Trajectory Planning of Dual Arm Free Flying Space Robot using Polynomial Approach.

R. Rathee and P. M. Pathak

Abstract

The paper presents path planning of dual arm free flying space robot using smooth functions of time. Kinematic and dynamic modeling of dual arm free flying space robot is presented first. Using kinematic model the Jacobian of the system and using dynamic model equation of motion are derived. A path planning methodology for planar system is developed using smooth function of time such as polynomials. Due to nonholonomic behavior of the manipulator in the zero gravity environment linear and angular momentum are conserved. The proposed method yields input trajectories that drive both the manipulator and the base to a desired configuration. Joint torque curves can be obtained by introducing this joint trajectory curves in equation of motion of the space robot.

Keywords: Free-flying space robot, Dynamics, Polynomial

1 Introduction

Space introduces a complicating factor to a robotic system that is not apparent on Earth i.e. the manipulator base is not fixed in space due to zero or microgravity environment. This introduces a high degree of dynamic complexity.

Path planning of free flying space robot considering non holonomic nature of base can be done by bidirectional approach and checking its stability by defining Lyapunov function as in [1]. Yoshida *et al*.[2, 3] has developed the equation of motion for multiple arm free flying robotic system and torque optimization for its redundant arms. He has also provided an overview of its dynamics and control which was verified on ETS-VII. Papadopoulos and Moosavian [4] have used barycentric vector method for studying the dynamic behavior of multi-arm space robots during chase and capture operations. Papadopoulos *et al.* [5] also developed a path planning methodology for single arm planar free floating space manipulator systems defining joint angles as a smooth function of polynomials. In order to overcome the difficulty that the dynamic equations of dual-arm space robot system cannot be linearly parameterized, Chen and Guo [6] modeled the system as under-actuated and asymptotic stability of adaptive control scheme is proved with Lyapunov method. Huang *et al.*[7] derive the impact dynamic equations according to the dynamic model of space robot system and proposed a genetic algorithm (GA) based on approach to search the optimal configuration of space robot at capturing moment in order to minimize or avoid the impact. Sagara and Taira [8] presented cooperative manipulation of a floating object by space robots. They also discussed application of a tracking control method using the transpose of the generalized Jacobian matrix. The dynamics control of a dual-arm space robot installed on a free-flying spacecraft without base position and orientation control holding a single object was discussed by Zhao *et al.*[9]

In this paper Jacobian of dual arm free flying space robot is derived by representing its link lengths as a function of inertia parameters like mass. Equation of motion of system is derived and validated by simulation results. Path planning of

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dual arm planar space robot as a function of polynomial is proposed and it is validated by simulation results using MATLAB.

2 Kinematic and Dynamic Modeling of Dual Arm Free Flying Space Robot

The free flying manipulator have total kn + 6 Degree of Freedom (DOF) with n number of links in each k number of arms where base is having six DOF. The authors consider the case of dual arm (k = 2) free flying manipulator mounted on a base and consist of dual links (n = 2) in each arm as shown in Fig. 1. The arms are attached on a base with the help of revolute joints, one of these arms is called mission arm (m) which is used to accomplish the space mission, and the other is the balance arm (b). The balance arm can also be used to accomplish the mission like the mission arm if given an appropriate trajectory to its end-effector. The system Center of Mass (CM) remains fixed in space and the frame is considered as inertial frame. Let θ_1^m, θ_2^m, θ_1^b and θ_2^b be the joint angles of the joints attached to mission and balance arm. Here in the absence of external forces or torque (τ), linear and angular momentum of the system is conserved.

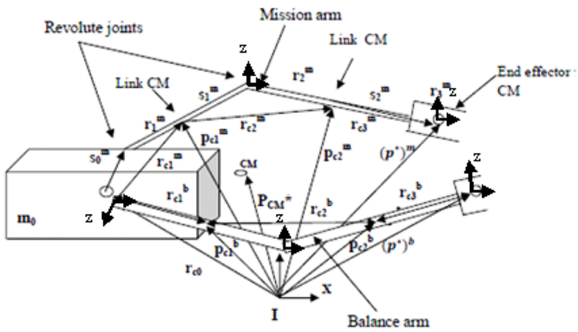

Figure 1: Dual arm free flying space robot.

