
-0.5	-2.0	-2.0	-2.0	-1.9	-1.9	-1.8	-1.8	-1.7	-1.7	-1.6	-1.5	-1.4	-1.3
-0.33	0.0	-0.8	-1.0	-1.2	-1.7	-2.3	-2.2	-2.2	-2.0	-2.0	-1.0	-1.0	0.0
-0.16	1.0	1	0.5	-0.5	-1.0	-1.2	-1.5	-1.7	-1.0	-1.0	-1.0	-0.5	-0.5
0	1.3	1.2	1.0	0.8	0.6	0.0	-0.2	-0.4	-0.6	-0.8	-1.0	-1.0	-1.0
0.16	2.0	2.0	1.9	1.8	1.8	1.8	1.8	1.8	1.5	0.0	-0.3	-1.0	-0.8
0.33	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.2	0.8	0.0	0.0
0.5	2.0	2.1	2.3	2.5	2.5	2.6	2.6	2.7	2.7	2.8	2.9	2.9	3.0
0.66	2.7	2.7	2.8	2.9	2.9	3.0	3.1	3.1	3.2	3.2	3.6	3.7	3.9
0.83	3.6	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.2	4.3	4.3	4.6	4.7
1	4.4	4.4	4.5	4.6	4.7	4.8	5.0	5.0	5.1	5.2	5.3	5.6	5.6

TABLE 2: COG lookup table in fuzzy sliding mode controller

Table 2 has 169 cells to shows the PD fuzzy part behavior. For instance if $e = 0$ and $\dot{e} = 0$ then the output= -0.2.

3.3 On-line Tunable Gain to Adjust Fuzzy Logic Controller

All conventional fuzzy logic controller have common difficulty, they need to find several parameters. Tuning PID like FLC method can tune automatically the scale parameters using new method. To keep the structure of the controller as simple as possible and to avoid heavy computation, a mathematical supervisor tuner is selected [13-14]. In this method the tuneable controller tunes the input scaling factors using gain updating factors. In this method the first gain updating factor, k_1, is updated by a new coefficient factor, k_n, Where k_n is a function of system error.

$$K_n = e^2 - \frac{(r_v - r_{vmin})^2}{1 + |e|} + r_{vmin} \tag{7}$$

$$r_v = \frac{\dot{e}(t) - e^{\cdot}(t-1)}{\dot{e}(0)} \qquad \text{(8)}$$
$$if\ e^{\cdot}(0) = \begin{cases} \dot{e}(t) & if\ e^{\cdot}(t) \geq \dot{e}(t-1) \\ \dot{e}(t-1) & if\ e^{\cdot}(t) < \dot{e}(t-1) \end{cases}$$

Figure 3 is shown the PID like fuzzy logic controller with proposed tunable gain.

