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Trajectory Tracking Control and Robustness Analysis of a Robotic Manipulator Using Advanced Control Techniques

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Abstract

The main focuses are to design controlling systems of good disturbance, stability rejection, and small error-tracking. Trajectory tracking of robot manipulators are controlled by several methodologies, but when robot manipulator works with uncertain dynamic models, some limitations of this technique appear. Concerning the control perspective, such uncertainty can be divided into two groups: the unstructured inputs (e.g. disturbance effect) and the structure dynamics (e.g. the changes of parameter). Within a small number of applications, some environments, could be unknown or unstructured, make use of robot manipulators, along with some tools of strong mechanics also can make use of new methods of control to design a controller of nonlinear robust with a reasonable performance. So in this paper we test the effect of disturbance in control the first DOF of PUMA 560 using non model based FO-Fuzzy-PID controller and compared its results with two model based controllers (CTC, ANN). Also we study the effect of change of inertias parameters in the 2 cases Model based control and non- Model based control and then discus which controller give the best results. The main objective of this paper is that the non model based FO-Fuzzy-PID is able to emulate the manipulator dynamic behaviour without the need to have a complex nonlinear mathematical model for the robot.

Index Terms: PUMA560, Quintic polynomial trajectories planning, Computed Torque Control (CTC), Artificial Neural Network (ANN), Fractional Order-Fuzzy-PID (FO-Fuzzy-PID), Fractional Order PID (FOPID).

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1. Introduction

Different applications are making use of robot manipulators [1]. As a result of exceptionally gathering dynamics of nonlinear and time varying, the robot tracking control becomes one of the problems we face. In addition to the parameters uncertainty of both manipulators mechanical parts and the actuating systems that makes the process more complex. The design of robotic manipulators control offers a new opportunity of research for the control engineers because of the advancements achieved in the techniques based on intelligent control. Several algorithms, that are based on model controllers, are used in position control, like the method of computed torque [2], optimal control [3], Variable Structure Control (VSC) [4], Neural Networks (NNs) [5, 6], Fuzzy system [1] and a model based adaptive FOPID [7]. In general, model-based controllers need a model of ideal mechanism for the controlled manipulators, and in this way however to be very complicated and computationally time consuming, especially for higher DOF manipulators. On the other hand, in the non-model based, there is no need for the parameters data of manipulators, actuators, and subsequently there would be no need for any mathematical models as well [5].

In spite of the new advance achieved in the control area, PID is the most widely strategies of control used in industry due to the simple design and implementation [8, 9]. There are four main shortcomings in the traditional PID control: noise degradation in the derivative control, error computation, over simplicity, performance loss in a linear-weighted sum form within the control law, and the resulted complications of the integral control [10]. To overhaul the performance and robustness of PID systems of control, Podlubny proposed a general sort of the PID controllers, called FOPID controllers [11]. Fractional analytics are the arithmetic field that uses non-integer order to arrange integrals and derivatives. FOPID control is a recently emerged technology that was proved better performance than PID in several applications.

Effort to merge FOPID control with fuzzy was exerted recently. The trade-off between PID parameters tuning and its terms of fractional order can be minimized by the fuzzy-logic adaptive mechanism when selecting either term adaptively.

This paper aims at tracking the trajectory control of PUMA 560 first three joints of robot manipulator using non model based FO-Fuzzy-PID controller to get a trajectory of a fine quantic polynomial and with the least state of steadiness, errors of RMS, and good disturbance rejection. An excellent joint space tracking must be granted in the controller, to a specific trajectory through providing stability and less errors of tracking [12]. Finally, the proposed controller performance FO-Fuzzy-PID is compared to the other two model based ones; Computed Torque Control (CTC) and Artificial Neural Network (ANN) respectively for the trajectory tracking task. Furthermore, to prove how effective the proposed non-model based controller is, both Root Mean Square (RMS) and Steady State Errors (SSE) are discussed.

