Research Article

Inertia Parameter Identification for an Unknown Satellite in Precapture Scenario

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The problem of dynamics and control using a space robot to capture a noncooperative satellite is an important issue for on-orbit services. Inertia parameters of the satellite should be identified before capturing such that the robot can design an active controller to finish the capturing task. In this paper, a new identification scheme is proposed for parameter identification of a noncooperative satellite. In this scheme, the space robot is controlled to contact softly and then maintain contact with the noncooperative target firstly, then the variation of momentum of the target during the contact-maintaining phase is calculated using the control force and torque acting on the base of the space robot and the kinematic information of the space robot, and finally, the momentum-conservation-based identification method is used to estimate inertia parameters of the target. To realize soft contact and then maintain contact, a damping contact controller is designed in this paper, in which a mass-damping system is designed to control the contact between the robot and the target. Soft contact and then contact maintenance can be realized by utilizing the buffering characteristics of the mass-damping system. The effectiveness of the proposed identification scheme is verified through numerical simulations at the end of this paper. Simulation results indicate that the proposed scheme can achieve high-precision identification results.

1. Introduction

The on-orbit service of spacecraft is an important research field in space technology. As the core of on-orbit service, autonomous space operation by a space robot arm plays a significant role in space activities including the capture, docking, repair, and maintenance of space structures on-orbit [1]. As the key step of on-orbit servicing, the capturing operation is the prerequisite of the subsequent servicing operation. In the past decade, many researchers paid attention to this issue and obtained many good studies. For example, Cyril and Jaar [2, 3] analyzed the postcapture dynamics of a spacecraft-manipulator-payload system and compared the controlled and uncontrolled simulation results. Yoshida et al. [4, 5] proposed an impedance match capturing control method based on the conventional impedance control. Zhang and Liu [6–8] carried out a series of studies on the capturing planning problem and designed a new space robotic capture system. Liu et al. [9] proposed a modified

impedance control method for grasping a tumbling target. Although autonomous space operation technology has made great progress, capturing an unknown noncooperative space object is still very challenging. One of the challenges comes from the unknown inertia parameters of the target. For capturing, if the inertia parameters of the target are known, we can employ the advanced model-based control methods to design the controller, which can increase the precision and reliability of space robot operation. Therefore, the need for identifying inertia parameters before capturing arises.

Up to now, many methodologies and strategies on inertia parameter identification of an unknown space target before capturing have been proposed in the literatures, which are mainly divided into passive methods and active methods. For the former, some optical sensors, such as a camera and laser, are employed to measure the kinematic information of the unknown target firstly, and then the optimization methods and Kalman filtering methods are used to estimate its inertia parameters. For example, Hillenbrand and

Lampariello [10] used the camera data to estimate the mass center position and normalized inertia tensor by a nonlinear optimization technique. Aghili and Parsa [11] proposed a computationally efficient noise-adaptive Kalman filter to identify the mass center position and normalized inertia tensor from laser and camera data. Similarly, Linares et al. [12] adopted the unscented Kalman Filter method to estimate the mass-specific inertia matrix from the photometric data. Benninghoff [13] used the least-squares method to estimate the mass center position and normalized inertia tensor of a target from optical sensor data. Tweddle et al. [14] proposed a new simultaneous localization and mapping method for measuring the kinematic information of an unknown object and then identify the inertia parameters by the measurement information. To improve the precision of identification result, Pesce et al. [15] used the extended Kalman filter method and iterated extended Kalman filter method to estimate the normalized inertia tensor of an unknown object from the measurement information obtained by a stereo camera. Different from the passive method, in the active method, the space robot is needed to actively change the motion state of the unknown target firstly, and then the variation of kinematics information of the unknown target is used to identify its inertia parameters. For example, Chu et al. [16] present a contact-based inertia parameter identification method. In this method, the rigid tip of the space robot is controlled to contact the unknown object firstly, and then the contact force and the variation of kinematics information are used to estimate all inertia parameters including mass, mass center position, and inertia tensor. Similarly, Christidi-Loumpasefski and Papadopoulos [17] and Wei et al. [18] also proposed to use the rigid part of the space robot to change the motion state of the unknown object and then identify all inertia parameters of an unknown object. Different from the work mentioned above, Meng et al. [19] proposed to use a flexible rod to change a target movement and utilize the variation of the target movement and the control torque exerted on the space robot to identify all the inertial parameters of a noncooperative object. Besides the contact approach, Xu and Wang [20] propose a new approach to change the motion state of the unknown target, in which the spacecraft shoots the unknown object with a bullet. By assuming that the moment of the bullet is completely absorbed by the target object, the variation of angular momentum can be calculated. On this basis, the non-normalized inertia can be identified.

