Design of Model Free Adaptive Fuzzy Computed Torque Controller: Applied to Nonlinear Second Order System

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Abstract

In this study, a model free adaptive fuzzy computed torque controller (AFCTC) is designed for a two-degree-of freedom robot manipulator to rich the best performance. Computed torque controller is studied because of its high performance. AFCTC has been also included in this study because of its robust character and high performance. Besides, this control method can be applied to non-linear systems easily. 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 both classical and non-classical theories have been applied successfully in many applications, but they also have some limitation. One of the most important nonlinear robust controller that can used in uncertainty nonlinear systems, are computed torque controller. This paper is focuses on applied non-classical method in robust classical method to reduce the limitations. Therefore adaptive fuzzy computed torque controller will be presented in this paper.

Keywords: Adaptive Fuzzy Computed Torque Controller, Robot Manipulator, Classical Control, Non-Classical Control, Computed Torque Controller.

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 [3]. One of the most important challenges in control algorithms is a linear behavior controller design for nonlinear systems. When system works with various parameters and hard nonlinearities this technique is very useful in order to implement easily but it has some limitations such as working near the system operating point [3]. 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, and multi input multi output (MIMO) [1-2]. To eliminate the above problems control researchers have used in nonlinear robust controller.

One of the most important powerful nonlinear robust controllers is computed torque controller (CTC), however this controller has analyzed by many researchers recently but the first proposed was in the 1948 [4]. This controller is used in wide range areas such as in robotics, in control process and in aerospace applications because it has an acceptable control performance and solve some main challenging topics in control such as resistivity to the external disturbance. However, this controller is used in wide range areas but, pure CTC has the following disadvantage: uncertainty problem and depending on the dynamic equation. This controller works very well when all dynamic and physical parameters are known but when the robotic manipulator has variation in dynamic parameters, in this situation the controller has no acceptable performance .Calculate the dynamic parameters control formulation is difficult because it depends on the system's dynamic equation [6].

On the other hand, 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 it cannot guarantee the basic requirement of stability and acceptable performance [5].

However both CTC and FLC have been applied successfully in many applications but they also have some limitations. Some researchers are applied fuzzy logic methodology in nonlinear controller to solve the nonlinear dynamic problems in classical controller so called fuzzy classical controller and the other researchers are applied nonlinear classical controller in fuzzy logic controller to improve the stability of systems. In this paper the researcher is applied fuzzy logic method in pure CTC to eliminate the nonlinear dynamic parameter to easy implementation.

Adaptive control is used in systems with various dynamic parameters and need to be training on line. In general states, adaptive control is classified into two main groups: traditional adaptive method and fuzzy adaptive method. Traditional adaptive method need to have some information about dynamic plant and some dynamic parameters must be known. Fuzzy adaptive method can train the parameters variation by expert knowledge. Combined adaptive method for artificial sliding mode controllers can solve the uncertainty challenge in nonlinear systems.

This paper is organized as follows: In section 2, main subject of modelling two degrees of freedom robot manipulator formulation are presented. Detail of fuzzy logic controllers and fuzzy rule base is presented in section 3. In section 4, the main subject of computed torque controller and formulation are presented. The main subject of design fuzzy CTC is presented in section 5. In section 6, design adaptive fuzzy CTC is presented. This section covered the self tuning proposed fuzzy CTC. In section 7, the simulation result is presented and finally in section 8, the conclusion is presented.

2. DYNAMIC FORMULATION OF ROBOT MANIPULATOR

It is well known that the equation of an *n-DOF* robot manipulator governed by the following equation [1-2]:

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

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:

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

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 variableq_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [2, 15-22]:

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

This technique is very attractive from a control point of view. Figure 1 shows the 2 DOF's robot manipulator.

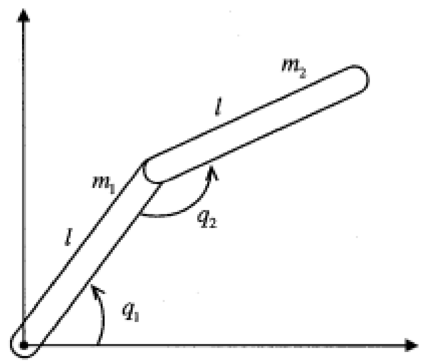

FIGURE 1: 2 DOF robotic manipulators

3. FUZZY INFERENCE SYSTEM

In recent years, artificial intelligence theory has been used in CTC 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). After the invention of fuzzy logic theory in 1965 by Zadeh [10], 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 [11-15] 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 [11]. 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).

