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Kinematics and Dynamics of Lower Body of Autonomous Humanoid Biped Robot

Deepak Bharadwaj, Manish Prateek

***Abstract:** This paper presents the mathematical modeling of ten degree of freedom of manipulator. Workspace of each leg calculated by applying the method of Denavit_Hatretnberg notation scheme. Forward and inverse kinematics obtained for the manipulator of lower body of humanoid robot. Static forces on the joint calculated for the joint to hold the particular position of the lower body. Dynamics torque obtained by applying the principles of Lagrangian dynamics. A nonlinear feedback measured from the output end to control the movement of leg. A computed control torque approach has been used to avoid the oscillation of the system. Several experiment done of the mat lab to verify the analytical and simulation result*

***Index Terms:** Humanoid Robot, Transform approach, Partitioned-proportional derivative*

I. INTRODUCTION

From the last 20 years robotics community focus on the development of humanoid robot. Humanoid robot [1] is typically complex in design, having numerous Degree-of Freedom. Some of the most studied architecture found in the literature include 30 DOF. This paper suggests the five degree of freedom in each leg similar to the Human Skeleton. Three degree of freedom near to the torso, one in knee and one in ankle movement. Currently reinforcement control algorithm is developed by the robotics community. Reinforcement algorithm able to take the decision by the robot in different situation. This paper focus on the lower body of humanoid robot to control the manipulator in different environment. Biomechanics used to get the dimension of lower body of humanoid robot. According to that the length of lower leg is equal to upper leg length. For finding the inverse a new transform approach has been used. In other literature they have used trigonometric approach. While moving in forward direction joint1, joint 4 and joint 5 are coming in action and while turn joint 1, joint2, joint4 and joint 5 are responsible. Computed control torque getting the feedback from the joint movement to control the posture of the body. To decide the gain of the PD controller, stiffness of the material is considered. While developing the mathematical model excitation frequency kept point five times of natural frequency, so that there is no resonance occurs. MATLAB multibody dynamics helps to create the physical model of robot. Multibody dynamics consists of three parts; body, joint and actuation blocks. With the help of these blocks a physical modeling can be done easily. ASimMechanics model [2] is a representation of physical structure of lower body of humanoid robot, specified through some variables such as mass, link length, geometric and kinematic relations between its components. In multibody dynamics toolbox joint position is sense and feed to the PID controller. PID controller linearize the nonlinear feedback of the system. When the feet are touching the ground, at that instant there is no oscillation produced by the system, otherwise the body will be tuple.

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II. FORWARD AND INVERSE KINEMATICS

Figure 1,2 and 3 shows the step by step of simMecnaics toolbox in MATLAB to create the model of lower body of humanoid robot which consists ten degree of freedom. Each leg has 5 degree of freedom with base attached to the top of the leg.

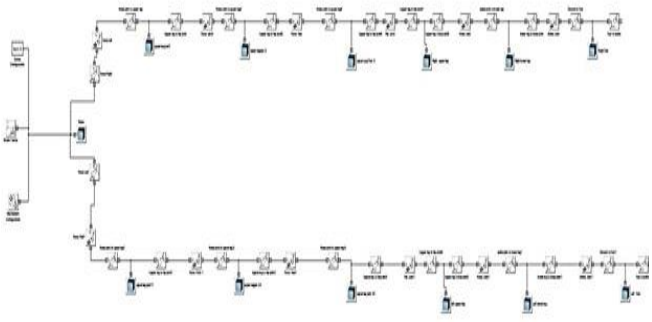

Figure1.simMechanics Block of lower body of Humanoid robot

To model the lower body of humanoid robot on MATLAB simMechanics toolbox is created with the help of joint blocks, rigid body and rigid transform blocks. Parameters are taken based on the biomechanics. Length of lower leg is equal to upper leg of the body. Each leg has five degree of freedom, considering three degree of freedom near the torso, hip joint and knee joint and ankle joint. Base frame is fixed to the middle of torso. Weight of the upper body is acting on the middle of the torso. Zero moment point is located at the middle of torso.

