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Applied Mathematics and Computation 185 (2007) 1149–1159

APPLIED MATHEMATICS AND COMPUTATION

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Impact dynamics and control of a flexible dual-arm space robot capturing an object

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Abstract

In this paper, we present the effect of payload collision on the dynamics and control of a flexible dual-arm space robot capturing an object. The dynamics model of the robot system is derived with Lagrangian formulation. The two flexible links are modeled as Euler–Bernoulli beams with two bending modes each. Initial conditions are derived from the impact model to simulate the post-impact dynamics of the whole systems. A PD controller is designed, whose purpose is to maintain stabilization of the robot system after the capture of the object. The dynamical simulations are carried out in two cases: the robot system is uncontrolled and controlled after impact. The simulation result shows that impact effect of the object on the space robot is great. It also shows that the joint angles of base and manipulators quickly reach steady state through feedback control.

Keywords: Flexible manipulator; Space robot; Impact; Dynamics; PD-control scheme

1. Introduction

On-orbit capturing operations by a space robot will become routine work in future space operations such as inspection, assembly and retrieval of malfunctioning satellites. Astronaut extra vehicular activities (EVA) can be valuable in meeting these requirements. However, the cost of human life support facilities, the limited time available for astronaut EVA, and the high risks involved make space robotic devices candidate astronaut assistants or alternatives. To increase the mobility of such devices, free-flying systems in which one or more manipulators are mounted on a spacecraft equipped with thrusters have been proposed [1]. However, extended use of thrusters severely limits the operational life of free-flyers. Operation in a free-floating mode can increase the life of the system [2].

There are a lot of achievements of the research on rigid arm space robot [1,14]. Considering the following characteristics of space robot: light mass, long manipulator, heavy payload, etc., the flexibility of manipulators

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doi:10.1016/j.amc.2006.07.035

should be considered to get the excellent control precision and performance. In the same time, there also are many achievements of the research on the dynamic modeling and control of flexible single-arm space robot [10]. In [6] the author described a modeling scheme for collision dynamics of space robots. However, there are few researches on flexible multi-arm space robot. Except Wu et al. [4] used the assumed mode method to describe the elastic deformation, built the dynamic model by Lagrangian formulation and studied the control and simulation of flexible dual-arm space manipulator.

A capturing operation comprises three specific phases [3]: the pre-impact phase, the impact phase, and the post-impact phase. The pre-impact phase determines the initial conditions of the object. During the impact phase, contact between the end-effectors of the space robot and the object is established. The impact could damage the links of the robot and result in the undesired base attitude drift and structural motion of flexible links. In general, it is expected that relative velocities between the end-effectors of space robot and the target grapple point should be zero. However, it can hardly be achieved in practice. Thus, the impact always exists when a space robot captures an object.

Till now, the impact problem has been mainly discussed with regard to ground-fixed robots [11–13], focusing on the force impulse occurring at the point of contact. In the case of a space robot, however, the analysis of impact dynamics of a free-floating space robot is complicated because of the presence of the free-floating base dynamics and dynamic coupling effects between the base and the manipulator motion. There are few studies on this problem. Shibli and Aghili [17] studied the unified control-oriented modeling of a free-flying space robot to deal with the kinematics, constraints and dynamics of a free-flying space robot interacting with a target satellite. Yoshida et al. [6] have studied the impact for free-floating space robots. They introduced the *extended-inverse inertia tensor* (*Ex-IIT*) notation and developed a comprehensive framework for the impact dynamics with regard to the force impulse acting at the hand of the manipulator. Yoshida and Nakanishi [15] have also researched the contact motion between rigid bodies floating in the space and investigated the dynamic conditions on capturing a non-cooperative target. Dimitrov and Yoshida [16] have discussed the capture of a tumbling satellite by a space robot. They took the chaser's base attitude motion as a priority task. A joint space orthogonal decomposition procedure involving the so-called reaction null space during the pre-impact and post-impact phases is used. The main conclusion was that the pre-impact angular momentum distribution was closely related with the attitude profile after the contact with the target. A more technically sound solution was proposed in [8], where a so-called "space leech" was attached to the tumbling object. But the way of attachment has not been discussed. Wee and Walker [9] tackled the problem of force impulse minimization through a configuration-dependent scalar function. The minimization was achieved by proper trajectory planning in configuration space, based on the gradient project technique. However, the motion along a specified trajectory introduced an additional constraint into the system. The combination of this constraint with impulse minimization task yielded a highly non-linear system equation. Thus, the gradient project approach might run into a local minimum.