The basic structure of a fuzzy controller is shown in Figure 2.

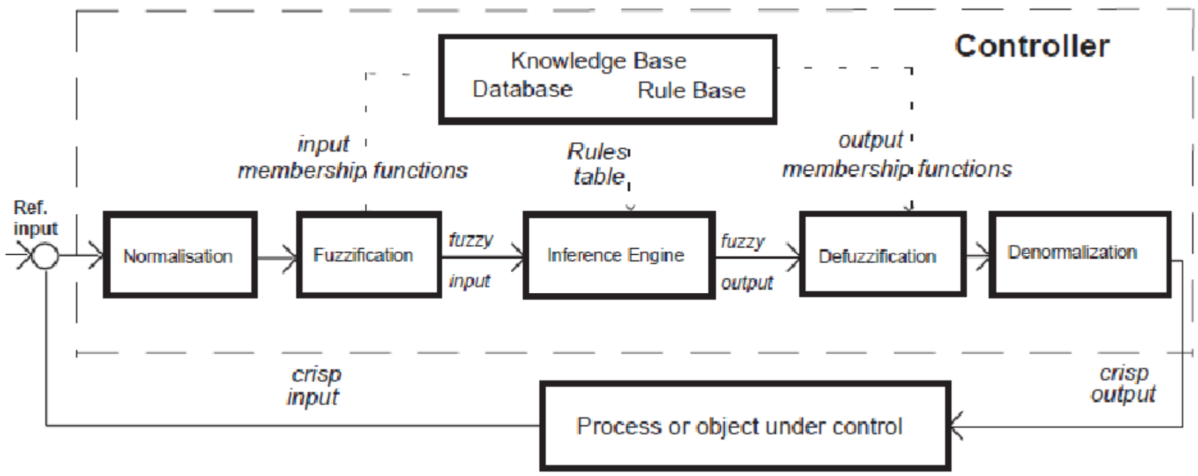

FIGURE 2: Block diagram of a fuzzy controller with details.

4. DESIGN OF A COMPUTED TORQUE CONTROLLER FOR ROBOT ARM

The central idea of Computed torque controller (CTC) is feedback linearization so, originally this algorithm is called feedback linearization controller. It is assumed that the desired motion trajectory for the manipulator $\boldsymbol{q_d(t)}$, as determined, by a path planner. Define the tracking error as:

$$\boldsymbol{e(t) = q_d(t) - q_a(t)} \quad \textbf{(4)}$$

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

$$\dot{\boldsymbol{x}} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \boldsymbol{x} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{I} \end{bmatrix} \boldsymbol{U} \quad \textbf{(5)}$$

With $\boldsymbol{U} = -\boldsymbol{M^{-1}(q)}.\boldsymbol{N(q,\dot{q})} + \boldsymbol{M^{-1}(q)}.\boldsymbol{\tau}$ and this is known as the Brunousky canonical form. By equation (4) and (5) the Brunousky canonical form can be written in terms of the state $\boldsymbol{x} = [\boldsymbol{e^T}\ \dot{\boldsymbol{e}}^{\boldsymbol{T}}]^{\boldsymbol{T}}$ as:

$$\frac{\boldsymbol{d}}{\boldsymbol{dt}}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} . \begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{I} \end{bmatrix} \boldsymbol{U} \quad \textbf{(6)}$$

With $\mathrm{U} = \ddot{\mathrm{q}}_{\mathrm{d}} + \mathrm{M}^{-1}(\mathrm{q}).\{\mathrm{N}(\mathrm{q}.\dot{\mathrm{q}}) - \tau\}$ **(7)**

Then compute the required arm torques using inverse of equation (7), namely, [2]

$$\boldsymbol{\tau} = \boldsymbol{M(q)}(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} - \boldsymbol{U}) + \boldsymbol{N}(\dot{\boldsymbol{q}},\boldsymbol{q}) \quad \textbf{(8)}$$

