PUMA-560 Robot Manipulator Position Computed Torque Control Methods Using MATLAB/SIMULINK and Their Integration into Graduate Nonlinear Control and MATLAB Courses

Farzin Piltan SSP.ROBOTIC@yahoo.com
Industrial Electrical and Electronic
Engineering SanatkadeheSabze
Pasargad. CO (S.S.P. Co), NO:16
,PO.Code 71347-66773, Fourth floor
Dena Apr , Seven Tir Ave , Shiraz , Iran

Mohammad Hossein Yarmahmoudi SSP.ROBOTIC@yahoo.com
Industrial Electrical and Electronic
Engineering SanatkadeheSabze
Pasargad. CO (S.S.P. Co), NO:16
,PO.Code 71347-66773, Fourth floor
Dena Apr , Seven Tir Ave , Shiraz , Iran

Mohammad Shamsodini SSP.ROBOTIC@yahoo.com
Industrial Electrical and Electronic
Engineering SanatkadeheSabze
Pasargad. CO (S.S.P. Co), NO:16
,PO.Code 71347-66773, Fourth floor
Dena Apr , Seven Tir Ave , Shiraz , Iran

Ebrahim Mazlomian SSP.ROBOTIC@yahoo.com
Industrial Electrical and Electronic
Engineering SanatkadeheSabze
Pasargad. CO (S.S.P. Co), NO:16
,PO.Code 71347-66773, Fourth floor
Dena Apr , Seven Tir Ave , Shiraz , Iran

Ali Hosainpour SSP.ROBOTIC@yahoo.com
Industrial Electrical and Electronic
Engineering SanatkadeheSabze
Pasargad. CO (S.S.P. Co), NO:16
,PO.Code 71347-66773, Fourth floor
Dena Apr , Seven Tir Ave , Shiraz , Iran

Abstract

This paper describes the MATLAB/SIMULINK realization of the PUMA 560 robot manipulator position control methodology. This paper focuses on design, analyzed and implements nonlinear computed torque control (CTC) methods. These simulation models are developed as a part of a software laboratory to support and enhance graduate/undergraduate robotics courses, nonlinear control courses and MATLAB/SIMULINK courses at research and development company (SSP Co.) research center, Shiraz, Iran.

Keywords: MATLAB/SIMULINK, PUMA 560 Robot Manipulator, Position Control Method, Computed Torque Control, Robotics, Nonlinear Control.

1. INTRODUCTION

Computer modeling, simulation and implementation tools have been widely used to support and develop nonlinear control, robotics, and MATLAB/SIMULINK courses. MATLAB with its toolboxes such as SIMULINK [1] is one of the most accepted software packages used by researchers to enhance teaching the transient and steady-state characteristics of control and robotic courses [3_7]. In an effort to modeling and implement robotics, nonlinear control and advanced MATLAB/SIMULINK courses at research and development SSP Co., authors have developed MATLAB/SIMULINK models for learn the basic information in field of nonlinear control and industrial robot manipulator [8, 9].

Controller is a device which can sense information from linear or nonlinear system (e.g., robot manipulator) to improve the systems performance [3]. The main targets in designing control systems are stability, good disturbance rejection, and small tracking error[5]. Several industrial robot manipulators are controlled by linear methodologies (e.g., Proportional-Derivative (PD) controller, Proportional- Integral (PI) controller or Proportional- Integral-Derivative (PID) controller), but when robot manipulator works with various payloads and have uncertainty in dynamic models this technique has limitations. From the control point of view, uncertainty is divided into two main groups: uncertainty in unstructured inputs (e.g., noise, disturbance) and uncertainty in structure dynamics (e.g., payload, parameter variations). In some applications robot manipulators are used in an unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design nonlinear robust controller with an acceptable performance (e.g., minimum error, good trajectory, disturbance rejection). 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 design a feedback controller that allows the actual motion ($q_a(t)$) tracking of the desired motion ($q_d(t)$). 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 [6]. Figure 1 shows the main block diagram of joint space controller. 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[6]. Figure 2 shows the main block diagram of operational space control.

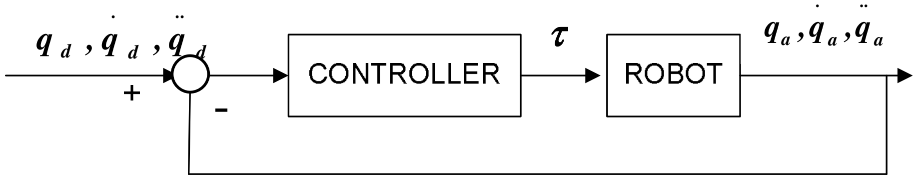

FIGURE 1: Block diagram of joint space control

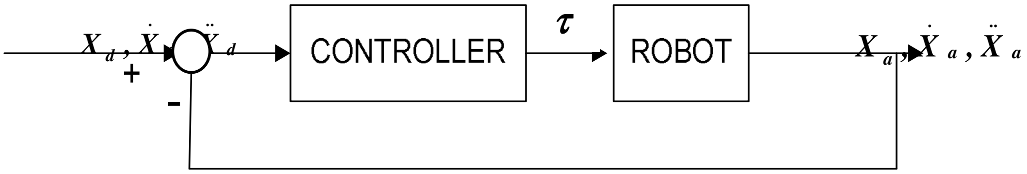

FIGURE 2: Block diagram of operational space control

Computed torque controller (CTC) is a powerful nonlinear controller which it widely used in control of robot manipulator. It is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. This controller works very well when all dynamic and physical parameters are known but when the robot manipulator has variation in dynamic parameters, in this situation the controller has no acceptable performance[14]. In practice, most of physical systems (e.g., robot manipulators) parameters are unknown or time variant, therefore, computed torque like controller used to compensate dynamic equation of robot manipulator[1, 6]. Research on computed torque controller is significantly growing on robot manipulator application which has been reported in [1, 6, 15-16]. Vivas and Mosquera [15]have proposed a predictive functional controller and compare to computed torque controller for tracking response in uncertain environment. However both controllers have been used in feedback linearization, but predictive strategy gives better result as a performance. A computed torque control with non parametric regression models have been presented for a robot arm[16]. This controller also has been problem in uncertain dynamic models. Based on [1, 6]and [15-16] computed torque controller is a significant nonlinear controller to certain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law.

This paper is organized as follows:
In section 2, dynamic formulation of robot manipulator is presented. Detail of classical CTC and MATLAB/SIMULINK implementation of this controller is presented in section 3. In section 4, the simulation result is presented and finally in section 5, the conclusion is presented.

2. PUMA 560 ROBOT MANIPULATOR DYNAMIC FORMULATION

Dynamics of PUMA560 Robot Manipulator: To position control of robot manipulator, the second three axes are locked the dynamic equation of PUMA robot manipulator is given by [77-80];

$$M(\theta)\begin{bmatrix}\ddot{\theta}1\\ \ddot{\theta}_2\\ \ddot{\theta}_3\end{bmatrix}+\mathrm{B}(\theta)\begin{bmatrix}\dot{\theta}_1\dot{\theta}_2\\ \dot{\theta}_1\dot{\theta}_3\\ \dot{\theta}_2\dot{\theta}_3\end{bmatrix}+C(\theta)\begin{bmatrix}\dot{\theta}_1^2\\ \dot{\theta}_2^2\\ \dot{\theta}_3^2\end{bmatrix}+G(\theta)=\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\end{bmatrix} \tag{1}$$

Where

$$M(q)=\begin{bmatrix}M_{11} & M_{12} & M_{13} & 0 & 0 & 0\\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0\\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0\\ 0 & 0 & 0 & M_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & M_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & M_{66}\end{bmatrix} \tag{2}$$

M is computed as

$$\begin{aligned}&M_{11} =\\ &I_{m1}+I_1+I_3\times\cos(\theta_2)\cos(\theta_2)+I_7\sin(\theta_2+\theta_3)\sin(\theta_2+\theta_3)+I_{10}\sin(\theta_2+\theta_3\\ &I_{11}\sin(\theta_2)\cos(\theta_2)+I_{21}\sin(\theta_2+\theta_3)\sin(\theta_2+\theta_3)+2+[I_5\cos(\theta_2)\sin(\theta_2+\theta_3)\\ &I_{12}\cos(\theta_2)\cos(\theta_2+\theta_3)+I_{15}\sin(\theta_2+\theta_3)\sin(\theta_2+\theta_3)+I_{16}\cos(\theta_2)\sin(\theta_2+\theta_3)\\ &\theta_3)\cos(\theta_2+\theta_3)\end{aligned} \tag{3}$$

$$M_{12}=I_4\sin(\theta_2)+I_8\cos(\theta_2+\theta_3)+I_9cos(\theta_2)+I_{13}\sin(\theta_2+\theta_3)-I_{18}\cos(\theta_2+ \tag{4}$$

$$M_{13} = I_8\cos(\theta_2 + \theta_3) + I_{13}\sin(\theta_2 + \theta_3) - I_{18}\cos(\theta_2 + \theta_3) \tag{5}$$

$$M_{22} = I_{m2} + I_2 + I_6 + 2[I_5\sin(\theta_3) + I_{12}\cos(\theta_2) + I_{15} + I_{16}\sin(\theta_3) \tag{6}$$

$$M_{23} = I_5\sin(\theta_3) + I_6 + I_{12}\cos(\theta_3) + I_{16}\sin(\theta_3) + 2I_{15} \tag{7}$$

$$M_{33} = I_{m3} + I_6 + 2I_{15} \tag{8}$$

$$M_{35} = I_{15} + I_{17} \tag{9}$$

$$M_{44} = I_{m4} + I_{14} \tag{10}$$

$$M_{55} = I_{m5} + I_{17} \tag{11}$$

$$M_{66} = I_{m6} + I_{23} \tag{12}$$

$$M_{21} = M_{12}\ , M_{31} = M_{13}\ and\ M_{32} = M_{23} \tag{13}$$

and Corilios (B) matrix is calculated as the following

$$B(q) = \begin{bmatrix} b_{112} & b_{113} & 0 & b_{115} & 0 & b_{123} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & b_{214} & 0 & 0 & b_{223} & 0 & b_{225} & 0 & 0 & b_{235} & 0 & 0 & 0 & 0 \\ 0 & 0 & b_{314} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ b_{412} & b_{412} & 0 & b_{415} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & b_{514} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{14}$$

