Volume 5, Special Issue, June 2018 ISSN: 2348-8565 (Online)

International Journal of Modern Engineering and Research Technology

Website: http://www.ijmert.org Email: editor.ijmert@gmail.com

National Conference on
Advances in Mechanical Engineering and Nanotechnology (AMENT2018)
29-30 June, 2018
Organized by
Department of Mechanical Engineering, University College of Engineering (A),
Osmania University, Hyderabad, TS, India

Control of Multi-Link Robots with Link Flexibility

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Abstract

Flexibility in manipulators/robots is due to both flexibility at the joints and as well as deflection of the links. These robots are favoured in space applications and industries over conventional rigid robots due to their fast response, low consumption of energy, light weight and operations at high speed. The end point positioning accuracy of the end effector is affected due to both joint and link flexibility. In this paper link flexibility is considered. Flexibility makes it an infinite degree freedom system, and the related mathematical equations developed were based on deflections in Euler-Bernoulli beams. The main objective of this paper is to design PI, PD and PID controllers to reduce the error at the tip position due to link flexibility of a two link Revolut e- Revolute Type Manipulator and ensure that the end effector follows a prescribed vertical path while carrying a payload equal to the link mass.

Keywords:—*Manipulator, link flexibility, PI, PD and PID controllers, end effector, MATLAB.*

I. Introduction

Robotic manipulators are widely used to help in dangerous, monotonous, and tedious jobs. Most of the existing robotic manipulators are designed and build in a manner to maximize stiffness in an attempt to minimize the vibration of the end-effector to achieve good position accuracy. This high stiffness is achieved by using heavy material and a bulky design.

The advantages of using a lighter weight manipulator as against the rigid link manipulator include: higher manipulation speed, less power consumption, they require less material for their construction, they required smaller actuator. By making the weight of the manipulator to be lighter results in the flexibility of the manipulator that makes the modeling of such a system to become very cumbersome.

Flexible manipulators can find many applications but since the main problem is to control their vibrations, this problem can be solved by improving the dynamic models and incorporating different control strategies. The study on the control of a flexible arm manipulator started as a part of the space robots research, as a space manipulator should be as light as possible in order to reduce its launching cost and due to the space and weight restriction issues.

The overall flexibility in a robot is due to the flexibility of joints and the flexibility of the links. The flexibility at the joint is due to the lack of rigidity in the drive, deformation of the gear teeth and shaft, and due to the control action. The flexibility of the link due to the deformation in transverse direction and due to shearing and rotary inertia effect.

Link of the robotic system shown in Figure1 is initially at rest and when actuator is actuated to move the link through an angle θ it would move as a whole body to angle θ if it were a rigid link robot. However due to its structural flexibility, robot goes to final position but deforms from its steady state position and it vibrates at steady state position and finally settles to a new steady state position after some time depending upon damping ratio of the flexible system.

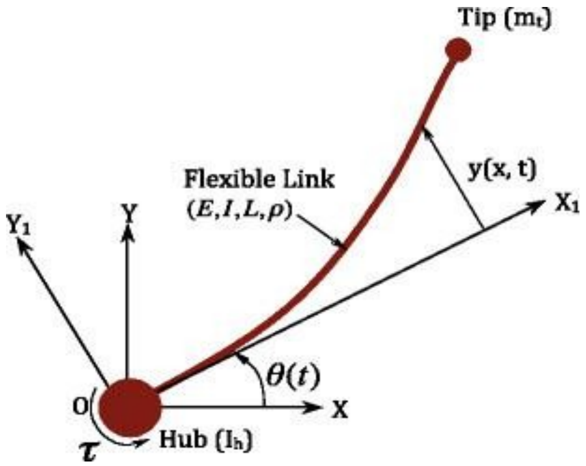

Figure. 1: Vibration of Flexible Beam

Considering the flexible link robotic arm as shown in the Figure 1, the flexible link undergoes deformation in motion due to the flexibility of the link. One can observe that a point on this link has a deviation y (x,t) from the un- deformed position. Therefore, the motion of the point, related to y (x, t), is not completely determined by joint angle θ and it can also be concluded that an infinite number of θ's needed to describe the motion of the entire link. The motion of the end effector is calculated based on Assumed Mode Method (AMM). The links are assumed to behave like Euler- Bernoulli beams.

