Impact Analysis of Flexible Space-based Robot Capturing Non-cooperated Targets and Backstepping Control and Vibration Suppression

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ABSTRACT

This paper discusses stability control problem for compounded body of flexible space-based robot and non-cooperated target after capturing operation is completed. The dynamical model of the flexible space-based robot system is derived with Lagrange formula, and the dynamical model of the satellite is derived with the Newton-Euler method. And based on it, coupling momentum and impulse transfer during operation process of flexible space-based robot to capture the target satellite, mathematical models which been suit for the design of control system that for free-floating flexible space-based robot to on-orbit capture non-cooperated target are established. Using said mathematical model, In order to damp out vibration, conception of virtual force is used to design hybrid desired trajectory which integrate both flexible mode and rigid motion, through transforming the original control scheme and a backstepping control based on virtual force conception is proposed. Thus, the effective control is realized for capturing a target non-cooperated target and vibration suppression of flexible link. A complete analysis on the stability and the performance are performed by using Lyapunov theory. The correctness and applicability of the control scheme are manifested by simulation and experiment.

1 INTRODUCTION

In recent years, the research work in the space science has transform from the science explore stage to the practical application stage as the development of the space science. More and more space equipments are employed as the development; such as the satellite, space telescope, space laboratory, spaceship etc. Therefore assembly and repair for these space equipments have become the important assignment for the astronaut. But the space manipulator is the special equipment, it can help the astronaut to assemble and repair the space equipment which will reduce the risk of the astronautic assignment. It is the good assistant of the astronaut[1-3].

The space manipulator has been employed for a long time, the Canada arm is the successful application of the space manipulator which installed in the International Space Station. This kind of space manipulator is similar to the earth manipulator which is fixed in a stationary base. As the development of the technology, the free floating base space manipulator is a new kind of space manipulator, and it is becoming the research focus. The free floating space is a special kind of space manipulator which the base is freedom of movement under the micro-gravity space environment. There are dynamic coupling between the manipulator and the base of the free floating space manipulator[4-5]. Capture the free motion target and move the target to the specified location are the main assignment of the free floating space manipulator. The impact between the manipulator end capture hand and the target is inevitable during the capture operation. The impact will affect the free floating space manipulator greatly[6-7].

A capture operation comprised three phase: the pre-impact phase which the manipulator do not impact the target, the impact phase which the manipulator impact the target in a micro-short time, the post-impact phase which the manipulator capture the target successfully or separate[8].

Many research work of the free floating space manipulator capture operation control focus on the pre-impact phase and post-impact phase in current. And the impact phase operation research works are less. Taira etc introduced the inverse kinematics computer simulation and experimental simulation which base on the generalized Jacobi kinematics matrix[9-10]. Chen Li etc finished too many research works on the dynamic control during the pre-impact phase operation and post-impact phase operation[11-14]. The impact phase during the manipulator capture the target is complex. Yoshida etc introduced the extended inertia tensor concept, and the impact dynamic model derivation is introduced base on the extended inertia tensor concept, the impact phase effect for the space manipulator is calculated base on the impact dynamic model[13]. Yoshikawa etc introduced the method which could estimate the effect of the impact for manipulator base on the Laplace transform theory. Huang etc considered the impact effect base on the impulses of impact theory[7].

The purpose of this paper are to study the effect of impact during a free floating space manipulator capture a target and design a dynamic controller to calm down space manipulator and target compound system after the successful capture. The paper is organized as follows: The dynamic equation derivation of the free floating space manipulator and target. The effect of the impact force for the space manipulator and target are calculated base on the impulse theory. A feedback controller is designed to calm down the manipulator base on the compound dynamic model of the space manipulator and the target. Finally, the computer simulation result and discussion are presented.

2 DYNAMIC MODEL

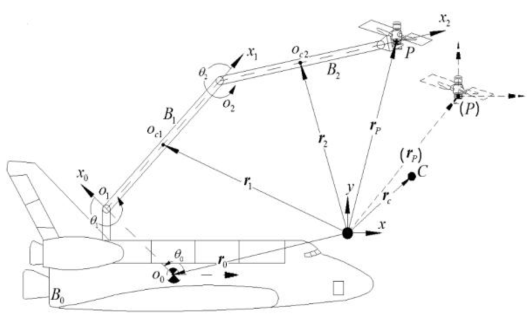

Figure 1: Free-floating flexible space-based robot

The structure of the planar free floating flexible space manipulator is shown in Figure 1. The free floating flexible space manipulator comprises a free floating flexible space shuttle base, series links which connect with the base. The flexible space manipulator and the target are assumed as rigid bodies. $(O-xy)$ is the inertial coordinate, $(O_i - x_i y_i),(i=0,1,2)$ are the coordinates of base, links and the target. $\boldsymbol{O}_0$ is the center of the base, $\boldsymbol{O}_0$, $\boldsymbol{O}_1$, $\boldsymbol{O}_2$ are the joint center of the manipulator, l_0 is the diatance between $\boldsymbol{O}_0$ and $\boldsymbol{O}_1$, $l_i(i=1,2)$ are the length of links.