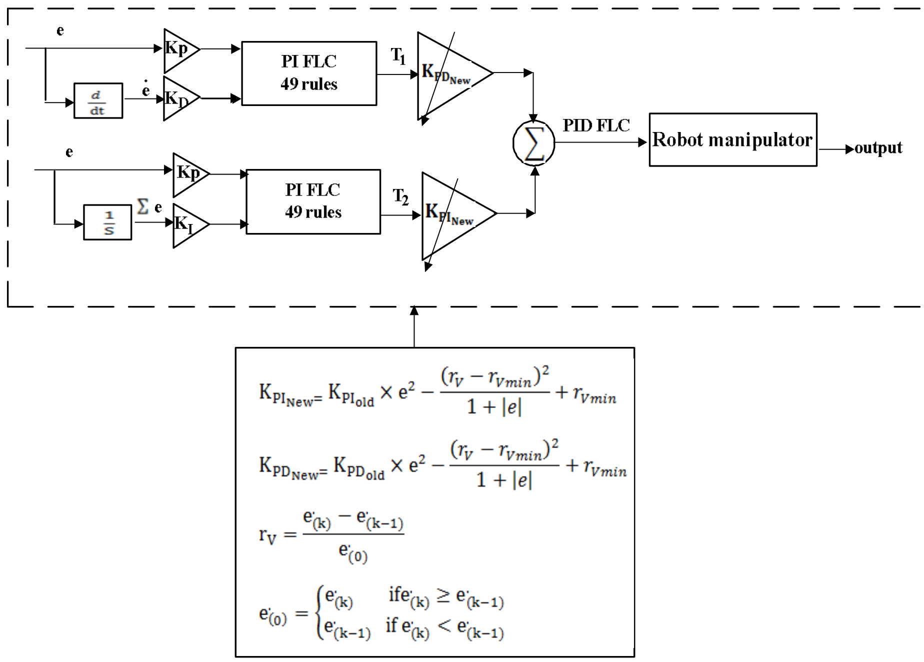

FIGURE 3: PID like fuzzy logic controller with proposed tunable gain

4 SIMULATION RESULTS

Pure fuzzy logic controller (FLC) and gain tuning PID like fuzzy controller (GTFLC) are implemented in Matlab/Simulink environment. Tracking performance, disturbance rejection and error are compared.

4.1 Tracking Performances

From the simulation for first, second and third trajectory without any disturbance, it was seen that FLC and GTFLC have the same performance. This is primarily because this system is worked on certain environment. The GTFLC gives significant trajectory good following when compared to FLC. Figure 4 shows tracking performance without any disturbance for FLC and GTFLC.