The paper in hand is organized as follows: presentation of the robot manipulator dynamic model in the second section. The third and the fourth sections introduce trajectory tracking control of the robot arm using CTC and model based ANN respectively. The fifth section introduces the principle of FOPID, while the sixth section introduces the trajectory tracking control of robot manipulator using non-model based FO-Fuzzy-PID controller. The seventh section deals with an illustration for simulation results of all developed controllers. And the last section includes the concluding remarks.

2. Trajectory Tracking Control Of Robot Manipulator Using Model-based PID-CTC

Computed torque controller (CTC) is an intense nonlinear controller that broadly utilized in the robot manipulator control. It depends on linearization of the feedback, and registers the needed arm torques utilizing the control law of nonlinear feedback. The best performance of this controller is shown when all physical and dynamic parameters are known. However, in case of various dynamic parameters of the robot manipulator, there would be no adequate performance of the controller [16, 17].

The application of CTC is to test its efficiency for trajectory tracking control of PUMA 560 robot manipulator. Genetic algorithm (GA) applied for tuning of PID gains kp , kd and K_i utilizing Integral Square-Error (ISE) to guarantee ideal controlling performance at specific conditions of nominal operating, where GA parameter [$kp_{\ 1}ki_1\ kd_1kp_{\ 2}ki_2\ kd_2kp_{\ 3}ki_3\ kd_3$] lower bounds =[0 0 0 0 0 0 0 0 0], upper bounds=[100 100 100 100 100 100 100 100 100]. The dynamic model of joint space of a robot manipulator is usually explained in the following equation (1).

$$\tau = M(q)\tau + C(q,\dot{q})\ + G(q) \tag{1}$$

Where τ, is a n×1 joint torques vector, according to the state of the joint, if it is revolute or prismatic. M (q) is a n × n symmetric and positive definite inertia matrix, and G (q) is a n ×1 gravitational torque vector, q: is a n×1 joint displacements vector, $\dot{q}$: is a n × 1 joint velocities vector,$\ddot{q}$: is a n×1 joint accelerations vector and *n* corresponds to the degrees number of robot freedom [14].

The linearization loop is accomplished with picking a torque τ applied to the robot as shown in “Fig. 1” [17].

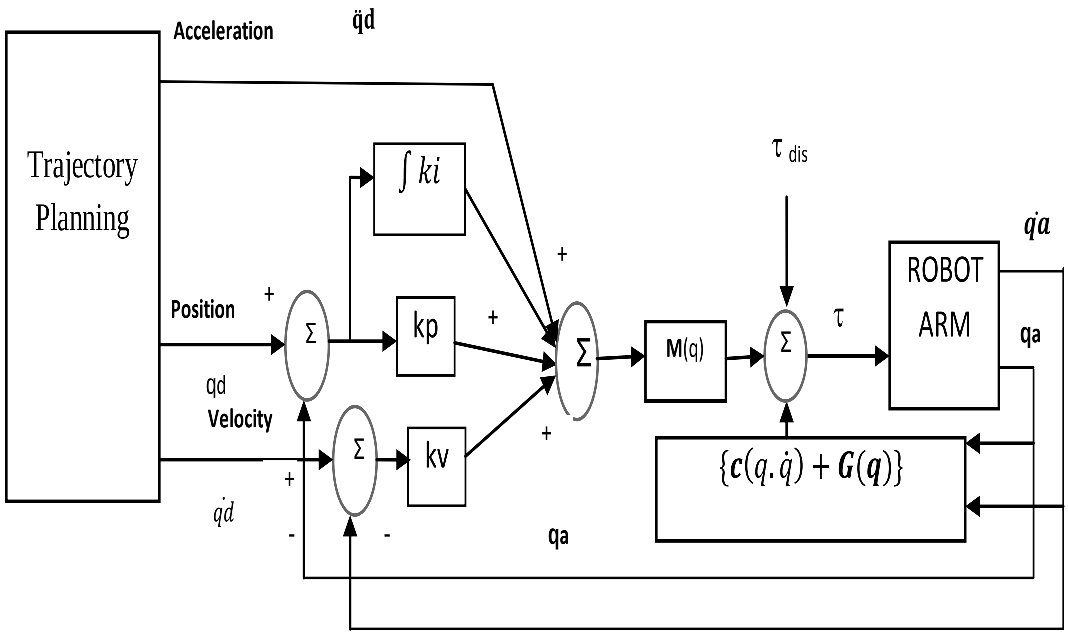

Fig.1. The Overall Block Diagram of the System based on PD-CTC Controller

$$\tau = M(q)\tau_0 + C(q,\dot{q})\ + G(q) \tag{2}$$

Substituting τ in equation (1) and considering *M* (*q*) that is a regular matrix, we have *n* decoupled linear systems:

$$\ddot{q} = \tau_0 \tag{3}$$

Where, τ_0 is an assistant input of the choice controller. A *PID* control is a common decision for τ_0 , shown in the equation:

$$\tau_0 = \ddot{q}_d + k_d(\dot{q}_d - \dot{q}) + k_p(q_d - q) + k_i \int (q_d - q) \quad (4)$$

Where, k_p, k_d *and* k_i are positive definite diagonal matrices q_d, $\dot{q}_d$ and $\ddot{q}_d$: are respectively the vectors of required position, velocity, and acceleration.

By the substitution of (3) in (4), the result is the following error equation:

$$[\ddot{E} + k_d\dot{E} + k_pE + k_i \int E(t)\, dt] = 0 \quad (5)$$

We posture in the following:

$E = qd - qa$: Vector of the position error, (6)

$\dot{E} = \dot{q}_d - \dot{q}_a$:Vector of the velocity error (7)

The error equation (6) has answer for an error *E* (*t*) that tends to zero. The aim of PID is to outline a trajectory tracking a robot arm controller by determination of a PID parameters gains k_p , k_d and k_i using genetic algorithm (GA).

The three gains of PID controller are calculated by ISE cost functions performance indices using GA where, the fitness value of the classical PID-GA is decreased to 1.15 x 10^{-10} after 51 generations. The three PID controller gains after tuning for joint1 (kp1=45.75 kv1=61.938 ki1=33.5) and for joint2 (kp2=51.5 kv2=56.599 ki2=24.5) and for joint3 (kp3=130.962 kv3=55.25 ki3=58.526) then modify this error signal to produce control input for system. Through such control input; the system is forced to produce as close as possible output to the reference level. The system is driven under control in case of the difference between reference input and instantaneous output reaches zero.

3. Trajectory Tracking Control of Robot Arm using Model-based ANN Controller

In this section the PID controller has been replaced with Neural Network blocks. The desired inputs position and velocity are compared with their corresponding outputs from the dynamic robot arm to determine the errors in position and velocity $\mathbf{e_p}$ and $\mathbf{e_v}$, respectively. Furthermore these two error signals are passed through ANN. The network consists of a three layer neural – network with two input nodes connected to ten neurons in hidden layer (with tan sigmoid transfer function) which is functioned for receiving the input data from the input layer, multiplying them according to the synaptic weights values denoted by, and forwarding the result values to the output layer (with purelin transfer function) (2-10-1).

4. Trajectory Tracking Control of Robot Manipulator using Non-model Based FO-Fuzzy-PID Controller

Fractional-order calculus (FOC) is a speculation of the conventional differentiation and integration that incorporate non integer orders [18]. The most well-known fractional order PID controller type is the $PI^{\lambda}D^{\mu}$. Including an order integrator λ and an order differentiator μ where λ and μ have the value of any real numbers. The orders of integral and derivative are not necessarily integer, but any real numbers. The FOPID controller has a transferring function explained in the following equation 8**[19]:**

$$G_c(s) = \frac{U(s)}{E(s)} = k_p + k_I \frac{1}{s^{\lambda}} + k_D s^{\mu}, (\lambda, \mu > 0) \quad (8)$$

Where $G_c(s)$ is the controller transfer function, E(s) refers to an error, and U(s) refers to the controller output. The fuzzy tries to change the FOPID parameters on-line to upgrade the response of the system and also help in disturbances elimination. This method is also utilized to decrease the consumption of energy distributed in the systems of environmental control. Besides, it helps keeping a high comfortable level of occupancy. The fuzzy tries to give the controller output a nonlinear action making use of fuzzy reasoning, where the FOPID gains are tuned based on a system of fuzzy inference rather than depending on the classic methods. The FO-Fuzzy-PID controller designing process is described in detail in [20]. The robot manipulator block diagram controlled by FO-Fuzzy-PID controller is presented in Fig. 2.