Where,

$$b_{112} = 2[- I_3\sin(\theta_2)\cos(\theta_2) + I_5\cos(\theta_2 + \theta_2 + \theta_3) + I_7\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3 \\ \theta_2 + \theta_3) - I_{15}2\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) + I_{16}\cos(\theta_2 + \theta_2 + \theta_3) + I_{21}\sin(\theta_2 + \\ \theta_3) + I_{22}(1 - 2\sin(\theta_2 + \theta_3)\sin(\theta_2 + \theta_3))] + I_{10}(1 - 2\sin(\theta_2 + \theta_3)\sin(\theta_2 + \theta_3)) \\ 2\sin(\theta_2)\sin(\theta_2)) \tag{15}$$

$$b_{113} = 2[I_5\cos(\theta_2)\cos(\theta_2 + \theta_3) + I_7\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) - I_{12}\cos(\theta_2)\sin(\\ I_{15}2\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) + I_{16}\cos(\theta_2)\cos(\theta_2 + \theta_3) + I_{21}\sin(\theta_2 + \theta_3)\cos(\theta \\ I_{22}(1 - 2\sin(\theta_2 + \theta_3)\sin(\theta_2 + \theta_3))] + I_{10}(1 - 2\sin(\theta_2 + \theta_3)\sin(\theta_2 + \theta_3)) \tag{16}$$

$$b_{115} = 2[-\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) + I_{15}2\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) + I_{16}\cos(\theta \\ \theta_3) + I_{22}\cos(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3)] \tag{17}$$

$$b_{123} = 2[-I_8\sin(\theta_2 + \theta_3) + I_{13}\cos(\theta_2 + \theta_3) + I_{18}\sin(\theta_2 + \theta_3)] \tag{18}$$

$$b_{214} = I_{14}\sin(\theta_2 + \theta_3) + I_{19}\sin(\theta_2 + \theta_3) + 2I_{20}\sin(\theta_2 + \theta_3)(1 - 0.5) \tag{19}$$

$$b_{223} = 2[-I_{12}\sin(\theta_3) + I_5\cos(\theta_3) + I_{16}\cos(\theta_3)] \tag{20}$$

$$b_{235} = 2[I_{16}\cos(\theta_3) + I_{22}] \tag{21}$$

$$b_{314} = 2[I_{20}\sin(\theta_2 + \theta_3)(1 - 0.5)] + I_{14}\sin(\theta_2 + \theta_3) + I_{19}\sin(\theta_2 + \theta_3) \tag{22}$$

$$b_{412} = b_{214} = -[I_{14}\sin(\theta_2 + \theta_3) + I_{19}\sin(\theta_2 + \theta_3) + 2I_{20}\sin(\theta_2 + \theta_3)(1 - 0.5)] \tag{23}$$

$$b_{413} = -b_{314} = -2[I_{20}\sin(\theta_2 + \theta_3)(1 - 0.5)] + I_{14}\sin(\theta_2 + \theta_3) + I_{19}\sin(\theta_2 + \theta_3 \tag{24}$$

$$b_{415} = -I_{20}\sin(\theta_2 + \theta_3) - I_{17}\sin(\theta_2 + \theta_3) \tag{25}$$

$$b_{514} = -b_{415} = I_{20}\sin(\theta_2 + \theta_3) + I_{17}\sin(\theta_2 + \theta_3) \tag{26}$$

consequently coriolis matrix is shown as bellows;

$$B(q).\dot{q}\dot{q} = \begin{bmatrix} b_{112}.\dot{q}_1\dot{q}_2 + b_{113}.\dot{q}_1\dot{q}_3 + 0 + b_{123}.\dot{q}_2\dot{q}_3 \\ 0 + b_{223}.\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}.\dot{q}_1\dot{q}_2 + b_{413}.\dot{q}_1\dot{q}_3 + 0 \\ 0 \\ 0 \end{bmatrix} \tag{27}$$

Moreover Centrifugal (C) matrix is demonstrated as

$$C(q) = \begin{bmatrix} 0 & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & 0 & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ C_{51} & C_{52} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{28}$$

Where,

$$c_{12} = I_4\cos(\theta_2) - I_8\sin(\theta_2 + \theta_3) - I_9\sin(\theta_2) + I_{13}\cos(\theta_2 + \theta_3) + I_{18}\sin(\theta_2 + \theta \tag{29}$$

$$c_{13} = 0.5b_{123} = -I_8\sin(\theta_2 + \theta_3) + I_{13}\cos(\theta_2 + \theta_3) + I_{18}\sin(\theta_2 + \theta_3) \tag{30}$$

$$\begin{aligned} c_{21} = -0.5b_{112} = {} & I_3\sin(\theta_2)\cos(\theta_2) - I_5\cos(\theta_2 + \theta_2 + \theta_3) - I_7\sin(\theta_2 + \theta_3)\cos \\ & I_{12}\sin(\theta_2 + \theta_2 + \theta_3) + I_{15}2\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) - I_{16}\cos(\theta_2 + \theta_2 + \theta_3) - I \\ & \theta_3)\cos(\theta_2 + \theta_3) - I_{22}(1 - 2\sin(\theta_2 + \theta_3)\sin(\theta_2 + \theta_3)) - 0.5I_{10}(1 - 2\sin(\theta_2 + \theta \\ & \theta_3)) - 0.5I_{11}(1 - 2\sin(\theta_2)\sin(\theta_2)) \end{aligned} \tag{31}$$

$$c_{22} = 0.5b_{223} = -I_{12}\sin(\theta_3) + I_5\cos(\theta_3) + I_{16}\cos(\theta_3) \tag{32}$$

$$\begin{aligned} c_{23} = -0.5b_{113} = {} & -I_5\cos(\theta_2)\cos(\theta_2 + \theta_3) - I_7\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) + I_{12} \\ & \theta_2) - I_{15}2\sin(\theta_2 + \theta_3)\cos(\theta_2 + \theta_3) - I_{16}\cos(\theta_2)\cos(\theta_2 + \theta_3) - I_{21}\sin(\theta_2 + \theta_3) \\ & I_{22}(1 - 2\sin(\theta_2 + \theta_3)\sin(\theta_2 + \theta_3)) - 0.5I_{10}(1 - 2\sin(\theta_2 + \theta_3)\sin(\theta_2 + \theta_3)) \end{aligned} \tag{33}$$

$$c_{31} = -c_{23} = I_{12}\sin(\theta_3) - I_5\cos(\theta_3) - I_{16}\cos(\theta_3) \tag{34}$$

$$c_{32} = -0.5b_{115} = \\ \sin(\theta_2+\theta_3)\cos(\theta_2+\theta_3) - I_{15}2\sin(\theta_2+\theta_3)\cos(\theta_2+\theta_3) - I_{16}\cos(\theta_2)\cos(\theta_2 + \\ I_{22}\cos(\theta_2+\theta_3)\cos(\theta_2+\theta_3) \tag{35}$$

$$c_{52} = -0.5b_{225} = -I_{16}\cos(\theta_3) - I_{22} \tag{36}$$

In this research $q_4 = q_5 = q_6 = 0$, as a result

$$C(q).\dot{q}^2 = \begin{bmatrix} c_{112}.\dot{q}_2^2 + c_{13}.\dot{q}_3^2 \\ c_{21}.\dot{q}_1^2 + c_{23}.\dot{q}_3^2 \\ c_{13}.\dot{q}_1^2 + c_{32}.\dot{q}_2^2 \\ 0 \\ c_{51}.\dot{q}_1^2 + c_{52}.\dot{q}_2^2 \\ 0 \end{bmatrix} \tag{37}$$

Gravity (G) Matrix can be written as

$$G(q) = \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix} \tag{38}$$

Where,

$$G_2 = g_1\cos(\theta_2) + g_2\sin(\theta_2+\theta_3) + g_3\sin(\theta_2) + g_4\cos(\theta_2+\theta_3) + g_5\sin(\theta_2 + \tag{39}$$

$$G_3 = g_2\sin(\theta_2+\theta_3) + g_4\cos(\theta_2+\theta_3) + g_5\sin(\theta_2+\theta_3) \tag{40}$$

$$G_5 = g_5\sin(\theta_2+\theta_3) \tag{41}$$

Suppose $\ddot{q}$ is written as follows

$$\ddot{q} = M^{-1}(q).\{\tau - [B(q)\dot{q}\dot{q} + C(q)\dot{q}^2 + g(q)]\} \tag{42}$$

and K is introduced as

$$K = \{\tau - [B(q)\dot{q}\dot{q} + C(q)\dot{q}^2 + g(q)]\} \tag{43}$$

$\ddot{q}$ can be written as

$$\ddot{q} = M^{-1}(q).K \tag{44}$$

Therefore K for PUMA robot manipulator is calculated by the following equations

$$K_1 = \tau_1 - [\,b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3] - [\,C_{12}\dot{q}_2{}^2 + C_{13}\dot{q}_3{}^2] - g_1 \tag{45}$$

$$K_2 = \tau_2 - [\,b_{223}\dot{q}_2\dot{q}_3] - [\,C_{21}\dot{q}_1{}^2 + C_{23}\dot{q}_3{}^2] - g_2 \tag{46}$$

$$K_3 = \tau_3 - \left[C_{31}\dot{q}_1{}^2 + C_{32}\dot{q}_2{}^2\right] - g_3 \tag{47}$$

$$K_4 = \tau_4 - [\, b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3] - g_4 \tag{48}$$

$$K_5 = \tau_5 - [\, C_{51}\dot{q}_1{}^2 + C_{52}\dot{q}_2{}^2] - g_5 \tag{49}$$

$$K_6 = \tau_6 \tag{50}$$

An information about inertial constant and gravitational constant are shown in Tables 1 and 2 based on the studies carried out by Armstrong [80] and Corke and Armstrong [81].