The position vector along the length of the link depends on the lateral deformation 'y' of the link at that section at a given time. Value of 'y' can be found by Assumed Mode Method (AMM). The problem of flexible link can be solved assuming it as a Euler- Bernoulli's cantilever beam with a payload 'M_P' at the tip of the beam undergoing free vibration, the governing equation to represent the vibration of link can be written as follows

$$E\,I\,\frac{\partial^4 y(x,t)}{\partial x^4} + \rho\,A\,\frac{\partial^2 y(x,t)}{\partial t^2} = 0 \qquad (1)$$

Boundary Conditions: Since, the equation of motion Eq. 1 involves a second order derivative with time and a fourth order derivative with 'x', two initial conditions and four boundary conditions are needed for finding a unique solution for y (x, t) and they are given in following Equations 2 to 7.

$$y(x, t=0) = y_i \tag{2}$$

$$\frac{\partial y(x,t=0)}{\partial t} = \left.\frac{\partial y(x,t)}{\partial t}\right|_{t=0} = y_i' \tag{3}$$

$$y(x,t)|_{x=0} = 0 \tag{4}$$

$$\left.\frac{\partial y(x,t)}{\partial x}\right|_{x=0} = 0 \tag{5}$$

$$EI\left.\frac{\partial^2 y(x,t)}{\partial x^2}\right|_{x=L} = -J_L \frac{\partial^2}{\partial t^2}\left(\left.\frac{\partial y(x,t)}{\partial x}\right|_{x=L}\right) \tag{6}$$

$$EI\left.\frac{\partial^3 y(x,t)}{\partial x^3}\right|_{x=L} = -M_L \frac{\partial^2}{\partial t^2}\left(y(x,t)|_{x=L}\right) \tag{7}$$

The solution of the Equation 1 can be expressed as follows.

$$y(x,t) = \sum_{j=1}^{n} C_{1j}\sin(\omega_j t)\left\{\left(\cos(\beta_j x) - \cosh(\beta_j x)\right) - \alpha\left(\sin(\beta_j x) - \sinh(\beta_j x)\right)\right\} \tag{8}$$

where

$$\alpha = \frac{-\beta_j^3\cos(\beta_j L) - \beta_j^3\cosh(\beta_j L) + \frac{M_L}{\rho}\beta_j^4\sin(\beta_j L) - \frac{M_L}{\rho}\beta_j^4\sinh(\beta_j L)}{-\beta_j^3\sin(\beta_j L) - \beta_j^3\sinh(\beta_j L) - \frac{M_L}{\rho}\beta_j^4\cos(\beta_j L) + \frac{M_L}{\rho}\beta_j^4\cosh(\beta_j L)} \tag{9}$$

II. Literature Review

Hu Zhongling et al [1] presented a method of Co-simulation technology based on ADAMS and MATLAB for design and research of complex mechanical systems. Results showed that co-simulation is an effective method for the simulation analysis of complex dynamic systems.

F. Cheraghpour et al [2], presented Dynamic modeling and kinematic simulation of Stäubli TX40 robot using MATLAB/ ADAMS co-simulation and proposed a precise simulator to develop approaches for experimental simulation in kinematics, dynamics and control analysis.

H Liu et al. [3], studied Co-simulation using ADAMS and MATLAB for Active Vibration Control of Flexible beam with Piezoelectric Stack Actuator Co-simulation. The virtual prototype of flexible beam with piezoelectric actuator is created in ADAMS, the controller based on FXLMS algorithm is established in MATLAB. The results and analysis prove that active vibration control for flexible beam has a great suppression performance.

M.A. Ahmad [4], studied effects of Vibration and input tracking control of Flexible manipulator using LQR with Non-collocated PID Controller.

Jerzy et al. [5] Proposed a method for dynamic modeling and adaptive control of a single-link flexible manipulator.

Mahamood et al. [6], proposed PID Controller design for Two Link Flexible Manipulator.

III. Problem Statement

The objectives of this paper are to evaluate the effects of link flexibility on the variation in the tip position of a two-link RR type Robotic arm when the end effector (tip) is made to move in a vertical motion and the payload considered is equal to links mass. The difference between the end effector positions of flexible links robot and the rigid links at each time instant is taken as the positional error. Three different control methods (i.e. PI control, PD control and PID control) were adopted to reduce the positional error between the Rigid and Flexible links. Based on the results obtained better control strategy is adopted for future usage. The dimensions and properties considered in this paper are given in Table 1. Software's utilized are MSC Adams and MATLAB.