As mentioned above, the advantage of passive methods is that there is no interaction between the space robot and the unknown object. This reduces the control difficulty of space robots and makes the identification process safer. However, the disadvantage is that the object mass and the real inertia tensor cannot be estimated. Thus, the estimation result of passive methods cannot be used to design the capturing controller. In contrast, the active methods can identify all the inertial parameters of an unknown. However, the shortage of active methods is that the space robot needs to contact the unknown target. Considering that the end effector is rigid, the contact will yield a big impact on the space robot and the target, which will threaten their safety. Meanwhile,

the contact may cause the movement of the target to become more complex. Accordingly, the difficulty of the grasping operation will be raised. Although using a flexible rod to contact the target can reduce the contact impact, the space robot needs to equip an auxiliary device, which affects other on-orbit operations, such as grasping and repairing. So using the end effector to change the target's movement is still a simpler manner in engineering. However, it is needed to develop a suitable contact control method to avoid yielding a big contact impact and to acquire a wealth of identification information. It is a pity that the contact control problem is not considered in the literatures. Therefore, the inertia parameter identification needs to be studied in depth.

In this paper, a new identification scheme is presented. In this scheme, the space robot is controlled to actively change the motion state of a noncooperative unknown satellite by contact firstly and then to gather the variation of the target momentum. Finally, the momentum-conservation-based method is used to identify all the inertia parameters of the target. To obtain the variation of the target momentum without the contact force information, it is necessary to change the space robot and the target needs to a new combination and then use the control force and torque acting on the base of the space robot and the kinematic information of space robot to calculate the variation of the target momentum. Thus, the space robot needs to be controlled to contact and then maintain contact with the target. Meanwhile, to avoid the sharp change of the motion state of the target, the soft contact between the space robot and the target needs to be realized. For achieving these two control goals, a new damping contact control method is designed based on the study about the two ball collision problem. By this method, the space robot can be converted to a mass-damping system. Utilizing the buffer characteristics of the mass-damping system for the collision, the space robot can contact the target softly and then maintain the contact. Comparing with the identification schemes [8–10], this proposal can obtain the variation of the kinematics of the space robot without the contact force information. This can improve the identification precision since the control force and torque are more easily measured than the contact force and the precision of the former is higher. Besides, comparing with the identification scheme in Ref. [11], our proposal does not need an auxiliary flexible device, which can leave more space for other important devices. In the simulation section, the validity of the proposed method is demonstrated by the simulations of grasping a noncooperative satellite.

This paper is organized as follows. Section 2 briefly presents the expressions of a dynamic equation of the space robot and the contact model between the robot and the unknown space object. The contact control method is present in Section 3. The identification method is given in Section 4. Section 5 provides numerical simulations. Finally, a concluding remark is given in Section 6.

2. System Dynamics Modelling

2.1. Dynamics of Space Robot. In this paper, a simplified rigid space robot and a noncooperative object, shown in Figure 1,

FIGURE 1: Space robot and the noncooperative satellite to be captured: (a) the total diagram of the system; (b) enlarged drawing of the end effector and the target satellite.

are used to study the inertia parameter identification issue. The space robot is composed of a spacecraft base (body B_1), a 6 DOF robot arm that includes four rigid links (bodies B_2 - B_5), and an end effector (bodies B_6 and B_7). The end effector is a gripper having four fingers. The unknown noncooperative satellite is denoted by the body B_U . The frame O - XYZ is the inertial reference frame.

From Jourdain's velocity variation principle, the dynamic equation of the space robot system can be expressed as [21]

$$\sum_{i=1}^n \Delta \mathbf{v}_i^T (-\mathbf{M}_i \dot{\mathbf{v}}_i - \mathbf{f}_i^w + \mathbf{f}_i^v) + \Delta P = 0, \quad (1)$$

where $\mathbf{v}_i$ denotes the velocity of the i -th body composed of the translational velocity and angular velocity, $\mathbf{M}_i$ is the mass matrix of the i -th body, $\mathbf{f}_i^w$ is the velocity-dependent inertia force of the i -th body, $\mathbf{f}_i^v$ is the external force of the system acting on the i -th body that refers to the contact force in this paper, and ΔP is the sum of the virtual power of the inner forces of system. The robot system shown in Figure 1 is composed of seven bodies, so $n = 7$ in Equation (1). (It should be noted that the bold font of a symbol denotes the coordinate

vector or matrix in this paper, such as $\mathbf{v}$ is the coordinate vector of $\vec{v}$.)

In matrix form, Equation (1) can be written as

$$\Delta \mathbf{v}^T (-\mathbf{M} \dot{\mathbf{v}} - \mathbf{f}^w + \mathbf{f}^v) + \Delta P = 0, \quad (2)$$

where $\mathbf{v} = [\mathbf{v}_1^T, \dots, \mathbf{v}_n^T]^T$ is the configuration velocity of system, $\mathbf{M} = \text{diag} [M_1, \dots, M_n]$ is the mass matrix, and $\mathbf{f}^w = [\mathbf{f}_1^{wT}, \dots, \mathbf{f}_n^{wT}]^T$ and $\mathbf{f}^v = [\mathbf{f}_1^{vT}, \dots, \mathbf{f}_n^{vT}]^T$ are the velocity-dependent inertia force vector and the external force vector, respectively.