Let us suppose that object has the mass m_P, the inertial moment $\boldsymbol{I}_P$, the initial movement velocity v_x, v_y, and the initial rotation velocity ω_P. And the space robot is now capturing the object after suitable motion. During the capture operation and impact, the dynamic equations of space robot and object can be written as

$$\boldsymbol{M}\ddot{\boldsymbol{Q}} + \boldsymbol{C} + \boldsymbol{K}\boldsymbol{Q} = \boldsymbol{U} + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{F}_I ,$$

$$\boldsymbol{M}_P\ddot{\boldsymbol{\varphi}} + \boldsymbol{C}_P = -\boldsymbol{J}_P^{\mathrm{T}}\boldsymbol{F}_{\mathrm{I}} \tag{1}$$

where, $\boldsymbol{M}_P \in \Re^{3\times3}$ is the inertia matrix of object, $\boldsymbol{C}_P \in \Re^3$ is the Coriolis and centrifugal forces vector of object. $\boldsymbol{J}$ and $\boldsymbol{J}_P$ are the Jacobian matrix associated with the space robot and the object contact points respectively, $\boldsymbol{F}_I$ represent the vector of forces assiciated with impact.

Combining the above two equations, the impact forces can be eliminated and the following equation can be obtained

$$\boldsymbol{M}'\ddot{Q} + \boldsymbol{C}' + \boldsymbol{K}\boldsymbol{Q} = \boldsymbol{U} \tag{2}$$

where, $\boldsymbol{M}' = \boldsymbol{M} + \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}_{\mathrm{P}}^{\mathrm{T}})^{+}\boldsymbol{M}_{\mathrm{P}}\boldsymbol{J}_{\mathrm{P}}^{+}\boldsymbol{J}$,

$\boldsymbol{C}' = \boldsymbol{C} + \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}_{\mathrm{P}}^{\mathrm{T}})^{+}\boldsymbol{M}_{\mathrm{P}}\boldsymbol{J}_{\mathrm{P}}^{+}(\dot{\boldsymbol{J}} - \dot{\boldsymbol{J}}_{\mathrm{P}}\boldsymbol{J}_{\mathrm{P}}^{+}\boldsymbol{J})\dot{Q} + \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}_{\mathrm{P}}^{\mathrm{T}})^{+}\boldsymbol{C}_{\mathrm{P}}$.

3 BACKSTEPPING ADAPTIVE CONTROL ALGORITHM DESIGN OF FLEXIBLE MANIPULATOR FOR SUPPRESSING UNSTABLE MOTION DUE TO IMPACT EFFECT

The impact effect will cause the unstable motion of the combination system , such as the base movement , rotation , and joint irregular motion that will affect the normal operation of the solar panels and antenna , and damage the joint hinge due to over rotate . Therefore , in order to ensure the combination system normal operation , the applying ot control for suppressing motion is necessary . Based on (1) , a backstepping adaptive control algorithm of flexible space manipulator is designed to suppress the unstable motion of the combination system , and it can be used to under the inertial parameters unknown or uncertain and the base position being uncontrolled .

The coupling interactions between the rigid motions and the flexible modes will reduce the positioning accuracy of space flexible manipulator. Therefore, we need to separate this system into the rigid and the flexible systems before we design a controller for the rigid system. To obtain the rigid system of space flexible manipulator, the equation (2) can be rewritten as

$$\begin{bmatrix} \boldsymbol{M}_{rr}^{'} & \boldsymbol{M}_{rf}^{'} \\ \boldsymbol{M}_{fr}^{'} & \boldsymbol{M}_{ff}^{'} \end{bmatrix}\begin{bmatrix} \ddot{\boldsymbol{q}} \\ \ddot{\boldsymbol{\eta}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{C}_r^{'} \\ \boldsymbol{C}_f^{'} \end{bmatrix} + \begin{bmatrix} 0 \\ \boldsymbol{K}_f\boldsymbol{\eta} \end{bmatrix} = \begin{bmatrix} \boldsymbol{u} \\ 0 \end{bmatrix} \tag{3}$$

where, $\boldsymbol{M}_{rr}^{'} \in \Re^{3\times3}$, $\boldsymbol{M}_{rf}^{'} = \boldsymbol{M}_{fr}^{'\mathrm{T}} \in \Re^{3\times2}$ and $\boldsymbol{M}_{ff}^{'} \in \Re^{2\times2}$ are the sub-matrices of $\boldsymbol{M}^{'}$; $\boldsymbol{K}_f = diag(K_1, K_2)$.