$I_1 = 1.43 \pm 0.05$	$I_2 = 1.75 \pm 0.07$
$I_3 = 1.38 \pm 0.05$	$I_4 = 0.69 \pm 0.02$
$I_5 = 0.372 \pm 0.031$	$I_6 = 0.333 \pm 0.016$
$I_7 = 0.298 \pm 0.029$	$I_8 = -0.134 \pm 0.014$
$I_9 = 0.0238 \pm 0.012$	$I_{10} = -0.0213 \pm 0.0022$
$I_{11} = -0.0142 \pm 0.0070$	$I_{12} = -0.011 \pm 0.0011$
$I_{13} = -0.00379 \pm 0.0009$	$I_{14} = 0.00164 \pm 0.000070$
$I_{15} = 0.00125 \pm 0.0003$	$I_{16} = 0.00124 \pm 0.0003$
$I_{17} = 0.000642 \pm 0.0003$	$I_{18} = 0.000431 \pm 0.00013$
$I_{19} = 0.0003 \pm 0.0014$	$I_{20} = -0.000202 \pm 0.0008$
$I_{21} = -0.0001 \pm 0.0006$	$I_{22} = -0.000058 \pm 0.00001$
$I_{23} = 0.00004 \pm 0.00002$	$I_{m1} = 1.14 \pm 0.27$
$I_{m2} = 4.71 \pm 0.54$	$I_{m3} = 0.827 \pm 0.093$
$I_{m4} = 0.2 \pm 0.016$	$I_{m5} = 0.179 \pm 0.014$
$I_{m6} = 0.193 \pm 0.016$	

TABLE 1: Inertial constant reference (Kg.m^2)

$g_1 = -37.2 \pm 0.5$	$g_2 = -8.44 \pm 0.20$
$g_3 = 1.02 \pm 0.50$	$g_4 = 0.249 \pm 0.025$
$g_5 = -0.0282 \pm 0.0056$	

TABLE 2: Gravitational constant (*N.m*)

3. CONTROL: COMPUTED TORQUE CONTROLLER ANALYSIS, MODELLING AND IMPLEMENTATION ON PUMA 560 ROBOT MANIPULATOR

Computed torque controller (CTC) is a powerful nonlinear controller which it widely used in control of robot manipulator. It is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. This controller works very well when all dynamic and physical parameters are known but when the robot manipulator has variation in dynamic parameters, in this situation the controller has no acceptable performance[14]. In practice, most of physical systems (e.g., robot manipulators) parameters are unknown or time variant, therefore, computed torque like controller used to compensate dynamic equation of robot manipulator[1, 6]. Research on computed torque controller is significantly growing on robot manipulator application which has been reported in [1, 6, 15-16]. Vivas and Mosquera [15]have proposed a predictive functional controller and compare to computed torque controller for tracking response in uncertain environment. However both controllers have been used in feedback linearization, but predictive strategy gives better result as a performance. A computed torque control with non parametric regression models have been presented for a robot arm[16]. This controller also has been problem in uncertain dynamic models. Based on [1, 6]and [15-16] computed torque controller is a significant nonlinear controller to certain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. When all dynamic and physical parameters are known, computed torque controller works fantastically; practically a large amount of systems have uncertainties, therefore sliding mode controller is one of the best case to solve this challenge.

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

$$e(t) = q_d(t) - q_a(t) \tag{51}$$

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

$$\dot{x} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ I \end{bmatrix} U \tag{52}$$

With $U = -M^{-1}(q).N(q,\dot{q}) + M^{-1}(q).\tau$ and this is known as the Brunousky canonical form. By equation (51) and (52) the Brunousky canonical form can be written in terms of the state $x = [e^T\ \dot{e}^T]^T$ as [1]:

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} . \begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} U \tag{53}$$

With

$$U = \ddot{q}_d + M^{-1}(q).\{N(q,\dot{q}) - \tau\} \tag{54}$$

Then compute the required arm torques using inverse of equation (55), is;

$$\tau = M(q)(\ddot{q}_d - U) + N(\dot{q},q) \tag{55}$$

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 [6];

$$\tau = M(q)\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) + N(q,\dot{q}) \tag{56}$$

and the resulting linear error dynamics are

$$\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) = 0 \tag{57}$$

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. The result 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.

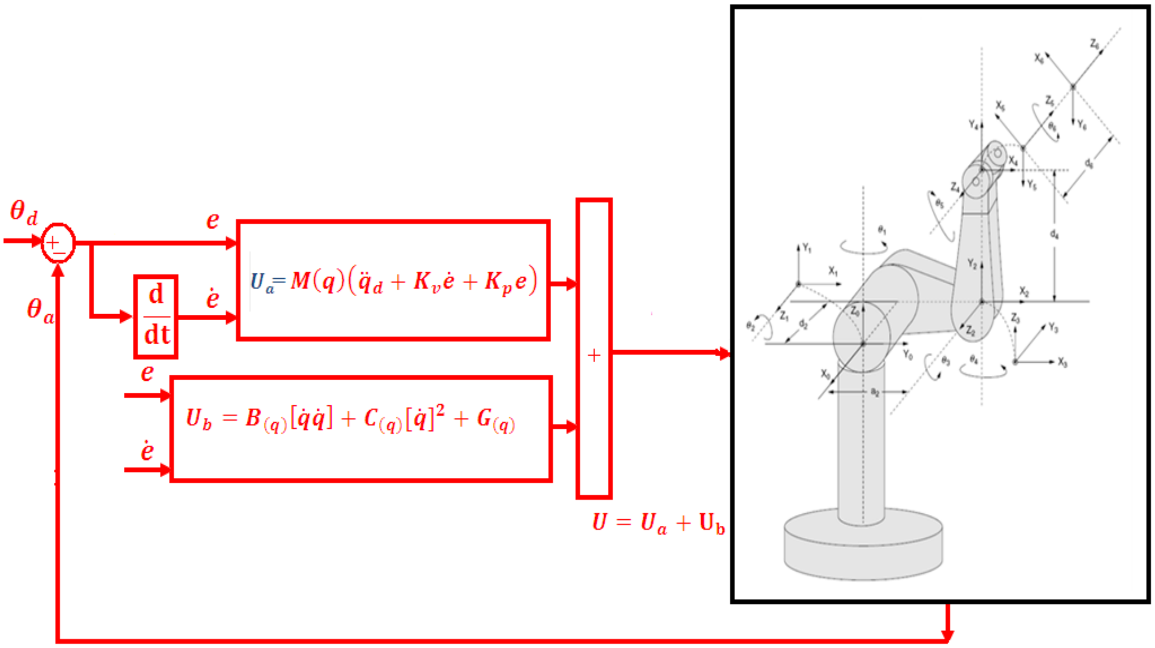

FIGURE 3: Block diagram of PD-computed torque controller (PD-CTC)

The application of proportional-plus-derivative (PD) computed torque controller to control of PUMA 560 robot manipulator introduced in this part. Suppose that in (58) the nonlinearity term defined by the following term

$$N(q,\dot{q}) = B(q)\dot{q}\dot{q} + C(q)\dot{q}^2 + g(q) \tag{58}$$

$$\begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^{\,2} + C_{13}\dot{q}_3^{\,2} \\ C_{21}\dot{q}_1^{\,2} + C_{23}\dot{q}_3^{\,2} \\ C_{31}\dot{q}_1^{\,2} + C_{32}\dot{q}_2^{\,2} \\ 0 \\ C_{51}\dot{q}_1^{\,2} + C_{52}\dot{q}_2^{\,2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

Therefore the equation of PD-CTC for control of PUMA 560 robot manipulator is written as the equation of (59);

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \\ \widehat{\tau_4} \\ \widehat{\tau_5} \\ \widehat{\tau_6} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix} \begin{bmatrix} \ddot{q}_{d1} + K_{v1}\dot{e}_1 + K_{p1}e_1 \\ \ddot{q}_{d2} + K_{v2}\dot{e}_2 + K_{p2}e_2 \\ \ddot{q}_{d3} + K_{v3}\dot{e}_3 + K_{p3}e_3 \\ \ddot{q}_{d4} + K_{v4}\dot{e}_4 + K_{p4}e_4 \\ \ddot{q}_{d5} + K_{v5}\dot{e}_5 + K_{p5}e_5 \\ \ddot{q}_{d6} + K_{v6}\dot{e}_6 + K_{p6}e_6 \end{bmatrix} \tag{59}$$

$$+\begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2{}^2 + C_{13}\dot{q}_3{}^2 \\ C_{21}\dot{q}_1{}^2 + C_{23}\dot{q}_3{}^2 \\ C_{31}\dot{q}_1{}^2 + C_{32}\dot{q}_2{}^2 \\ 0 \\ C_{51}\dot{q}_1{}^2 + C_{52}\dot{q}_2{}^2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

The controller based on a formulation (59) is related to robot dynamics therefore it has problems in uncertain conditions.

Implemented Computed Torque Controller

In first step, constructed dynamics and kinematics blocks (i.e., plant) with power supply will be put in work space. The main object is implementation of controller block. According to PD equation which is $\ddot{q}_d + K_v\dot{e}_1 + K_p e$, the linearized part will be created like Figure 4. The linearized part so called PID. As it is obvious, the parameter e is the difference of actual and desired values and $\dot{e}$ is the change of error. K_p and k_v are proportional and derivative gains and $\ddot{q}_d$ is double derivative of the joint variable. A sample of PD controller block for one joint is like Figure 5.

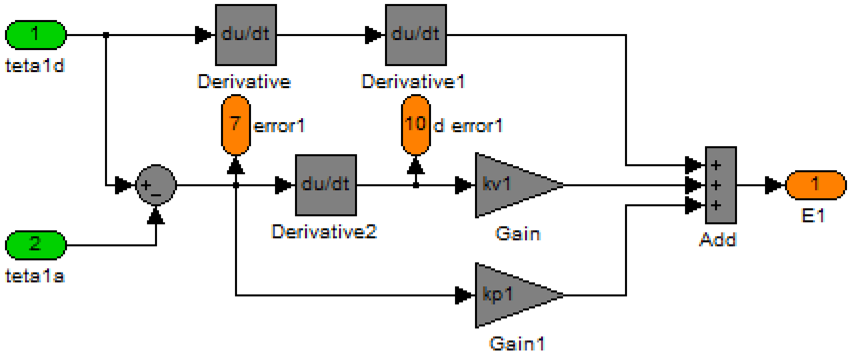

FIGURE 4: PD Controller for a joint variable

As it is seen in Figure 4 the error value and the change of error were chosen to exhibit in measurement center. In this block by changing gain values, the best control system will be applied. In the second step according to torque formulation in CTC mode, all constructed blocks just connect to each other as blew. In Figure 5 the N $(q, \dot{q})$ is the dynamic parameters block (i.e., A set of Coriolis, Centrifugal and Gravity blocks).