The symbols required for the formulation of equations and Fig. 1 are defined as follows:

Frame I : Inertia frame

Frame i : i-th body frame or i-th link frame of manipulator for i = 1. . . n. For the base frame i = 0.

m_i : Mass of i-th body (kg).

m_T : Total mass of the system (kg).

$\boldsymbol{r}_i$: Distance from CM of i-th link to the preceding joint represented in the inertia frame.

$\boldsymbol{s}_i$: Distance from CM of i-th link to the subsequently joint represented in the inertia frame.

$\boldsymbol{I}_i$: Inertia matrix of i-th link with respect to inertia frame.

$\boldsymbol{p}^*$: Position vector of CM of the end effectors with respect to inertia frame.

$\boldsymbol{p}^*_{\mathrm{CM}}$: Position vector of CM of the system with respect to inertia frame.

$\boldsymbol{R}_i$: Rotation matrix of i-th link with respect to the base frame.

$\boldsymbol{J}^*_n$: Jacobian matrix with n number of links in the manipulator

$\boldsymbol{M}^*$: Generalized inertia matrix.

$\boldsymbol{C}^*$: Centrifugal and Coriolis term.

$\emptyset$: Joint variables and base variables.

$\boldsymbol{E}_3$: Identity matrix.

$\boldsymbol{p}_{ci}$: Position vector of CM of i-th link with respect to inertia frame.

$\boldsymbol{r}_{c0}$: Position vector of CM of base with respect to inertia frame.

$\boldsymbol{s}_0$: Position vector of the first joint between the link and the base with respect to the CM of base in the inertia frame.

For free-flying robotic manipulator the Denavit-Hartenberg formulation is presented in Ellery [10]. The desired end-effector position for mission arm with respect to inertia frame is,

$$(\boldsymbol{p}^*)^m = \boldsymbol{p}^*_{CM} + \boldsymbol{R}_0^m \boldsymbol{s}_0^m m_{0n+1}^m/m_T - \boldsymbol{R}_0^b \boldsymbol{s}_0^b m_{0n+1}^b/m_T + \sum_{i=1}^n (\boldsymbol{R}_i^m \lambda_i^m) - \sum_{i=1}^n (\boldsymbol{R}_i^b \mu_i^b) - [m_{n+1}^m \boldsymbol{R}_{n+1}^m \boldsymbol{r}_{n+1}^m + m_{n+1}^b \boldsymbol{R}_{n+1}^b \boldsymbol{r}_{n+1}^b]/m_T \quad (1)$$

where $\lambda_i^m = [(m_{0i}^m + m_{1n+1}^b)\,(\text{kinematic parameter})_i^m - m_i^m r_i^m]/m_T$,

$\mu_i^b = [(m_{(i+1)(n+1)}^b)(\text{kinematic parameter})_i^b + m_i^b r_i^b]/m_T$.

The desired end-effector position for balance arm with respect to inertia frame is,

$$(\boldsymbol{p}^*)^b = \boldsymbol{p}^*_{CM} + \boldsymbol{R}_0^b \boldsymbol{s}_0^b m_{0n+1}^b/m_T - \boldsymbol{R}_0^m \boldsymbol{s}_0^m m_{0n+1}^m/m_T + \sum_{i=1}^n (\boldsymbol{R}_i^b \lambda_i^b) - \sum_{i=1}^n (\boldsymbol{R}_i^m \mu_i^m) - [m_{n+1}^b \boldsymbol{R}_{n+1}^b \boldsymbol{r}_{n+1}^b + m_{n+1}^m \boldsymbol{R}_{n+1}^m \boldsymbol{r}_{n+1}^m]/m_T \quad (2)$$

where $\lambda_i^b = [(m_{0i}^b + m_{1n+1}^m)\,(\text{kinematic parameter})_i^b - m_i^b r_i^b]/m_T$,

$\mu_i^m = [(m_{(i+1)(n+1)}^m)(\text{kinematic parameter})_i^m + m_i^m r_i^m]/m_T$.