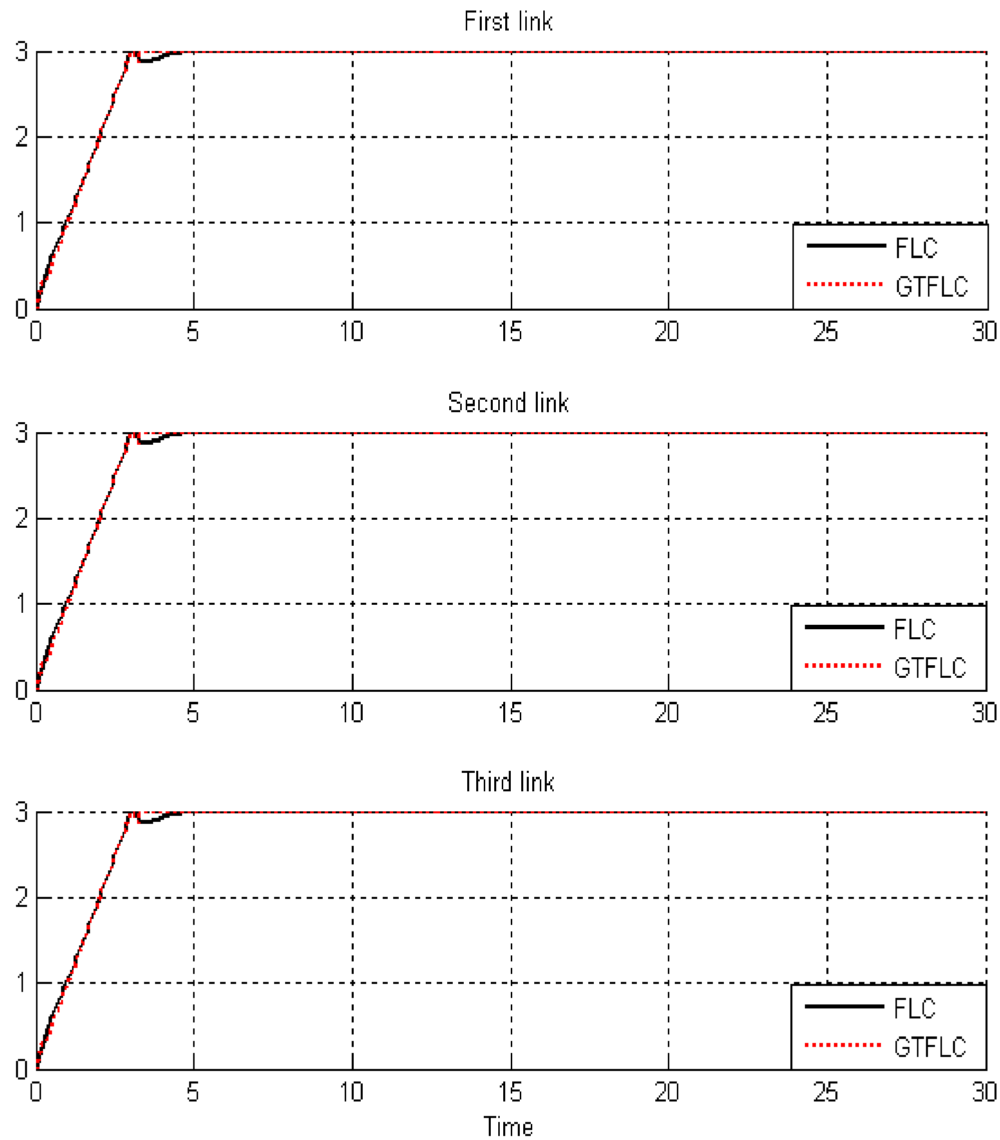

FIGURE 4: FLC and GTFLC for First, second and third link trajectory

By comparing trajectory response without disturbances in FLC and GTFLC it is found that the GTFLC overshoot **(0%)** is lower than FLC's **(1%)**, although both of them have about the same rise time.

4.2 Disturbance Rejection

Figure 5 has shown the power disturbance elimination in FLC and GTFLC. The main target in these controllers is disturbance rejection as well as the other responses. A band limited white noise with predefined of 40% the power of input signal is applied to the FLC and GTFLC. It found fairly fluctuations in FLC trajectory responses.

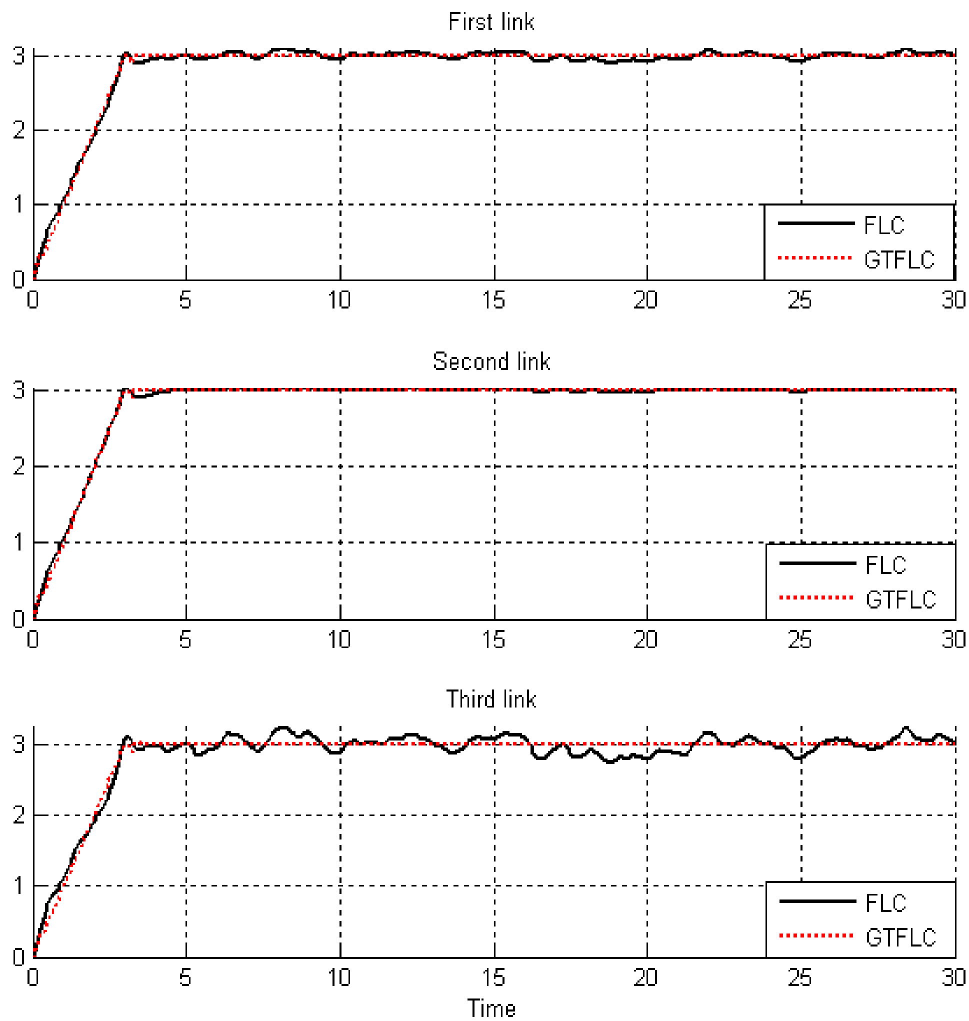

FIGURE 5: FLC and GTFLC for First, second and third link trajectory with external disturbances.