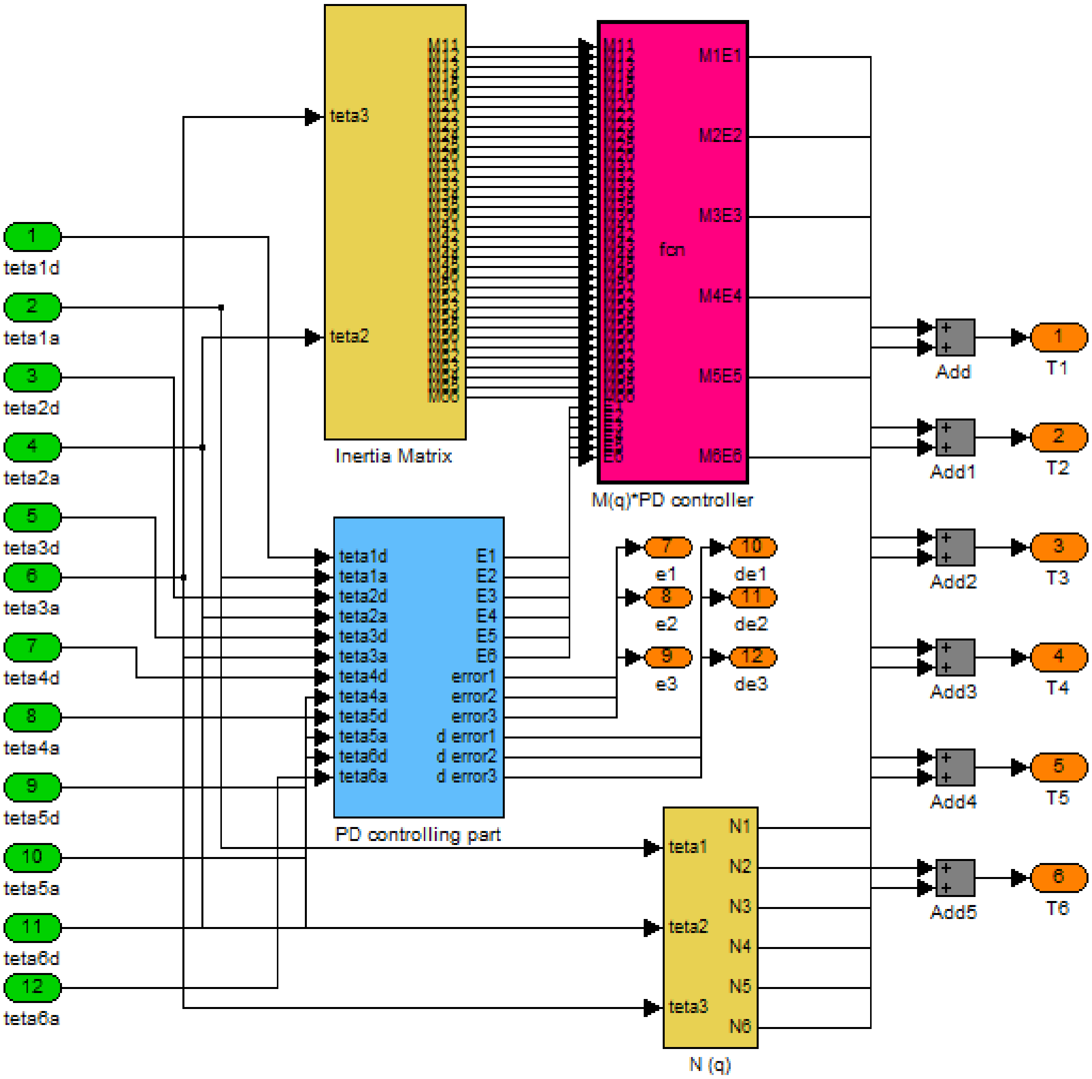

FIGURE 5: The general diagram of controller

The inputs are thetas and the final outputs are torque values. The relations between other blocks are just multiplication and summation as mentioned in torque equation. In the next step transform our subsystems into a general system to form controller block and the outputs will be connected to the plant, in order to execute controlling process. Then, trigger the main inputs with power supply to check validity and performance. In Figure 6, Dynamics, Kinematics and Controller blocks are shown.

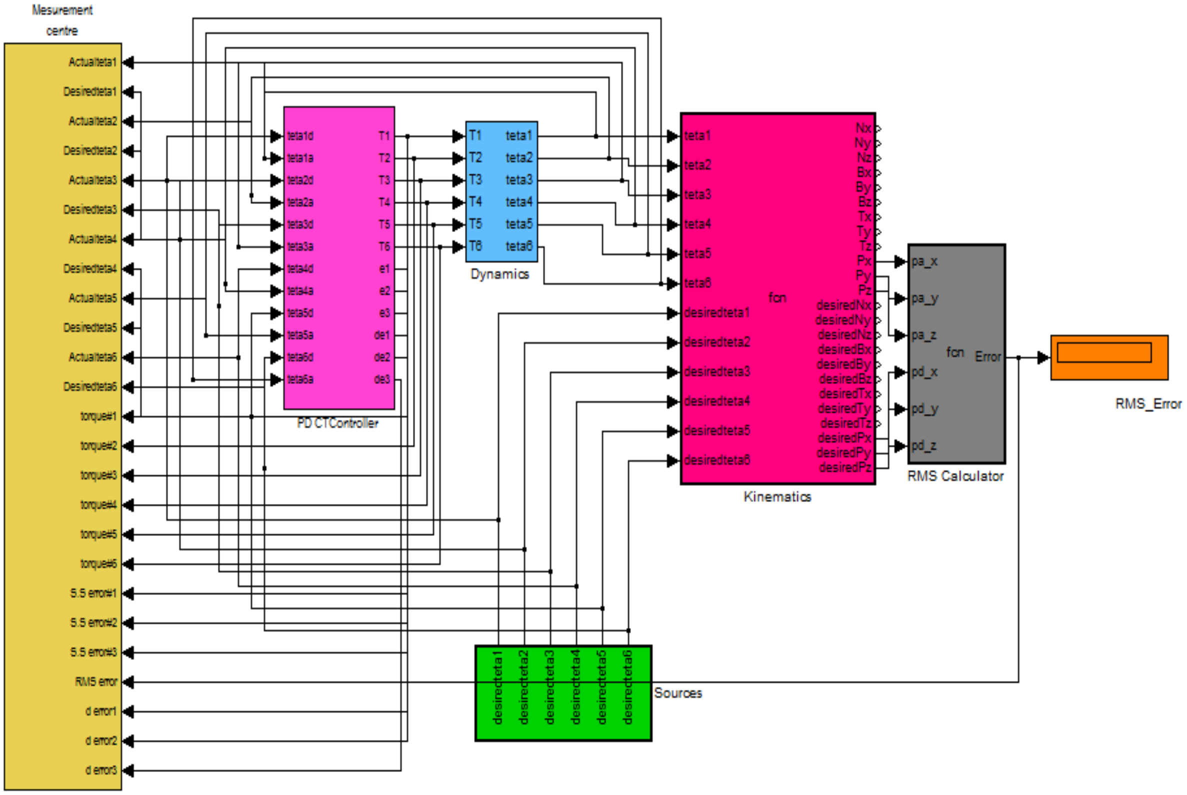

FIGURE 6 : Controller, Dynamics and Kinematics Blocks

4. RESULTS

PD-Computed torque controller (PD-CTC) and PID-Computed torque controller (PID-CTC) were tested to Step and Ramp responses. In this simulation the first, second, and third joints are moved from home to final position without and with external disturbance. The simulation was implemented in MATLAB/SIMULINK environment. It is noted that, these systems are tested by band limited white noise with a predefined 40% of relative to the input signal amplitude which the sample time is equal to 0.1. This type of noise is used to external disturbance in continuous and hybrid systems.

Trajectory Performance

Figures 7 and 8 show tracking performance for PD-CTC and PID CTC without disturbance for two type trajectories. The optimal coefficients in Step PID CTC are; $K_p = 70, K_v = 15, and\ K_i = 75$ and in Ramp PID CTC are; $K_p = 50, K_v = 10, and\ K_i = 25$ as well as similarly in Step and Ramp PD CTC are; $K_p = 30\ and\ \ K_v = 4$; From the simulation for first, second, and third links, it was seen that the different controller gains have the different performance. Tuning parameters of PID-CTC and PD-CTC for PUMA robot manipulator are shown in Tables 3 to 6.

	k_{P_1}	k_{V_1}	k_{I_1}	k_{p_2}	k_{V_2}	k_{I_2}	k_{p_3}	k_{V_3}	k_{I_3}	RMS error	SS error^{1}	SS error^{2}	SS error^{3}
1	70	24	70	70	24	70	70	24	70	2.276e-5	-3.81e-5	-3.81e-5	-3.81e-5
2	50	24	70	50	24	70	50	24	70	3.34e-5	-5.6e-5	-5.6e-5	-5.6e-5
3	70	15	75	70	15	75	70	15	75	0	0	0	0
4	70	24	50	70	24	50	70	24	50	3.7e-5	-6.2e-5	-6.2e-5	-6.2e-5

TABLE 3: Tuning parameters of a step PID-CTC

	k_{P_1}	k_{V_1}	k_{I_1}	k_{p_2}	k_{V_2}	k_{I_2}	k_{p_3}	k_{V_3}	k_{I_3}	RMS error	SS error^{1}	SS error^{2}	SS error^{3}
1	90	10	25	90	10	25	90	10	25	-1.2e-6	-1.6e-6	-1.6e-6	-1.6e-6
2	50	10	25	50	10	25	50	10	25	-4.5e-9	-6e-9	-6e-9	-6e-9
3	90	3	25	90	3	25	90	3	25	-8.8e-7	-1.17e-6	-1.17e-6	-1.17e-6
4	90	10	10	90	10	10	90	10	10	-2.4e-5	-3.2e-5	-3.2e-5	-3.2e-5

TABLE 4: Tuning parameters of a ramp PID-CTC

	k_{P_1}	k_{V_1}	k_{p_2}	k_{V_2}	k_{p_3}	k_{V_3}	RMs error	SS error^{1}	SS error^{2}	SS error^{3}
1	8	4	8	4	8	4	2.276e-5	-3.81e-5	-3.81e-5	-3.81e-5
2	30	4	30	4	30	4	1.34e-5	-3.6e-5	-2.54e-5	-1.6e-5
3	1	4	1	4	1	4	0.0039	0.0065	0.0065	0.0065
4	8	40	8	40	8	40	0.502	5.043	5.043	5.043
5	8	0.5	8	0.5	8	0.5	0.0026	0.0043	0.0043	0.0043