From the equation (3) can obtain a dynamics equation of rigid motion the said system

$$\boldsymbol{M}_{eq}\ddot{\boldsymbol{q}} + \boldsymbol{C}_{eq} = \boldsymbol{u} \tag{4}$$

where, $\boldsymbol{M}_{eq} = \boldsymbol{M}_{rr}^{'} - \boldsymbol{M}_{rf}^{'}\boldsymbol{M}_{ff}^{'-1}\boldsymbol{M}_{fr}^{'}$,

$\boldsymbol{C}_{eq} = \boldsymbol{C}_r^{'} - \boldsymbol{M}_{rf}^{'}\boldsymbol{M}_{ff}^{'-1}(\boldsymbol{C}_f^{'} + \boldsymbol{K}_f\boldsymbol{\eta})$.

Though the control method designed in the equation (4) can control flexible space manipulator to complete rigid motion -- the base's attitude, trajectory tracking of mechanical arm joint motion, but it doesn't inhibit the vibration of flexible pole. So, we'll take the optimal linear quadratic to get virtual control force, and utilize the concept of f virtual control force to structure the mixed desired trajectory which can reflect flexible mode and rigid motion at the same time, and by reforming original control method, we put forward the control strategy based on the virtual control force concept. Thus we may ensure rigid trajectory tracking and initiatively suppress for flexible vibration by only designing one control input.

To employ the virtual control force concept, we need to define errors $\boldsymbol{e}_h = \boldsymbol{q}_d - \boldsymbol{\theta}_h$ between the hybrid trajectory $\boldsymbol{\theta}_h = (x_{0h}, y_{0h}, \theta_{0h} \quad \theta_{1h} \quad \theta_{2h})^{\mathrm{T}}$ to be determined later. Then the hybrid control scheme associated with $\boldsymbol{e}_{\mathrm{h}}$ is suggested as

$$\ddot{\boldsymbol{e}}_h + \boldsymbol{A}\dot{\boldsymbol{e}}_h + \boldsymbol{B}\boldsymbol{e}_h = \boldsymbol{F} \tag{5}$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ are greater than zero scalar constant; $\boldsymbol{F}$ is the virtual control force vector which play a major role in generating the hybrid trajectory $\boldsymbol{\theta}_{\mathrm{h}}$ to stabilize the flexible vibration and maintain the robustness of control developed for rigid coordinated motion in Section 3.1.

The equation $\boldsymbol{e}_r = \boldsymbol{\theta}_h - q$ derivation of time, obtain

$$\dot{\boldsymbol{y}}_1 = \dot{\boldsymbol{\theta}}_h - \boldsymbol{v} \tag{6}$$

where $\boldsymbol{y}_1 = \boldsymbol{e}_r$, $\boldsymbol{v} = \dot{\boldsymbol{q}}$ as a virtual control volume, the following variables according to the inverse regression design method

$$\boldsymbol{y}_2 = \boldsymbol{v} - \boldsymbol{\Lambda}_1\boldsymbol{y}_1 - \dot{\boldsymbol{\theta}}_h \tag{7}$$

where, $\boldsymbol{\Lambda}_1 = diag(\Lambda_{11}, \cdots, \Lambda_{15}) > 0$ is the parameters matrix designed.

Time derivative of The equation

$$\dot{\boldsymbol{y}}_2 = \dot{\boldsymbol{v}} - \boldsymbol{\Lambda}_1\dot{\boldsymbol{y}}_1 - \ddot{\boldsymbol{\theta}}_h = \boldsymbol{M}_{eq}^{-1}(\boldsymbol{u} - \boldsymbol{C}_{eq}) - \boldsymbol{\Lambda}_1\dot{\boldsymbol{y}}_1 - \ddot{\boldsymbol{\theta}}_h \tag{8}$$