There are a lot of references related to the dynamics and control of flexible multi-body systems in general or flexible manipulators, in particular. But only the studies related to capture dynamics or impact dynamics will be discussed here. Chapnik et al. [5] considered elastic frictionless impact of a spherical mass on a one-link flexible robotic arm. The rigid body rotational motion of the beam was considered negligible during the time of impact, but not the elastic deflection. Thus the beam could be modeled as a cantilever beam during the impact. The principle of conservation of energy during an elastic impact was combined with momentum considerations to establish the post-impact velocity of the striking mass and vibration energy of the beam. The main conclusion of the work was that the elastic deflection caused by impact could be neglected. Cyril et al. [7] have discussed the dynamics of a spacecraft-mounted flexible robotic manipulator capturing a spinning satellite, but the capture operation was assumed to be smooth. Later, the authors [19] simulated the post-impact dynamics at the condition of considering a velocity difference between the target grapple point and the end-effectors of the flexible manipulator carried by the chaser.

Control of space manipulators introduces a challenge to the control systems designer. This is due to the highly non-linear equations of motion and the strong coupling between its generalized coordinates. In [18] the authors proposed the use of reaction wheels and/or jet thrusters to control the spacecraft attitude and position by canceling the force and torque disturbances caused by the manipulator and manipulated payload. Another scheme [6] proposed an active attitude control system (ACS) that maintains the spacecraft's attitude related to the orbital frame, which was achieved by applying appropriate corrective torques. The spacecraft's center of mass, however, was still free to translate in response to the force disturbances of the manipulator and its payload. Very few researches have investigated the effect of capturing an object. In [6] the problem was formulated, however, the post-capture dynamics was not simulated.

The purposes of this paper are to study the effect of capturing an object in orbit with specific velocity on the dynamics of the uncontrolled flexible space robot and to design a controller to maintain stabilization of the robot system after the capture of the object. The paper is organized as follows: In Section 2, the dynamic model of the space robot is derived using Lagrangian formulation. Besides, initial conditions for the post-impact dynamics of the robot systems are derived from the impact model. Then post-impact controller design is presented in Section 3. Finally, the simulation results and discussion are presented in Sections 4 and 5 respectively.

2. Dynamics model

2.1. Dynamics model of the flexible dual-arm space robot

In this section, the dynamical equations of the robot system are derived using Lagrangian formulation. The travel of the system is of relatively short length and duration and therefore the dynamical effects due to orbital mechanics are neglected. The motion of the planar flexible dual-arm space robot shown in Fig. 1 is described with respect to an in-orbit inertial frame of reference ($x_0y_0z_0$). The space robot system includes a cylindrical base and two symmetrical dual-links manipulators, which are briefly called link 1 (the cylindrical base), link 2, link 3, link 4, and link 5, respectively. Link 3 and link 5 are flexible. Let the length of these links be l_i, $i = 1, 2, \ldots, 5$, where l_1 is the radius of the cylindrical base. Let Σ_i be the frame of $x_io_iy_i$, Σ_0 be the inertial frame. Each link has a freedom of joint angle θ_i, which is driven by joint torque N_i, $i = 1, 2, \ldots, 5$. Link 1 has two other translation freedoms, which are described by the coordinate of point $o_1(x_1, y_1)$ and driven by f_x and f_y. All joints are described in plane $x - y$. Flexible links are assumed as Euler–Bernoulli beams, whose elastic deflection is described by assumed mode method as

$$u_{ix} = \sum_{j=1}^{n} \varphi_{ij}(x)q_{ij}(t) = \phi_i(x)Q_i(t), \quad i = 3, 5, \tag{1}$$

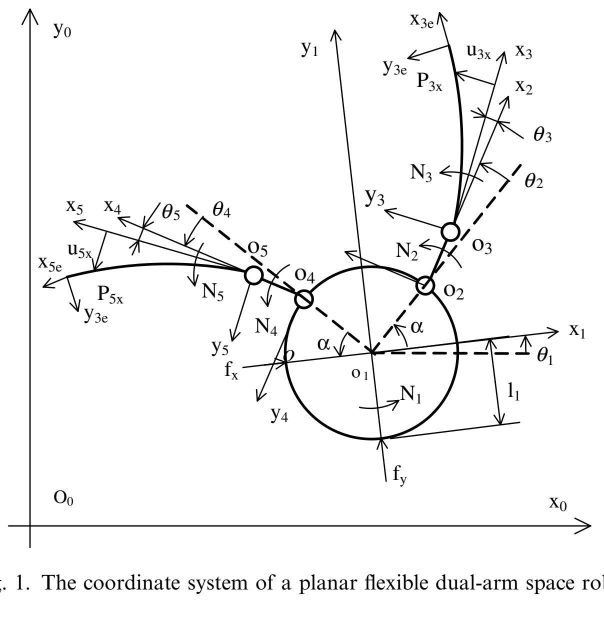

Fig. 1. The coordinate system of a planar flexible dual-arm space robot.