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; [1-2]; [6]; [7-8]

$$\boldsymbol{\tau} = \boldsymbol{M(q)}\left(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{K_v}\dot{\boldsymbol{e}} + \boldsymbol{K_p e}\right) + \boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}}) \quad \textbf{(9)}$$

and the resulting linear error dynamics are

$$\left(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{K_v}\dot{\boldsymbol{e}} + \boldsymbol{K_p e}\right) = \boldsymbol{0} \quad \textbf{(10)}$$

According to linear system theory, convergence of the tracking error to zero is guaranteed [2, 9].
Where $\boldsymbol{K_p}$ and $\boldsymbol{K_v}$ are the controller gains.
The resulting schemes is shown in Figure 3, in which two feedback loops, namely, inner loop and outer loop, which an inner loop is a compensate loop and an outer loop is a tracking error loop. However, mostly parameter $\boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is all unknown. So the control cannot be implementation because non linear parameters cannot be determined. In the following section computed torque like controller will be introduced to overcome the problems.

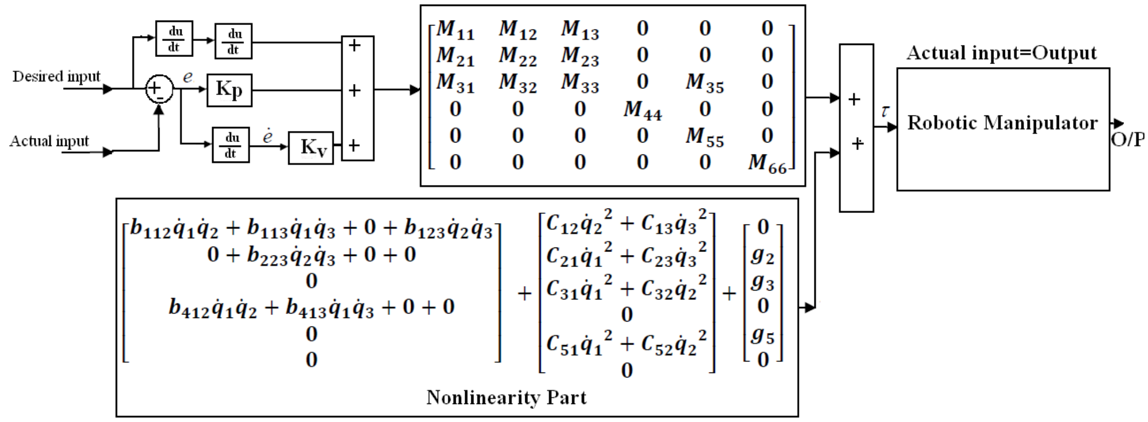

FIGURE 3: Block diagram of PD-computed torque controller (PD-CTC)

5. FUZZY LOGIC AND ITS APPLICATION TO COMPUTED TORQUE CONTROLLER

As mention previously, computed torque fuzzy controller (CTFC) is fuzzy controller based on computed torque method for easy implementation, stability, and robustness. The main drawback of CTFC is the value of gain updating factor K_p *and* K_v must be pri-defined very carefully and the most important advantage of CTFC compare to pure CTC is a nonlinearity dynamic parameter. It is basic that the system performance is sensitive to the gain updating factors for both computed torque controller and computed torque fuzzy controller application. For instance, if large value of K_V is chosen the response is very fast but the system is very unstable and conversely, if small value of K_V considered the response of system is very slow but the system is very stable. Therefore, calculate the optimum value of gain updating factors for a system is one of the most important challenging works. However most of time the control performance for FLC and CTFC is similar to each other, but CTFC has two most important advantages:
The number of rule base is smaller
Increase the robustness and stability
In this method the control output can be calculated by

$$\boldsymbol{\tau} = \hat{\boldsymbol{\tau}} + \boldsymbol{\tau}_{\mathbf{fuzzy(S)}} \quad \textbf{(11)}$$

Where $\hat{\tau}$ the nominal compensation is term and $\tau_{fuzzy(s)}$ is the output of computed torque fuzzy controller. The most important target in fuzzy computed torque controller (FCTC) is design computed torque control combined to fuzzy logic systems to solve the problems in classical computed torque controller [9, 15-19]. To compensate the nonlinearity of nonlinear dynamic part several researchers used model base fuzzy controller instead of classical nonlinear dynamic part that was employed to obtain the desired control behaviour and a fuzzy switching control was applied to reinforce system performance. In proposed fuzzy computed torque controller the author design fuzzy rule base to estimate the dynamic nonlinear part. A block diagram for proposed fuzzy computed controller is shown in Figure 4. In this method author obtained the following fuzzy rules for linear part to design fuzzy error base-like nonlinear dynamic parameter control. This rules used instead of nonlinear dynamic equation control to eliminate the nonlinear formulation of dynamic equivalent control term [21-22].

