Overwhelming Trajectory Control of Flexible Space Robot

Amit Kumar*, Pushparaj Mani Pathak **, N. Sukavanam*
* Department of Mathematics, Indian Institute of Technology Roorkee, 247667, India,
** Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, 247667, India (Phone-91-1332-285608; Fax-91-1332-285665;

* Corresponding author (email-pushpfme@iitr.ernet.in)

Abstract

This paper presents a trajectory tracking control method for flexible space robot. The advantage of the method is that it is free from spill-over instability as it uses a robust overwhelming trajectory controller. The proposed controller is conceptualized for a single rotational degree of freedom case. The efficacy of the scheme is illustrated by simulation results. The stability analysis of the manipulator is carried out by Routh Hurwitz criterion.

Keywords: Flexible space roots, bond graphs, stability analysis.

1.0 Introduction

The flexible manipulator will be useful for space application due to their light weight, less power requirement, ease of manoeuvrability and ease of transportability. Because of the light weight, they can be operated at high speed. For flexible manipulators flexibility of manipulator have considerable influence on its dynamic behaviours. The flexibility of the link affects the overall performance of the system. The control of such flexible manipulator is very much influenced by the non-linear coupling of large rigid body motions and small elastic vibrations. In case of space robots the position and orientation of the satellite main body will change due to manipulator motion. The motion of the space robots also induces vibrating motions in structurally flexible manipulators. Researchers working on terrestrial flexible robot arms principally have focused on issues such as dynamic modeling and vibration control. Murotsu *et al* [1] proposed control schemes for flexible space manipulator using a virtual rigid manipulator concept. Samanta and Devasia [2] have discussed modeling and control of flexible terrestrial manipulates using distributed actuator. The nonlinear coupling of large rigid body motion and small elastic vibration of the flexible arms has been taken into consideration in the model. The concept of using distributed piezoelectric transducers for controlling elastic vibration of arms has been incorporated in the analysis. Lichang *et al.* [3] worked on dynamic modeling, control and simulation of flexible dual arm space robot based on the Lagrange method and described the elastic deflection by the assumed mode method. The inversion dynamic control method is performed to solve the tracking problem. Pathak *et al.* [4] has discussed impedance control of space robots using passive degree of freedom in controller domain. Murotsu et *al*. [5] proposed a methodology for designing stable manipulation variable feedback control of a space robot with flexible links for positioning control to a static target and continuous path tracking control. Zhang and Yu [6] developed the dynamic equations of planar cooperative manipulators with link flexibility in absolute coordinate with the help of Timoshenko beam theory and the finite element method. Stieber *et al*. [7] addressed the stability and control problems arising in vision based control of flexible space robot where the motion of a robot payload relative to the work space is measured at a considerable distance from the control actuator in the robot joints. Jiang [8] developed a concept of compenstability for free floating flexible space robot arms. Using this concept the end-

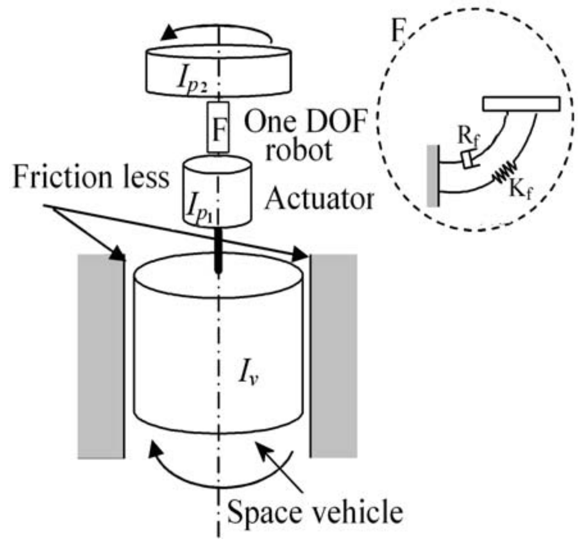


Figure 1. Schematic representation of one DOF space robot

effector behaviour caused by the link flexural behaviour and the satellite motion in response to the arm motion is considered as errors in the end-effector motion and this error is compensated by the joint behaviour. Lee [9] developed a new trajectory control of a flexible link robot based on distributed parameter. He designed a moment feedback trajectory tracking control scheme. Pathak *et al.* [12] worked on a scheme for robust trajectory control of space robot.