Now,
$$\boldsymbol{J}_n^* = \begin{bmatrix} \boldsymbol{J}_{Ti} \\ \boldsymbol{J}_{Ri} \end{bmatrix}_{6\times kn} \quad (3)$$

$\boldsymbol{J}_{Ti}$ is $3\times kn$ the Jacobian matrix for linear velocity of link i.

$\boldsymbol{J}_{Ri}$ is $3\times kn$ the Jacobian matrix for angular velocity of link i.

For mission and balance arm Jacobian is,

$$(\boldsymbol{J}_n^*)^m = \sum_{i=1}^n \sum_{j=1}^i \frac{\partial \boldsymbol{R}_i^m}{\partial \theta_j^m} \lambda_i^m - \sum_{i=1}^n \sum_{j=1}^i \frac{\partial \boldsymbol{R}_i^b}{\partial \theta_j^b} \mu_i^b \quad (4)$$

$$(\boldsymbol{J}_n^*)^b = \sum_{i=1}^n \sum_{j=1}^i \frac{\partial \boldsymbol{R}_i^b}{\partial \theta_j^b} \lambda_i^b - \sum_{i=1}^n \sum_{j=1}^i \frac{\partial \boldsymbol{R}_i^m}{\partial \theta_j^m} \mu_i^m \quad (5)$$

The brief concept of equation of motion of a free flying space robot as a multi body system is presented elsewhere [7] is,

$$\boldsymbol{M}^* \ddot{\emptyset} + \boldsymbol{C}^* = \boldsymbol{\tau}. \quad (6)$$

where

$$\emptyset = [X_0 \quad Y_0 \quad Z_0 \quad \theta_{0x} \quad \theta_{0y} \quad \theta_{0z} \quad \theta_1^m \quad \theta_2^m \quad \theta_1^b \quad \theta_1^b]^T \quad (7)$$

$$\boldsymbol{M}^* = \begin{bmatrix} \boldsymbol{M_{Base}} & \boldsymbol{M_{Coupling}} \\ \boldsymbol{M^T_{Coupling}} & \boldsymbol{M_{Arms}} \end{bmatrix}_{(6+kn)\times(6+kn)} \quad (8)$$

$$\boldsymbol{M}_{base} = \begin{bmatrix} m_T \boldsymbol{E}_3 & -m_T \tilde{\boldsymbol{P}}_{0cm} \\ m_T \tilde{\boldsymbol{P}}_{cm} & \boldsymbol{I}_0 + [\sum_{i=1}^n (\boldsymbol{I}_i)]^m + [\sum_{i=1}^n (\boldsymbol{I}_i)]^b - \sum_{i=1}^n (m_i \tilde{\boldsymbol{P}}_{ci} \tilde{\boldsymbol{P}}_{0ci})^m - \sum_{i=1}^n (m_i \tilde{\boldsymbol{P}}_{ci} \tilde{\boldsymbol{P}}_{0ci})^b \end{bmatrix}_{6\times 6} \quad (9)$$

$$\boldsymbol{M}_{Arms} = [\sum_{i=1}^n (\boldsymbol{J}_{Ri}^T I_i \boldsymbol{J}_{Ri} + m_i \boldsymbol{J}_{Ti}^T \boldsymbol{J}_{Ti})^m + \sum_{i=1}^n (\boldsymbol{J}_{Ri}^T \boldsymbol{I}_i \boldsymbol{J}_{Ri} + m_i \boldsymbol{J}_{Ti}^T \boldsymbol{J}_{Ti})^b]_{kn\times kn} \quad (10)$$