where

$$\phi_i(x) = (\varphi_{i1}, \varphi_{i2}, \ldots, \varphi_{in}) \tag{2}$$

and

$$Q_i(t) = (q_{i1}, q_{i2}, \ldots, q_{in})^{\mathrm{T}}, \tag{3}$$

where n is the number of mode, $Q_i(t)$ is vector of mode generalized coordinates and $\phi_i(x)$ is vector of mode shape functions. This system uses clamped-free-beam mode shape function while dynamic modeling. Let the generalized coordinate vector of the system be

$$p = (x_1, y_1, \theta_1, \theta_2, \theta_3, \theta_4, \theta_5, Q_3^{\mathrm{T}}, Q_5^{\mathrm{T}})^{\mathrm{T}}. \tag{4}$$

After deriving the kinetic energy, flexible potential energy and virtual work of the system and including them into Lagrangian formulation, a set of dynamical equation is obtained in the form

$$M\ddot{p} + C + Kp = u, \tag{5}$$

where M is the inertia mass matrix which is symmetric and positive definite, C is the vector included Coriolis and centrifugal forces, u is the vector of generalized driving forces, K is the stiffness matrix given by

$$K = \mathrm{diag}(0, K_3, K_5)^{\mathrm{T}}, \tag{6}$$

where

$$K_i = \int_0^{l_i} EI_i \phi_{\mathrm{i}}''^{\mathrm{T}} \phi_{\mathrm{i}}'' \,\mathrm{d}x, \quad i = 3, 5. \tag{7}$$

Let the vector of generalized driving forces be

$$u_{\mathrm{Q}} = (f_x, f_y, N_1, N_2, N_3, N_4, N_5, 0_{1\times n}, 0_{1\times n})^{\mathrm{T}}. \tag{8}$$

Then $u = u_{\mathrm{Q}}$ when the end-tip is free, $u = u_{\mathrm{Q}} - u_{\mathrm{f}}$ when the end-tip is not free, where $u_{\mathrm{f}} = J^{\mathrm{T}} f_{\mathrm{e}}$. u_{f} is the joint torque which make the end-tip has force or torque f_{e} to act on the environment, J is the system's Jacobian matrix.

2.2. The initial conditions for post-impact dynamical simulation

There is a basic assumption that is made in the formulation of the impact model. The generalized coordinates of the system remain the same over the impact duration although the generalized velocities change substantially [5]. During the impact, the equations of motion of the robot system and the object system can be expressed in a form similar to Eq. (5) except that the impact force. Thus we can write

$$M\ddot{p} + C + Kp = u + J^{\mathrm{T}} f_{\mathrm{I}} \tag{9}$$

and

$$M_{\mathrm{o}}\ddot{\psi}_{\mathrm{o}} + C_{\mathrm{o}} = -J_{\mathrm{o}}^{\mathrm{T}} f_{\mathrm{I}}, \tag{10}$$

where the subscript o is used for the object, M_{o} is the generalized mass matrix of the object, ψ_{o} is the vector of independent generalized coordinates of the object, vector C_{o} contains the Coriolis and centrifugal forces terms, J and J_{o} are the Jacobian matrix associated with the robot and the object contact points respectively, and f_{I} represents a vector of forces associated with impact.

By combining the two equations of motion (9) and (10), the impact force can be eliminated to yield the following equation:

$$M\ddot{p} + C + Kp = u - J^{\mathrm{T}}(J_{\mathrm{o}}^{\mathrm{T}})^{+}(M_{\mathrm{o}}\ddot{\psi}_{\mathrm{o}} + C_{\mathrm{o}}), \tag{11}$$

where $(J_{\mathrm{o}}^{\mathrm{T}})^{+}$ is the Moore–Penrose generalized inverse matrix of $J_{\mathrm{o}}^{\mathrm{T}}$.