This paper presents the trajectory control strategy for a flexible space robot. This strategy can also be applied to take care of joint flexibility. There are several works available in literature [10 and 11] which considers the joint flexibility by considering springs in series or parallel. The control strategy is based on the overwhelming control [12] concept. The controller is provided with tip velocity information. The advantage of the control strategy is that the spill over effect [13, 14, and 15] in control of link is minimized with the proposed strategy. Another advantage of the proposed control strategy is that it does not require base moment feedback as proposed by Lee [9]. Bond graphs are used to represent both rigid body and flexible dynamics of the link in a unified manner. SYMBOLS Shakti software [16] is used for bond graph modeling and simulation.

2.0 Conceptualisation of Overwhelming Controller for Flexible Manipulators

To design a controller, let us consider a simple flexible space robot with one rotational degree of freedom as shown in Figure 1. Let there be two rotational inertias represented by I_{p1} and I_{p2}. Let these values represents the discretized rotational inertias of a link. It is assumed that these inertias be connected by a torsional spring of stiffness K_f and damping R_f. Let I_v represents the inertia of the space vehicle.

Due to flexibility in link it is difficult for the tip to follow the desired trajectory and the tip will have vibrations also. Thus the control objective is to have the flexible-link robot track a desired trajectory as accurately as possible while promptly suppressing the resulting link vibration asymptotically to zero.

The bond graph of space robot with overwhelming controller is shown in Figure 2. The state equation for physical system can be derived as

$$\dot{P}_2 = e_{22} - R_f\left(P_2/I_{p1} - P_7/I_{p2}\right) - K_9 Q_9 \tag{1}$$

$$\dot{P}_7 = R_f\left(P_2/I_{p1} - P_7/I_{p2}\right) + K_9 Q_9 \tag{2}$$

$$\dot{Q}_9 = \left(P_2/I_{p1} - P_7/I_{p2}\right) \tag{3}$$

$$\dot{P}_{21} = -e_{23} = -e_{22} \tag{4}$$

Writing (1), (2), (3) and (4) in state space form

$$\begin{bmatrix} \dot{P}_2 \\ \dot{P}_7 \\ \dot{P}_{21} \\ \dot{Q}_9 \end{bmatrix} = \begin{bmatrix} -R_f/I_{p1} & R_f/I_{p2} & 0 & -K_f \\ R_f/I_{p1} & -R_f/I_{p2} & 0 & K_f \\ 0 & 0 & 0 & 0 \\ 1/I_{p1} & -1/I_{p2} & 0 & 0 \end{bmatrix} \begin{bmatrix} P_2 \\ P_7 \\ P_{21} \\ Q_9 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix} [e_{22}] \tag{5}$$

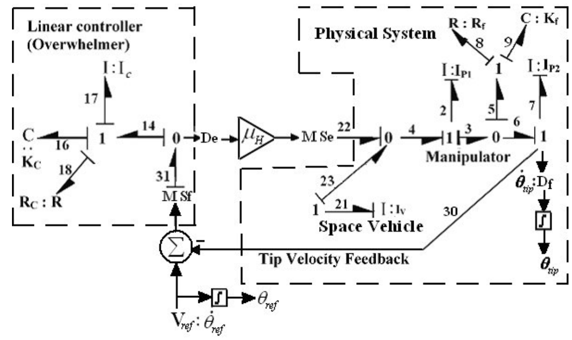


Figure 2. Bond graph model of one DOF flexible space robot with proposed controller

and the equation for the output (i.e. the tip velocity) is given by

$$f_7 = \begin{bmatrix} 0 & \dfrac{1}{I_{p2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} P_2 \\ P_7 \\ P_{21} \\ Q_9 \end{bmatrix} \tag{6}$$