Based on the recursive construction method, the velocity and acceleration of the robot system can be expressed as [21]

$$\mathbf{v} = \mathbf{G} \dot{\mathbf{y}}, \quad \dot{\mathbf{v}} = \mathbf{G} \ddot{\mathbf{y}} + \mathbf{g} \mathbf{1}_N, \quad (3)$$

where $\mathbf{y} = [\mathbf{y}_{\text{base}}; \varphi_{\text{arm}}; \varphi_{\text{gripper}}] \in \mathcal{R}^{14 \times 1}$ is the independent generalized coordinate vector of the robot system, in which $\mathbf{y}_{\text{base}} \in \mathcal{R}^{6 \times 1}$ is the generalized coordinates of the space robot base, $\varphi_{\text{arm}} \in \mathcal{R}^{6 \times 1}$ is the joint coordinates of the robot arm, and $\varphi_{\text{gripper}} \in \mathcal{R}^{2 \times 1}$ is the joint coordinates of the end effector. The expressions of $\mathbf{G}$ and $\mathbf{g}$ can be found in Ref. [13].

Using Equation (3), Equation (2) can be written as

$$\Delta \dot{\mathbf{y}}^T [-\mathbf{Z}\ddot{\mathbf{y}} - \mathbf{z} + \mathbf{h} + \mathbf{f}^y] = 0, \quad (4)$$

where $\mathbf{Z} = \mathbf{G}^T \mathbf{M} \mathbf{G}$, $\mathbf{z} = \mathbf{G}(\mathbf{f} + \mathbf{M} \mathbf{g} \mathbf{1}_N)$, $\mathbf{h} = \mathbf{G}^T \mathbf{f}^o$, and $\mathbf{f}^y$ is the vector of the generalized force of the system.

Since all the elements of $\mathbf{y}$ are independent, Equation (4) becomes

$$-\mathbf{Z}\ddot{\mathbf{y}} - \mathbf{z} + \mathbf{h} + \mathbf{f}^y = 0. \quad (5)$$

This formula is the dynamic equation of the space robot system. We have now established the dynamic model for this system; for details, please see Ref. [21].

2.2. Contact Dynamics Model. There are two mainstream methods to simulate the collision phenomenon. The first is the momentum-based method, in which the impact impulse is used to calculate the dynamic behaviors of two contact bodies. Accordingly, the contact process is discontinuous, which can be divided into two phases: precontact and post-contact. The other method is the force-based method, in which the contact force is used to calculate the dynamic behaviors of two contact bodies. Accordingly, the contact process is continuous. In contrast to the first method, the second one can get a description of the real contact behavior. In this paper, a nonlinear contact model combining Hertz's model and a nonlinear damping item is used to describe the contact force, which is first proposed by Hunt and Crossley in 1975 [22] and used in many studies, such as Ref. [22]. Different from the classical Hertz's model [23] that is used to describe the static contact force, the Ref. [21] model can consider the effect of the relative velocity of the collision bodies on the contact force by introducing a nonlinear damping item. When the relative velocity is zero, Ref. [1]'s model will become Hertz's model. It can be said that Ref. [21]'s model can describe the contact force during collision more accurately than Hertz's model. Considering the relative velocity of the robot end effector and the target is not zero, employing Ref. [1]'s model to calculate the contact force is more reasonable. According to Ref. [21]'s model, the contact force during a collision can be expressed as [21, 22]

$$F_c = k_c d^e + c_c \dot{d}, \quad (6)$$

in which k_c and c_c are the contact stiffness and damping determined by material properties of the two contact objects, respectively, d is the penetration depth, and the superscript e is the contact exponent whose value is taken as 1.5 usually [23].

3. Contact Control

Contact control problem is a classical control in the robot field. There are many control methods proposed [4, 5, 24–26]. In these methods, the robot is controlled like a mass-spring-damping system for realizing hybrid force/position control when a robot arm contacts with a static target that will not change the motion state after contact. In the identi-

FIGURE 2: Schematic diagram of the contact of two objects.

fying task, however, the target is a dynamic object that will change the motion state after contact. Thus, the conventional control method is not suitable for dealing with the contact control during identification. For the identification problem, the contact control method is needed to realize two control goals: soft contact and maintaining contact. The soft contact means minimizing the effect of collision, that is, the movement changes of the target and the space robot are small after collision. The maintaining contact means that the space robot and the target will not separate after a collision. This will help to calculate the variation of the target momentum using the control force and torque acting on the base of the space robot and the kinematic information of the space robot. To realize the above two control goals, a new contact control method is proposed in this section, which is organized as follows: the inspiration of the proposed method is given firstly, and then its designing process is presented in detail.