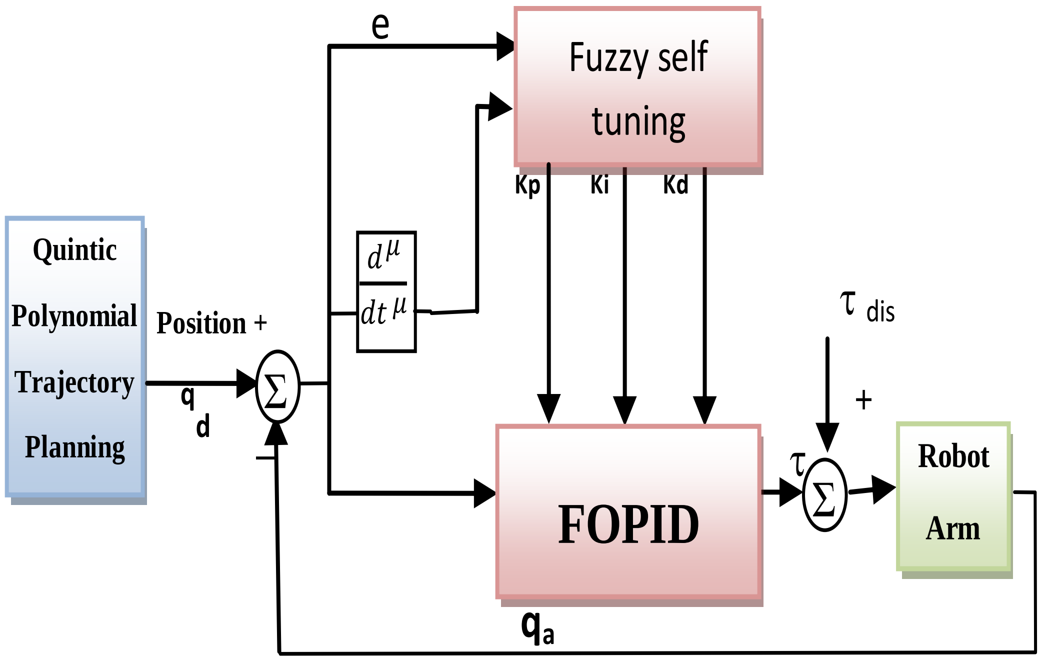

Fig.2. Structure of the block Diagram based on FO-Fuzzy-PID Controller.

5. Simulation Results

Through considering the PUMA 560 robot manipulator dynamics, the simulation is performed for the PUMA 560 first three DOF, by using MATLAB 2013b [14, 13]. According to the implemented studies of Armstrong and Corke; all data of the gravitational and inertial constants are presented in Appendix [4, 20] based on [13]. The main aim of implementing this simulation is to show how efficient the suggested FO-Fuzzy-PID is, by tracking controller compared with two model based controllers namely CTC and ANN where, all controllers tested to quintic polynomial trajectories [20].

1.1. CTC Results Without Any Effect Of Disturbances Or Parameters Uncertainty

The simulation is carried out to see its effect on the robot arm where, the position error angle for joints 1, 2 and 3 of PUMA 560 robot arm controlled using CTC are shown in Figs. 3, 4 and 5 respectively.