$1 > if\ L\ is\ N.B\ then\ \tau\ \ is\ N.B$
$2 > if\ L\ is\ Z\ then\ \tau\ is\ Z$

The sliding surface is defined as follows:

$$\boldsymbol{L} = \boldsymbol{M}(\boldsymbol{q})\big(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{K}_{\boldsymbol{v}}\dot{\boldsymbol{e}} + \boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{e}\big) \quad \textbf{(12)}$$

Based on classical computed torque controller for a multi DOF robot manipulator:

$$\hat{\boldsymbol{\tau}} = \hat{\boldsymbol{\tau}}_{\boldsymbol{nonlinear}} + \boldsymbol{\tau}_{\boldsymbol{lin}} \quad \textbf{(13)}$$

where, the model-based component $\hat{\tau}_{nonlinear}$ compensate for the nominal dynamics of systems. So $\hat{\tau}_{nonlinear}$ can calculate as follows:

$$\hat{\boldsymbol{\tau}}_{\boldsymbol{nonlinear}} = \boldsymbol{B}(\boldsymbol{q})\dot{\boldsymbol{q}}\dot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q})\dot{\boldsymbol{q}}^2 + \boldsymbol{g}(\boldsymbol{q}) \quad \textbf{(14)}$$

and $\boldsymbol{\tau}_{\boldsymbol{lin}}$ can calculate as follows:

$$\boldsymbol{\tau}_{\boldsymbol{lin}} = \boldsymbol{M}(\boldsymbol{q})\left(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} + \boldsymbol{K}_{\boldsymbol{v}}\dot{\boldsymbol{e}} + \boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{e}\right) \quad \textbf{(15)}$$

In proposed FSMC nonlinear control part replaced by Mamdani's fuzzy inference term, therefore (13) can be rewrite as the following equation

$$\hat{\boldsymbol{\tau}} = \boldsymbol{\tau}_{\boldsymbol{fuzzy}} + \boldsymbol{\tau}_{\boldsymbol{lin}} \quad \textbf{(16)}$$

Design fuzzy logic controller for FCTC has five steps:

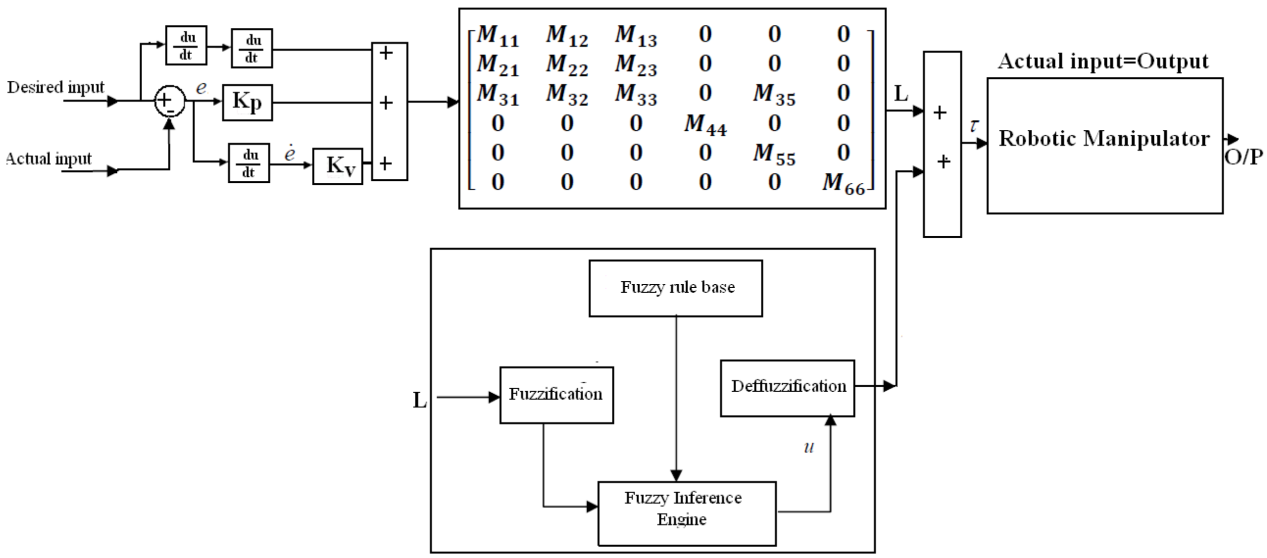

FIGURE 3: Block diagram of proposed fuzzy computed torque controller with minimum rule base