Next, integrating the above equation over the period of impact τ, we get

$$\int_0^{\tau} M\ddot{p}\,\mathrm{d}t + \int_0^{\tau} (C + Kp)\mathrm{d}t = -\int_0^{\tau} J^{\mathrm{T}}(J_{\mathrm{o}}^{\mathrm{T}})^{+} M_{\mathrm{o}}\ddot{\psi}_{\mathrm{o}}\,\mathrm{d}t + \int_0^{\tau} (u - J^{\mathrm{T}}(J_{\mathrm{o}}^{\mathrm{T}})^{+} C_{\mathrm{o}})\mathrm{d}t. \tag{12}$$

Notice the assumption that all generalized coordinates of the system remain fixed during this period although their rates may change. Since J, J_o, M, and M_o depend only on the former and not on the latter, and there are no joint torques applied during impact, i.e. $u = 0$. Besides, the impact force f_I is usually very large and acts for a very short time τ. Thus, it can be said that

$$\tau = O(\varepsilon), \quad \ddot{p}, \ddot{\psi}_o = O\left(\frac{1}{\varepsilon}\right), \quad p, \dot{p}, \psi_o, \dot{\psi}_o = O(1), \qquad \varepsilon << 1. \tag{13}$$

So, integration result of Eq. (12) can be written as

$$M(\dot{p}_f - \dot{p}_i) + J^T(J_o^T)^+ M_o(\dot{\psi}_{of} - \dot{\psi}_{oi}) = \int_0^\tau (-C + u - J^T(J_o^T)^+ C_o)\mathrm{d}t, \tag{14}$$

where the subscript f and i represent after and before the impact respectively. Clearly the left hand side of Eq. (14) is O(1). The integrand on the right hand side is also of O(1), however, the interval of the integration is of O(ε) and hence, the right hand side is O(ε) and can be ignore compared to the left hand side. Thus Eq. (14) can be written as

$$M(\dot{p}_f - \dot{p}_i) + J^T(J_o^T)^+ M_o(\dot{\psi}_{of} - \dot{\psi}_{oi}) = 0. \tag{15}$$

Eq. (15) can be used for all collisions ranging from plastic impact to perfectly elastic impact. Here the case of the plastic impact is considered, that is to say, the robot captures the object successfully. In plastic impact, the velocity of the contact point of each system is the same immediately after the impact, thus

$$J\dot{p}_f = J_o\dot{\psi}_{of}. \tag{16}$$

From Eq. (16), the generalized velocities of the object can be expressed in terms of those of the robot as

$$\dot{\psi}_{of} = (J_o^T J_o)^{-1} J_o^T J \dot{p}_f. \tag{17}$$

Upon substituting Eq. (17) into Eq. (15) the following is obtained:

$$\dot{p}_f = G^{-1}H, \tag{18}$$

where

$$G = M + J^T(J_o^T)^+ M_o(J_o^T J_o)^{-1} J_o^T J \tag{19}$$

and

$$H = M\dot{p}_i + J^T(J_o^T)^+ M_o\dot{\psi}_{oi}. \tag{20}$$

Once the initial velocities of the object $\dot{\psi}_{oi}, \dot{p}_i$ have been determined, $\dot{p}_f$ can be evaluated according to (18), $\dot{\psi}_{of}$ can be solved from (17). The final values $\dot{p}_f, \dot{\psi}_{of}$ of Eqs. (18) and (17) are used as the initial velocity conditions for the post-impact dynamical simulation of the system.

2.3. The post-impact dynamic model of the space robot capturing the object

When the flexible dual-arm space robot captures the object successfully the velocities of the end-effectors of the robot are equal to those of the object at the contact point. The captured object will be one segment of the robot system. The post-impact dynamic model will be the combination of the equations of robot and object, that is to say, the following equation will hold good:

$$J_o\dot{\psi}_o = J\dot{p}. \tag{21}$$

By differentiating Eq. (21), we can obtain

$$\ddot{\psi}_o = (J_o^T J_o)^{-1} J_o^T J \ddot{p} + (J_o^T J_o)^{-1} J_o^T (\dot{J} - \dot{J}_o (J_o^T J_o)^{-1} J_o^T J)\dot{p}. \tag{22}$$

Upon substituting Eq. (22) into Eq. (10) the following is obtained:

$$M_o(J_o^T J_o)^{-1} J_o^T J \ddot{p} + M_o(J_o^T J_o)^{-1} J_o^T (\dot{J} - \dot{J}_o (J_o^T J_o)^{-1} J_o^T J)\dot{p} + C_o = -J_o^T f_I. \tag{23}$$