From Eq. (5) and Eq. (6) the transfer function between tip velocity and the torque input to motor is given by

$$\frac{Y(s)}{U(s)} = \frac{F_7(s)}{E_{22}(s)} = \begin{bmatrix} 0 & \dfrac{1}{I_{p2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} s+\dfrac{R_f}{I_{p1}} & -\dfrac{R_f}{I_{p2}} & 0 & K_f \\ -\dfrac{R_f}{I_{p1}} & s+\dfrac{R_f}{I_{p2}} & 0 & -K_f \\ 0 & 0 & s & 0 \\ -\dfrac{1}{I_{p1}} & \dfrac{1}{I_{p2}} & 0 & s \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix}$$

or, $$\frac{F_7(s)}{E_{22}(s)} = \frac{\dfrac{1}{I_{p2}}\left\{\left(R_f/I_{p1}\right)s^2 + K_f\left(s/I_{p1}\right)\right\}}{\left\{s^4 + s^3\left(R_f/I_{p2} + R_f/I_{p1}\right) + s^2\left(K_f/I_{p2} + \dfrac{K_f}{I_{p1}}\right)\right\}}$$

$$\frac{F_7(s)}{E_{22}(s)} = \frac{\left(R_f s + K_f\right)}{I_{p1}I_{p2}s^3 + R_f\left(I_{p1}+I_{p2}\right)s^2 + K_f\left(I_{p1}+I_{p2}\right)s} \tag{7}$$

The bond graph shown in Figure 2 can be represented by a block diagram and is shown in Figure 3. In this figure controller transfer function has been derived from bond graph shown in Figure (2). From Figure (3) transfer function between manipulator tip velocity and reference

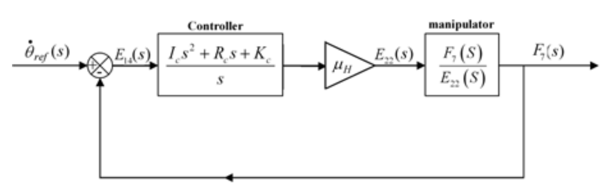


Figure 3. Block diagram of overwhelming controller

input can be derived as

$$\frac{F_7(s)}{\dot{\theta}_{ref}(s)}=\frac{\left\{\left(\frac{I_c s^2+R_c s+K_c}{s}\right)\mu\left(\frac{R_f s+K_f}{I_{p1}I_{p2}s^3+R_f\left(I_{p1}+I_{p2}\right)s^2+K_f\left(I_{p1}+I_{p2}\right)s}\right)\right\}}{1+\left\{\left(\frac{I_c s^2+R_c s+K_c}{s}\right)\mu\left(\frac{R_f s+K_f}{I_{p1}I_{p2}s^3+R_f\left(I_{p1}+I_{p2}\right)s^2+K_f\left(I_{p1}+I_{p2}\right)s}\right)\right\}} \quad (8)$$

Here I_c, K_c and R_c are the inertia (differential gain), stiffness (integral gain) and resistance (proportional gain) respectively of the overwhelming controller.
If $\mu >> 1$ then Eq. (8) becomes

$$\frac{F_7(s)}{\dot{\theta}_{ref}(s)}=1 \quad (9)$$

Thus tip velocity will be same as the reference velocity command.

3.0 Stability analysis by Routh Hurwitz criterion

The stability analysis of the system with overwhelming controller can be carried out by simplifying and analysing Eq. (8). One can simplify Eq.(8) as

$$\frac{F_7(s)}{\dot{\theta}_{ref}(s)}=\frac{\left(I_c s^2+R_c s+K_c\right)\mu\left(R_f s+K_f\right)}{\left\{\begin{array}{l}I_{p1}I_{p2}s^4+R_f\left(I_{p1}+I_{p2}\right)s^3+K_f\left(I_{p1}+I_{p2}\right)s^2\\+\mu\left(I_c s^2+R_c s+K_c\right)\left(R_f s+K_f\right)\end{array}\right\}} \quad (10)$$