Determine inputs and outputs; find membership function and linguistic variable, type of membership function, fuzzy rule table, and defuzzification. This controller has one input (L) and one output (τ_{fuzzy}). The input is linear part (L) and the output is torque(τ_{fuzzy}). The linguistic variables for linear part (L) 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 torque (τ_{fuzzy}) 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: -85, -70.8, -56.7, -42.5, -28.3, -14.2, 0, 14.2, 28.3, 42.5, 56.7, 70.8, 85. The triangular membership function selected in this paper that can be shown in Figure 5. Design the rule base of fuzzy logic controller can play important role to design best performance FCTC. The complete rule base for this controller is shown in Table 1.

TABLE 1: Rule table for proposed FCTC

L	NB	NM	NS	Z	PS	PM	PB
τ	LL	ML	SL	Z	SR	MR	LR

The final step to design fuzzy logic controller is deffuzification , there are many deffuzzification methods in the literature, in this controller the COG method will be used, which COG method used the following equation to calculate the defuzzification

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} . \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} . \mu_u(x_k, y_k, U_i)} \quad \textbf{(17)}$$

However, pure FLC, CTC, FCTC, and CTFC used in wide range but they have common limitation to adjust several factors, that the next section is discussed about self tuning the scale factor without using fuzzy rule base.

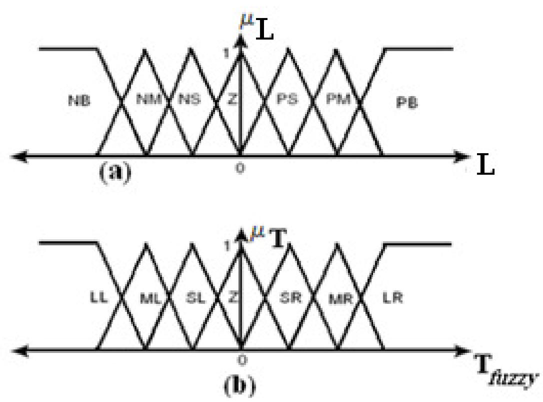

FIGURE 5: Membership function: a) sliding surface b) torque

6. DESIGN OF SELF TUNING FUZZY COMPUTED TORQUE CONTROL (AFCTC) FOR ROBOT ARM

It is a basic fact that the system performance in FCTC is sensitive to gain updating factor, K. Thus, determination of an optimum *K* value for a system is an important problem. If the system parameters are unknown or uncertain, the problem becomes more highlighted. This problem is solved by adjusting the proportional and derivative gain updating factor of the computed torque controller continuously in real-time. Several researchers are worked on adaptive computed torque control and their applications in robotic manipulator in the following references [1-2]; [7-8]. In this way, the performance of the overall system is improved with respect to the classical computed torque controller. Therefore this section focuses on, self tuning gain updating factor for two type most important factor in FCTC, namely, proportional gain updating factor (K_P) and derivative gain updating factor (K_v). Self tuning-FCTC has strong resistance and solves the uncertainty problems. The block diagram for this method is shown in Figure 6.

In this controller the actual gain updating factor (K_{new}) is obtained by multiplying the old gain updating factor (K_{old}) with the output of supervisory fuzzy controller(α). The output of fuzzy supervisory controller (α) is calculated on-line by fuzzy dynamic model independent which has sliding surface (S) as inputs.. The value of α is not longer than 1 but it calculated on-line from its rule base. The scale factor, Kv and Kp are updated by equations (18) and (19),