$$\boldsymbol{M}_{Coup} = \begin{bmatrix} [\sum_{i=1}^n m_i \boldsymbol{J}_{Ti}]^m + [\sum_{i=1}^n m_i \boldsymbol{J}_{Ti}]^b \\ [\sum_{i=1}^n (\boldsymbol{I}_i \boldsymbol{J}_{Ri} + m_i \tilde{\boldsymbol{P}}_{ci} \boldsymbol{J}_{Ti})]^m + [\sum_{i=1}^n (\boldsymbol{I}_i \boldsymbol{J}_{Ri} + m_i \tilde{\boldsymbol{P}}_{ci} \boldsymbol{J}_{Ti})]^b \end{bmatrix}_{6\times kn} \quad (11)$$

$$\boldsymbol{p}_{0cm} = [\boldsymbol{p}^*_{cm} - \mathbf{r}_{c0}]_{3\times 1}, \quad \boldsymbol{p}_{0ci} = [\boldsymbol{p}_{ci} - \mathbf{r}_{c0}]_{3\times 1} \quad (12)$$

$\widetilde{\boldsymbol{P}}_{cm}, \widetilde{\boldsymbol{P}}_{ci}, \widetilde{\boldsymbol{P}}_{0cm}$ and $\widetilde{\boldsymbol{P}}_{0ci}$ are the 3×3 skew symmetric matrix of position vectors $\boldsymbol{p}^*_{cm}, \boldsymbol{p}_{ci}, \boldsymbol{p}_{0cm}$ and $\boldsymbol{p}_{0ci}$ respectively.

We have assume that there is no external force acting on the system therefore, the centrifugal and Coriolis term is,

$$\boldsymbol{C}^* = \dot{\boldsymbol{M}}^* \dot{\phi} \tag{13}$$

3. Path Planning for Dual Arm Free Flying Space Robot

The non integrability property of angular momentum introduces non-holonomic characteristics to free floating systems. For simplicity we consider the planar case of the dual arm model i.e. *kn* + 1 DOF system in which base is having one DOF about *z* direction θ_0. In this section the path planning for single arm as in [5], is implemented for dual arm case.

The linear and angular momentum conservations for both mission and balance arm are represented by the following equations,

$$D_0\dot{\theta}_0 + D_1\dot{\theta}_1^m + D_2\,\dot{\theta}_2^m = 0 \tag{14}$$

$$D_0\dot{\theta}_0 + D_3\dot{\theta}_1^b + D_4\,\dot{\theta}_2^b = 0 \tag{15}$$

where D_0, D_1, D_2, D_3, D_4 are functions of system inertial parameters. For mission arm effect of θ_1^b and θ_2^b is neglected, hence the scleronomic constraint can be written in the form;

$$D_0(\theta_0,\theta_1^m,\theta_2^m)d\theta_0 + D_1(\theta_0,\theta_1^m,\theta_2^m)d\theta_1^m + D_2(\theta_0,\theta_1^m,\theta_2^m)d\theta_2^m = 0. \tag{16}$$

For balance arm effect of θ_1^m and θ_2^m is neglected, hence the scleronomic constraint can be written in the form,

$$D_0(\theta_0,\theta_1^b,\theta_2^b)d\theta_0 + D_3(\theta_0,\theta_1^b,\theta_2^b)d\theta_1^b + D_4(\theta_0,\theta_1^b,\theta_2^b)d\theta_2^b = 0. \tag{17}$$

The coefficients of the nonholonomic constraint become,

$$\left.\begin{aligned}
D_0(\theta_0,\theta_1^m,\theta_2^m) &= D_0(\theta_0,\theta_1^b,\theta_2^b) = \Delta_0,\\
D_1(\theta_0,\theta_1^m,\theta_2^m) &= \Delta_1^m + \Delta_3^m\cos(\theta_1^m - \theta_2^m),\\
D_2(\theta_0,\theta_1^m,\theta_2^m) &= \Delta_2^m + \Delta_3^m\cos(\theta_1^m - \theta_2^m),\\
D_3(\theta_0,\theta_1^b,\theta_2^b) &= \Delta_1^b + \Delta_3^b\cos(\theta_1^b - \theta_2^b),\\
D_4(\theta_0,\theta_1^b,\theta_2^b) &= \Delta_2^b + \Delta_3^b\cos(\theta_1^b - \theta_2^b)
\end{aligned}\right\} \tag{18}$$

where Δ's are the function of inertia, length and masses of the links and base.