From Eq. (10) characteristic equation of system can be written as

$$I_{p1}I_{p2}s^4+R_f\left(I_{p1}+I_{p2}\right)s^3+K_f\left(I_{p1}+I_{p2}\right)s^2$$
$$+\mu\left(I_c s^2+R_c s+K_c\right)\left(R_f s+K_f\right)=0$$

or, $I_{p1}I_{p2}s^4+\left\{R_f\left(I_{p1}+I_{p2}\right)+\mu I_c R_f\right\}s^3+$

$$\left\{K_f\left(I_{p1}+I_{p2}\right)+\mu R_c R_f+\mu I_c K_f\right\}s^2+$$
$$\left\{\mu K_c R_f+\mu R_c K_f\right\}s+\mu K_c K_f=0 \quad (11)$$

Routh tabulation from Eq. (11) can be derived and is shown in Table 1.
From Routh table we can see that for the system to be stable the following conditions must be satisfied

(1) $R_f\left(I_{p1}+I_{p2}\right)+\mu I_c R_f>0$

or, $\mu I_c>-\left(I_{p1}+I_{p2}\right)$ (12)

Because we are considering only positive gains these are trivially satisfied.
(2) $b_1>0$

$$K_f\left(I_{p1}+I_{p2}\right)+\mu R_c R_f+\mu I_c K_f-\frac{I_{p1}I_{p2}\left(\mu K_c R_f+\mu R_c K_f\right)}{\left(R_f\left(I_{p1}+I_{p2}\right)+\mu I_c R_f\right)}>0 \quad (13)$$

or, $\left(R_f\left(I_{p1}+I_{p2}\right)+\mu I_c R_f\right)\left(K_f\left(I_{p1}+I_{p2}\right)+\mu R_c R_f+\mu I_c K_f\right)$

$$-I_{p1}I_{p2}\left(\mu K_c R_f+\mu R_c K_f\right)>0$$

Table 1: Routh stability criterion for flexible manipulator with controller

s^4	$K_f\left(I_{p1}+I_{p2}\right)+\mu R_c R_f+\mu I_c K_f$	$\mu K_c R_f$	$I_{p1} I_{p2}$
s^3	$R_f\left(I_{p1}+I_{p2}\right)+\mu I_c K_f$	$\mu K_c R_f$ $+\mu R_c K_f$	0
s^2	$K_f\left(I_{p1}+I_{p2}\right)+\mu R_c R_f+\mu I_c K_f$ $-\frac{I_{p1}I_{p2}(\mu K_c R_f+\mu R_c K_f)}{R_f\left(I_{p1}+I_{p2}\right)+\mu I_c R_f}$ $=b_1$	$\mu K_c R_f$	0
s^1	$\mu K_c R_f+\mu R_c K_f$ $-\frac{\mu K_c K_f\left(R_f\left(I_{p1}+I_{p2}\right)+\mu I_c R_f\right)}{b_1}$ $=b_2$	0	0
s^0	$\mu K_c K_f$	0	0

Let $\left(I_{p1}+I_{p2}\right)=S$ and $\left(I_{p1}I_{p2}\right)=P$, then

$$\left\{\left(R_f S+\mu I_c R_f\right)\right\}\left\{K_f S+\mu R_c R_f+\mu I_c K_f\right\}$$
$$-P\left(\mu K_c R_f+\mu R_c K_f\right)>0$$
$$or, \mu^2\left\{I_c R_f^2 R_c+I_c^2 R_f K_f\right\}+$$
$$\mu\left\{R_c R_f^2 S+2I_c K_f R_f S-P\left(K_c R_f+R_c K_f\right)\right\}+R_f K_f S^2>0 \quad (14)$$

Let $\left\{I_c R_f{}^2 R_c+I_c{}^2 R_f K_f\right\}=A$,

$\left\{R_c R_f{}^2 S+2I_c K_f R_f S-P\left(K_c R_f+R_c K_f\right)\right\}=B$, and

$R_f K_f S^2=C$ then Eq. (14) can be written as

$$\mu^2 A+\mu B+C>0 \quad (15)$$

(i) For large value of μ neglecting $B\mu+C$ term, we get $\mu^2 A>0$, that is always positive.