The following will be obtained by combining the two Eqs. (23) and (9):

$$M'\ddot{p} + C' + Kp = U, \tag{24}$$

where

$$M' = M + J^{\mathrm{T}}J_{\mathrm{o}}(J_{\mathrm{o}}^{\mathrm{T}}J_{\mathrm{o}})^{-1}M_{\mathrm{o}}(J_{\mathrm{o}}^{\mathrm{T}}J_{\mathrm{o}})^{-1}J_{\mathrm{o}}^{\mathrm{T}}J \tag{25}$$

and

$$C' = C + J^{\mathrm{T}}J_{\mathrm{o}}(J_{\mathrm{o}}^{\mathrm{T}}J_{\mathrm{o}})^{-1}M_{\mathrm{o}}(J_{\mathrm{o}}^{\mathrm{T}}J_{\mathrm{o}})^{-1}J_{\mathrm{o}}^{\mathrm{T}}(\dot{J} - \dot{J}_{\mathrm{o}}(J_{\mathrm{o}}^{\mathrm{T}}J_{\mathrm{o}})^{-1}J_{\mathrm{o}}^{\mathrm{T}}J)\dot{p} + J^{\mathrm{T}}(J_{\mathrm{o}}^{\mathrm{T}})^{+}C_{\mathrm{o}}. \tag{26}$$

In the above equation, M' is the generalized mass matrix of the system, which is symmetric and positive definite. Vector C' contains the Coriolis, centrifugal terms. Eq. (24) is the post-impact dynamic model of the robot combining the object.

3. Post-impact controller design

In this section, the purpose of the control system is to maintain stabilization of the whole system after the capture of the object. The control scheme used is the computed torque method in which the equations of motion are linearized via feedback. Therefore, this control method is sometimes referred to as feedback linearization control.

At present, active control of both the rotational and elastic coordinates is still in the experimental stage and has not been used in an actual situation. In this section, the elastic effects are included in the mathematical model, and their amplitudes could be determined from the sensor readings by means of an estimator. This model treats the elastic deformations as known disturbances, but does not explicitly control them. In the same time, the captured object is considered as a deterministic disturbance, i.e. the inertia and dynamic properties are known.

It is more convenient for simulation and control to partition Eq. (24) into the following form:

$$\begin{bmatrix} M'_{aa} & M'_{ap} \\ M'_{pa} & M'_{pp} \end{bmatrix}\begin{bmatrix} \ddot{p}_a \\ \ddot{p}_p \end{bmatrix} + \begin{bmatrix} C'_a \\ C'_p \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & K_{pp} \end{bmatrix}\begin{bmatrix} p_a \\ p_p \end{bmatrix} = \begin{bmatrix} U \\ 0 \end{bmatrix}, \tag{27}$$

where the subscripts a and p represent matrices and vectors related to the coordinate $p_a = (x_1, y_1, \theta_1, \theta_2, \theta_3, \theta_4, \theta_5)^{\mathrm{T}}$ and the elastic coordinate $p_p = (Q_3^{\mathrm{T}}, Q_5^{\mathrm{T}})^{\mathrm{T}}$, respectively. The elastic coordinate $p_p = (Q_3^{\mathrm{T}}, Q_5^{\mathrm{T}})^{\mathrm{T}}$ could be solved in terms of the coordinate $p_a = (x_1, y_1, \theta_1, \theta_2, \theta_3, \theta_4, \theta_5)^{\mathrm{T}}$ and Eq. (27) could be rearranged as

$$\widehat{M}\ddot{p}_a + \widehat{C}_a = U, \tag{28}$$

where $\widehat{M} = M'_{aa} - M'_{ap}M'^{-1}_{pp}M'_{pa}$, $\widehat{C}_a = C'_a - M'_{ap}M'^{-1}_{pp}C'_b - M'_{ap}M'^{-1}_{pp}K_{pp}p_b$.

The PD control torque law is designed, and it can be written in the form of

$$U = -\widehat{M}(D_1\dot{p}_a + D_2(p_a - p_{ad})) + \widehat{C}_a, \tag{29}$$

where

$$D_1 = \begin{bmatrix} 2\varsigma_1\omega_1 & & & \\ & 2\varsigma_2\omega_2 & & \\ & & \ddots & \\ & & & 2\varsigma_n\omega_n \end{bmatrix}, \quad D_2 = \begin{bmatrix} \omega_1^2 & & & \\ & \omega_2^2 & & \\ & & \ddots & \\ & & & \omega_n^2 \end{bmatrix}$$

are diagonal matrices containing the control gains and p_d is the desired coordinates vector, and $\widehat{C}_a$ represents the non-linear compensation term.