Initially reaction force is vertically up and weight of the body is acting vertically down. Hence there is no zero moment point occurs and the body is in stable condition.

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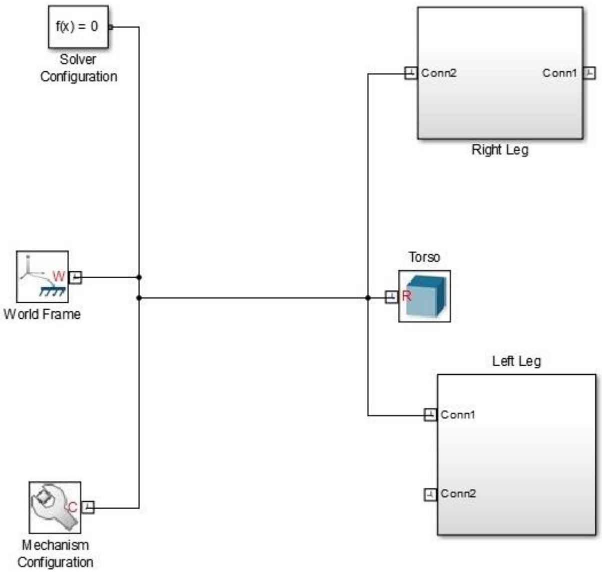

Figure2. Subsystem of Lower body of humanoid robot

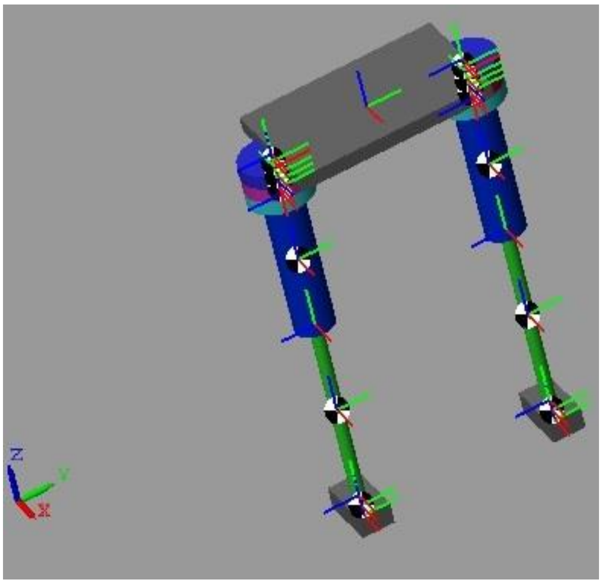

Figure3.Matlab Model

A complete link frame assignment [3] as shown in figure 4. Denavit_Hartenberg method used to calculate the workspace of each leg. In this paper workspace of right leg is calculated and assume same for left leg. Humanoid body is symmetrical about the sagittal plane. Table 1 gives the joint link parameter of leg. Applying the principle of Denavit_Hartenberg step by step, the transformation matrix of each joint can be calculated as;

$${}^0_1T := Rot(z, \Theta_1)*Trans(0,0,l_1)*Trans(0,0,0)*Rot(x,90) \quad (1)$$

$${}^1_2T := Rot(z, \Theta_2+90)*Trans(0,0,l_2)*Trans(0,0,0)*Rot(x,-90) \quad (2)$$

$${}^2_3T := Rot(z, \Theta_3-90)*Trans(0,0,0)*Trans(0,0,l_3)*Rot(x,90) \quad (3)$$

$${}^3_4T := Rot(z, \Theta_4)Trans(0,0,0)*Trans(0,0,l_4)*Rot(x,0) \quad (4)$$

$${}^4_5T := Rot(z, \Theta)*Trans(0,0,0)*Trans(0,0,l_5)*Rot(x,0) \quad (5)$$

Where ${}^{i-1}_{i}T$ represents the position of current link to previous link..