3.1. Effect of Spring-Damping on Collision. It is no doubt that the mass-spring-damping system can reduce the impact caused by collision, but it is not sure that it can realize soft contact and maintaining contact. To answer this problem, we take the classic two ball collision problem, as shown in Figure 2, to study the effect of spring-damping on collision. In Figure 2, the balls S_1 and S_2 refer to the last link of the space robot and the target satellite, respectively. Both balls have high stiffness. Considering the mass ratio of the last link of the space robot and the target satellite, the masses of the balls S_1 and S_2 are selected as 10 kg and 1000 kg in all of the simulations, respectively. The contact stiffness and damping of impact are selected as 1×10^8 N/m and 100 N/(m/sec), respectively. In the first simulation, the stiffness and damping of the spring-damping are considered as 1×10^6 N/m and 100 N/(m/sec), respectively. Before contact, S_1 is at rest and S_2 is moving to S_1 at 0.1 m/s. The simulation results are shown in Figure 3, which depicts the distance curve and the relative speed curve between S_1 and S_2 , respectively. As can be seen from Figure 3(a), the distance between S_1 and S_2 grows after maintaining a short period. In Figure 3(b), the speed of S_2 is kept constant after increasing a short period. And the speed curve of S_1 has a significant oscillation, especially during the beginning of the simulation. This illustrates that the contact between S_1 and S_2 occurs many times in the beginning, and then they completely separate from each other due to the contact force. Change the stiffness of spring-damping and conduct the same simulation. The results obtained with three different stiffness values (1×10^5 , 1×10^4 , and 0) and the same damping value are shown in Figures 4–6, respectively. According to Figures 4–6, we can get that when the stiffness is not zero, the results in Figures 4 and 5 are similar with the first simulation case shown in Figure 3. But when the stiffness is zero, it can be observed from

FIGURE 3: Dynamic response of two contact objects (stiffness = 1×10^6 , damping = 100): (a) relative distance of S_1 and S_2 ; (b) relative velocity of S_1 and S_2 .

FIGURE 4: Dynamic response of two contact objects (stiffness = 1×10^5 , damping = 100): (a) relative distance of S_1 and S_2 ; (b) relative velocity of S_1 and S_2 .

FIGURE 5: Dynamic response of two contact objects (stiffness = 1×10^4 , damping = 10): (a) relative distance of S_1 and S_2 ; (b) relative velocity of S_1 and S_2 .

Figure 6 that the separation of S_1 and S_2 is prevented after several times of contact, and the change of the speed of S_2 is slow. This indicates that the mass-spring-damping system is effective to realize soft contact and maintain contact only when the spring stiffness is taken to be zero. To validate this conclusion, consider that the stiffness is zero and only the damping is changed; the simulation results are given in Figures 7 and 8. It could be observed that the separation of S_1 and S_2 still is prevented for different damping values. Moreover, the time spent for eliminating the relative speed of S_1 and S_2 is shortened with the increase of the damping value. This demonstrates that the

mass-damping system can control the contact behavior but the mass-spring-damping system cannot.

3.2. Contact Control Strategy Design. From the study in Section 3.1, we know that the mass-damping system can realize soft contact and maintaining contact. However, the mechanism why the mass-damping system can do that is not given. Below, we will explain this mechanism, and then a new damping contact control method is given based on it.

In the simulations of Section 3.1, we know that the mass of S_2 is bigger than that of S_1 , S_2 moves to S_1 , and S_1 is at rest

FIGURE 6: Dynamic response of two contact objects (stiffness = 0, damping = 100): (a) relative distance of S_1 and S_2 ; (b) relative velocity of S_1 and S_2 .

FIGURE 7: Dynamic response of two contact objects (stiffness = 0, damping = 500): (a) relative distance of S_1 and S_2 ; (b) relative velocity of S_1 and S_2 .

FIGURE 8: Dynamic response of two contact objects (stiffness = 0, damping = 1000): (a) relative distance of S_1 and S_2 ; (b) relative velocity of S_1 and S_2 .

at the beginning of all the simulations. From the classical collision theory, when the contact stiffness is high, the velocity of S_2 will be reduced and S_1 will get a velocity moving away from S_2 that is bigger than the one of S_1 after the first contact. Then, the damping force acting on S_1 will slow down the velocity of S_1 , and finally, S_2 will catch up with S_1 and make contact with it. After that, the velocity of S_2 will be also reduced, and S_1 will again get a new velocity that is bigger than the velocity of S_2 . The following process is the same as the first contact case. After multiple times of collision, under

the action of damping force, S_1 and S_2 will get the same velocity and their contact will be maintained. The whole process is shown obviously in Figure 6. Considering that during the collision the contact force is much bigger than the damping force of the mass-damping system on S_1 and the contact duration is very short, the damping force can be ignored. This means that we can achieve our control goal without controlling the dynamic behavior during the contact process. Therefore, only using the kinematic response of the space robot as the control feedback, the tip of the robot will be

FIGURE 9: Control system block diagram.

FIGURE 10: Topology structure of space robot system.

controlled like a mass-damping system after contact. As a result, the soft contact and the maintaining contact between the end effector and the target satellite will be realized.