Among above graph relating to trajectory following with external disturbance, FLC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the GTFLC's overshoot **(0%)** is lower than FLC's **(4%)**, although both of them have about the same rise time**.**

4.3 Calculate Errors

Figure 6 has shown the error disturbance in FLC and GTFLC. The controllers with no external disturbances have the same error response. By comparing the steady state error and RMS error it found that the GTFLC's errors **(Steady State error = -0.0007 and RMS error=0.0008)** are fairly less than FLC's **(Steady State error $\cong$ 0.0012 and RMS error=0.0018)**, When disturbance is applied to the FLC error is about 13% growth.

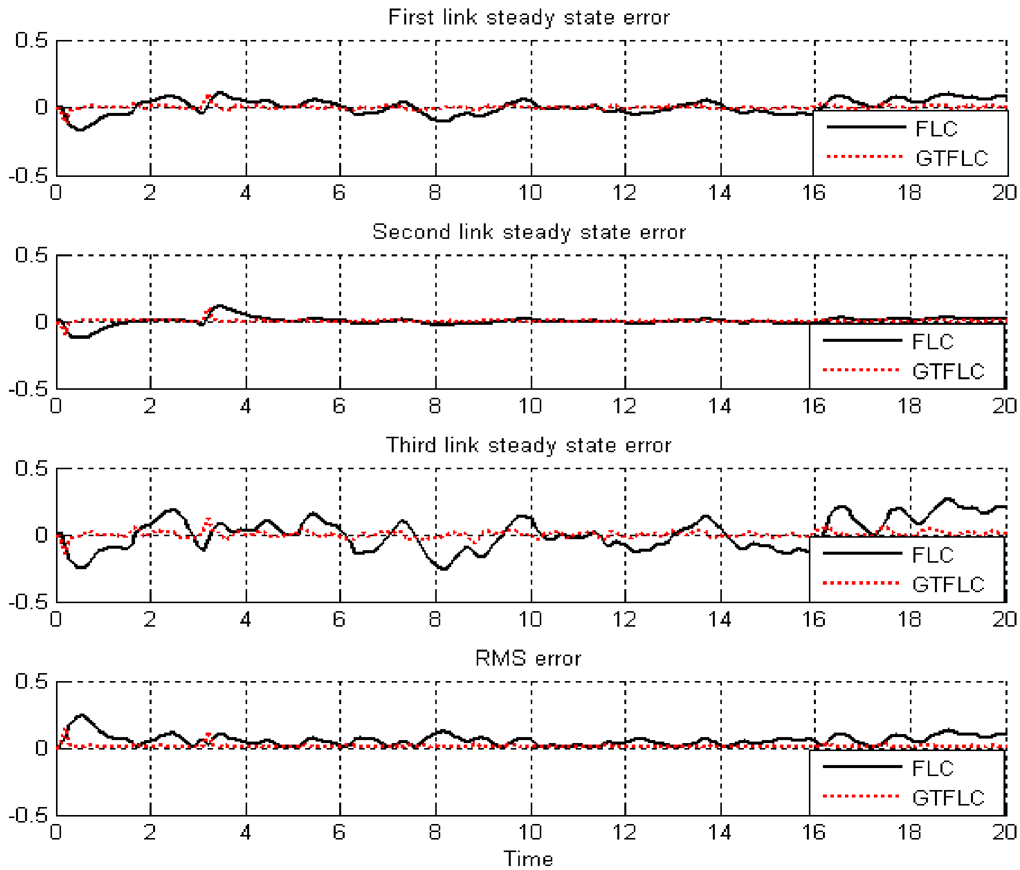

FIGURE 6: FLC and GTFLC for First, second and third link steady state and RMS error with external disturbances.

5 CONCLUSIONS

This paper presents a new methodology for designing s online tunable PID like fuzzy logic controller with minimum rule bases and high performance for 3 DOF robotic manipulator. From the simulation, it found that proposed PID fuzzy gain tuning has 98 rule base for main controller but in normal PID like fuzzy controller by the other researcher has about 343 rules for main controller. In GTFLC, the mathematical tunable controller can changed K_{PD} & K_{PI} to achieve the best performance. In this method the proposed mathematical supervisory controller is changed the gain updating factor of main FLC to get the best performance.

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