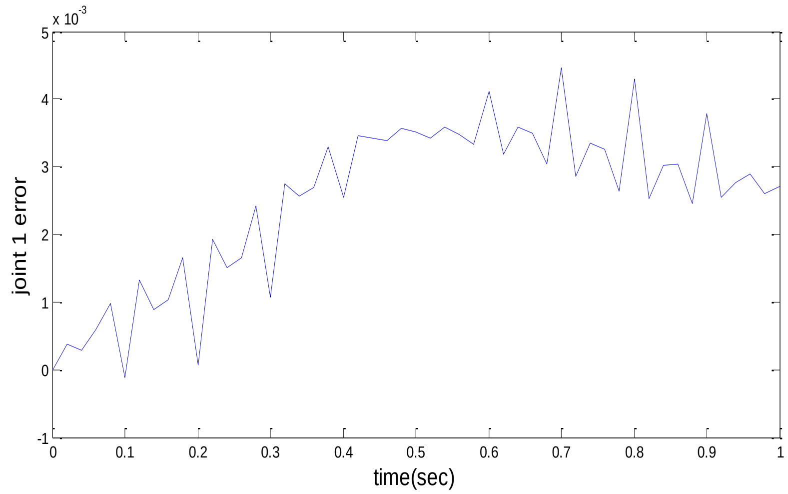

Fig.3. Error Angle for Joint 1 Controlled using PID-CTC.

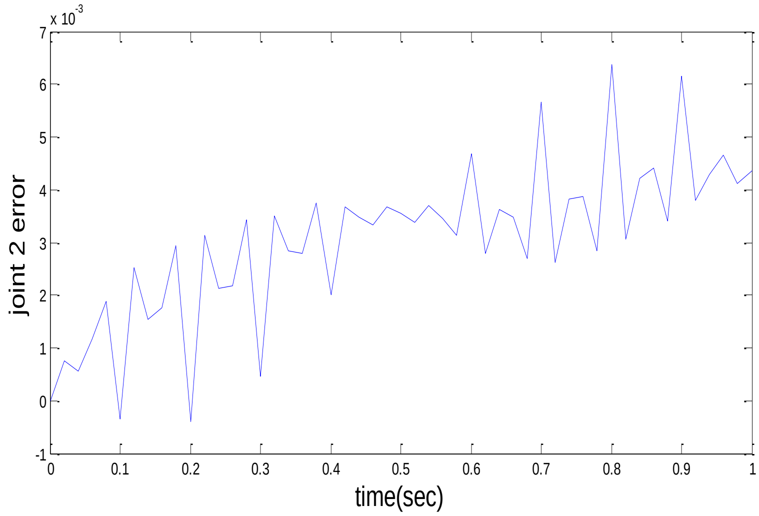

Fig.4. Error Angle for Joint 2 Controlled using PID-CTC.

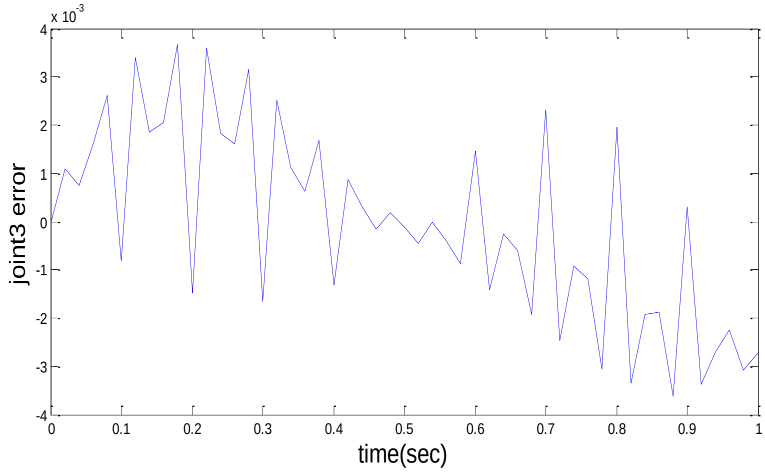

Fig.5. Error Angle for Joint 3 Controlled using PID-CTC.

Based on the results it was found with quintic polynomial trajectory tracking input that the model based CTC errors (Steady State error for joint1=0.0002922, joint2=0.0003984, joint3=-0.001and RMS error=0.0002818).

1.2. ANN Results Without Any Effect of Disturbances or Parameters Uncertainty

By simulation results it was appeared that the position error angle for joints 1, 2 and 3 of PUMA 560 robot arm controlled utilizing ANN controller are shown in Figures 6, 7 and 8 respectively.