In general form, $\text{Inertia} = \text{mass} \times (\text{radius of gyration})^2$

$$\left.\begin{aligned}
\Delta_0 = I_0,\ \Delta_1^m &= I_1^m + [(r_1^m)^2 m_0 m_1^m + m_1^m m_2^m (s_1^m)^2 + (a_1^m)^2 m_0 m_2^m]/m_T\\
\Delta_2^m &= I_2^m + [m_2^m(m_0 + m_1^m)(r_2^m)^2]\,/m_T,\\
\Delta_3^m &= [m_1^m m_2^m r_1^m r_2^m + m_0 m_2^m a_1^m r_2^m]\,/m_T\\
\Delta_1^b &= I_1^b + [(r_1^b)^2 m_0 m_1^b + m_1^b m_2^b (s_1^b)^2 + (a_1^b)^2 m_0 m_2^b]\,/m_T\\
\Delta_2^b &= I_2^b + [m_2^b(m_0 + m_1^b)(r_2^b)^2]\,/m_T\\
\Delta_3^b &= [m_1^b m_2^b r_1^b r_2^b + m_0 m_2^b a_1^b r_2^b]\,/m_T
\end{aligned}\right\} \tag{19}$$

Path planning can be done if this form is transformed to the Eq. consisting of two differentials. So non-integrable equations of the form of Eq. (16) and Eq. (17) can be written as,

$$du + v.dw = 0 \tag{20}$$

$$dx + y.dz = 0 \tag{21}$$

where *u*, *v*, *w* are properly selected functions of θ_0,θ_1^m,θ_2^m and *x*, *y*, *z* are properly selected functions of θ_0,θ_1^b, θ_2^b.

For mission arm and balance arm the forward transformation is given by,

$$\left.\begin{array}{c} u(\theta_0,\theta_1^m,\theta_2^m) = \Delta_0.\theta_0 + \Delta_2^m.\theta_2^m - \Delta_3^m.\sin(\theta_1^m - \theta_2^m) \\ v(\theta_0,\theta_1^m,\theta_2^m) = \Delta_1^m + 2\Delta_3^m.\cos(\theta_1^m - \theta_2^m), w(\theta_0,\theta_1^m,\theta_2^m) = \theta_1^m. \end{array}\right\} \quad (22)$$

$$\left.\begin{array}{c} x(\theta_0,\theta_1^b,\theta_2^b) = \Delta_0.\theta_0 + \Delta_2^b.\theta_2^b - \Delta_3^b.\sin(\theta_1^b - \theta_2^b), \\ y(\theta_0,\theta_1^b,\theta_2^b) = \Delta_1^b + 2\Delta_3^b.\cos(\theta_1^b - \theta_2^b), z(\theta_0,\theta_1^b,\theta_2^b) = \theta_1^b. \end{array}\right\} \quad (23)$$

Therefore, the planning problem reduces to choosing functions f and g given by Eq.(24). We choose function f as a fifth orders polynomial and g can be forth order polynomial, so that while finding coefficients of them the system initial and final configuration, velocity and acceleration can be satisfied.

$$\left.\begin{array}{l} w = z = f(t) = c_5 t^5 + c_4 t^4 + c_3 t^3 + c_2 t^2 + c_1 t + c_0 \\ u = x = g(w) = b_4 w^4 + b_3 w^3 + b_2 w^2 + b_1 w + b_0 \\ v = y = -g'(w) = -(4b_4 w^3 + 3b_3 w^2 + 2b_3 w + b_1) \end{array}\right\} \quad (24)$$

Here the coefficients of polynomial w are computed using the initial and final values of orientation θ_1^m, angular velocity $\dot{\theta}_1^m$ and angular acceleration $\ddot{\theta}_1^m$. The coefficients of polynomial z are computed using the initial and final values of orientation θ_1^b, angular velocity $\dot{\theta}_1^b$ and angular acceleration $\ddot{\theta}_1^b$.