Table 1: Links Parameters

	Length (mm)	Width (mm)	Depth (mm)	Mass (kg)	Density (kg/mm^3)
Link 1	300	40	20	2	7.8*10−6
Link 2	400	40	20	2.6	7.8*10−6
End base	80	20	20	0.5	7.8*10−6
Gripper1	50	10	20	0.045	7.8*10−6
Gripper2	50	10	20	0.045	7.8*10−6
payload	-	-	-	5.1	7.8*10−6

IV. Research Methodology

The method adopted in this paper is as follows. The dimensions of the links are taken such that they replicate the dimensions of human arm provided in the Journals. Using MSC Adams software, RR type two-link manipulators (both rigid and flexible) are modelled such that the end effector moves in a specified vertical path with a payload equal to the mass of the links.

The input Torques were applied at the two revolute joints resulting in the angular rotation of two links resulting in a linear motion of the end effector. The end effector is constrained to move in a specified vertical path.

Figure 2 shows the application of constraint in MSC Adams so that the end effector moves in vertical path. The two angular rotations at the two joints and the motion of the end effector are taken as the outputs which have to be monitored as the input torques are applied at the joints. The time taken for total end effector path is about ten seconds in 2000 steps. The end effector position of the rigid link RR type manipulator, angular rotations at joint 1 and joint 2 joint during these 10 seconds in 2000 steps are taken as the reference values. Then when the two links are replaced by flexible links in RR type manipulator and when same input torques are applied at the two joints resulting in the end effector positions, angular rotations at joints 1 and 2 are measured again for 10 seconds in 2000 steps. The figure 3 shows the way a flexible links is built in MSC Adams.

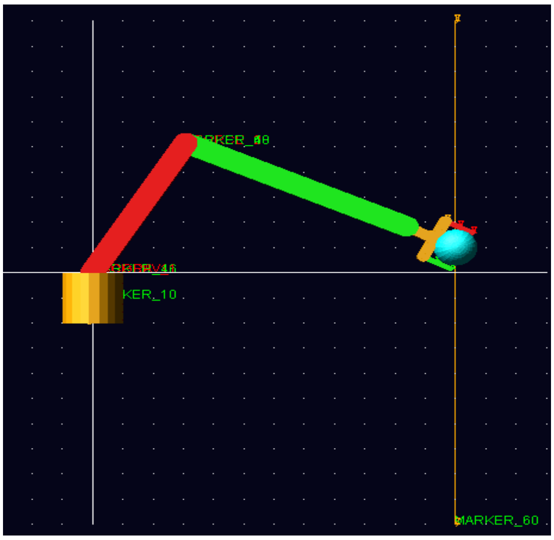

Figure 2: Building model with vertical constraint

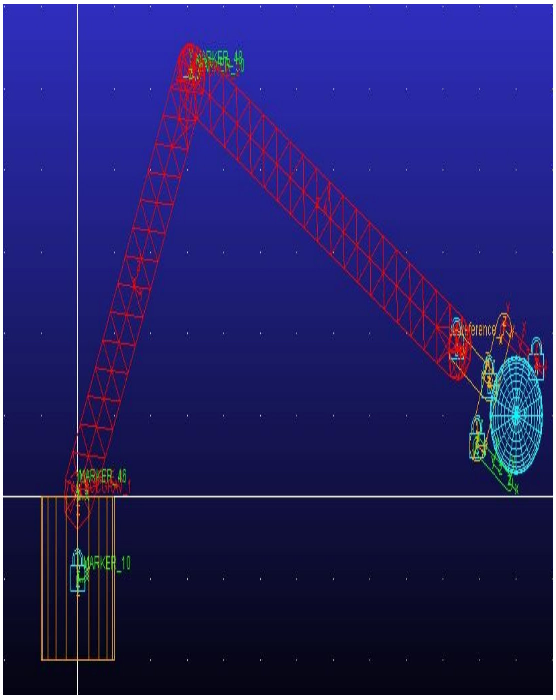

Figure. 3: Building flexible model with payload

Positional error is defined as difference between these two tip positions of the end effector and difference in angular rotations at joint 1 and 2 for 2000 steps of the vertical path. From the results obtained given in figure 4 one can conclude that as time and number of steps are increasing the positional error is increasing. Moreover, the end effector is also carrying a payload equal to the weight of two links (i.e. 5.1 kg) and this is also influencing the value of positional errors.