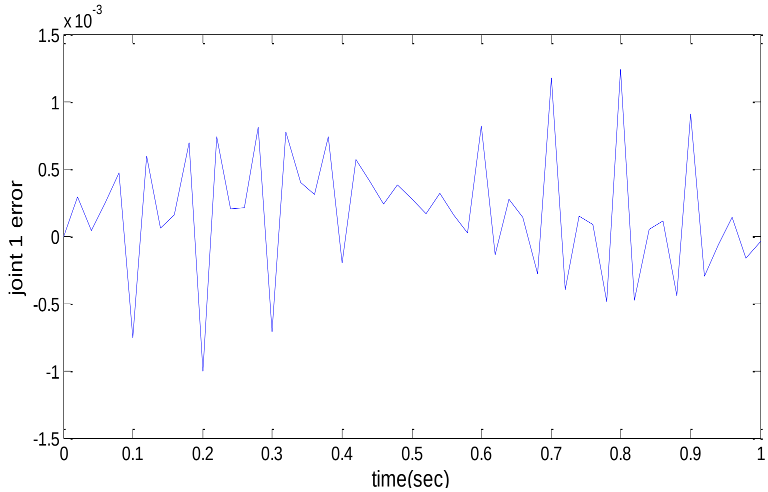

Fig.6. Error Angle for Joint 1 Controlled using model based ANN.

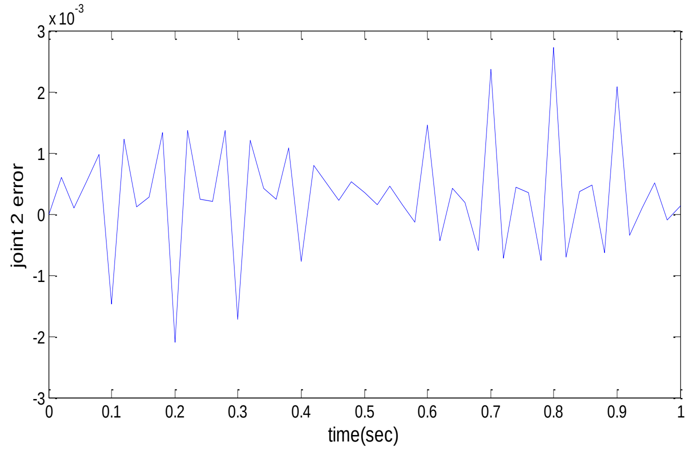

Fig.7. Error Angle for Joint 2 Controlled using model based ANN.

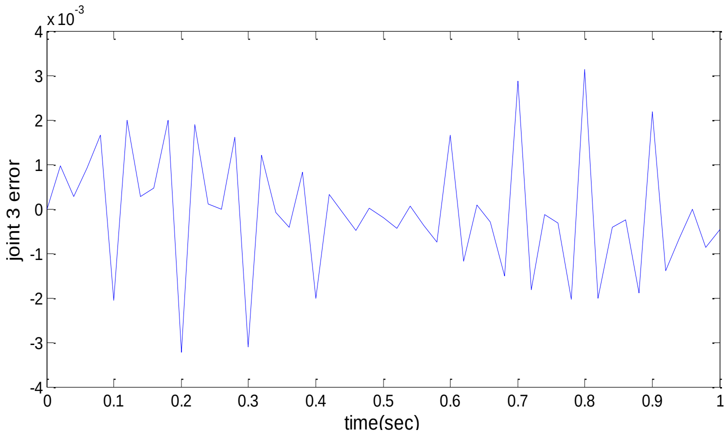

Fig.8. Error Angle between them for Joint 3 Controlled using model based ANN.

From the simulation results it was found with quintic polynomial trajectory tracking input that steady state and RMS errors in a system controlled using model based ANN's (Steady State error for joint1= 0.0002, joint2=0, joint3=0 and RMS error=0.0001591). Robot arm controlled using model based ANN controller has fast response and small errors compared with the CTC.

1.3. The Non Model based FO-fuzzy-PID Controller Results Without Any Effect of Disturbances or Parameters Uncertainty

In this section the results for joints 1, 2 and 3 of PUMA 560 robot manipulator controlled utilizing non-model based FO-fuzzy-PID controller with respect quintic polynomial trajectory tracking are presented .