(ii) For very small value of μ, $C>0$ i.e, $R_f K_f S^2>0$, which is always positive.

(iii) For in between value

(a) $B>0$ i.e., if $R_c R_f{}^2 S+2I_c K_f R_f S-P\left(K_c R_f+R_c K_f\right)>0$ (16)

then it is always stable.

Special case:

If $R_f=0$ (i.e. very low damping in arm such as in spring). Then Eq. (16) can be written as

$-PR_c K_f>0$.

i.e., $-\left(I_{p1}I_{p2}\right)R_c K_f>0$, (17)

which is impossible i.e., a hypothetically undamped manipulator could not be stable i.e. uncontrollable.

(b) If $B<0$ i.e.,
if $R_cR_f^2S+2I_cK_fR_fS-P\left(K_cR_f+R_cK_f\right)<0$,
result can not be guaranteed for intermediate values of μ.

(3) $b_2>0$, i.e.,

$$\mu K_cR_f+\mu R_cK_f-\frac{\mu K_cK_f\left\{R_f\left(I_{p1}+I_{p2}\right)+\mu I_cR_f\right\}}{b_1}>0$$

or, $\mu^2\left\{I_cR_cR_f\left(K_cR_f^2+R_cR_fK_f+I_cK_f^2\right)\right\}+$

$$\mu\left\{\begin{array}{l}R_cK_cR_f^3\left(I_{p1}+I_{p2}\right)+R_c^2R_f^2K_f\left(I_{p1}+I_{p2}\right)+\\2I_cR_cR_fK_f^2\left(I_{p1}+I_{p2}\right)-\left(K_cR_f+R_cR_f\right)^2I_{p1}I_{p2}\end{array}\right\}$$

$$+R_cR_fK_f^2\left(I_{p1}+I_{p2}\right)^2>0 \tag{18}$$

Let $\left\{I_cR_cR_f\left(K_cR_f^2+R_cR_fK_f+I_cK_f^2\right)\right\}=D$,

$$\left\{\begin{array}{l}R_cK_cR_f^3\left(I_{p1}+I_{p2}\right)+R_c^2R_f^2K_f\left(I_{p1}+I_{p2}\right)\\+2I_cR_cR_fK_f^2\left(I_{p1}+I_{p2}\right)-\left(K_cR_f+R_cR_f\right)^2I_{p1}I_{p2}\end{array}\right\}=E,$$

and $R_cR_fK_f^{\,2}\left(I_{p1}+I_{p2}\right)^2=F$

Then $\mu^2D+\mu E+F>0$ (19)

(i) For $\mu>>1,\mu^2D>0$, therefore D is positive so μ^2D will be always positive,

(ii) For $\mu\to 0$, $F>0$, which is always positive.

(iii) For in between values full condition can be evaluated i.e., Eq. (15) and Eq. (19) has to be plotted and common zone has to be found.

Open loop transfer function between manipulator tip velocity and reference input with pad dynamics for set of parameters shown in Table 2, and with μ = 1 can be given by

$$TF_o=\frac{F_7(s)}{E_{22}(s)}=\frac{25s^5+100250.3s^4+1001005s^3+20025s^2+100000s+0.24}{s^7+18.51s^6+70027.77s^5+70876.75s^4+707000s^3} \tag{20}$$

For in between values of the gain parameter the range can be evaluated for the given set of parameters as shown in Table 2. The evaluated value is found to be $0<\mu_H<12.245$.

For the closed loop with feed forward gain μ_H the transfer function can be given as

$$TF_c=\frac{\mu_H\,TF_o}{1+\mu_H\,TF_o} \tag{21}$$

Pole's and zero's from the transfer function of Eq. (21) can be derived and is shown in Table 3 for different gain values μ. Since for the different gain values μ_H = 1, 2, 5 and 12, all pole's and zero's lies in the left half of s plane it can be concluded that the system is stable. However for the gain value $\mu_H=12.3$ all the pole's do not lie on the left half of s plane implying that the system becomes unstable.

