PUMA Robot Dynamics Control System with Three Dimensional Approaches Using MATLAB/ SIMULINK

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Abstract:

The paper focuses to Implementation of 3D of PUMA Robot Dynamic Control System Using SIMULINK. In this Thesis to be the same real system and mathematical model of dynamics used the control system design, fine-tuning of controller is always needed. For better tuning fast simulation speed is desired. Since, Matlab incorporates LAPACK to increase the speed and complexity of matrix computation, dynamics, forward and inverse kinematics of PUMA Robot is modeled on Matlab/Simulink in such a way that all operations are matrix based which give very less simulation time. This paper compares PID parameter tuning using Genetic Algorithm, Simulated Annealing, Generalized Pattern Search (GPS) and Hybrid Search techniques. This system is implemented with MATLAB programming language.

Keywords:

PUMA Robot, Robot Dynamics Control System, MATLAB, SIMULINK, Stability Analysis

1. Introduction

Many industrialized countries are using robots in various fields even for military applications, medical fields, etc. Robot manipulators are highly coupled nonlinear systems; therefore real system and mathematical model of dynamics used for control system design are not same. Since, MATLAB incorporates LAPACK to increase the speed and complexity of matrix computation, dynamics, forward and inverse kinematics of PUMA Robot is modeled on MARLAB/SIMULINK in such a way that all operations are matrix based which give very less simulation time. The international organizations in order to standardize the robot definition have a special description as "an automatically controlled, reprogrammable, multipurpose manipulator with three or more axes." The institute of robotic in The United States Of America defines the robot as "a reprogrammable, multifunctional manipulator design to move material, parts, tools, or specialized devices through various programmed motions for the performance of variety of tasks" [1]. Robot manipulator is collection of links that connect to each other by joints, these joints can be revolute and prismatic that revolute joint has rotary motion around an axis and prismatic joint has linear motion around an axis. Each joint provides one or more degrees of freedom (DOF). From the mechanical point of view, robot manipulator is divided into two main groups, which called; serial robot links and parallel robot links.

In serial robot manipulator, links and joints is serially connected between base and final frame (end-effector). Parallel robot manipulators have many legs with some links and joints, where in these robot manipulators base frame has connected to the final frame. Most of industrial robots are serial links, which in serial robot manipulator the axis of the first three joints has a known as major axis, these axes show the position of end-effector, the axis number four to six are the minor axes that use to calculate the orientation of end-effector, at last the axis number seven to use to avoid the bad situation. Kinematics is an important subject to find the relationship between rigid bodies (e.g., position and orientation) and end-effector in robot manipulator. The mentioned topic is very important to describe the three areas in robot manipulator: practical application, dynamic part, and control purposed therefore kinematics play important role to design accurate controller for robot manipulators. Robot manipulator kinematics is divided into two main groups: forward kinematics and inverse kinematics where forward kinematics is used to calculate the position and orientation of end-effector with given joint parameters (e.g., joint angles and joint displacement) and the activated position and orientation of end-effector calculate the joint variables in Inverse Kinematics [2]. Dynamic modeling of robot manipulators is used to describe the behavior of robot manipulator, design of model based controller, and for simulation. The dynamic modeling describes the relationship between joint motion, velocity, and accelerations to force/torque or current/voltage and also it can be used to describe the particular dynamic effects (e.g., inertia, coriolios, centrifugal, and the other parameters) to behavior of system [3]. The Unimation PUMA 560 serially links robot manipulator was used as a basis, because this robot manipulator widely used in industry and academic. It has a nonlinear and uncertain dynamic parameters serial link 6 degrees of freedom (DOF) robot manipulator. A nonlinear robust controller design is major subject in this work.

2. PUMA Robot Manipulator

Robot manipulators have many applications in aerospace, manufacturing, automotive, medicine and other industries. Robot manipulators consist of three main parts: mechanical, electrical, and control. In the mechanical point of view, robot manipulators are collection of serial or parallel links which have connected by revolute and/or prismatic joints between base and end-effector frame. The robot manipulators electrical parts are used to links motion, which including the following subparts: power supply to supply the electrical and control parts, power amplifier to amplify the signal and driving the actuators, DC/stepper/servo motors or hydraulic/pneumatic cylinders to motion the links, and transmission part to transfer data between robot manipulator subparts. Control part is used to adjust the timing between the subparts of robot manipulator to reach the best performance (trajectory). It provides four main abilities in robot manipulators: controlling the manipulators movement in correct workspace, sensing the information from the environment, being able to intelligent control behavior and processing the data and information between all subparts.