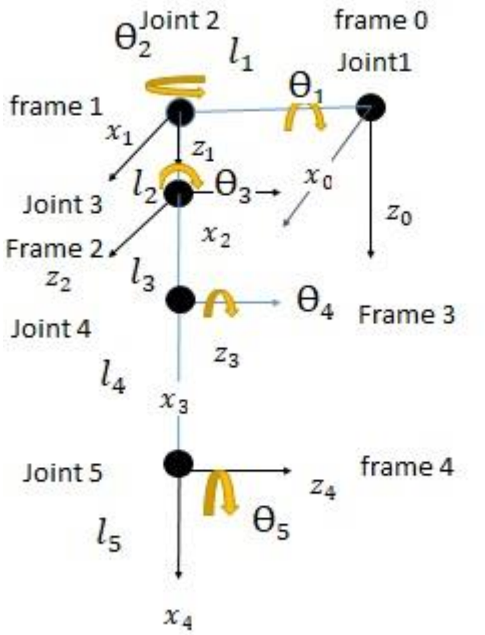

Figure4. Link-frame assignment of lower body

Table1: Joint link Parameters.

DH Parameters		**Link**			
	1	2	3	4	5
Θ_i	Θ_1	Θ_2+90	Θ_3-90	Θ_4	Θ_5
d_i	l_1	l_2	0	0	0
a_i	0	0	l_3	l_4	l_5
α_i	90	-90	90	0	0

Forward kinematic [4] of lower body of humanoid robot depends on the link length and joint values. Knowing these parameters, the workspace created by the right leg is

$${}^0_5T := {}^0_1T * {}^1_2T * {}^2_3T * {}^3_4T * {}^4_5T = T_{toe} \quad (6)$$

Computing the workspace of lower body of humanoid robot, the legs are capable to travel on the ground to reach the target.

Inverse kinematics

Inverse kinematics [5] gives the information about the joint values to reach in under different condition. Transform approach has been used to calculate the inverse of the manipulator.

Path1 : frame{0}------frame{4}--------frame{5}

While moving in forward direction joint1, joint 4 and joint 5 are coming in action. Applying these concept, the joint values are obtained as.

$$T_{toe} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & n_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^0_5T \quad (7)$$

Along this path the transformation ${}^0_5T$ can be obtained as

$${}^0_5T = {}^0_1T * {}^3_4T * {}^4_5T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & n_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Applying the inverse approach of matrix, the joint values obtained as

$$\theta_1 = \tan^{-1}\frac{(p_y - l_5 * n_y)}{(p_x - l_5 * n_x)}$$

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$$\theta_4 = \tan^{-1}\frac{(p_x - l_5 * n_x - l_1)}{\left(\pm\sqrt{((p_x - l_5 * n_x)^2)} + \left((p_y - l_5 * n_y)^2\right)\right)}$$

$$\theta_5 = \tan^{-1}\frac{\{(p_y + l_5 n_y) l_4 n_x - (p_x + l_5 n_x) l_4 n_y\}}{\{(p_x + l_5 n_x) l_4 o_y + (p_y + l_5 n_y) l_4 o_x\}}$$

To calculate the other joint values following the path2.
Path2: frame {0) ---frame {1} --frame {2} ----frame {3} -----Frame {4} ------frame {5}

$${}^0_5T = {}^0_1T * {}^1_2T * {}^2_3T * {}^3_4T * {}^4_5T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & n_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Since θ_2 and θ_3 are unknown. The inverse of matrix ${}^4_5T$ and ${}^3_4T$ can be computed. Substituting these values and post multiplying with the matrix ${}^0_5T$ can be computed.

$${}^0_5T * {}^4_5T^{-1} * {}^3_4T^{-1} = {}^0_1T * {}^1_2T * {}^2_3T \qquad (8)$$

Values of θ_2 and θ_3 are obtained as follows.

$$\theta_2 = \tan^{-1}\frac{(-(o_x * C\theta_{45} + n_x * S\theta_{45}))}{\left(\pm\sqrt{(o_x * C\theta_{45} + n_x * S\theta_{45})^2 + \left((o_y * C\theta_{45} + n_y * S\theta_{45})^2\right)}\right)}$$

$$\theta_3 = \tan^{-1}\frac{(n_x * C\theta_{45} - o_x * S\theta_{45})}{(-a_x)}$$

III. DYNAMIC ANALYSIS OF TORQUE

Lagrangian _Euler [6] approach used to calculate the joint torque. Torque is responsible to move the lower body from initial position to target point.