After simulation it was noticed that the position error angle for joints 1, 2 and 3 controlled utilizing FO-fuzzy-PID controllers with respect to quantic polynomial trajectory planning are appeared in Figs. 9, 10 and 11 respectively.

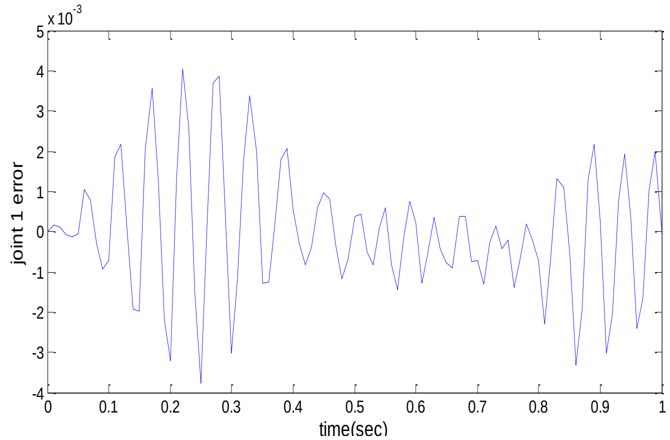

Fig.9. Error Angle for Joint 1 Controlled using Non-model based FO-Fuzzy-PID.

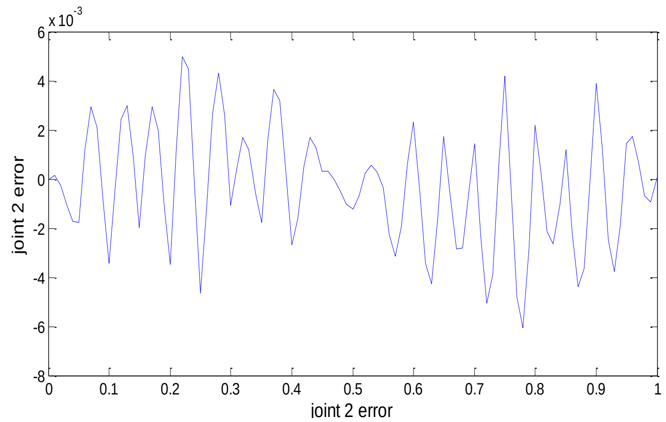

Fig.10. Error Angle for Joint 2 Controlled using Non-model based FO-Fuzzy-PID.

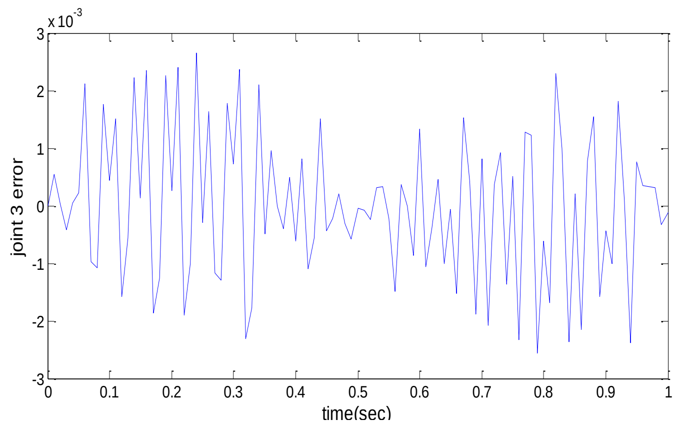

Fig.11. Error Angle for Joint 3 Controlled using Non-model based FO-Fuzzy-PID

It was appeared with quintic polynomial tracking input that the FO-Fuzzy-PID's errors (Steady State error for joint1=-6.953*10*10^{-5}, joint2=9.417*10^{-5}, joint3=-0.0001216 and RMS error=4.407*10^{-5}).

1.4. Comparisons Results between Model based Controllers (CTC, ANN) and Non-model based Controller (FO-Fuzzy-PID) with and Without Effect Of Disturbance or Parameter Uncertainty

From the previous two cases it was observed that trajectory tracking control utilizing non model based FO-Fuzzy-PID give a good results compared with trajectory tracking control utilizing model based PID-CTC and ANN controller without any effect of disturbances or parameters uncertainty as shown in table 1.