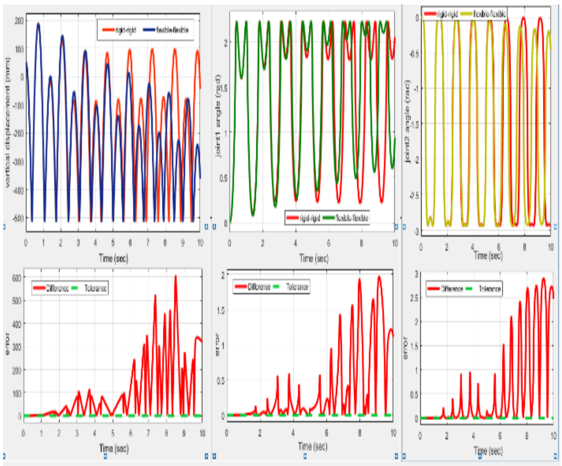

Figure. 4: Error at end effector, joint 1 & Joint 2 due to link flexibility

To keep this positional error at end effector, joints 1 and 2 to a minimum value, a control strategy needs to be adopted. From the Literature, three controls strategies i.e. Proportional Integral (PI), Proportional Derivate (PD) and Proportional Integral Derivate (PID) methods were selected.

Applying PI, PD and PID control strategy directly in MSC Adams posed problems and were unable to get the required response. Therefore, a co-simulation method using MSC Adams and MATLAB was envisaged. Both the rigid and flexible links models were developed in MSC Adams and these models was imported to MATLAB. Using Simulink, the Adams model was integrated in MATLAB and the block diagrams shown in figure 5,7 and 9 were developed for PI & PD&PID control strategies. The positional error in tip position is the output and the angular rotations are the input for the Simulink model.

The constants (Kp, Ki and Kd) in PI, PD and PID controllers are chosen in a trial and error basis, as the inputs are varied and the outputs are monitored till those values are reached for which the Proportional error become minimum.

V. Results and Discussion

When there was no control strategy to control the effect of flexibility, the maximum error in the tip position is equal to 600 mm and an average RMS error of 106 mm. the maximum angular position error at joint 1 and 2 is about 2 radians and 2.8 radians respectively. Figure 4 shows these results and one can conclude, these errors are considerably large implying the flexibility has significant effect on the tip positional accuracy.

To reduce these, three kinds of controllers are used to find the error at the tip position and ensure that the end effector will follow the specific vertical path.

5.1 Applying Proportional-Integral (PI) Controller at both Joints:

To reduce the error in vertical displacement and joint angles a PI controller for the two link RR manipulator with specific constant value (given in table 2) which ensure the reduction of the error is developed. The Figure 5 shows the Simulink model, so developed in MATLAB. Figure 6 shows the effect of PI controller.

Table 2: PI controller constants

	P constant	I constant
Joint 1	4794.88	2845.96
Joint 2	200	100

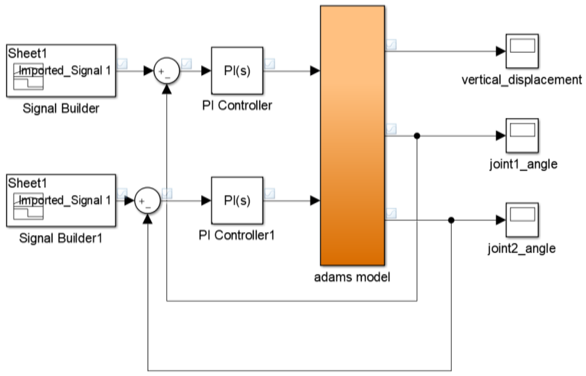

Figure. 5: Simulink model for PI controller

When PI control strategy was applied, the maximum error in the tip position reduced to 180 mm and Average RMS error of 34 mm. the maximum angular position error at joint 1 and 2 is about 0.76 radians and 1.2 radians respectively. Figure 6 shows these results and one can conclude, these errors are considerably reduced implying that PI control is satisfactorily countering the effects of flexibility.

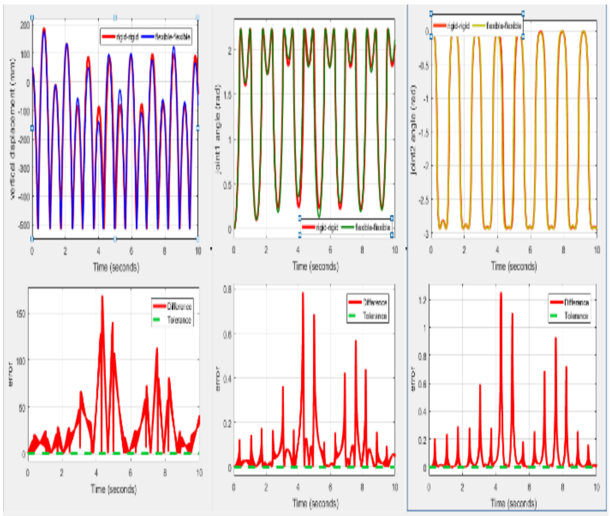

Figure. 6: The error in tip position, joint 1 & joint 2 angles with PI controller

5.2 Applying Proportional-Derivative (PD) Controller at the Joints:

The next two figures (Figure 7-8) shows the MATLAB Simulink configuration of PD controller and the errors in the tip position and joints angles.