TABLE 5: Tuning parameters of a step PD-CTC

	k_{P_1}	k_{V_1}	k_{p_2}	k_{V_2}	k_{p_3}	k_{V_3}	RMs error	SS error^{1}	SS error^{2}	SS error^{3}
1	8	4	8	4	8	4	3.2e-5	-2.81e-5	-2.6e-5	-2.1e-5
2	30	4	30	4	30	4	-6e-5	-8e-5	-8.6e-5	-8.9e-5
3	1	4	1	4	1	4	0.000305	0.00024	0.00024	0.00024
4	8	40	8	40	8	40	0.6	4.93	4.93	4.93
5	8	0.5	8	0.5	8	0.5	0.5	2.9	2.9	2.9

TABLE 6: Tuning parameters of a ramp PD-CTC

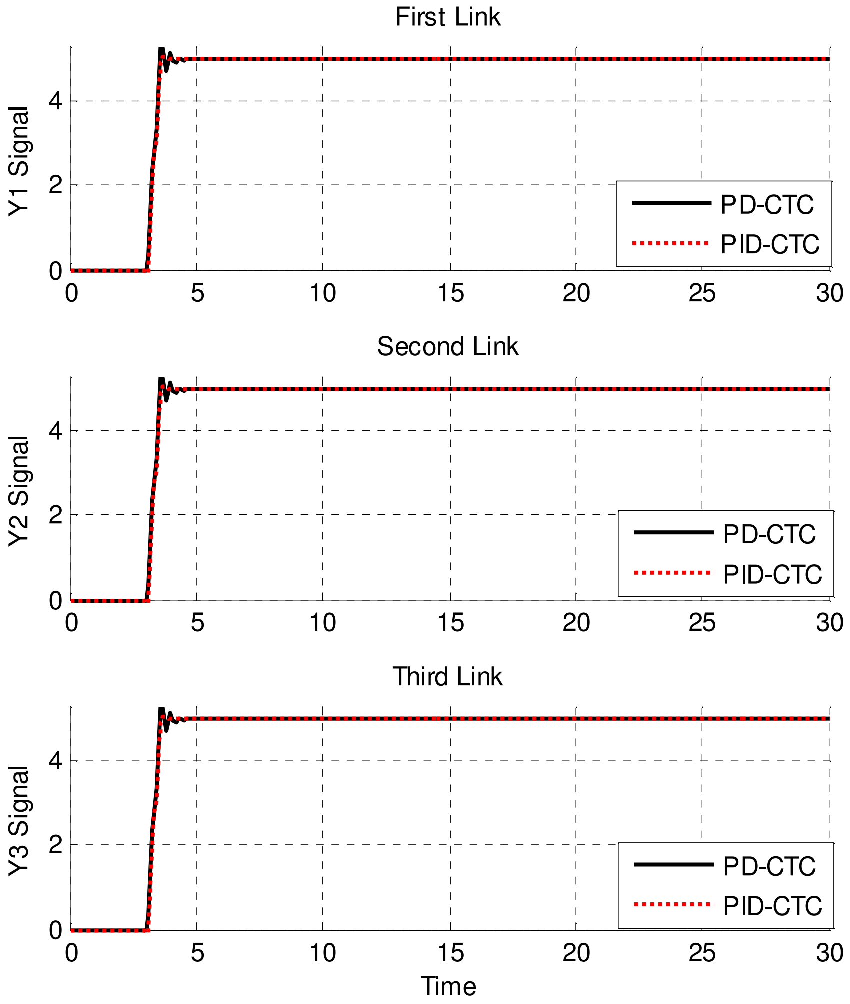

FIGURE 7: Step PID-CTC and PD-CTC for First, second and third link trajectory

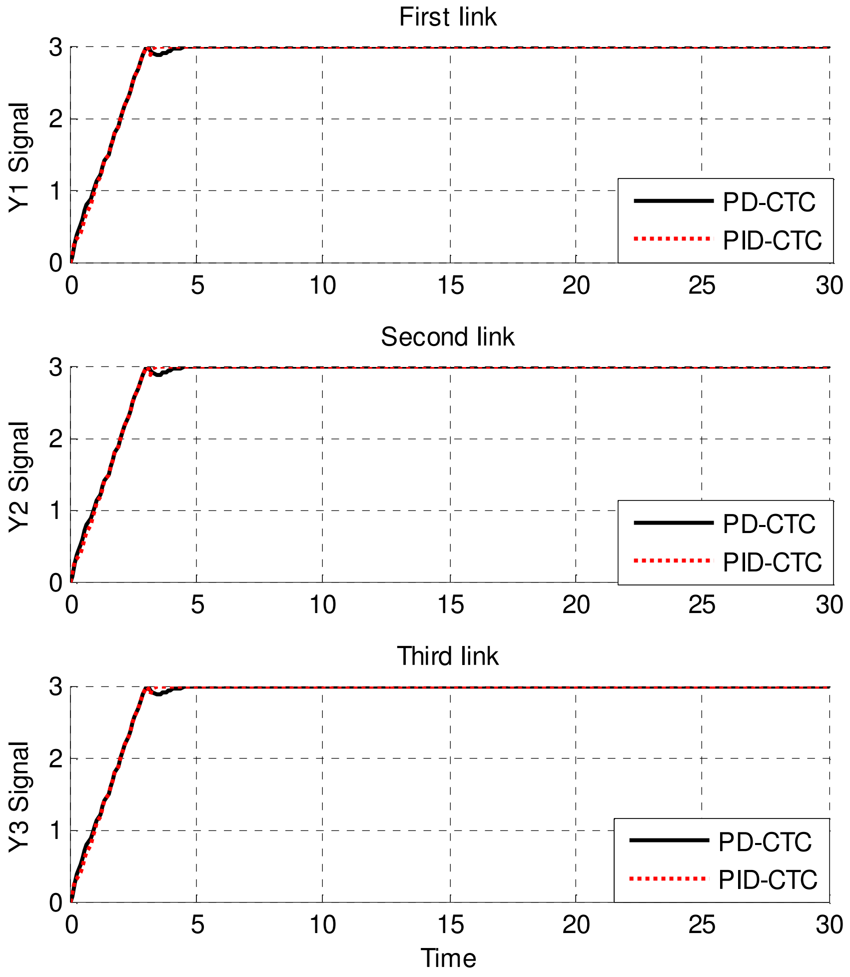

FIGURE 8: Ramp PID-CTC and PD-CTC for First, second and third link trajectory

By comparing step response trajectory without disturbance in PD and PID CTC, it is found that the PID's overshoot **(1.32%)** is lower than PD's **(6.44%)**, although both of them have about the same rise time; PID CTC **(0.5 sec)** and PD CTC **(0.403 sec)**. Besides the Steady State and RMS error in PID **(Steady State error =0 and RMS error=0)** is fairly lower than PD **(Steady State error $\cong -3^{-5}$ and RMS error=-1.6×10^{-5})**.

In above graphs over the same period, it is created that the PD and PID CTC are increased slightly, but PD CTC at $t = 3\,sec$ has very low distortion, after $t = 3\,sec$ bought of graphs remain are unchanged as mentioned to the Tables 4 and 6.

Disturbance Rejection: Figures 9 and 10 have shown the power disturbance elimination in PD and PID CTC. The main target in this controller 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 and Ramp PD and PID CTC. It found fairly fluctuations in trajectory responses. As mentioned earlier, CTC works very well when all parameters are known, this challenge plays important role to select the SMC as a based robust controller in this research.

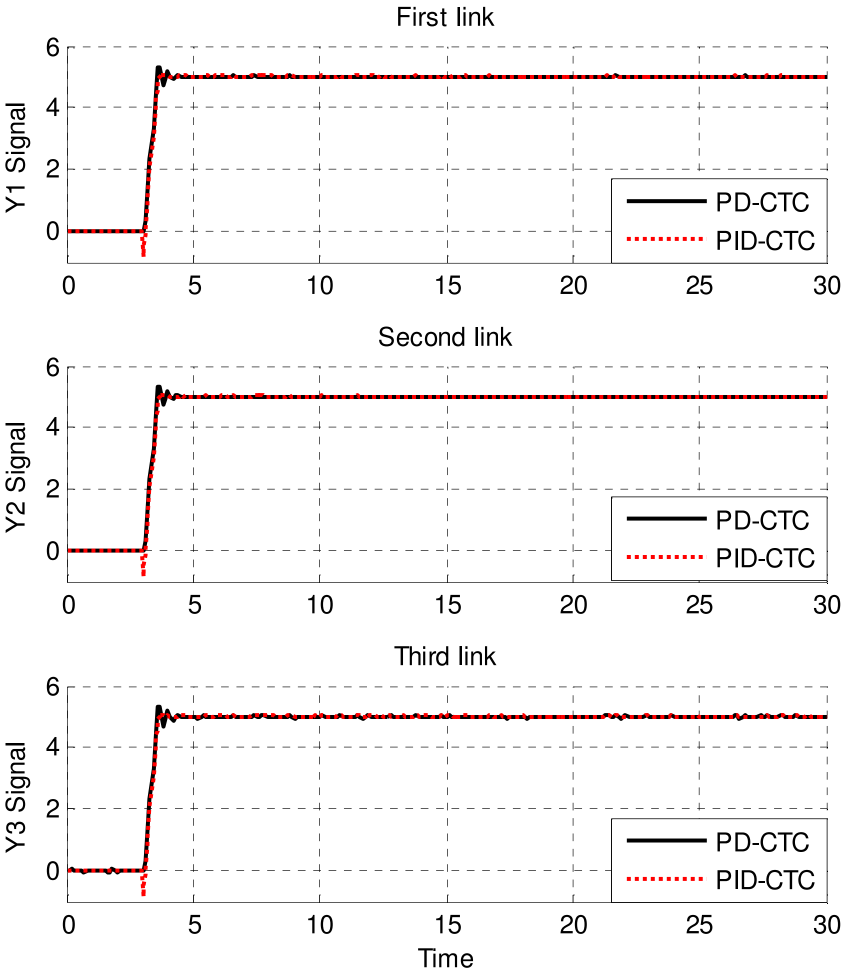

FIGURE 9: Step PID-CTC and PD-CTC for First, second and third link trajectory with disturbance.