For mission arm use initial and final conditions of θ_0,θ_1^m and θ_2^m in Eq. (22) to find u_{int}, u_{fin}, v_{int}, and v_{fin} and using the polynomial Eq. (24) we get unknown coefficients b_3, b_2, b_1, b_0 for mission arm. For balance arm use initial and final conditions of θ_0,θ_1^b and θ_2^b in Eq. (23) to find x_{int}, x_{fin}, y_{int}, and y_{fin} and using the polynomial Eq. (24) we get unknown coefficients b_3, b_2, b_1, b_0 for balance arm. Once f and g are found, the trajectories or $\theta_0, \theta_1^m, \theta_2^m, \theta_1^b, \theta_2^b$ are found using the inverse transformation from u, v, w to $\theta_0, \theta_1^m, \theta_2^m$ and x, y, z to $\theta_0, \theta_1^b, \theta_2^b$. It is seen that both the arms has a cumulative effect on orientation of base θ_0.

4 Simulation and Results

Dynamic model derived in Eq. (6) of space robot is simulated using MATLAB and Simulink software. Simulation of equation of motion is obtained by providing step input to four DC motors located at the four joints of the dual arm robot. Table1 shows the parameters used in simulation.

Table 1: Parameters used in simulating of joint motion

Mass of base(m_0)	4kg
Mass of 1st link of mission and balance arm $m_1^m = m_1^b$	0.2942 kg
Mass of 2st link of mission and balance arm including masses of their grippers $m_2^m = m_2^b$	0.2942 kg
Length of 1st link of mission and balance arm $a_1^m = a_1^b$	0.4 m
Length of 2st link of mission and balance arm $a_2^m = a_2^b$	0.3 m
Distance of CM of base to first joint of both the arms (s_0^m) = (s_0^b)	0.5 m
Inertia of 1st link of mission and balance arm I_1^m=I_1^b	0.03 kg m^2
Inertia of 2st link of mission and balance arm including end effectors inertia $I_2^m = I_2^b$	0.02 kg m^2
Inertia of base (I_0)	0.4 kg m^2

End effectors trajectory is obtain by first simulating joint motions of the robot and then transferring it to its tip using Jacobian given by Eq. (4) and Eq. (5). To validate equations of motion of the proposed model, base disturbance caused due to the effect of mass and inertia of links should be negligible, hence increasing base mass to 400 kg and inertia to 300 kg m^2. The two links of each arm are made straight and joint between them is locked by increasing the motor damping B_2 by 100 times. As expected the two end effectors of mission arm and balance arm plot a circular trajectory as shown in Fig. 2, radius equal to the summation of their dynamic link lengths.

For simulation of path planning parameters used are same as given in Table 1 the duration of motion is chosen equal to 10 s. Let initial system configuration of mission arm be $(\theta_1^m, \theta_2^m)^{\text{in}} \equiv (0°, 30°)$ and the final be $(\theta_1^m, \theta_2^m)^{\text{fin}} \equiv (30°, 60°)$. Let initial system configuration of balance arm be $(\theta_1^b, \theta_2^b)^{\text{in}} \equiv (180°, 150°)$ and the final be $(\theta_1^b, \theta_2^b)^{\text{fin}} \equiv (140°, 100°)$.The initial system configuration of base is $(\theta_0)^{\text{in}} \equiv 0°$ and the final is $(\theta_0)^{\text{fin}} \equiv 5°$