$$K_v^{new} = K_v^{old} \times KU \quad \textbf{(18)}$$

$$K_p^{new} = K_p^{old} \times KU \quad \textbf{(19)}$$

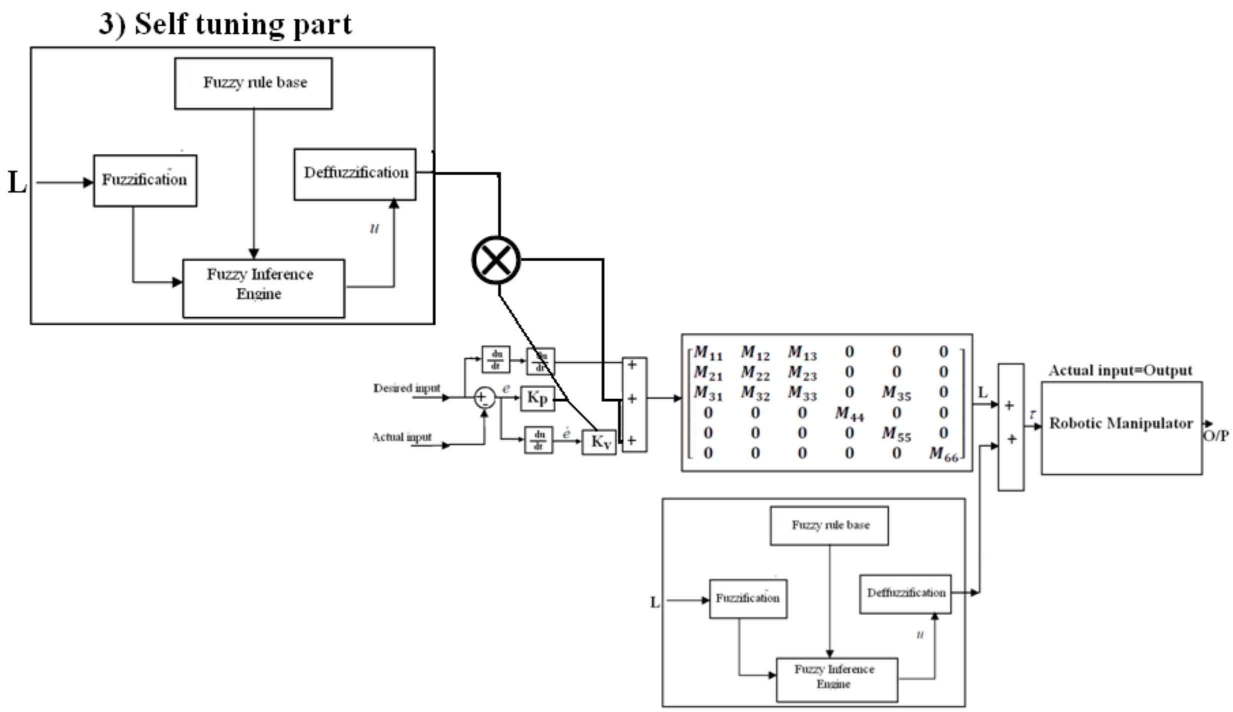

FIGURE 6: Block diagram of proposed self tuning fuzzy computed torque controller with minimum rule base in fuzzy nonlinear part and fuzzy supervisory.

7. SIMULATION RESULT

PD-Classical computed torque controller (PD-CTC), PD-fuzzy computed torque controller (PD-FCTC), and PD-self tuning fuzzy computed torque controller (PD-STFCTC) are implemented in Matlab/Simulink environment. Tracking performance, disturbance rejection and error are compared.

7.1 Tracking Performances:

From the simulation for first and second trajectory without any disturbance, it was seen that PD-STFCTC, PD-CTC and PD-FCTC have the same performance. This is primarily because this system is worked on certain environment. The STFCTC gives significant trajectory good following when compared to FCTC. Figure 7 shows tracking performance without any disturbance for STFCTC, PD-CTC and PD-FCTC.