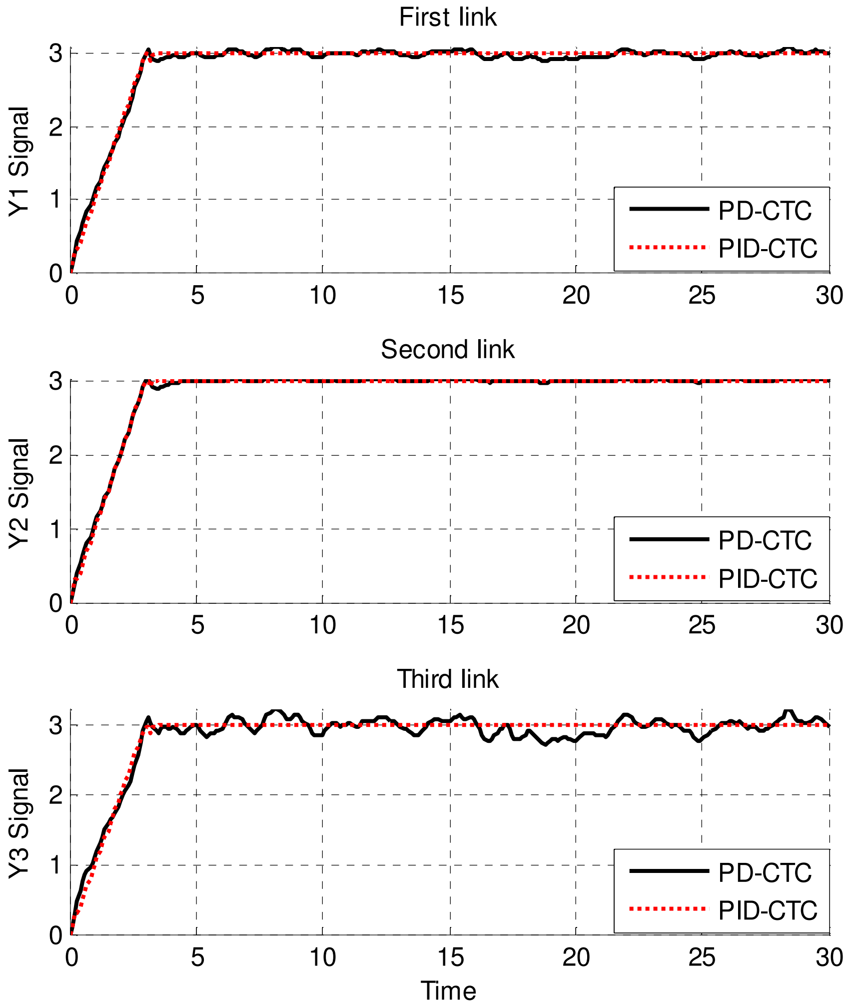

FIGURE 10: Ramp PID-CTC and PD-CTC for First, second and third link trajectory with disturbance.

Among above graphs (9 and 10) relating to Step and Ramp trajectories following with external disturbance, PID CTC and PD CTC have fairly fluctuations. By comparing some control parameters such as overshoot, rise time, steady state and RMS error it computed that the PID's overshoot **(1.8%)** is lower than PD's **(8%)**, although both of them have about the same rise time; PID CTC **(0.5 sec)** and PD CTC **(0.41 sec)**, the Steady State and RMS error in PID **(Steady State error = -0.0019 and RMS error=0.0025)** is fairly lower than PD **(Steady State error $\cong 0.005$ and RMS error=0.0042)**.

Errors in the model: Figures 11 and 12 have shown the error disturbance in PD and PID CTC. The controllers with no external disturbances have the same error response, but PID CTC has the better steady state error when the robot manipulator has external disturbance. Furthermore the RMS error profile for PID CTC is sharply dropped compared to the PD CTC.

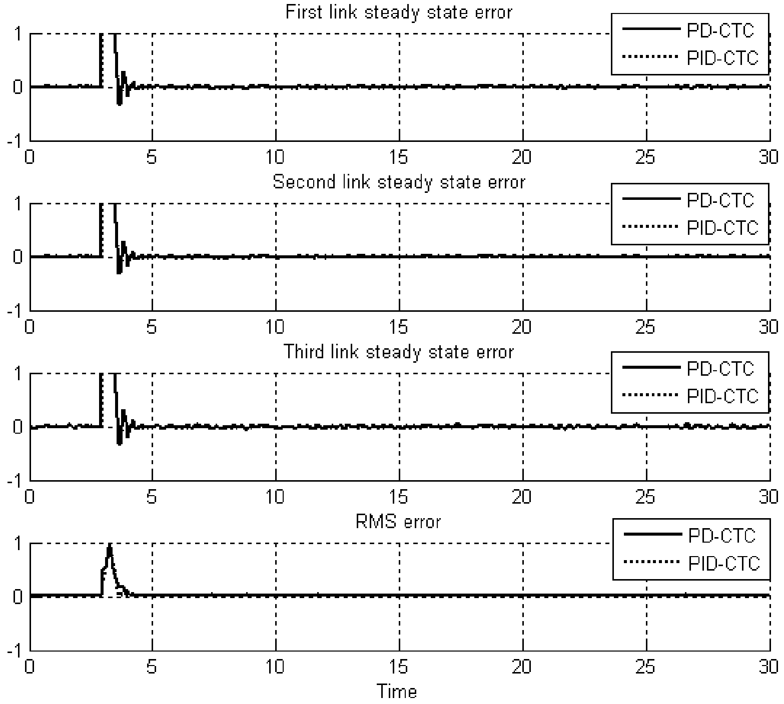

FIGURE 11: Step PID-CTC and PD-CTC for First, second and third link steady state and RMS error with disturbance.

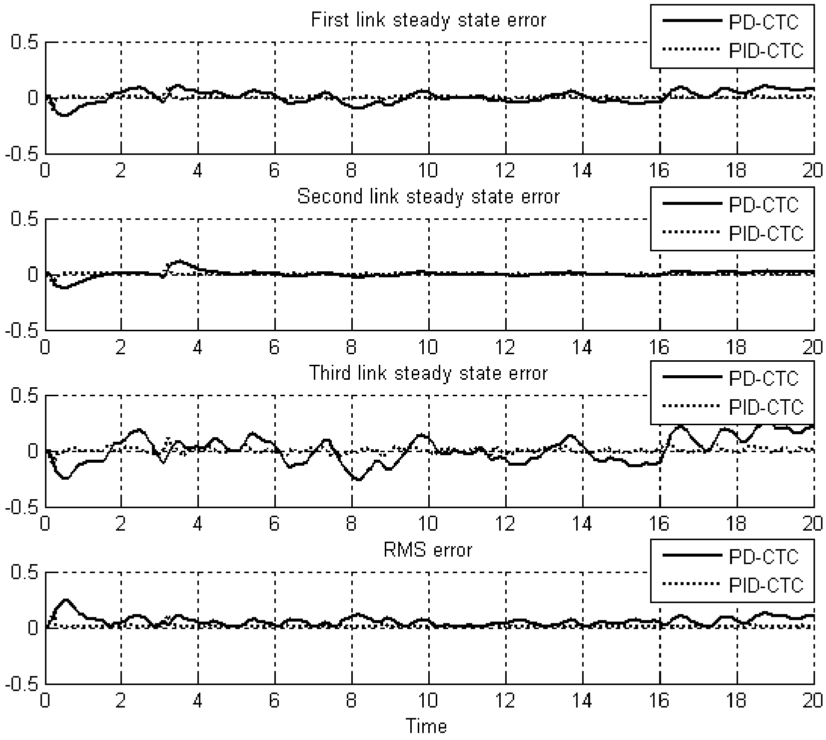

FIGURE 12: Ramp PID-CTC and PD-CTC for First, second and third link steady state and RMS error with disturbance.

The errors in PID CTC and PD CTC is widely increased among of error graphs (11 and 12) relating to Step and Ramp response with external disturbance. By comparing the steady state and RMS error it observed that the PID's State and RMS error **(Steady State error = -0.0019 and RMS error=0.0025)** is lower than PD's **(Steady State error $\cong 0.005$ and RMS error=0.0042)**. When applied disturbance in these controllers it is computed that the steady state and RMS error increased rapidly approximately 130%.

5. CONCLUSION

In this research we introduced, basic concepts of robot manipulator (e.g., PUMA 560 robot manipulator) and control methodology. PUMA 560 robot manipulator is a 6 DOF serial robot manipulator. From the control point of view, robot manipulator divides into two main parts i.e. kinematics and dynamic parts. The dynamic parameters of this system are highly nonlinear. To control of this system nonlinear control methodology (computed torque controller) is introduced. Computed torque controller (CTC) is an influential nonlinear controller to certain and partly uncertain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. When all dynamic and physical parameters are known computed torque controller works superbly.

REFERENCES

[1] T. R. Kurfess, *Robotics and automation handbook*: CRC, 2005.

[2] J. J. E. Slotine and W. Li, *Applied nonlinear control* vol. 461: Prentice hall Englewood Cliffs, NJ, 1991.

[3] K. Ogata, *Modern control engineering*: Prentice Hall, 2009.

[4] L. Cheng, Z. G. Hou, M. Tan, D. Liu and A. M. Zou, "Multi-agent based adaptive consensus control for multiple manipulators with kinematic uncertainties," 2008, pp. 189-194.

[5] J. J. D'Azzo, C. H. Houpis and S. N. Sheldon, *Linear control system analysis and design with MATLAB*: CRC, 2003.

[6] B. Siciliano and O. Khatib, *Springer handbook of robotics*: Springer-Verlag New York Inc, 2008.

[7] I. Boiko, L. Fridman, A. Pisano and E. Usai, "Analysis of chattering in systems with second-order sliding modes," *IEEE Transactions on Automatic Control,* No. 11, vol. 52,pp. 2085-2102, 2007.

[8] J. Wang, A. Rad and P. Chan, "Indirect adaptive fuzzy sliding mode control: Part I: fuzzy switching," *Fuzzy Sets and Systems,* No. 1, vol. 122,pp. 21-30, 2001.

[9] C. Wu, "Robot accuracy analysis based on kinematics," *IEEE Journal of Robotics and Automation,* No. 3, vol. 2, pp. 171-179, 1986.

[10] H. Zhang and R. P. Paul, "A parallel solution to robot inverse kinematics," *IEEE conference proceeding,* 2002, pp. 1140-1145.

[11] J. Kieffer, "A path following algorithm for manipulator inverse kinematics," *IEEE conference proceeding,* 2002, pp. 475-480.

[12] Z. Ahmad and A. Guez, "On the solution to the inverse kinematic problem(of robot)," *IEEE conference proceeding,* 1990, pp. 1692-1697.