The torque equation for the joint can be calculated as the Lagrangian- Euler mechanics.

$$L = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=i}^{i}\sum_{k}^{i} Tr\left[\left({}_{j-1}^{0}T\, Q_j\, {}^{j-1}_{i}T\right) I_i \left({}_{k-1}^{0}T\, Q_k\, {}^{k-1}_{i}T^T\right)\right]\dot{q}_j \dot{q}_k + \sum_{i=1}^{n} m_i\, g\, {}^0_iT\, {}^i_i\bar{r} \qquad (8)$$

Where L is the Lagrangian , sum of the kinetic energy of the system ,and potential energy of the system . The Lagrangian can now be differentiated in order to from the dynamic equation of motion. According to the Lagrangian-Euler dynamics formulation, the generalized torque τ_i of the actuator at joint i, to drive link i of the manipulator is given by

$$\tau_i = \frac{d}{dt}\left(\frac{\delta L}{\delta q_i}\right) - \frac{\delta L}{\delta q_i} \qquad (9)$$

Carrying out the differentiation , the generalized torque τ_i applied to link I to n-DOF manipulator is obtained.

$$\tau_i = \sum_{j=1}^{n} M_{ij}(q)\,\ddot{q}_j + \sum_{j=1}^{n}\sum_{k=1}^{n} h_{ijk}\,\dot{q}_j \dot{q}_k + G_i \qquad (10)$$

for i=1, 2………n

where

$$M_{ij} = \sum_{p=\max(i,j)}^{n} Tr\left[\, d_{pj}\ \ I_p\, {}^T_{pi}d\,\right]$$

$$h_{ijk} = \sum_{p=\max(i,j,k)}^{n} Tr\left[\frac{\partial(d_{pk})}{\partial q_p}\, I_p\, {}^T_{pi}d\right]$$

$$G_i = -\sum_{p=i}^{n} m_p\, g\, d_{pi}\, {}^p_p\bar{r}_p$$

and

$$d_{ij} = \begin{cases} {}_{j-1}^{0}T\, Q_j\, {}^{j-1}_{i}T & for\ j \le i \\ 0 & for\ j > i \end{cases}$$

and

$$\frac{\partial d_{ij}}{\partial q_k} = \begin{cases} {}_{j-1}^{0}T\, Q_j\, {}_{k-1}^{j-1}T\, Q_k\, {}^{k-1}_{i}T & for\ i \ge k \ge j \\ {}_{k-1}^{0}T\, Q_k\, {}_{j-1}^{k-1}T\, Q_j\, {}^{j-1}_{i}T & for\ i \ge j > k \\ 0 & for\ i < j\ or\ i < k \end{cases}$$

From equation (8), (9) and (10)

The joint torque can be computed for all the joint. Joint torque depends on the joint values trajectory.

IV. TRAJECTORY OF THE JOINT

Trajectory is the sequence of movement of the joint with respect to the time. Based on the study biomechanics of human body the joint motion [7] range values are in the table2. When the torso of lower body has given an input in Cartesian trajectory [8] to move the body from one point to another point. The joint trajectory [9] converts the Cartesian space vales in the joint vales form. The fifth order polynomial is assuming by initial condition as initial velocity and acceleration and final velocity and acceleration is zero.

Table2. Joint range motion

Joint			Human leg(deg)	Lower Body leg(deg)
Waist	Joint1	Roll	-15 to 130	-15 to 100
	Joiint2	Pitch	-30 to 45	0 to 45
	Joint 3	Yaw	-45 to 50	-45 to 45
Knee		Joint4	-10 to 155	0 to 120
Ankle		Joint5	-20 to 50	-20 to 40

Based on the polynomial calculation the joint trajectory for the lower body of each individual joint is

$\theta_1 = -45^o + 7.2\,t^3 - 2.16\,t^4 + .1728t^5$ (11)

$\theta_2 = -15^o + 9.2t^3 - 2.76t^4 + .2208t^5$ (12)

$\theta_3 = 3.6t^3 - 1.08t^4 + .0864t^5$

(13)

$\theta_4 = 9.6t^3 - 2.88t^4 + .2304t^5$ (14)

$\theta_5 = -20 + 4.8t^3 - 1.44t^4 + .1152t^5$ (15)

So when the lower body is reaching near by the target it will be in stable condition.