From the above analysis, it can be known that only one motion controller can realize the contact control goal. Based on this conclusion, we present a new damping contact control method for identifying all of the inertia parameters of an unknown uncooperative satellite. In this method, the mass-spring-damping system of the conventional impedance method is substituted by the mass-damping system, given by

$$\mathbf{M}^e \ddot{\mathbf{x}}^e + \mathbf{C}^e \dot{\mathbf{x}}^e = 0, \quad (7)$$

where $\mathbf{x}^e$ is the pose coordinate vector of the tip of the space robot, $\mathbf{M}^e$ is the equivalent mass matrix, and $\mathbf{C}^e$ is the equivalent damping matrix.

During contact control, $\mathbf{x}^e$ and $\dot{\mathbf{x}}^e$ are chosen as the feedback information, which can be calculated by the following equation:

$$\mathbf{x}^e = \mathbf{T}_{\text{tip}} \mathbf{y}, \quad \dot{\mathbf{x}}^e = \mathbf{G}_{\text{tip}} \dot{\mathbf{y}}, \quad (8)$$

where $\mathbf{T}_{\text{tip}}$ is the position and attitude transfer matrix [21] and $\mathbf{G}_{\text{tip}}$ is the velocity transfer matrix. By substituting the two terms into the dynamic equation of the mass-damping system (Equation (7)) and solving it, the dynamic response of $\mathbf{x}_t^e$, $\dot{\mathbf{x}}_t^e$, and $\ddot{\mathbf{x}}_t^e$ at the next sampling moment could be obtained. Using them as the desired motion of the tip of the robot arm and controlling the position and attitude of unchanged space robot, the desired joint states φ_d , $\dot{\varphi}_d$, and $\ddot{\varphi}_d$ of the space robot

could be obtained easily through inverse kinematics. Accordingly, the desired states of space robot are

$$\mathbf{y}_d = [0; \varphi_d], \quad \dot{\mathbf{y}}_d = [0; \dot{\varphi}_d], \quad \ddot{\mathbf{y}}_d = [0; \ddot{\varphi}_d]. \quad (9)$$

Substituting $\mathbf{y}_d$, $\dot{\mathbf{y}}_d$, and $\ddot{\mathbf{y}}_d$ into a motion tracking controller, the tip of the robot arm will be controlled like a mass-damping system. The control system block diagram is shown in Figure 9, where $\mathbf{u}$ is the control torque vector whose calculation process will be given in the following section.

In this paper, the computed torque method is employed to design the motion controller.

4. Identification Method

In this section, the momentum of conservation-based identification method is used to estimate all inertia parameters of an unknown object. As shown in Figure 10, when the contact between the space robot and the unknown satellite is held, they will conduct a new multibody system. The linear momentum and angular momentum of the system can be expressed as

$$\mathbf{P} = \sum_{i=1}^n \mathbf{P}_i + \mathbf{P}_U, \quad \mathbf{L} = \sum_{i=1}^n \mathbf{L}_i + \mathbf{L}_U, \quad (10)$$

$$\mathbf{L} = \sum_{i=1}^n \mathbf{L}_i + \mathbf{L}_U = \sum_{i=1}^n \mathbf{L}_i + \mathbf{J}_{O_U} \omega_U + m_U \rho_{C_U} \times \dot{\mathbf{r}}_{O_U}, \quad (11)$$

where $\mathbf{P}_i$ and $\mathbf{L}_i$ are the linear momentum and angular momentum of the body B_i , respectively; $\mathbf{P}_U$ and $\mathbf{L}_U$ are the

linear momentum and angular momentum of the body B_U

$$\mathbf{P}_U = m_U (\dot{\mathbf{r}}_{O_U} + \boldsymbol{\omega}_U \times \boldsymbol{\rho}_{C_U}), \quad (12)$$

$$\mathbf{L}_U = \mathbf{J}_{O_U} \boldsymbol{\omega}_U + m_U \boldsymbol{\rho}_{C_U} \times \dot{\mathbf{r}}_{O_U}, \quad (13)$$

where m_U is the mass of body B_U ; $\dot{\mathbf{r}}_i$ and $\boldsymbol{\omega}_i$ are the linear velocity and the angular velocity of B_i , respectively; $\mathbf{J}_{O_U}$ is the inertia tensor of the body B_U about the point O_U ; $\mathbf{r}_{O_U}$ and $\boldsymbol{\rho}_{C_U}$ are the absolute position of point O_U and the relative position between O_U and the mass center C_U , respectively; and $\boldsymbol{\omega}_U$ is the angular velocity of B_U . In the frame Σ_{O_U} , $\mathbf{J}_{C_U}$ and $\boldsymbol{\rho}_{C_U}$ can be written as

$$\mathbf{J}_{C_U} = \mathbf{A}_U \mathbf{J}_{C_U}' \mathbf{A}_U^T, \boldsymbol{\rho}_{C_U} = \mathbf{A}_U \boldsymbol{\rho}_{C_U}', \quad (14)$$

where $\mathbf{A}_U$ is the direction cosine matrix of the frame Σ_{O_U} with respect to the frame Σ_O , $\mathbf{J}_{C_U}'$ is the inertia tensor of B_U in the frame Σ_{O_U} , and $\boldsymbol{\rho}_{C_U}'$ is the position of the mass center C_U of B_U in the frame Σ_{O_U} . Substituting Equation (14) into Equations (12) and (13), the following equations are obtained:

$$\mathbf{P}_U = m_U (\dot{\mathbf{r}}_{O_U} + \tilde{\boldsymbol{\omega}}_U \mathbf{A}_U \boldsymbol{\rho}_{C_U}'), \quad (15)$$

$$\mathbf{L}_U = \mathbf{A}_U \mathbf{J}_{O_U}' \boldsymbol{\omega}_U' - \tilde{\mathbf{r}}_{O_U} \mathbf{A}_U m_U \boldsymbol{\rho}_{C_U}'. \quad (16)$$