By substituting Eq. (29) into Eq. (28), we can obtain

$$\ddot{p}_a + D_1\dot{p}_a + D_2(p_a - p_{ad}) = 0. \tag{30}$$

Table 1
Physical parameters of the flexible dual-arm space robot and object systems

Body	Length (m)	Mass (kg)	EI (N m^2)
Base	2	40	0
Link 2	2	2	0
Link 3	10	10	1000
Link 4	2	2	0
Link 5	10	10	1000
Object	2	4	0

Table 2
Pre-impact initial conditions of the flexible dual-arm space robot and object systems

Body	Generalized coordinates (° or m)	Generalized velocities (rad s^{-1} or m s^{-1})
Base	0	0
Link 2	15	0.2
Link 3	38.14	0.1
Link 4	−15	−0.1
Link 5	−38.14	−0.05
Object	0	$V_x = -0.2$, $V_y = -0.2$, $w = -1$

4. Simulation results

In this section, the flexible dual-arm space robot in Fig. 1 is used in the simulation. The physical parameters of the robot and object systems and pre-impact initial conditions are respectively given in Tables 1 and 2. The flexibility of the link 3 and link 5 are modeled by two bending modes.

The dynamics simulations are carried out in two cases: the robot system is uncontrolled and controlled after impact.

(1) A dynamical simulation of the uncontrolled system after capture is carried out. Figs. 2 and 3 show the post-impact dynamics of the uncontrolled robot system. It is found that the base attitude ((c) in Fig. 2) drifts by about 25° in 5 s without control. Furthermore, the other joint angles ((d)–(g) in Fig. 2) drift more quickly than base attitude, which will probably cause the breakage of the joint angles. All of these will also add the difficulty to control the system. The tip displacements of the link 3 and link 5 ((a) and (b) in Fig. 3) show an oscillatory behavior, which are reasonable because of the flexible vibration. The displacement will not damp out because we do not consider the structural damping in the model.

(2) A simulation is carried out using the feedback linearization control torque (29) whose purpose is to control the degrees of the base and the rotational degrees of the manipulators only. The initial velocities of the whole system for the post-impact were calculated through Eqs. (17) and (18). The desired coordinate vector p_d just is the initial coordinate of the robot system. It is found that the response of the dynamical system to the applied corrective torques is very good. The base attitude angle ((a) in Fig. 4) is maintained at zero throughout the simulation period. The link joint angles ((b)–(e) in Fig. 4) reach the desired final values of the joint coordinates quickly. It is also noted that the tip displacements of flexible link 3 and link 5 ((a) and (b) in Fig. 5) show the oscillatory behavior. In the same time the amplitudes will damp. These are reasonable for the excitation of the control torques.

5. Conclusions

In this paper, the system dynamics model and impact dynamics model of a flexible dual-arm space robot are derived by Lagrangian formulation. A method is proposed for the determination of initial conditions for post-impact dynamic simulation of the system. Based on the simulation, the following conclusions can be made.