Automation play important role in new industry which changed the slow and heavy systems to faster, lighter and smarter systems. In the recent years robot manipulators not only have been used in manufacturing but also used in vast area such as medical area and working in International Space Station. Control methodologies and the mechanical design of robot manipulators have started in the last two decades and the most of researchers work in these methodologies. In next two sections, classification of robot manipulators and their effect on design controller are presented. The following sections are focused on analysis the kinematic and dynamic equations to control of robot manipulator [4,5].

Research about mechanical parts and control methodologies in robotic system is shown; the mechanical design, type of actuators, and type of systems drive play important roles to have the best performance controller. This section has focused on the robot manipulator mechanical classification. More over types of kinematics chain, i.e., serial Vs. parallel manipulators, and types of connection between link and join actuators, i.e., highly geared systems Vs. direct-drive systems are presented in the following sections because these topics played important roles to select and design the best acceptable performance controllers[6]. Study of robot manipulators is classified into two main groups: kinematics and dynamics. Calculate the relationship between rigid bodies and end-effector without any forces is called Robot manipulator Kinematics. Study of this part is pivotal to calculate accurate dynamic part, to design with an acceptable performance controller, and finally in real situations and practical applications. As expected the study of manipulator kinematics is divided in two main challenges: forward and inverse kinematics. Forward kinematics has been used to find the position and orientation of task (end-effector) frame when angles and/or displacement of joints are known and inverse kinematics has been used to find possible joints variable (displacements and angles) when all position and orientation of end-effector be active[7,8].

2.1. Implementation

$$M(q).\ddot{q} + V(q,\dot{q}).\dot{q} + G(q) = \Gamma$$

where,

q : nx1 position vector ,

$M(q)$: nxn inertia matrix of the manipulator,

$V(q,\dot{q})$: nx1 vector of Centrifugal and Coriolis terms

$G(q)$: nx1 vector of gravity terms

Γ : nx1 vector of torques

By writing the velocity dependent term $V(q,\dot{q})$ in a different form, all the matrices become functions of only the manipulator position; in this case the dynamic equation is called configuration space equation and has the following form:

$$\Gamma = M(q).\ddot{q} + B(q).[\dot{q}.\dot{q}] + C(q).[\dot{q}^2] + G(q)$$

where,

$B(q)$: nxn(n-1)/2 matrix of Coriolis torques

$C(q)$: nxn matrix of Centrifugal torques

$[\dot{q}\dot{q}]$: n(n-1)/2x1 vector of joint velocity products given by: $[\dot{q}_1.\dot{q}_2, \dot{q}_1.\dot{q}_3, ..., \dot{q}_1.\dot{q}_n, \dot{q}_2.\dot{q}_3, \dot{q}_2.\dot{q}_4, ..., \dot{q}_{n-2}.\dot{q}_n, \dot{q}_{n-1}.\dot{q}_n]^T$ $[\dot{q}^2]$: nx1 vector given by: $[\dot{q}_1{}^2, \dot{q}_2{}^2, ..., \dot{q}_n{}^2]$

In this context, the configuration space equation presented in [6] will be used. The robot is disassembled and the inertial properties of each link are found. The explicit dynamic model is then obtained with a derivation procedure comprised of several heuristic rules for simulation.

To derive the model of the robot arm, Khatib et al. started by generating the kinetic energy matrix and gravity vector symbolic elements by performing the summation of either Lagrange's or the Gibbs-Alembert formulation; these elements are then simplified by combining inertia constants that multiply common variable expressions. The Coriolis and centrifugal matrix elements are then calculated in terms of partial derivatives of kinetic energy, and then reduced using four relations that hold on the partial derivatives. Finally, the necessary partial derivatives are formed, and the Coriolis and centrifugal matrices are found. A simplification step is then done by combining the inertia constants that multiply the common variable expressions.