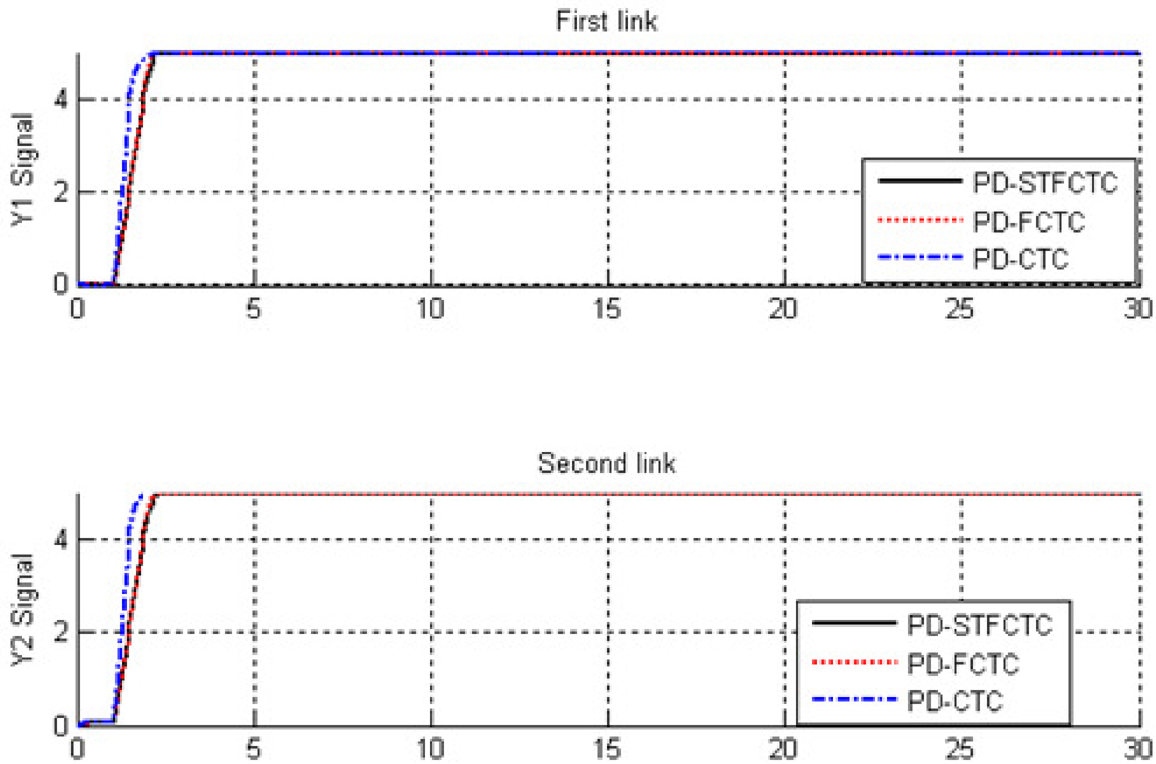

FIGURE 7: Step PD-CTC, PD-FCTC and PD-STFCTC for First and second link trajectory.

By comparing step response trajectory without disturbances in PD-CTC, PD-FCTC and PD-STFCTC it is found that the STFCTC's overshoot **(0%)** is lower than FCTC's **(1%)** and CTC's **(6.4%)**, although all of them have about the same rise time; CTC **(0.403 sec)**, FCTC and STFCTC **(0.5 sec)**.

7.2 Disturbance Rejection

Figure 8 has shown the power disturbance elimination in PD-CTC, PD-FCTC and PD-STFCTC. 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 Step CTC, FCTC and STFCTC. It found fairly fluctuations in CTC and FCTC trajectory responses. As mentioned earlier, CTC works very well when all parameters are known, this challenge plays important role to select the AFCTC as a based robust controller.