Linearizing the above equations, we can get

$$\mathbf{P}_U = [\dot{\mathbf{r}}_{O_U} \tilde{\boldsymbol{\omega}}_U \mathbf{A}_U] \begin{bmatrix} m_U \\ m_U \boldsymbol{\rho}_{C_U}'^x \\ m_U \boldsymbol{\rho}_{C_U}'^y \\ m_U \boldsymbol{\rho}_{C_U}'^z \end{bmatrix}, \quad (17)$$

$$\mathbf{L}_U = \begin{bmatrix} -\tilde{\mathbf{r}}_{O_U} \mathbf{A}_U & \mathbf{A}_U \{\boldsymbol{\omega}_U'\} \end{bmatrix} \begin{bmatrix} m_U \boldsymbol{\rho}_{C_U}'^x \\ m_U \boldsymbol{\rho}_{C_U}'^y \\ m_U \boldsymbol{\rho}_{C_U}'^z \\ J_{O_U}'^{xx} \\ J_{O_U}'^{xy} \\ J_{O_U}'^{xz} \\ J_{O_U}^{yy} \\ J_{O_U}^{yz} \\ J_{O_U}^{zz} \end{bmatrix}, \quad (18)$$

TABLE 1: Inertia parameters of the space robot.

Body	Mass (kg)	J_{xx}' (kg·m ²)	J_{yy}' (kg·m ²)	J_{zz}' (kg·m ²)
B_1	2740	456	456	456
B_2	3.5	6.04e-4	4.6e-2	4.6e-2
B_3	3.5	6.04e-4	4.6e-2	4.6e-2
B_4	3	3.5e-4	3e-2	3e-2
B_5	2	3e-4	2.5e-2	2.5e-2
B_6	1.3	1.41e-2	8.8e-3	7.9e-3
B_7	1.3	1.41e-2	8.8e-3	7.9e-3

where

$$\{\boldsymbol{\omega}_U'\} = \begin{bmatrix} \boldsymbol{\omega}_U'^x & \boldsymbol{\omega}_U'^y & \boldsymbol{\omega}_U'^z & 0 & 0 & 0 \\ 0 & \boldsymbol{\omega}_{U_x}'^x & 0 & \boldsymbol{\omega}_U'^y & \boldsymbol{\omega}_U'^z & 0 \\ 0 & 0 & \boldsymbol{\omega}_U'^x & 0 & \boldsymbol{\omega}_U'^y & \boldsymbol{\omega}_U'^z \end{bmatrix}. \quad (19)$$

In the above equation and throughout the text, the symbol “ $\sim$ ” denotes a skew symmetric matrix, such as

$$\tilde{\mathbf{a}} = -\tilde{\mathbf{a}}^T = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & a_1 \\ -a_2 & a_1 & 0 \end{bmatrix}, \mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}. \quad (20)$$

Considering that during maintaining contact, the space robot is controlled, from momentum conservation, we have

$$\Delta \mathbf{P}_U = \Delta \mathbf{P} - \Delta \sum_{i=1}^n \mathbf{P}_i = \int_{t_0}^{t_0+\Delta t} \mathbf{F}(t) dt - \Delta \sum_{i=1}^n \mathbf{P}_i, \quad (21)$$

$$\Delta L_U = \Delta L - \Delta \sum_{i=1}^n L_i = \int_{t_0}^{t_0+\Delta t} \mathbf{T}(t) dt - \Delta \sum_{i=1}^n L_i. \quad (22)$$

Substituting Equations (17) and (18) into the above equations yields

$$[\Delta \dot{\mathbf{r}}_{O_U} \quad \Delta(\tilde{\boldsymbol{\omega}}_U \mathbf{A}_U)] \begin{bmatrix} m_U \\ m_U \boldsymbol{\rho}_{C_U}'^x \\ m_U \boldsymbol{\rho}_{C_U}'^y \\ m_U \boldsymbol{\rho}_{C_U}'^z \end{bmatrix} = \int_{t_0}^{t_0+\Delta t} \mathbf{F}(t) dt - \sum_{i=1}^n \Delta \mathbf{P}_i, \quad (23)$$

FIGURE 11: Initial configuration of space robot and noncooperative satellite: (a) whole system; (b) end effector.