The difference between the effects of the disturbance joint torques on the joint positions in model based case can be clearly appeared in table 2 where the disturbance torque of the joints has a greater effect on the angular position of the all joints than the effect of the disturbance torque on joints angular position in case of non-model based. As appeared in table5 and table3 gives a complete comparison between the two cases with effect of disturbances and model parameter uncertainty.

Due to a non-model based control methodology did not need a prerequisite knowledge of the manipulator parameters and hence no mathematical model for the manipulator was required and practically difficult to implemented. By comparing the results of the previous two cases we can conclude that robot arm control utilizing non model based FO-Fuzzy-PID controller didn't effected by the disturbance and uncertainty parameters compared with the model based control as appeared in the simulation results and tables.

Table 1. Comparison between Non Model FO- Fuzzy-PID and Model based PID-CTC, ANN, for Trajectory Tracking Control of Robot Manipulator Without Effect of Disturbances or Parameter Uncertainties.

Controller type		RMS error	SSE for j1	SSE for j2	SSE for j3
Non-model based	FO-Fuzzy–PID controller	4.407*10^{-5}	-7.953*10^{-5}	9.417*10^{-5}	-0.000121
Model based	PID-CTC	0.0002818	0.0002922	0.0003984	-0.001
	ANN controller	0.0001591	0	0	0

Table 2. Comparison between Non Model based FO- Fuzzy-PID and Model based PID-CTC and ANN for Trajectory Tracking Control of Robot Manipulator with Effect of Disturbances.

Controller type		Disturbance value 1.0 sin 50t			
		J1	J2	J3	All joint
Non-model based	FO-Fuzzy–PID controller	0.0001172	0.0001072	4.286*10^{-5}	0.0001172
Model based	PID-CTC	0.000281	0.000284	0.0002856	0.0002862
	ANN controller	0.0001589	0.0001576	0.0001253	0.000124

Table 3. Comparison between Non Model FO- Fuzzy-PID and Model based PID-CTC and ANN for Trajectory Tracking Control of Robot Manipulator with Effect of Parameter Uncertainty.

Controller type		RMSE	SSE for j1	SSE for j2	SSE for j3
Non-model based	FO-Fuzzy–PID controller	0.0006234	0.001249	0.0006579	0
Model based	PID-CTC	0.002731	-0.0004123	-0.0007618	0.005554
	ANN controller	0.005054	-0.0007479	-0.002394	-0.009216

6. Conclusion

This paper investigated the possibility of improving the trajectory tracking performance of a PUMA 560 robotic manipulator utilizing non-model based FO-Fuzzy-PID controllers dependent on joint space control in its main target. Its results are compared with two model based controllers namely CTC and ANN. Also it was tested the effect of disturbance in all controllers, study the effect of change of inertias parameters in the joints of the robot arm in 2 cases Model based control and non- Model based control. The performance of each of the controllers based control strategy was compared with that of the others controllers through carrying out several simulations of the robotic arm using SIMULINK under MATLAB2013a.

From the simulation results it was concluded that:

- These results appear that non model based FO-Fuzzy-PID controller has performed a response of better, fast, and smaller errors for quintic polynomial trajectory control of robot arm than the other model based controllers without any effect of disturbance or parameters uncertainty.
- By simulation results it was observed that non model based FO-Fuzzy-PID controller performance is better than the other controllers for the external disturbance rejection.
- The fast convergence of learning enables the proposed non model based FO-Fuzzy-PID controller to adaptively adjust the parameters and keep the tracking error at a low level in spite of external disturbances and uncertain conditions.
- From the previous two cases it was observed that trajectory tracking control using non model based FO-Fuzzy-PID give good results compared with trajectory tracking control using model based PID-CTC and ANN controller with effect of disturbances or parameters uncertainty.
- Non model based FO-Fuzzy-PID is able to emulate the manipulator dynamic behavior without the need to have a complex nonlinear mathematical model for the robot.

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