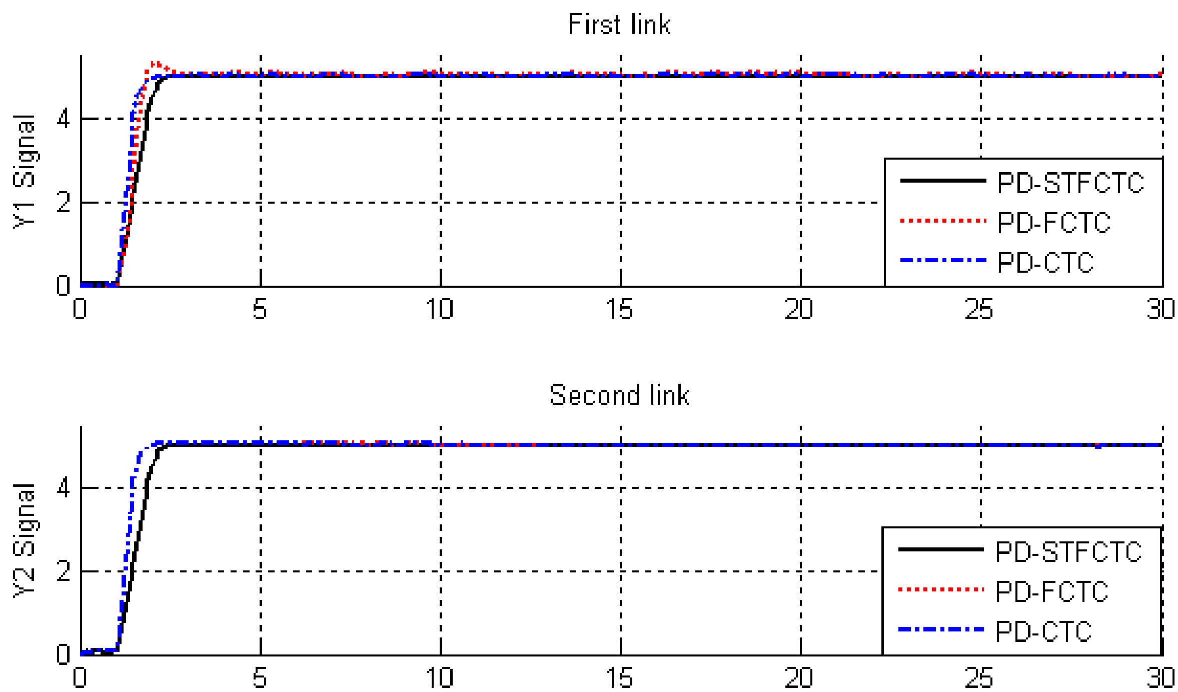

FIGURE 8: Step PD-CTC, PD-FCTC and PD-STFCTC for First and second link trajectory with external disturbances.

Among above graph relating to Step trajectory following with external disturbance, PD-CTC and PD-FCTC have fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the STFCTC's overshoot **(0%)** is lower than FCTC's **(8%)** and CTC's **(4%)**, although all of them have about the same rise time; CTC **(0.403 sec)** and FCTC and STFCTC **(0.5 sec).**

7.3 Calculate Errors

The values of RMS and steady state errors for various controllers are tabulated in tables 2 and 3.

8. CONCLUSION

This paper presents a new methodology for designing s self tuning fuzzy computed torque controller with minimum rule bases and high performance for 2 DOF robotic manipulator. From the simulation, it found that self tuning-FCTC has 7 rule base for supervisory and 7 rule base for main controller but in previous design by the other researcher has about 49 rules for supervisory and 49 rules for main controller because it has 2 inputs for main controller (PD) and also it has 2 inputs for supervisory controller $(e, and\ \dot{e})$therefore proposed method is easy to implement. The classical CTC works very well when all parameters are known. In self tuning FCTC, the fuzzy supervisory controller can changed K_p & K_v to achieve the best performance and in this method the supervisory controller is changed the gain updating factor of main FCTC to get the best performance. In one word the implementation of self tuning FCTC is easier than the previous method with more rule base and this reason plays important role in system controller.

Setup input without disturbance	*Overshoot%*		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	6.44%	1 %	0
Second link	6.44%	1%	0
	$Rise\ time_{(sec)}\ (Tr)$		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	0.403	0.5	0.5
Second link	0.403	0.5	0.5
	Steady state error		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	-3.6e-5	4e-5	0
Second link	-2.54e-5	4e-5	0
	$settling\ time_{(sec)}\ (Ts)$		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	0.9	0.76	0.65
Second link	0.9	0.76	0.60
	RMS error		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
RMS error	-1.34e-5	1.5e-5	0

TABLE 2: Three types of controllers summaries without disturbance.

Setup input with 40% disturbance	*Overshoot%*		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	4%	8 %	0
Second link	4%	8%	0
	$Rise\ time_{(sec)}\ (Tr)$		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	0.403	0.5	0.5
Second link	0.403	0.5	0.5
	Steady state error		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	0.005	-0.0019	0
Second link	0.005	-0.0019	0
	$settling\ time_{(sec)}\ (Ts)$		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
First link	1	0.8	0.65
Second link	1	0.8	0.60
	RMS error		
	PD-CTC	**PD-FCTC**	**PD-STSCTC**
RMS error	0.0042	0.0025	0.0001632

TABLE 3: Three types of controllers summaries with external disturbance.

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