TABLE 2: Inertia parameters of the unknown satellite.

m_U (kg)	$\rho'^x_{C_U}$ (m)	$\rho'^y_{C_U}$ (m)	$\rho'^z_{C_U}$ (m)	$J'^{xx}_{O_U}$ (kg·m ²)	$J'^{xy}_{O_U}$ (kg·m ²)	$J'^{yx}_{O_U}$ (kg·m ²)	$J'^{yy}_{O_U}$ (kg·m ²)	$J'^{yz}_{O_U}$ (kg·m ²)	$J'^{zz}_{O_U}$ (kg·m ²)
1000	-0.5	0.5	0.5	650	250	250	650	-250	650

$$\begin{bmatrix} \Delta(-\tilde{\mathbf{r}}_{O_U} \mathbf{A}_U) & \Delta(\mathbf{A}_U [\omega'_U]^+) \end{bmatrix} \begin{bmatrix} m_U \rho'^x_{C_U} \\ m_U \rho'^y_{C_U} \\ m_U \rho'^z_{C_U} \\ J'^{xx}_{O_U} \\ J'^{xy}_{O_U} \\ J'^{yz}_{O_U} \\ J'^{yy}_{O_U} \\ J'^{yz}_{O_U} \\ J'^{zz}_{O_U} \end{bmatrix} = \int_{t_0}^{t_0+\Delta t} \mathbf{T}(t) dt - \sum_{i=1}^n \Delta \mathbf{L}_i. \quad (24)$$

Merging Equations (23) and (24) yields

$$\begin{bmatrix} \Delta \tilde{\mathbf{r}}_{O_U} & \Delta(\tilde{\omega}_U \mathbf{A}_U) & 0_{3 \times 6} \\ 0_{1 \times 3} & \Delta(-\tilde{\mathbf{r}}_{O_U} \mathbf{A}_U) & \Delta(\mathbf{A}_U \{\omega'_U\}) \end{bmatrix} \mathbf{I}_U = \begin{bmatrix} \int_{t_0}^{t_0+\Delta t} \mathbf{F}(t) dt - \sum_{i=1}^n \Delta \mathbf{P}_i \\ \int_{t_0}^{t_0+\Delta t} \mathbf{T}(t) dt - \sum_{i=1}^n \Delta \mathbf{L}_i \end{bmatrix}, \quad (25)$$

where $\mathbf{I}_U = [m_U, m_U \rho'^x_{C_U}, m_U \rho'^y_{C_U}, m_U \rho'^z_{C_U}, J'^{xx}_{O_U}, J'^{xy}_{O_U}, J'^{xz}_{O_U}, J'^{yy}_{O_U}, J'^{yz}_{O_U}, J'^{zz}_{O_U}]$ includes all inertia parameters of B_U . In

the above equation, the right-hand side and all elements of the first matrix on the left-hand side can be calculated from measurements. However, since its dimensions are smaller than the dimensions of inertia parameter vector $\mathbf{I}_U$, multisets of measurements are needed for identification [27].

5. Numerical Simulations

In this section, numerical simulations are carried out to demonstrate the validity of the proposed identification scheme. During simulations, the space robot system considered is a typical 6DOF space robot shown in Figure 1, where the body B_1 is the spacecraft, the bodies B_2 – B_5 are the manipulator's arms, B_6 and B_7 are the end effectors who are fixed during identification, and the body B_U is the unknown target. The inertia parameters of the bodies B_1 – B_7 in their body-fixed frames Σ_{C_1} – Σ_{C_7} are given in Table 1. The origins of body-fixed frames Σ_{C_1} – Σ_{C_7} are the mass centers of the bodies B_1 – B_7 . The mass parameters of the space robot are listed in Table 1, and the mass centers of robot parts are all $[0, 0, 0]$.

5.1. Control Method Effectiveness Evaluation. To verify the effectiveness of the presented controller, two simulations are performed. In these two simulations, we assume that

FIGURE 12: Initial configuration of space robot and noncooperative satellite.

FIGURE 13: Attitude of the target satellite during identification: (a) X axis, (b) Y axis, and (c) Z axis.

FIGURE 14: Angular velocity of the target satellite during identification: (a) X axis, (b) Y axis, and (c) Z axis.

FIGURE 15: Position of the point O_U during identification: (a) X axis, (b) Y axis, and (c) Z axis.

FIGURE 16: Linear velocity of the point O_U during identification: (a) X axis, (b) Y axis, and (c) Z axis.