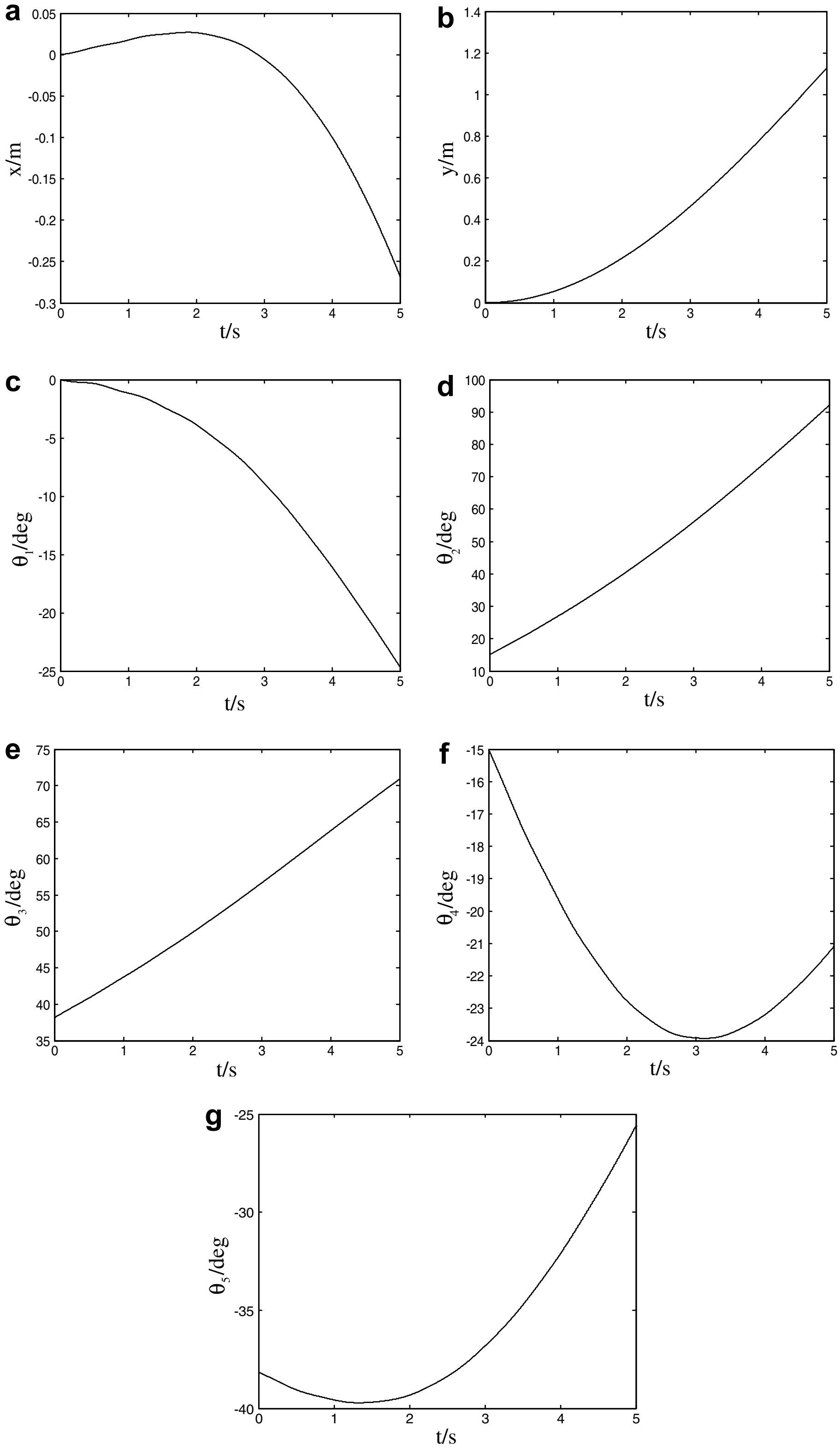

Fig. 2. Joint coordinates of the uncontrolled system after capture.

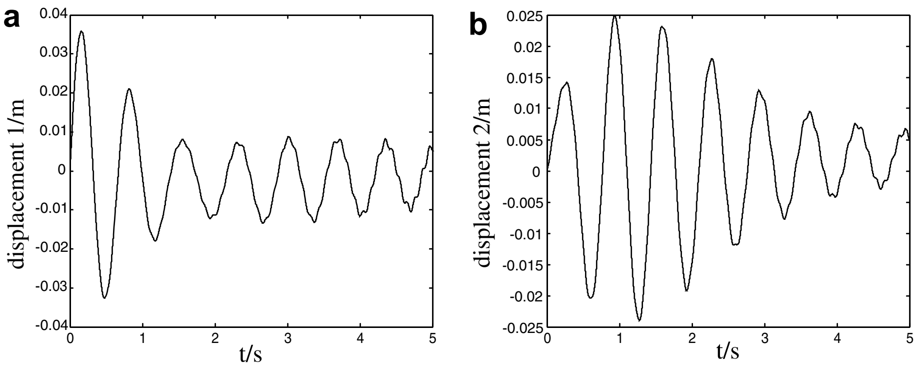

Fig. 3. Elastic displacements of the uncontrolled system after capture.