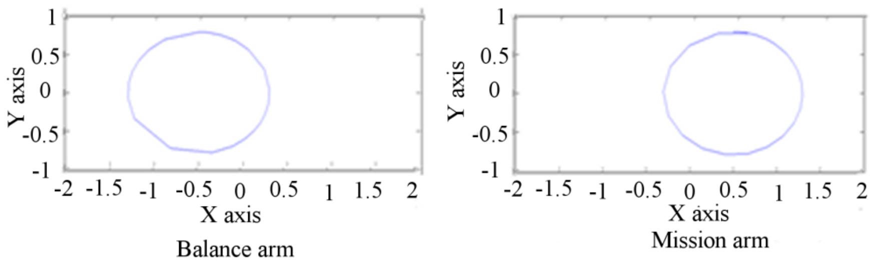

Figure 2: Plot of X_{tip} v/s Y_{tip} of dual arm space robot for both the arms.

This requirement may result in a range of possible b_4. Of these, b_4 is chosen so that the range of allowable final spacecraft attitudes is maximized. For this case, for both the arms $b_4 = 20$. Joint torques curves can be obtained by simplifying Eq. (6) to the planar case.

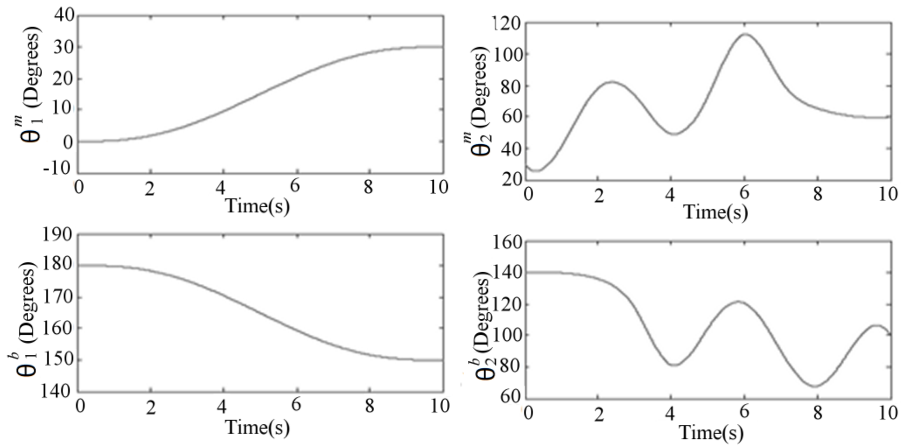

Figure 3: Path followed by all four joints of both the arms using polynomial approach for $(\theta_1^m, \theta_2^m)^{\text{in}} \equiv (0°, 30°)$, $(\theta_1^m, \theta_2^m)^{\text{fin}} \equiv (30°, 60°)$, $(\theta_1^b, \theta_2^b)^{\text{in}} \equiv (180°, 150°)$ and $(\theta_1^b, \theta_2^b)^{\text{fin}} \equiv (140°, 100°)$.

As shown in Fig. 3, the desired configuration is reached in the specified time. Also, all trajectories are smooth throughout the motion, and the system starts and stops smoothly at zero velocities, as expected and shown in Fig. 4. As shown in Fig. 5, the required torques can be easily be applied by the joint actuators to reach the final configuration. From Fig. 6 total base orientation changes from 53.27° to -6.85° which contains the desired 5°, but the total base disturbance is around 60° which is undesirable. Hence increasing the base mass to 10 kg and its inertia to 1 kg-m^2 for feasible solution we can minimize total base disturbance to 10° as shown in Fig. 7.

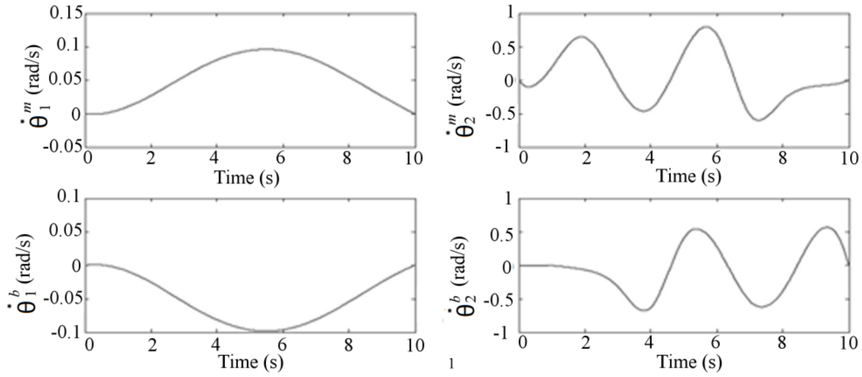

Figure 4: Rate of change of joint angles of both the arms.