Recall that only three links of PUMA robot are used in this thesis, $q_4 = q_5 = q_6 = 0$. The configuration space equation is,

$$\Gamma = A(q).\ddot{q} + B(q).[\dot{q}.\dot{q}] + C(q).[\dot{q}^2] + G(q)$$

With,

Matrix A is a symmetric 6x6 matrix:

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

Where,

$$a_{23} = I_5.S3 + I_6 + I_{12}.C3 + I_{16}.S3 + 2.I_{15}$$

$$a_{33} = I_{m3} + I_6 + 2.I_{15}$$

$$a_{35} = I_{15} + I_{17}$$

$$a_{44} = I_{m4} + I_{14}$$

$$a_{55} = I_{m5} + I_{17}$$

$$a_{66} = I_{m6} + I_{23}$$

$a_{21} = a_{12}$, $a_{31} = a_{13}$ and $a_{32} = a_{23}$

While matrix B is:

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$$a_{11} = I_{m1} + I_1 + I_3.CC2 + I_7.SS23 + I_{10}.SC23 + I_{11}.SC2 + I_{21}.SS23 + \\ + 2.[I_5.C2.S23 + I_{12}.C2.C23 + I_{15}.SS23 + I_{16}.C2.S23 + I_{22}.SC23]$$

$$a_{12} = I_4.S2 + I_8.C23 + I_9.C2 + I_{13}.S23 - I_{18}.C23$$

$$a_{13} = I_8.C23 + I_{13}.S23 - I_{18}.C23$$

$$a_{22} = I_{m2} + I_2 + I_6 + 2.[I_5.S3 + I_{12}.C2 + I_{15} + I_{16}.S3]$$

$$B(q) = \begin{bmatrix} b_{112} & b_{113} & 0 & b_{115} & 0 & b_{123} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & b_{214} & 0 & 0 & b_{223} & 0 & b_{225} & 0 & 0 & b_{235} & 0 & 0 & 0 & 0 \\ 0 & 0 & b_{314} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ b_{412} & b_{413} & 0 & b_{415} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & b_{514} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Where,

$$b_{112} = 2.[-I_3.SC2 + I_5.C223 + I_7.SC23 - I_{12}.S223 + I_{15}.2.SC23 + I_{16}.C223 + I_{21}.SC23 + \\ + I_{22}.(1-2.SS23)] + I_{10}.(1-2.SS23) + I_{11}.(1-2.SS2)$$

$$b_{113} = 2.[I_5.C2.C23 + I_7.SC23 - I_{12}.C2.S23 + I_{15}.2.SC23 + I_{16}.C2.C23 + I_{21}.SC23 + \\ + I_{22}.(1-2.SS23)] + I_{10}.(1-2.SS23)$$

$$b_{115} = 2.[-SC23 + I_{15}.SC23 + I_{16}.C2.C23 + I_{22}.CC23]$$

$$b_{123} = 2.[-I_8.S23 + I_{13}.C23 + I_{18}.S23]$$

$$b_{214} = I_{14}.S23 + I_{19}.S23 + 2.I_{20}.S23.(1-0.5)$$

$$b_{223} = 2.[-I_{12}.S3 + I_5.C3 + I_{16}.C3]$$

$$b_{225} = 2.[I_{16}.C3 + I_{22}]$$

$$b_{235} = 2.[I_{16}.C3 + I_{22}]$$

$$b_{314} = 2.[I_{20}.S23.(1-0.5)] + I_{14}.S23 + I_{19}.S23$$

$$b_{412} = -b_{214} = -[I_{14}.S23 + I_{19}.S23 + 2.I_{20}.S23.(1-0.5)]$$

$$b_{413} = -b_{314} = -2.[I_{20}.S23.(1-0.5)] + I_{14}.S23 + I_{19}.S23$$

$$b_{415} = -I_{20}.S23 - I_{17}.S23$$

$$b_{514} = -b_{415} = I_{20}.S23 + I_{17}.S23$$

Matrix C is:

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

Where,

$$c_{12} = I_4.C2 - I_8.S23 - I_9.S2 + I_{13}.C23 + I_{18}.S23$$

$$c_{13} = 0.5.b_{123} = -I_8.S23 + I_{13}.C23 + I_{18}.S23$$

$$c_{21} = -0.5.b_{112} = I_3.SC2 - I_5.C223 - I_7.SC23 + I_{12}.S223 - I_{15}.2.SC23 - I_{16}.C223 - I_{21}.SC23 - \\ - I_{22}.(1-2.SS23) - 0.5.I_{10}.(1-2.SS23) - 0.5.I_{11}.(1-2.SS2)$$

$$c_{23} = 0.5.b_{223} = -I_{12}.S3 + I_5.C3 + I_{16}.C3$$

$$c_{31} = -0.5.b_{113} = -I_5.C2.C23 - I_7.SC23 + I_{12}.C2.S23 - I_{15}.2.SC23 - I_{16}.C2.C23 - I_{21}.SC23 - \\ - I_{22}.(1-2.SS23) - 0.5.I_{10}.(1-2.SS23)$$

$$c_{32} = -c_{23} = I_{12}.S3 - I_5.C3 - I_{16}.C3$$

$$c_{51} = -0.5.b_{115} = SC23 - I_{15}.SC23 - I_{16}.C2.C23 - I_{22}.CC23$$

$$c_{52} = -0.5.b_{225} = -I_{16}.C3 - I_{22}$$

And matrix G is:

$$g(q) = \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

$$g_2 = g_1.C2 + g_2.S23 + g_3.S2 + g_4.C23 + g_5.S23$$

$$g_3 = g_2.S23 + g_4.C23 + g_5.S23$$

$$g_5 = g_5.S23$$

Where,

Si = sin(θi), Ci = cos(θi), Cij = cos(θi+ θj), Sijk = sin(θi +θj +θk),

CCi = cos(θi).cos(θi) and Csi = cos(θi).sin(θi).

Table 1 and Table 2 contain the computed values for the constants appearing in the equations of forces of motion,

Table 1. *Inertial Constains (kg.m^2).*

$I_1 = 1.43 \pm 0.05$	$I_2 = 1.75 \pm 0.07$
$I_3 = 1.38 \pm 0.05$	$I_4 = 0.69 \pm 0.02$
$I_5 = 0.372 \pm 0.031$	$I_6 = 0.333 \pm 0.016$
$I_7 = 0.298 \pm 0.029$	$I_8 = -0.134 \pm 0.014$
$I_9 = 0.0238 \pm 0.012$	$I_{10} = -0.0213 \pm 0.0022$
$I_{11} = -0.0142 \pm 0.0070$	$I_{12} = -0.011 \pm 0.0011$
$I_{13} = -0.00379 \pm 0.0009$	$I_{14} = 0.00164 \pm 0.000070$
$I_{15} = 0.00125 \pm 0.0003$	$I_{16} = 0.00124 \pm 0.0003$
$I_{17} = 0.000642 \pm 0.0003$	$I_{18} = 0.000431 \pm 0.00013$
$I_{19} = 0.0003 \pm 0.0014$	$I_{20} = -0.000202 \pm 0.0008$
$I_{21} = -0.0001 \pm 0.0006$	$I_{22} = -0.000058 \pm 0.000015$

$I_{23} = 0.00004 \pm 0.00002$	$I_{m1} = 1.14 \pm 0.27$
$I_{m2} = 4.71 \pm 0.54$	$I_{m3} = 0.827 \pm 0.093$
$I_{m4} = 0.2 \pm 0.016$	$I_{m5} = 0.179 \pm 0.014$
$I_{m6} = 0.193 \pm 0.016$	

***Table 2.** Gravitational Constants (N.M).*

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

Note: tolerance is due to measurement and calculation errors.

2.2. Using PUMA Robot as 3-DOF Robot

The three degree of freedom PUMA robot has the same configuration space equation general form as its 6-DOF convenient. In this type, the last three joints are blocked so they keep their initial states while the robot is moving. Using the configuration equation of the robot, and by setting the last joints as zero always, we can define a general equation that allows us to use PUMA robot as a 3-DOF robot.