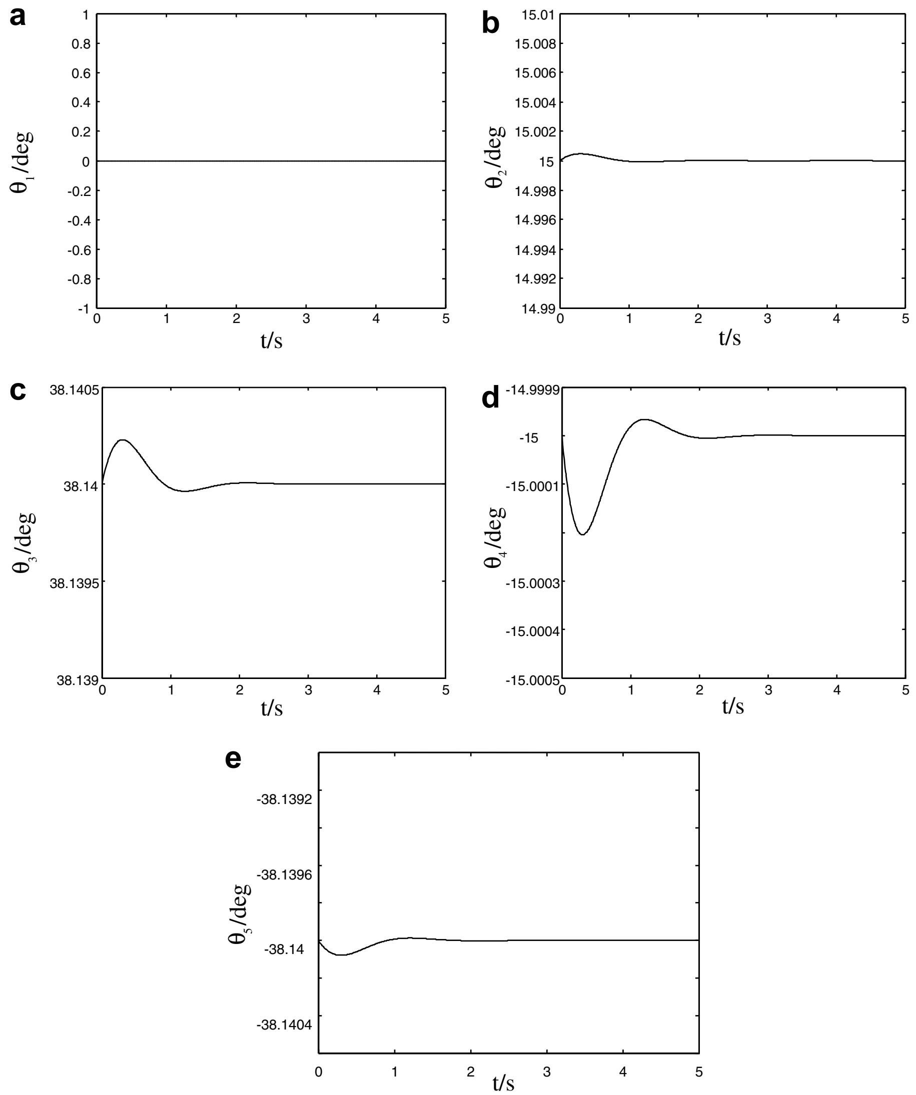

Fig. 4. Joint coordinates of the controlled space robot system.

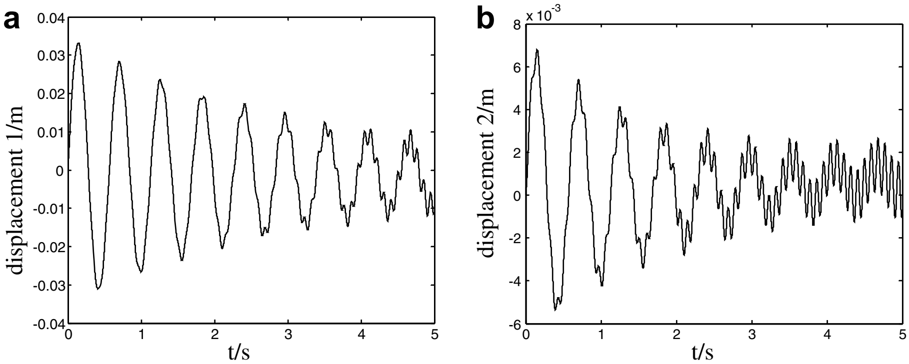

Fig. 5. The elastic displacements of the controlled system after capture.

Firstly, the impact effect of capturing an object with a specific velocity on the system dynamics is great, and the structure vibration of the flexible link could influence the position accuracy of the robot. So, while studying on space robot capturing objects, the impact effect on its attitude drift must be taken into account and structure damping should be added in the model. In addition, it is also important to determine the exact pre-impact conditions of the captured object.

Secondly, a control algorithm whose purpose is to maintain stabilization of the whole system after the capture is designed. Simulation results show joint angles of base and manipulators quickly reach steady state. But the elastic vibrations are not explicitly controlled.

Finally, in this paper, it is assumed that the object is successfully captured, i.e. the impact is fully plastic. In our future work, we will discuss the other kind of, such as fully elastic impact. In the same time, the control of structure vibration of the flexible link should be considered.

Acknowledgement

The authors wish to express their gratitude to the National Natural Science Foundation of China (Grant No. 50405002 and No. 50375007) for providing the funding for this research.

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