V. COMPUTED PARTITIONED PD CONTROL

The computed torque control scheme [10] also comprise two portions- a model based and a servo portion. The model-based portion defines the nx1 vector of control torques τ using a structure.

$$\tau = M(q)\hat{\tau} + H(q,\dot{q}) + G(q) \qquad (16)$$

where $\hat{\tau}$ is the nx1 torque vector specified by the servo portion.

$$\hat{\tau} = \ddot{q} \qquad (17)$$

Thus the model based portion effectively linearizes as well as decouples the system dynamics by employing a nonlinear feedback of the actual positions and velocities of joints. The schematic representation of this nonlinear control scheme is shown in figure5.

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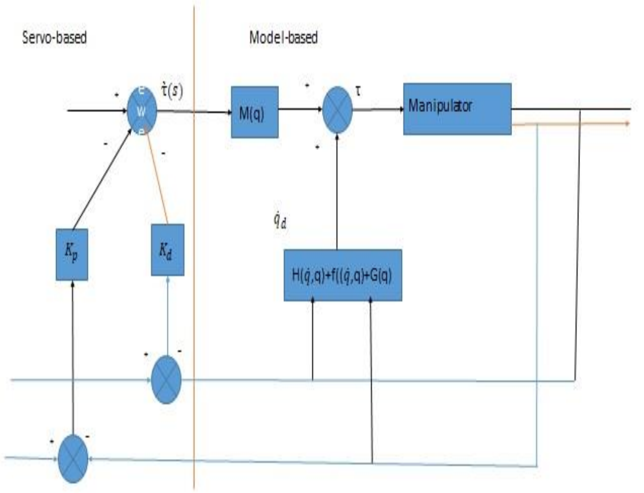

Figure 5: A nonlinear control scheme for multi in and multi output system

On the MATLAB platform the computed control scheme developed for the multi input and multi output as shown in figure6.

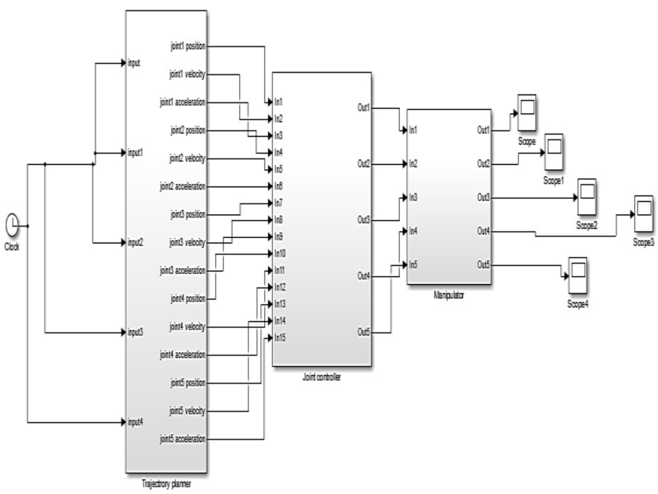

Figure6: Computed Partitioned PD control

After developing the control law, it is applied to the different joint of lower body of autonomous humanoid robot. Figure7 show the interface of control and simMechanics plant.

VI. RESULT

Simulation is carried out the model parameter in table4 for the trajectory given to the lower body of humanoid robot for different condition.

From the trajectory planner the joint has to travel from intial position to final position without the jerk. If jerk occurs during travel the joint of lower body get damaged. For avoiding the jerk fifith –order polynomial hass been designed byy considering the initial and final velocity is zero . Also the inotial and final accerleration of the joint also be zero.

Figure8 shows the variation of input joint position with respect to time.