To find the kinematics of the 3-DOF robot, a new D-H coordinate system is established, and a homogenous transformation matrix relating the 3rd coordinate frame to the first coordinate frame is developed. However, the 3-DOF PUMA will have the same kinematics of its 6-DOF convenient with q_4, q_5 and q_6 set to zero.

For the configuration space equation of the robot

$$\Gamma = A(q).\ddot{q} + B(q).\dot{q}\dot{q} + C(q).\dot{q}^2 + g(q)$$

We set $q_4 = q_5 = q_6 = 0$, this yields

$$\ddot{q} = [\ddot{q}_1 ... \ddot{q}_2 ... \ddot{q}_3 ... 0 ... 0 ... 0\ ]^T$$

$$[\dot{q}\dot{q}] = [\dot{q}_1\dot{q}_2 ... \dot{q}_1\dot{q}_3 ... 0 ... 0 ... 0 ... \dot{q}_2\dot{q}_3 ... 0 ... 0 ... 0 ... 0 ... 0 ... 0 ... 0 ... 0 ... 0]^T$$

$$[\dot{q}^2] = [\dot{q}_1{}^2 ... \dot{q}_2{}^2 ... \dot{q}_3{}^2 ... 0 ... 0 ... 0]^T$$

$$B(q).\dot{q}\dot{q} = [b_{112}.\dot{q}_1\dot{q}_2 + b_{113}.\dot{q}_1\dot{q}_3 + b_{123}.\dot{q}_2\dot{q}_3 .. b_{223}.\dot{q}_2\dot{q}_3 ... 0 .. b_{412}.\dot{q}_1\dot{q}_2 + b_{413}.\dot{q}_1\dot{q}_3 ... 0 ... 0]^T$$

and

$$C(q).\dot{q}^2 = [c_{12}.\dot{q}_2{}^2 + c_{13}.\dot{q}_3{}^2 ... c_{21}.\dot{q}_1{}^2 + c_{23}.\dot{q}_3{}^2 ... c_{31}.\dot{q}_1{}^2 + c_{32}.\dot{q}_2{}^2 ... 0 ... c_{51}.\dot{q}_1{}^2 + c_{52}.\dot{q}_2{}^2 ... 0]^T$$

The angular acceleration is found as to be

$$\ddot{q} = A^{-1}(q).\{\Gamma - [B(q).\dot{q}\dot{q} + C(q).\dot{q}^2 + g(q)]\}$$

Now let

$$I = \{\Gamma - [B(q).\dot{q}\dot{q} + C(q).\dot{q}^2 + g(q)]\} \Rightarrow \quad \ddot{q} = A^{-1}(q).I$$

$$I_1 = \Gamma_1 - [b_{112}.\dot{q}_1\dot{q}_2 + b_{113}.\dot{q}_1\dot{q}_3 + b_{123}.\dot{q}_2\dot{q}_3] - [c_{12}.\dot{q}_2{}^2 + c_{13}.\dot{q}_3{}^2]$$

$$I_2 = \Gamma_2 - \left[b_{223}.\dot{q}_2\dot{q}_3\right] - \left[c_{21}.\dot{q}_1{}^2 + c_{23}.\dot{q}_3{}^2\right] - g_2$$

$$I_3 = \Gamma_3 - \left[c_{31}.\dot{q}_1{}^2 + c_{32}.\dot{q}_2{}^2\right] - g_3$$

$$I_4 = \Gamma_4 - \left[b_{412}.\dot{q}_1\dot{q}_2 + b_{413}.\dot{q}_1\dot{q}_3\right]$$

$$I_5 = \Gamma_5 - \left[c_{51}.\dot{q}_1{}^2 + c_{52}.\dot{q}_2{}^2\right] - g_5$$

$$I_6 = \Gamma_6$$

These equations tell us that in order to ensure that $\ddot{q}_4, \ddot{q}_5$ and $\ddot{q}_6$ keep their zero values, it is better to set $I_4 = I_5 = I_6 = 0$; so by holding the control torques of the last three joints as

$$\Gamma_4 = \left[b_{412}.\dot{q}_1\dot{q}_2 + b_{413}.\dot{q}_1\dot{q}_3\right]$$

$$\Gamma_5 = \left[c_{51}.\dot{q}_1{}^2 + c_{52}.\dot{q}_2{}^2\right] + g_5$$

and $\Gamma_6 = 0$, the last three joints are blocked at their initial states.