4.0 Simulation and Results

The space robot and controller parameters used in simulation are given in Table 2. In this table I_{p1} and I_{p2} represents the inertia of the manipulator, Ic, Kc, and Rc are the controller parameters, I_V represents the inertia of space vehicle, R_f and K_f represents the manipulator damping and manipulator stiffness respectively and a is a constant. Let us assume that the reference displacement command for robot tip is given by $\theta_{ref}=\theta_d\left(1-e^{(-a\,t)}\right)$. Then the Reference velocity command is given by $\dot{\theta}_{ref}=F_{ref}=\theta_d a e^{(-a\,t)}$. Here a is constant and θ_d is the desired trajectory.

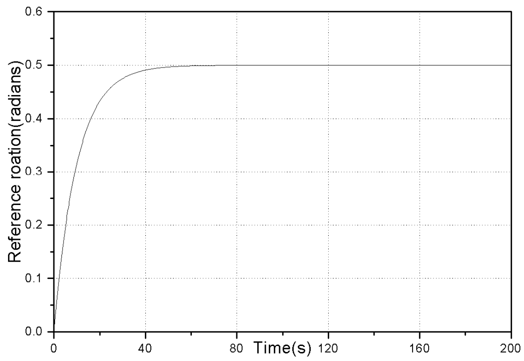
Table 2: Simulation parameters and values

Parameter	Value
Inertia of plant	I_{p1} = 0.2 kg, I_{p2} = 0.5 kg.
Controller	I_c = 1, K_c = 0.1, R_c = 0.01
Desired joint rotation	θ_d = 0.5 rad.
Mass of the space vehicle	I_V = 7.0 kg.
Manipulator damping	R_f = 2.5
Manipulator stiffness	K_f= 10000.0
Constant	a = 0.100

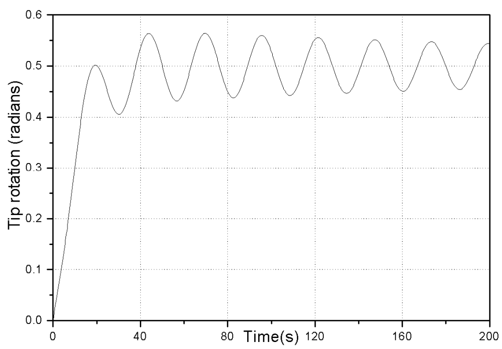
Table 3: Pole's and zero's with different gain values

	Pole' s	Zero's
μ_H = 1.0	0, 0, 0, -0.505 ± 3.14 j, -8.75 ± 264.430 j.	0, -0.004 ± 0.316j, -10, -4000.
μ_H = 2.0	0, -0.004 ± 721j, -1.931 ± 5.906j, -7.320 ± 264.441j.	-0.002, -0.004 ± 0.316 j, -10, -4000.
μ_H = 5.0	0, -0.004 ± 0.296 j, -4.077 ± 8.052 j, -5.174 ± 264.499j.	0, -0.005 ± 0.316 j, -10, -4000.
μ_H = 12	0, -0.004 ± 0.307 j, -9.075 ± 9.934 j, -0.175 ± 264.839 j.	0, -0.004± 0.316 j, -10, -4000.
μ_H =12.3	0, -0.004 ± 0.307 j, -9.289 ± 9.951 j,	0, -0.004± 0.316 j, -10,

Simulation is performed for 200s. Figure 4 and Figure 5 shows the plots with proposed controller. Figure 4(a) shows the variation of reference rotation with respect to



(a)