So, system control law of system is designed

$$\boldsymbol{u} = \boldsymbol{M}_{eq}(\ddot{\boldsymbol{\theta}}_h + \boldsymbol{\Lambda}_1\dot{\boldsymbol{y}}_1 - \boldsymbol{\Lambda}_2\boldsymbol{y}_2 + \boldsymbol{y}_1 + \boldsymbol{M}_{eq}^{-1}\boldsymbol{C}_{eq}) \tag{9}$$

4 SIMULATIONS

To reveal the impact effect during the capture operation and verify the validity of the colltrol algorithm， a simulation of free-flaoating flexible space manipulator capturing a non-cooperated targets shown in Figure 1 is carried out． The parameters are taken as follows：

$m_0 = 40\mathrm{kg}$ ， $\boldsymbol{l}_0 = 1.5\mathrm{m}$ ， $J_0 = 35\mathrm{kg}\cdot\mathrm{m}^2$ ； $m_1 = 4\mathrm{kg}$ ， $l_1 = 2\mathrm{m}$ ， $a_1 = 1\mathrm{m}$ ， $J_1 = 2\mathrm{kg}\cdot\mathrm{m}^2$ ， $l_2 = 2\mathrm{m}$ ， $\rho = 1\mathrm{kg/m}$ ， $EI = 200\mathrm{N}\cdot\mathrm{m}^2$.

After capturing operation, we hold the assumption that the velocities of object is $\varphi_i = [-1, 1, 0.2]^{\mathrm{T}}$, the end-effector of space manipulator also achieve the contact point. Before capturing operation, it is assumed that the mass and inertial moment of object is unknown, and their initial estimated values are zero.

The desired trajectories of base's attitude and two joint angles are chosen as

$$q_d = [0, 0, 0, 5, 35]^{\mathrm{T}}$$

The initial state of the space robot system is as follows:

$$q_i = [0, 0, 0.1, 5.2, 35.3]^{\mathrm{T}} .$$

where, the unit is in radian. The time taken for simulation is 10.0 seconds.

Figures 2-3 show the simulation results. Figure 2 shows the change curve of the base's position and the arm's joint angles θ_1 、 θ_2 and the first-order vibration mode and the second-order vibration mode when the system is uncontrolled after impact. Figure 3 shows the change curve of when the Control law (9) tracking hybrid trajectory.

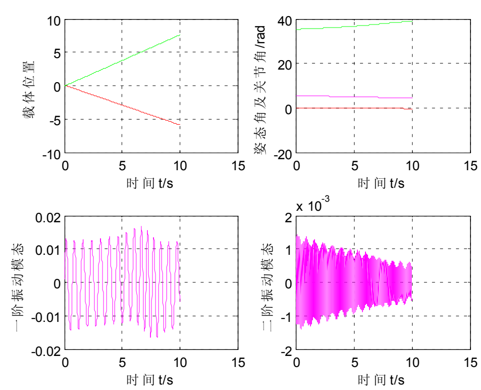

Figure 2: The change curve of system (System is uncontrolled after impact)

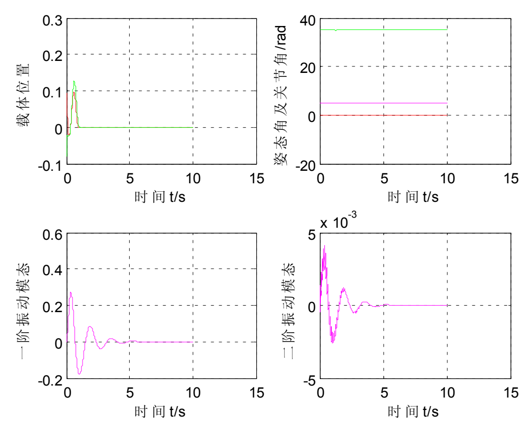

Figure 3: Control law (9) tracking hybrid trajectory

5 CONCLUSION

In this paper the post-impact dynamics of a flexible space robot capturing a non-cooperated targets is modelled and propose the post-impact control of a space robot. The dynamic equations of the system are obtained by Lagrangian formulation. Then the impact dynamics of system is modeling. To simulate the post-impact dynamics, the velocities of base's attitude and each joint after impact are derived from the impact model. Based on the results and considering the uncertain parameters, the backstepping adaptive control algorithm is designed for the free-floating flexible space robot. In particular, it doesn't require measuring the position, velocity nor acceleration of the base because of an effective exploitation of the particular property of the system dynamics during the derivation of the system dynamic model in the post-impact phase. The numerical simulation is carried out, which confirms the controller proposed is feasible and effective.

Acknowledgement

This work was supported by Applied Basic Research Project of Sichuan Province (No. 2016JY0210).

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