[13] F. T. Cheng, T. L. Hour, Y. Y. Sun and T. H. Chen, "Study and resolution of singularities for a 6-DOF PUMA manipulator," *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on, No. 2,* vol. 27, pp. 332-343, 2002.

[14] M. W. Spong and M. Vidyasagar, *Robot dynamics and control*: Wiley-India, 2009.

[15] A. Vivas and V. Mosquera, "Predictive functional control of a PUMA robot," Conference Proceedings, 2005.

[16] D. Nguyen-Tuong, M. Seeger and J. Peters, "Computed torque control with nonparametric regression models," *IEEE conference proceeding,* 2008, pp. 212-217.

[17] V. Utkin, "Variable structure systems with sliding modes," *Automatic Control, IEEE Transactions on,* No. 2, vol. 22, pp. 212-222, 2002.

[18] R. A. DeCarlo, S. H. Zak and G. P. Matthews, "Variable structure control of nonlinear multivariable systems: a tutorial," *Proceedings of the IEEE,* No. 3, vol. 76, pp. 212-232, 2002.

[19] K. D. Young, V. Utkin and U. Ozguner, "A control engineer's guide to sliding mode control," *IEEE conference proceeding,* 2002, pp. 1-14.

[20] O. Kaynak, "Guest editorial special section on computationally intelligent methodologies and sliding-mode control," *IEEE Transactions on Industrial Electronics,* No. 1, vol. 48, pp. 2-3, 2001.

[21] J. J. Slotine and S. Sastry, "Tracking control of non-linear systems using sliding surfaces, with application to robot manipulators†," *International Journal of Control,* No. 2, vol. 38, pp. 465-492, 1983.

[22] J. J. E. Slotine, "Sliding controller design for non-linear systems," *International Journal of Control,* No. 2*,* vol. 40, pp. 421-434, 1984.

[23] R. Palm, "Sliding mode fuzzy control," *IEEE conference proceeding,*2002, pp. 519-526.

[24] C. C. Weng and W. S. Yu, "Adaptive fuzzy sliding mode control for linear time-varying uncertain systems," *IEEE conference proceeding,* 2008, pp. 1483-1490.

[25] M. Ertugrul and O. Kaynak, "Neuro sliding mode control of robotic manipulators," *Mechatronics Journal,* No. 1, vol. 10, pp. 239-263, 2000.

[26] P. Kachroo and M. Tomizuka, "Chattering reduction and error convergence in the sliding-mode control of a class of nonlinear systems," *Automatic Control, IEEE Transactions on,* No. 7, vol. 41, pp. 1063-1068, 2002.

[27] H. Elmali and N. Olgac, "Implementation of sliding mode control with perturbation estimation (SMCPE)," *Control Systems Technology, IEEE Transactions on,* No. 1, vol. 4, pp. 79-85, 2002.

[28] J. Moura and N. Olgac, "A comparative study on simulations vs. experiments of SMCPE," *IEEE conference proceeding,* 2002, pp. 996-1000.

[29] Y. Li and Q. Xu, "Adaptive Sliding Mode Control With Perturbation Estimation and PID Sliding Surface for Motion Tracking of a Piezo-Driven Micromanipulator," *Control Systems Technology, IEEE Transactions on,* No. 4, vol. 18, pp. 798-810, 2010.

[30] B. Wu, Y. Dong, S. Wu, D. Xu and K. Zhao, "An integral variable structure controller with fuzzy tuning design for electro-hydraulic driving Stewart platform," *IEEE conference proceeding,* 2006, pp. 5-945.

[31] Farzin Piltan , N. Sulaiman, Zahra Tajpaykar, Payman Ferdosali, Mehdi Rashidi, “Design Artificial Nonlinear Robust Controller Based on CTLC and FSMC with Tunable Gain,” International Journal of Robotic and Automation, 2 (3): 205-220, 2011.

[32] Farzin Piltan, A. R. Salehi and Nasri B Sulaiman.,” Design artificial robust control of second order system based on adaptive fuzzy gain scheduling,” world applied science journal (WASJ), 13 (5): 1085-1092, 2011.

[33] Farzin Piltan, N. Sulaiman, Atefeh Gavahian, Samira Soltani, Samaneh Roosta, “Design Mathematical Tunable Gain PID-Like Sliding Mode Fuzzy Controller with Minimum Rule Base,” International Journal of Robotic and Automation, 2 (3): 146-156, 2011.

[34] Farzin Piltan , A. Zare, Nasri B. Sulaiman, M. H. Marhaban and R. Ramli, , “A Model Free Robust Sliding Surface Slope Adjustment in Sliding Mode Control for Robot Manipulator,” World Applied Science Journal, 12 (12): 2330-2336, 2011.

[35] Farzin Piltan , A. H. Aryanfar, Nasri B. Sulaiman, M. H. Marhaban and R. Ramli “Design Adaptive Fuzzy Robust Controllers for Robot Manipulator,” World Applied Science Journal, 12 (12): 2317-2329, 2011.

[36] Farzin Piltan, N. Sulaiman , Arash Zargari, Mohammad Keshavarz, Ali Badri , “Design PID-Like Fuzzy Controller With Minimum Rule Base and Mathematical Proposed On-line Tunable Gain: Applied to Robot Manipulator,” International Journal of Artificial intelligence and expert system, 2 (4):184-195, 2011.

[37] Farzin Piltan, Nasri Sulaiman, M. H. Marhaban and R. Ramli, “Design On-Line Tunable Gain Artificial Nonlinear Controller,” Journal of Advances In Computer Research, 2 (4): 75-83, 2011.

[38] Farzin Piltan, N. Sulaiman, Payman Ferdosali, Iraj Assadi Talooki, “ Design Model Free Fuzzy Sliding Mode Control: Applied to Internal Combustion Engine,” International Journal of Engineering, 5 (4):302-312, 2011.

[39] Farzin Piltan, N. Sulaiman, Samaneh Roosta, M.H. Marhaban, R. Ramli, “Design a New Sliding Mode Adaptive Hybrid Fuzzy Controller,” Journal of Advanced Science & Engineering Research , 1 (1): 115-123, 2011.

[40] Farzin Piltan, Atefe Gavahian, N. Sulaiman, M.H. Marhaban, R. Ramli, “Novel Sliding Mode Controller for robot manipulator using FPGA,” Journal of Advanced Science & Engineering Research, 1 (1): 1-22, 2011.

[41] Farzin Piltan, N. Sulaiman, A. Jalali & F. Danesh Narouei, “Design of Model Free Adaptive Fuzzy Computed Torque Controller: Applied to Nonlinear Second Order System,” International Journal of Robotics and Automation, 2 (4):232-244, 2011.

[42] Farzin Piltan, N. Sulaiman, Iraj Asadi Talooki, Payman Ferdosali, “Control of IC Engine: Design a Novel MIMO Fuzzy Backstepping Adaptive Based Fuzzy Estimator Variable Structure Control ,” International Journal of Robotics and Automation, 2 (5):360-380, 2011.

[43] Farzin Piltan, N. Sulaiman, Payman Ferdosali, Mehdi Rashidi, Zahra Tajpeikar, "Adaptive MIMO Fuzzy Compensate Fuzzy Sliding Mode Algorithm: Applied to Second Order Nonlinear System," International Journal of Engineering, 5 (5): 380-398, 2011.

[44] Farzin Piltan, N. Sulaiman, Hajar Nasiri, Sadeq Allahdadi, Mohammad A. Bairami, "Novel Robot Manipulator Adaptive Artificial Control: Design a Novel SISO Adaptive Fuzzy Sliding Algorithm Inverse Dynamic Like Method," International Journal of Engineering, 5 (5): 399-418, 2011.

[45] Farzin Piltan, N. Sulaiman, Sadeq Allahdadi, Mohammadali Dialame, Abbas Zare, "Position Control of Robot Manipulator: Design a Novel SISO Adaptive Sliding Mode Fuzzy PD Fuzzy Sliding Mode Control," International Journal of Artificial intelligence and Expert System, 2 (5):208-228, 2011.

[46] Farzin Piltan, SH. Tayebi HAGHIGHI, N. Sulaiman, Iman Nazari, Sobhan Siamak, "Artificial Control of PUMA Robot Manipulator: A-Review of Fuzzy Inference Engine And Application to Classical Controller ," International Journal of Robotics and Automation, 2 (5):401-425, 2011.

[47] Farzin Piltan, N. Sulaiman, Abbas Zare, Sadeq Allahdadi, Mohammadali Dialame, "Design Adaptive Fuzzy Inference Sliding Mode Algorithm: Applied to Robot Arm," International Journal of Robotics and Automation , 2 (5): 283-297, 2011.

[48] Farzin Piltan, Amin Jalali, N. Sulaiman, Atefeh Gavahian, Sobhan Siamak, "Novel Artificial Control of Nonlinear Uncertain System: Design a Novel Modified PSO SISO Lyapunov Based Fuzzy Sliding Mode Algorithm ," International Journal of Robotics and Automation, 2 (5): 298-316, 2011.

[49] Farzin Piltan, N. Sulaiman, Amin Jalali, Koorosh Aslansefat, "Evolutionary Design of Mathematical tunable FPGA Based MIMO Fuzzy Estimator Sliding Mode Based Lyapunov Algorithm: Applied to Robot Manipulator," International Journal of Robotics and Automation, 2 (5):317-343, 2011.

[50] Farzin Piltan, N. Sulaiman, Samaneh Roosta, Atefeh Gavahian, Samira Soltani, "Evolutionary Design of Backstepping Artificial Sliding Mode Based Position Algorithm: Applied to Robot Manipulator," International Journal of Engineering, 5 (5):419-434, 2011.

[51] Farzin Piltan, N. Sulaiman, S.Soltani, M. H. Marhaban & R. Ramli, "An Adaptive sliding surface slope adjustment in PD Sliding Mode Fuzzy Control for Robot Manipulator," International Journal of Control and Automation , 4 (3): 65-76, 2011.

[52] Farzin Piltan, N. Sulaiman, Mehdi Rashidi, Zahra Tajpaikar, Payman Ferdosali, "Design and Implementation of Sliding Mode Algorithm: Applied to Robot Manipulator-A Review ," International Journal of Robotics and Automation, 2 (5):265-282, 2011.