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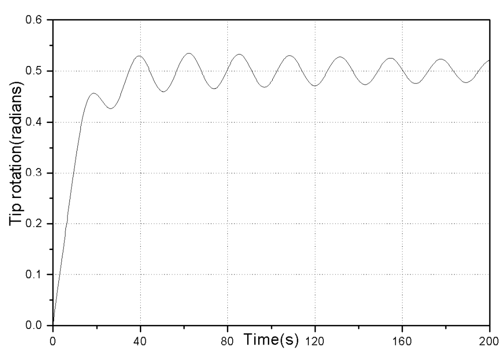
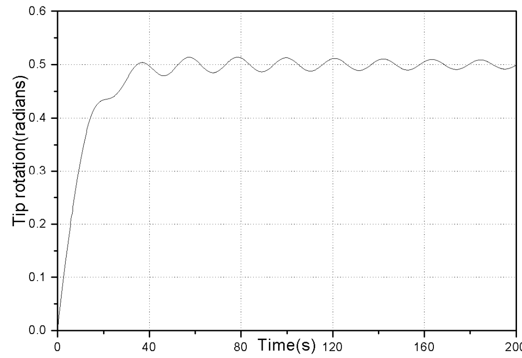


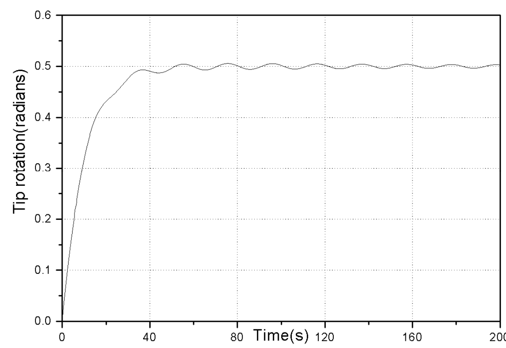
(c)

Figure. 4 (a) Variation of reference rotation with respect to time, (b) Plot of tip rotation with respect to time with gain value $\mu_H = 1$, (c) Plot of tip rotation with respect to time with gain value $\mu_H = 2$.

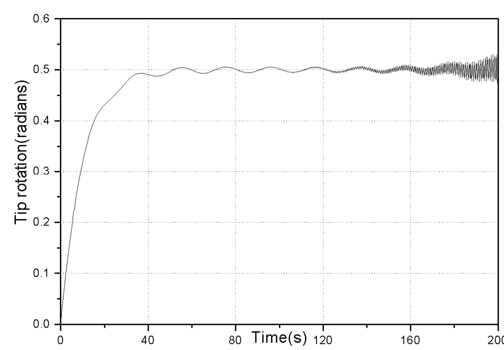
time. Figure 4 (b) shows the variation of tip rotation with respect to time with gain value $(\mu_H = 1.0)$. From



(a)



(b)



(c)

Figure 5 (a) Plot of tip rotation with respect to time with gain value, (b) Plot of tip rotation with respect to time with gain value μ_H =12, (c) Plot of tip rotation with respect to time with gain value μ_H =12.3.

this figure it is seen that the tip has got oscillations and tip trajectory is also not accurate. Figure 4 (c) shows the

tip rotation with respect to time with gain value $(\mu_H = 2.0)$. Figure 4 (c) shows that the tip has oscillations and trajectory does not follow accurately although there is improved performance as compared to Figure 4(b).
Figure 5 (a) shows the tip rotation with respect to time with gain value $(\mu_H = 5.0)$. Here again it is seen that the tip oscillations are reduced further as compare to previous (i.e., $\mu_H = 2.0$) value. Figure 5(b) shows the tip rotation with respect to time with gain value $(\mu_H = 12.0)$. Again the tip oscillations are further reduced and trajectory follows closer to desire value. Figure 5(c) shows the tip rotation for gain value $(\mu_H = 12.3)$. From this figure it is seen that the tip becomes unstable.

5 .0 Conclusions

In this paper a new control scheme for flexible space manipulator has been designed. The control scheme is based on robust overwhelming control of the manipulator. The scheme requires tip velocity information of manipulator to be given to controller. Simulation results show that the tip rotational vibrations can be reduced effectively using the proposed scheme and also the tip can be dragged in the commanded path. The proposed control scheme does not require additional actuators, which simplifies the joint and link design.

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