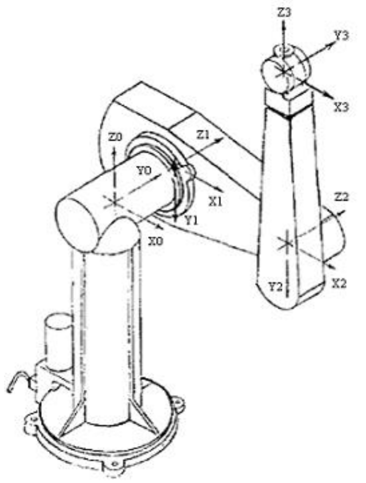

Figure 1. *D-H Coordinate frames of the 3DOF PUMA Robot.*

3. Simulation Results

The SIMULINK Model for 3D-PUMA robot is illustrated in Figure 2. The scope results for comparison of theta one to six is also mentioned from Figure 3 to Figure 5.

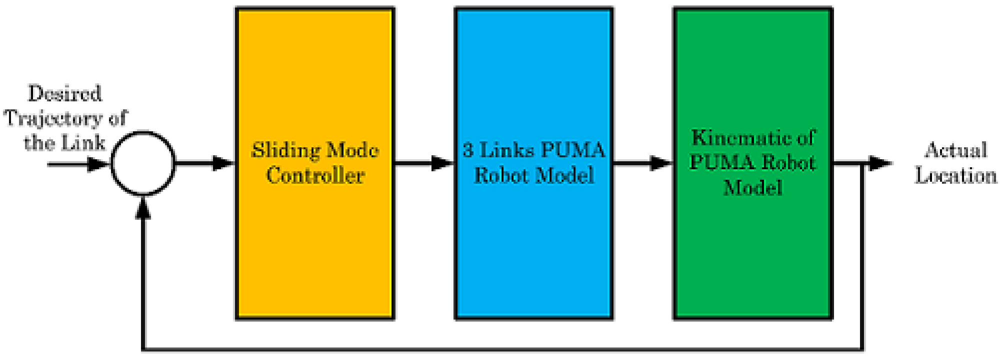

Figure 2. *SIMULINK Model of 3D-PUMA Robot.*

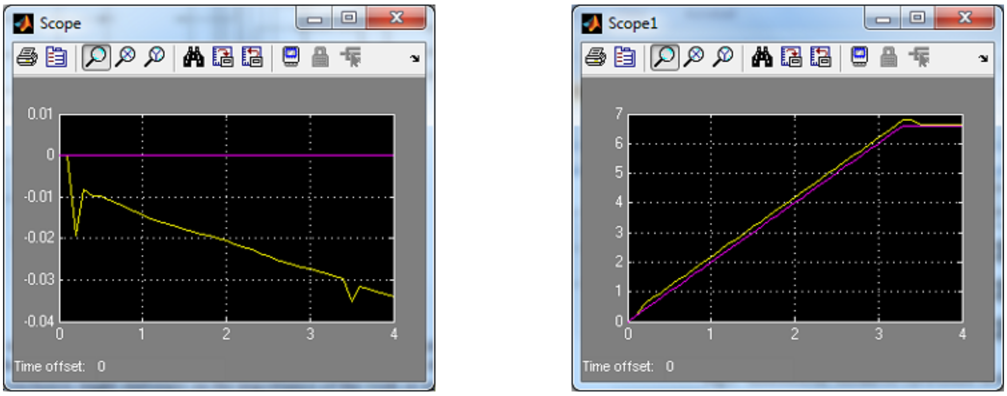

Figure 3. *Scope Results for Comparison of Theta One and Two.*

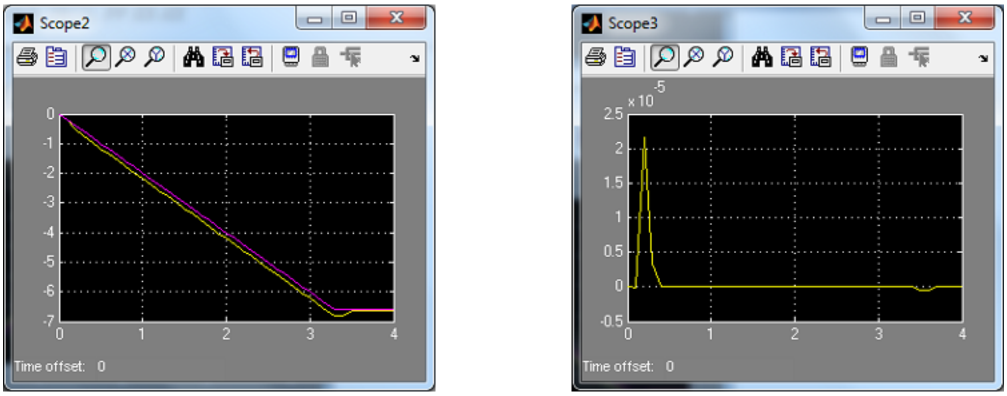

Figure 4. *Scope Results for Comparison of Theta Three and Four.*

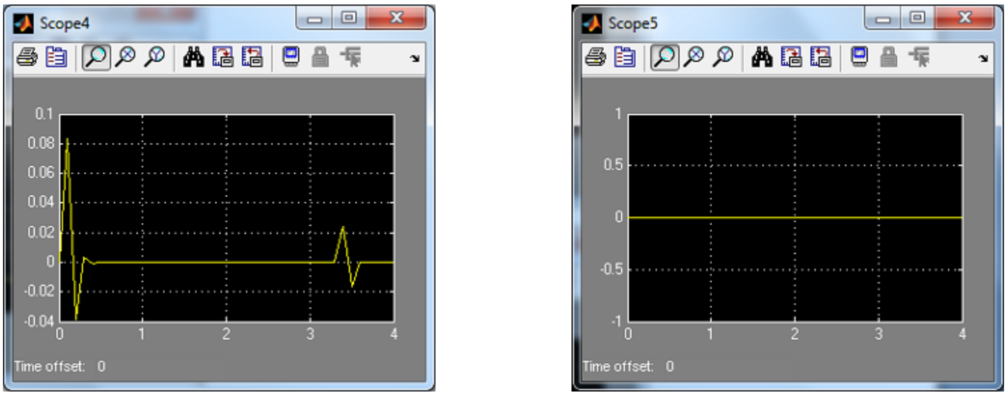

Figure 5. *Scope Results for Comparison of Theta Five and Six.*

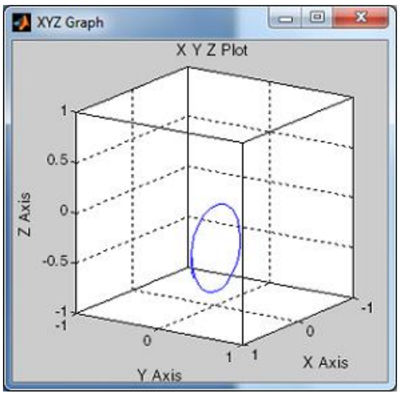

Figure 6. *3D Plot Results for PUMA Robot Dynamics Analysis.*

In this SIMULINK model, the main control law is the sliding model control approaches. According to the comparison of theta one to six for 3D PUMA robot, the reference value and the simulated results are very similar to get the stability state for dynamics system analysis. The 3D plot results for PUMA robot dynamics analysis is shown in Figure 6. The movement of arms for 3D PUMA robot is expressed by xyz directional space.

4. Conclusions

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.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Author Contributions

This study is mainly focused on the PUMA robot dynamics control system with three dimensional approaches using MATLAB/ SIMULINK. There have been several literature background ideas for implementing the mathematical modeling of the robot dynamics control system in MATLAB environments for experimental studies. This work emphasizes on the numerical analysis to develop the applied robot dynamics control system for various applications such as communication design or biomedical applications. This work could be provided the fundamental concepts with the help of numerical analysis especially computer supported applied design for implementation of mathematical expressions for undergraduate students.

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