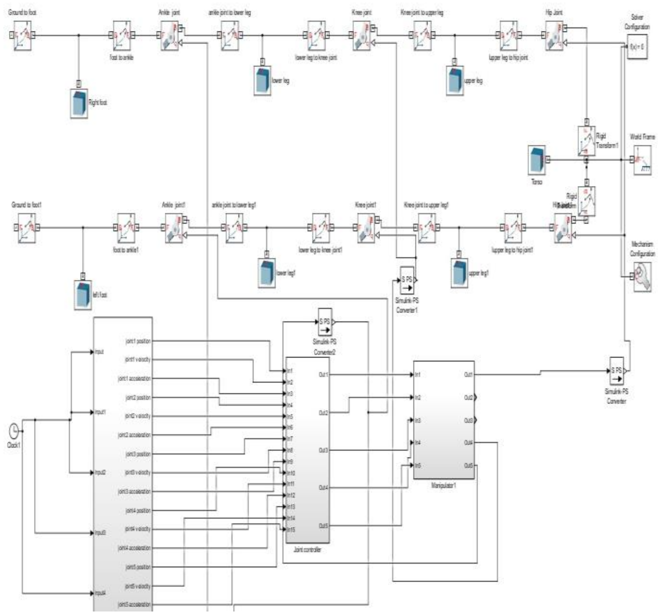

Figure7.Control scheme applied to plant

Table4: Model Parameter

Parameter	Values
m_1	5 Kg
m_2	3 Kg
m_3	2Kg
m_4	1Kg
m_5	.5 Kg
l_1	.05m
l_2	.02m
l_3	.01m
l_4	.03m
l_5	.02m

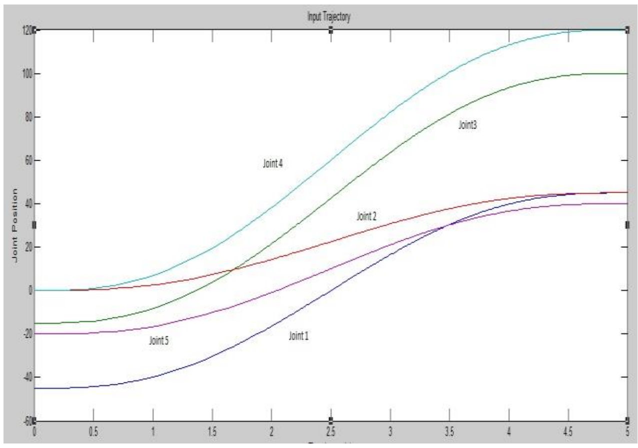

Figure 8. Input trajectory of lower body

Gravity plays the importannt role in the humanoid robot. Since garvity depends on the spatial position of the feet in space. Hens gravity is changing by the movement of the joint from one position to another position.This gravity effect gives the extra torque to resist the motion Hence the computed control torque must be incorporated this value instnat by instant.

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Figure9 shows the variation of gravity of joint movement position with respect to time.

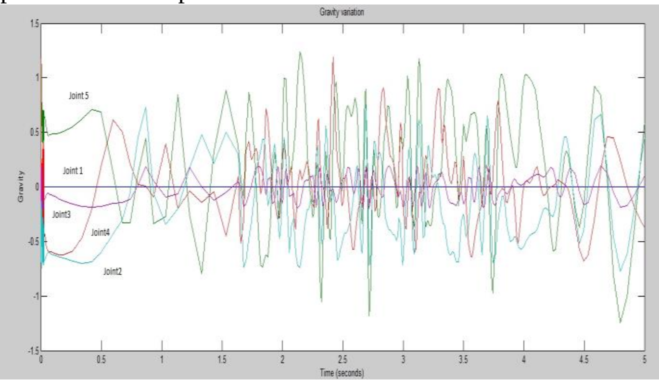

Figure9. Gravity varies with respect to time

When the links are moving to each other, then Coriolis and centrifugal forces resist the motion of joint movement. And it depends on the joint velocity and joint position with respect to time. Computed control scheme measure the feedback form the output trajectory position and incorporates to the controller. So that the oscillation can be removed from the system. Figure10 shows the variation ofcoriolis and centrifugal force of joint with respect to time