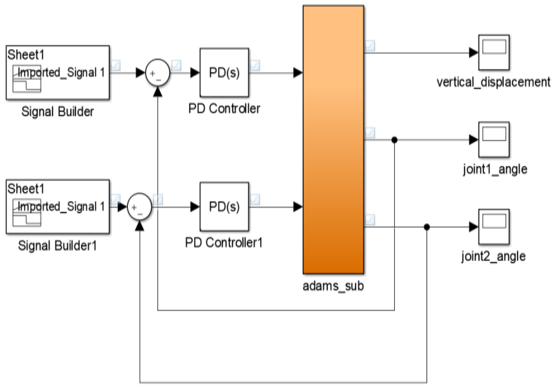

Figure. 7: Simulink Model of PD controlle

Table 3: PD Controller Constants

When PD control strategy was applied, the maximum error in the tip position reduced to 165 mm and average RMS error of 30 mm. the maximum angular position error at joint 1 and 2 reduced to 0.78 radians and 1.22 radians respectively. Figure 8 shows these results and one can conclude, these errors are considerably reduced implying that PD control is satisfactorily countering the effects of flexibility.

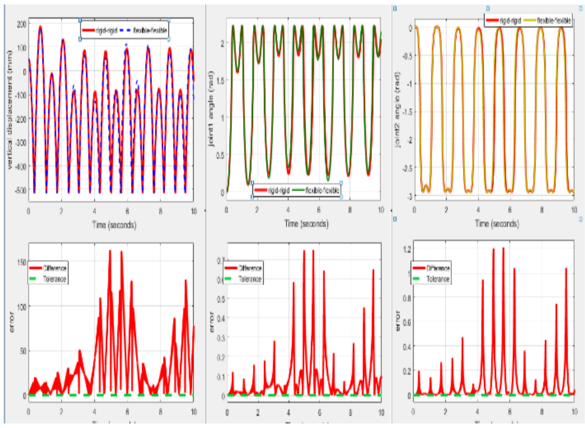

Figure. 8: The errors at tip position, joint1 & joint2 with PD control

5.3 Applying Proportional-Integral-Derivative (PID) Controller at the Joints:

The next two figures (Figure 9-10) shows the MATLAB Simulink configuration of PID controller and the errors in the tip position and joints angles.

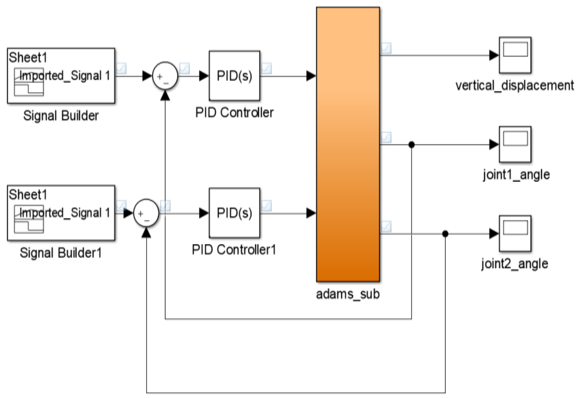

Figure 9. Simulink Model of PID controller

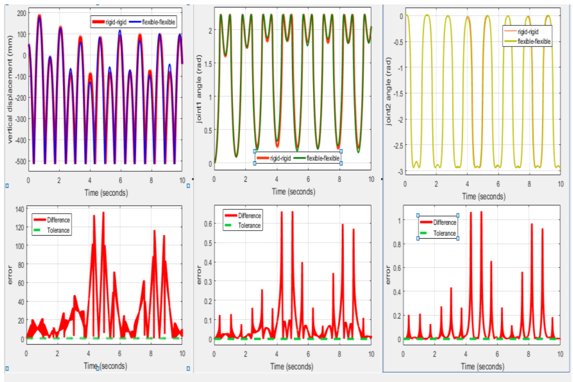

Figure 10. The errors at tip position, joint1 & joint2 with PID control

Table 3: PID Controller Constants

	P constant	I constant	D constant	Filter coefficient
Joint 1	4794.88	1500	1800	1
Joint 2	200	100	100	4

When PID control strategy was applied, the maximum error in the tip position reduced to 136 mm and average RMS error of 28.1 mm. the maximum angular position error at joint 1 and 2 reduced to 0.66 radians and 1.07 radians respectively. Figure 10 shows these results and one can conclude, these errors are considerably reduced implying that PID control is satisfactorily countering the effects of flexibility.