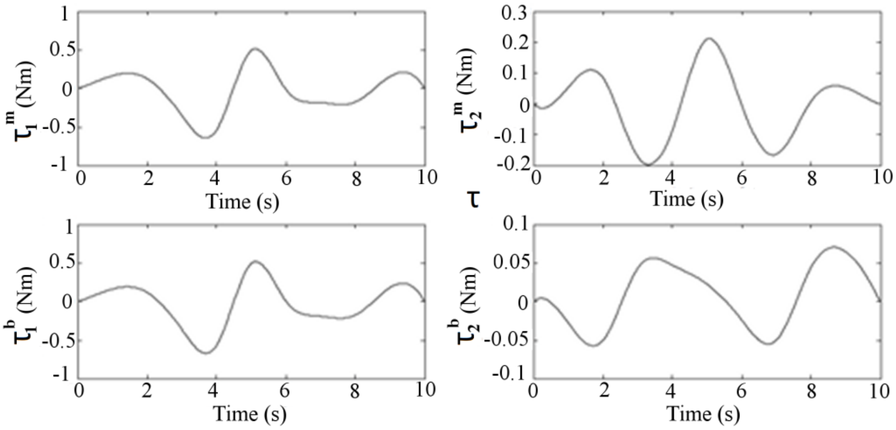

Figure 5: Manipulator torques of both the arms.

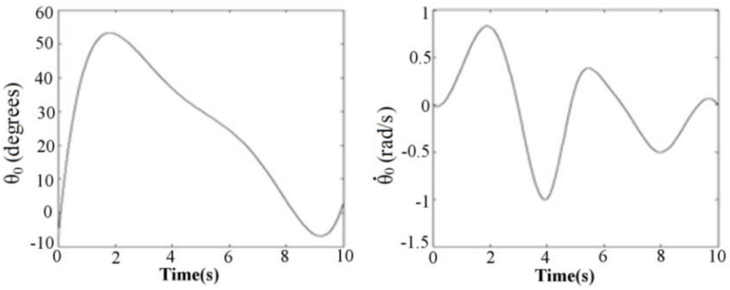

Figure 6: Base disturbance and base velocity variation with time.

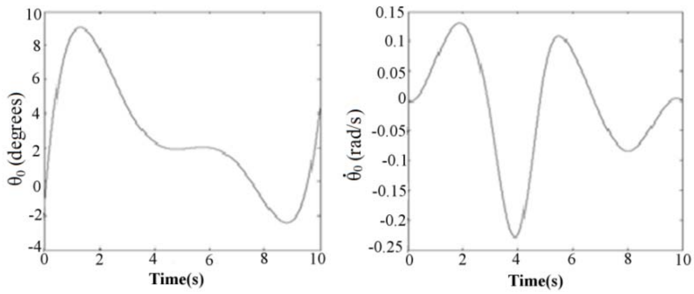

Figure 7: Base disturbance and base velocity variation with time for increased mass and inertia.

5. Conclusions

In this paper dynamic modeling and path planning of dual arm free flying space robot is presented. Equation of motion for the case of dual arm free flying is derived and simulated in Simulink. A path planning methodology was implemented for dual arm free flying space manipulators using smooth and continuous functions such as polynomials. From the practical point of view, one should investigate the applicability of the method to more than two arms and three dimensional systems. One can also see the effect of increasing the degree of polynomial considering uncertainties in inertial parameters during path planning.

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