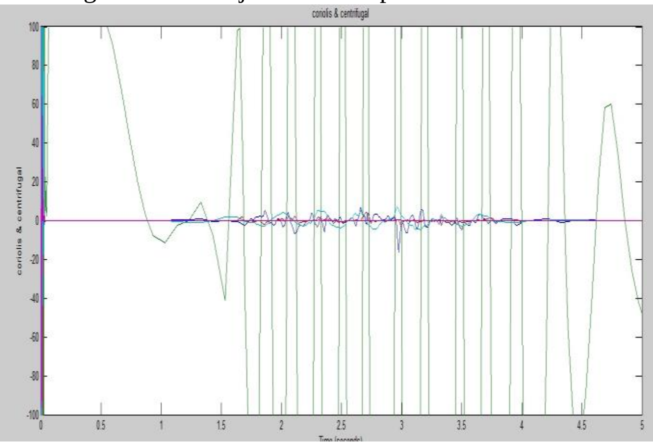

Figure 10. Variation of Coriolis and centrifugal torque with respect to time

Torque value depends on the joint movement, gravity, Coriolis and centrifugal force. Each moment of the time joint position is changes with respect to the time. Gravity and Coriolis force depends on the feedback provided by the sensor. Hence torque is changing rapidly. Figure11 shows the variation of torque of joint with respect to time

Actual trajectory depends on the serval parameter like inertia, gravity and Coriolis and centrifugal force. The desired trajectory obtained in the figure Figure12. Figure shows the variation of actual joint position with respect to time.

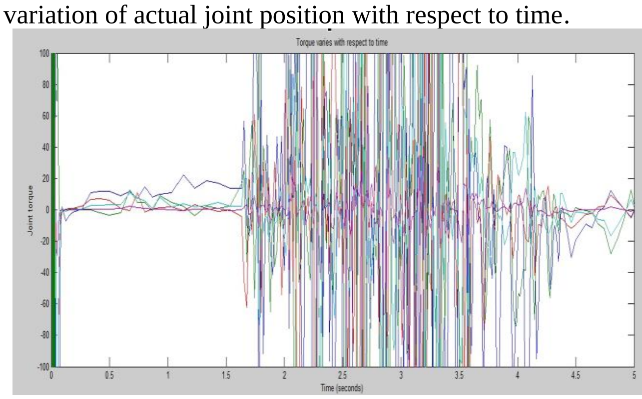

Figure 11: Variation of torque with respect to time

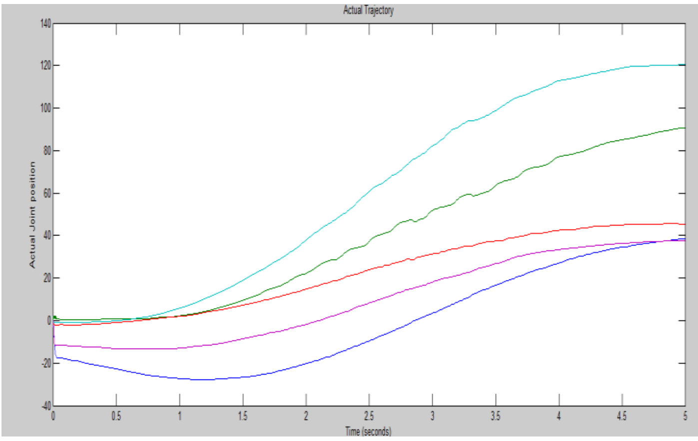

Figure 12: Actual joint trajectory

VII. Discussion

Actual position of lower body affected by the disturbance. In this present context a nonlinear disturbance assumed during the simulation. Some of the joints are not reaching to the desired position. Hence tuning of PID is required. By tune the PID controller gain it will be reached to the desired position.

VIII. Conclusion

Controlling is multi input and multi output system is not easy. If gain values is increasing, then system will be coming in unstable condition. So the controller gain must be in the limit. If disturbance is more, Integral control of PID can be added to the system. So the error can be minimized.

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