5.4 The Effect of the Controllers on the Input and Output Response:

The figure 11 shows the effect of PI, PD and PID control strategies to control and reduce the position error at the tip position and joints angles with respect to a system with no control. When PI control is adopted the maximum positional error reduced by 70%, 72.5% reduction using PD control and 77.3% reduction using PID control. The angular error reduced by 60% at joint 1 and 39% at joint 2 using PI control. When PD control is used, the error at joint 1 reduced by 62 % and 40 % at joint 2 and when PID control is used, the error at joint 1 reduced by 67 % and 61.7 % at joint 2 It is obvious from the figure 11 that the PID controller is performing better than PI and PD control for the given conditions and therefore it should be chosen to reduce error and follow the desired path.

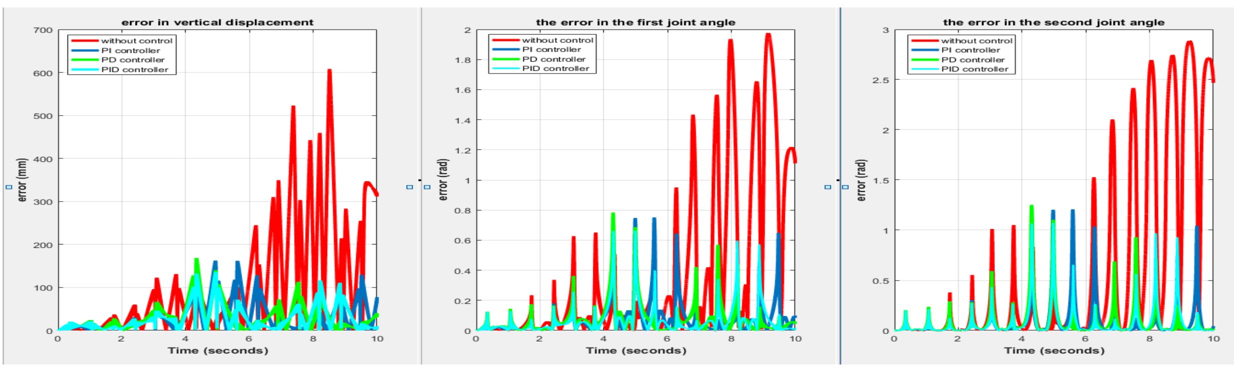

Figure. 11. Effects of PI, PD and PID control strategies

IV. CONCLUSIONS

A two-link rigid and flexible manipulator has been successfully co-simulated in Adams software and MATLAB. From the model created in ADAMS it is found that the flexibility of link significantly affects the system behavior. The tip position, first joint angle and second joint angle values are compared by using MATLAB and three types of controllers were (i.e. PI & PD&PID) applied. The conclusions inferred are:

- The link flexibility has considerable effect on tip position, joint angles.
- For the robotic system without control the averaged RMS error in the tip position is equal to 106.2 mm.
- The averaged RMS error in the first joint angle in the case of both links are flexible is equal to 0.37 radians.
- The averaged RMS error in the second joint angle in the case of both links are flexible is equal to 0.59 radians.

1) With PI controller: - the average error in the tip position when both links are flexible is equal to 33.49 mm.

- The average RMS error in the first joint angle in the case of both links are flexible is equal to 0.08 rad.
- The average RMS error in the second joint angle in the case of both links are flexible is equal to 0.09 rad.

2) With PD controller: - the average error in the tip position when both links are flexible is equal to 30.21 mm.

- The average RMS error in the first joint angle in the case of both links are flexible is equal to 0.07 rad.
- The average RMS error in the second joint angle in the case of both links are flexible is equal to 0.07 rad.

3) With PID controller: - the average RMS error in the tip position when both links are flexible is equal to 28.1 mm.

- The average RMS error in the first joint angle in the case of both links are flexible is equal to 0.06 rad.
- The average RMS error in the second joint angle in the case of both links are flexible is equal to 0.07 rad.

4) the performance of PID controller is better than PI controller for the given conditions

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