[53] Farzin Piltan, N. Sulaiman, Amin Jalali, Sobhan Siamak, and Iman Nazari, "Control of Robot Manipulator: Design a Novel Tuning MIMO Fuzzy Backstepping Adaptive Based Fuzzy Estimator Variable Structure Control ," International Journal of Control and Automation, 4 (4):91-110, 2011.

[54] Farzin Piltan, N. Sulaiman, Atefeh Gavahian, Samaneh Roosta, Samira Soltani, "On line Tuning Premise and Consequence FIS: Design Fuzzy Adaptive Fuzzy Sliding Mode Controller Based on Lyaponuv Theory," International Journal of Robotics and Automation, 2 (5):381-400, 2011.

[55] Farzin Piltan, N. Sulaiman, Samaneh Roosta, Atefeh Gavahian, Samira Soltani, “Artificial Chattering Free on-line Fuzzy Sliding Mode Algorithm for Uncertain System: Applied in Robot Manipulator,” International Journal of Engineering, 5 (5):360-379, 2011.

[56] Farzin Piltan, N. Sulaiman and I.AsadiTalooki, “Evolutionary Design on-line Sliding Fuzzy Gain Scheduling Sliding Mode Algorithm: Applied to Internal Combustion Engine,” International Journal of Engineering Science and Technology, 3 (10):7301-7308, 2011.

[57] Farzin Piltan, Nasri B Sulaiman, Iraj Asadi Talooki and Payman Ferdosali.,” Designing On-Line Tunable Gain Fuzzy Sliding Mode Controller Using Sliding Mode Fuzzy Algorithm: Applied to Internal Combustion Engine,” world applied science journal (WASJ), 15 (3): 422-428, 2011.

[58] B. K. Yoo and W. C. Ham, "Adaptive control of robot manipulator using fuzzy compensator," *Fuzzy Systems, IEEE Transactions on,* No. 2, vol. 8, pp. 186-199, 2002.

[59] H. Medhaffar, N. Derbel and T. Damak, "A decoupled fuzzy indirect adaptive sliding mode controller with application to robot manipulator," *International Journal of Modelling, Identification and Control,* No. 1, vol. 1, pp. 23-29, 2006.

[60] Y. Guo and P. Y. Woo, "An adaptive fuzzy sliding mode controller for robotic manipulators," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on,* No. 2, vol. 33, pp. 149-159, 2003.

[61] C. M. Lin and C. F. Hsu, "Adaptive fuzzy sliding-mode control for induction servomotor systems," *Energy Conversion, IEEE Transactions on,* No. 2, vol. 19, pp. 362-368, 2004.

[62] N. Sulaiman, Z. A. Obaid, M. Marhaban and M. Hamidon , "Design and Implementation of FPGA-Based Systems-A Review," *Australian Journal of Basic and Applied Sciences,* No. 4, vol. 3, pp. 3575-3596, 2009.

[63] X. Shao and D. Sun, "Development of an FPGA-based motion control ASIC for robotic manipulators," *IEEE Conference ,* 2006, pp. 8221-8225.

[64] Y. S. Kung, K. Tseng, C. Chen, H. Sze and A. Wang, "FPGA-implementation of inverse kinematics and servo controller for robot manipulator," *Proc. IEEE Int. on Robotics and Biomimetics,* pp. 1163–1168, 2006.

[65] X. Shao, D. Sun and J. K. Mills, "A new motion control hardware architecture with FPGA-based IC design for robotic manipulators," *IEEE Conference,* 2006, pp. 3520-3525.

[66] Y. S. Kung, C. S. Chen and G. S. Shu, "Design and Implementation of a Servo System for Robotic Manipulator," CACS, 2005.

[67] U. D. Meshram and R. Harkare, "FPGA Based Five Axis Robot Arm Controller," *IEEE Conference,* 2005, pp. 3520-3525.

[68] U. Meshram, P. Bande, P. Dwaramwar and R. Harkare, "Robot arm controller using FPGA," *IEEE Conference,* 2009, pp. 8-11.

[69] Y. S. Kung and G. S. Shu, "Development of a FPGA-based motion control IC for robot arm," *IEEE Conference,* 2006, pp. 1397-1402.

[70] Z. A. Obaid, N. Sulaiman and M. Hamidon, "Developed Method of FPGA-based Fuzzy Logic Controller Design with the Aid of Conventional PID Algorithm," *Australian Journal of Basic and Applied Sciences,* No. 3, vol. 3, pp. 2724-2740, 2009.

[71] S. T. Karris, *Digital circuit analysis and design with Simulink modeling and introduction to CPLDs and FPGAs*: Orchard Pubns, 2007.

[72] K. D. Rogers, "Acceleration and implementation of a DSP phase-based frequency estimation algorithm: MATLAB/SIMULINK to FPGA via XILINX system generator," Citeseer, 2004.

[73] F. J. Lin, D. H. Wang and P. K. Huang, "FPGA-based fuzzy sliding-mode control for a linear induction motor drive," IEEE journal of electrical power application, No. 5, Vol. 152, 2005, pp. 1137-1148.

[74] R. R. Ramos, D. Biel, E. Fossas and F. Guinjoan, "A fixed-frequency quasi-sliding control algorithm: application to power inverters design by means of FPGA implementation," *Power Electronics, IEEE Transactions on,* No. 1, vol. 18, pp. 344-355, 2003.

[75] Xiaosong. Lu, "An investigation of adaptive fuzzy sliding mode control for robot manipulator," *Carleton university Ottawa,*2007.

[76] S. Lentijo, S. Pytel, A. Monti, J. Hudgins, E. Santi and G. Simin, "FPGA based sliding mode control for high frequency power converters," *IEEE Conference,* 2004, pp. 3588-3592.

[77] B. S. R. Armstrong, "Dynamics for robot control: friction modeling and ensuring excitation during parameter identification," 1988.

[78] C. L. Clover, "Control system design for robots used in simulating dynamic force and moment interaction in virtual reality applications," 1996.

[79] K. R. Horspool, *Cartesian-space Adaptive Control for Dual-arm Force Control Using Industrial Robots*: University of New Mexico, 2003.

[80] B. Armstrong, O. Khatib and J. Burdick, "The explicit dynamic model and inertial parameters of the PUMA 560 arm," *IEEE Conference,* 2002, pp. 510-518.

[81] P. I. Corke and B. Armstrong-Helouvry, "A search for consensus among model parameters reported for the PUMA 560 robot," *IEEE Conference,* 2002, pp. 1608-1613.

[82] Farzin Piltan, N. Sulaiman, M. H. Marhaban, Adel Nowzary, Mostafa Tohidian," "Design of FPGA based sliding mode controller for robot manipulator," International Journal of Robotic and Automation, 2 (3): 183-204, 2011.

[83] I. Eksin, M. Guzelkaya and S. Tokat, "Sliding surface slope adjustment in fuzzy sliding mode controller," *Mediterranean Conference,* 2002, pp. 160-168.

[78] Samira Soltani & Farzin Piltan, "*Design Artificial Nonlinear Controller Based on Computed Torque like Controller with Tunable Gain*". World Applied Science Journal,14 (9): 1306-1312, 2011.

[71] Farzin Piltan, H. Rezaie, B. Boroomand, Arman Jahed," Design robust back stepping online tuning feedback linearization control applied to IC engine," International Journal of Advance Science and Technology, 42: 183-204, 2012.

[72] Farzin Piltan, I. Nazari, S. Siamak, P. Ferdosali ,"Methodology of FPGA-based mathematical error-based tuning sliding mode controller" International Journal of Control and Automation, 5(1): 89-110, 2012.

[73] Farzin Piltan, M. A. Dialame, A. Zare, A. Badri ,"Design Novel Lookup table changed Auto Tuning FSMC: Applied to Robot Manipulator" International Journal of Engineering, 6(1): 25-40, 2012.

[74] Farzin Piltan, B. Boroomand, A. Jahed, H. Rezaie ,"Methodology of Mathematical Error-Based Tuning Sliding Mode Controller" International Journal of Engineering, 6(2): 96-112, 2012.

[75] Farzin Piltan, F. Aghayari, M. R. Rashidian, M. Shamsodini, "A New Estimate Sliding Mode Fuzzy Controller for Robotic Manipulator" International Journal of Robotics and Automation, 3(1): 45-58, 2012.

[76] Farzin Piltan, M. Keshavarz, A. Badri, A. Zargari , "Design novel nonlinear controller applied to robot manipulator: design new feedback linearization fuzzy controller with minimum rule base tuning method" International Journal of Robotics and Automation, 3(1): 1-18, 2012.

[77] Piltan, F., et al. "Design sliding mode controller for robot manipulator with artificial tunable gain". Canaidian Journal of pure and applied science, 5 (2), 1573-1579, 2011.

[78] Piltan, F., et al. "Design sliding mode controller for robot manipulator with artificial tunable gain". Canaidian Journal of pure and applied science, 5 (2), 1573-1579, 2011.

[79] Farzin Piltan, A. Hosainpour, E. Mazlomian, M.Shamsodini, M.H Yarmahmoudi. "Online Tuning Chattering Free Sliding Mode Fuzzy Control Design: Lyapunov Approach" International Journal of Robotics and Automation, 3(3): 2012.

[80] Farzin Piltan, R. Bayat, F. Aghayari, B. Boroomand. "Design Error-Based Linear Model-Free Evaluation Performance Computed Torque Controller" International Journal of Robotics and Automation, 3(3): 2012.

[81] Farzin Piltan, S. Emamzadeh, Z. Hivand, F. Shahriyari & Mina Mirazaei . " PUMA-560 Robot Manipulator Position Sliding Mode Control Methods Using MATLAB/SIMULINK and Their Integration into Graduate/Undergraduate Nonlinear Control, Robotics and MATLAB Courses" International Journal of Robotics and Automation, 3(3): 2012.

[82] Farzin Piltan, J. Meigolinedjad, S. Mehrara, S. Rahmdel. " Evaluation Performance of 2nd Order Nonlinear System: Baseline Control Tunable Gain Sliding Mode Methodology" International Journal of Robotics and Automation, 3(3): 2012.

[83] Farzin Piltan, S. Rahmdel, S. Mehrara, R. Bayat." Sliding Mode Methodology Vs. Computed Torque Methodology Using MATLAB/SIMULINK and Their Integration into Graduate Nonlinear Control Courses" International Journal of Engineering, 3(3): 2012.

[84] Farzin Piltan, M. Mirzaie, F. Shahriyari, Iman Nazari & S. Emamzadeh." Design Baseline Computed Torque Controller" International Journal of Engineering, 3(3): 2012.