the unknown satellite B_U is a cube depicted in Figure 11, whose side length is 1 m. The mass center of B_U is at its geometric center. Its body-fixed frame Σ_{O_U} is established at the vertex O_U of the cube. The contact stiffness and damping are 1×10^8 N/m and 100 N/(m/sec), respectively. The unknown inertia parameters of B_U are listed in Table 2. In the first simulations, the space robot is controlled through the presented control method with stiffness item. In the second one, the space robot is controlled without the stiffness item. At the beginning of all simulations, the configuration of the space robot and unknown satellite is considered as shown in Figure 11. Moreover, the space robot is at rest and the target satellite is moving to the space robot at -0.1 m/s along the Y axis, and its angular velocity is 0.15 rad/s, 0.04 rad/s, and 0.04 rad/s. For the closed loop control, the equivalent matrix M_e (in Equation (16)) is considered equal to the real mass matrix of B_5 . The equivalent damping in Equation (16) is selected as 100, and K_p and K_D in the computed torque controller are chosen as $200 \times I_{12 \times 12}$ and $20 \times I_{12 \times 12}$, respectively. For the closed loop control with equivalent stiffness, this item is 100000. The results of the two simulations are depicted in Figures 12–17, where Figure 12 shows the time histories of the distance from the tips of the end effectors, shown in Figure 1, to the target, Figures 13 and 14 plot the time histories of the attitude and angular velocity of the target, Figures 15 and 16 show the time histories of the position and the linear velocity of the

point O_U , and Figure 17 depicts the time histories of the control forces and torques on the base of the space robot. As could be seen from Figure 12, when the controller has the stiffness item, the distance between the tips of the space robot and the target is oscillating all the time, which illustrates that the collision between the space robot and the target occurs many times. However, when the controller does not have the stiffness item, the distance between the tips of the space robot and the target is kept less than 0 after several oscillation times. This demonstrates that the proposed control method is effective for maintaining contact between the space robot and the target. Observing Figures 13–16, we can get that when the controller does not have the stiffness item, the change of the target motion is smaller. This illustrates that the proposed control method can decrease the collision impact on the target, that is, the proposal can realize soft contact. As can be seen from Figure 17, when the controller does not have the stiffness item, the control forces and torques on the base of the space robot are smaller, and their change is slower. This illustrates that the proposed control method is realized more easily in engineering.

5.2. Case Study and Simulation Results. To validate the identification scheme, the space robot will be controlled to contact three unknown targets and identify their inertia parameters in this section, which have different inertia parameters and motion states. This information of the

FIGURE 17: Control force and torque on the base of the space robot: (a) force in X axis, (b) force in Y axis, (c) force in Z axis, (d) torque about X axis, (e) torque about Y axis, and (f) torque about Z axis.

TABLE 3: Inertia parameters of the unknown targets.

No.	m_U (kg)	$\rho'_{C_U}{}^x$ (m)	$\rho'_{C_U}{}^y$ (m)	$\rho'_{C_U}{}^z$ (m)	$J'_{O_U}{}^{xx}$ (kg·m ²)	$J'_{O_U}{}^{xy}$ (kg·m ²)	$J'_{O_U}{}^{yx}$ (kg·m ²)	$J'_{O_U}{}^{yy}$ (kg·m ²)	$J'_{O_U}{}^{yz}$ (kg·m ²)	$J'_{O_U}{}^{zz}$ (kg·m ²)
1	500	-0.4	0.5	0.5	325	125	125	325	-125	325
2	1000	-0.5	0.5	0.5	650	250	250	650	-250	650
3	5000	-0.5	0.5	0.6	3250	1250	1250	3250	-1250	3250

unknown targets is listed in Tables 3 and 4. The dynamic responses of the three targets during contact are plotted in Figures 18–21. The control forces and torques on the base of the space robot are depicted in Figure 22. During simulations, the control parameters are the same with the settings in Section 5.1. Substituting the simulation results into

TABLE 4: Kinematics information of the unknown targets.

No.	v_x	v_y	v_z	ω_x	ω_y	ω_z
1	-0.2	0	0	0.05	0.2	0.03
2	-0.1	0	0	0.15	0.04	0.04
3	-0.1	0	0	0.15	-0.03	0.04

FIGURE 18: Attitude of the target satellite during identification: (a) X axis, (b) Y axis, and (c) Z axis.

FIGURE 19: Angular velocity of the target satellite during identification: (a) X axis, (b) Y axis, and (c) Z axis.

FIGURE 20: Position of the point O_U during identification: (a) X axis, (b) Y axis, and (c) Z axis. FIGURE 21: Linear velocity of the point O_U during identification: (a) X axis, (b) Y axis, and (c) Z axis.

FIGURE 22: Control force and torque on the base of the space robot: (a) force in X axis, (b) force in Y axis, (c) force in Z axis, (d) torque about X axis, (e) torque about Y axis, and (f) torque about Z axis.

Equation (25) and solving it by the least-squares optimization method, the identification results can be obtained, which are listed in Table 5. As can be seen from Table 5, it can be observed that the proposed scheme is effective for obtaining high-precision identification results.

6. Conclusion

In this paper, the inertia parameter identification issue in the precapture scenario is studied. To obtain a high-precision

identification result, we proposed to use the variation of the target momentum to identify the inertia parameters of a non-cooperative space target. To obtain the variation of the target momentum, a new damping control method is presented. By this method, the space robot and the target can be changed from two individual objects to a combination. Using the control force and torque acting on the base of the space robot and the kinematic information of the space robot, we can get the variation of the target momentum based on the momentum conservation. The simulation results not only

TABLE 5: Inertia parameters of the unknown targets.

No.		m_U (kg)	$\rho_{C_U}^{ix}$ (m)	$\rho_{C_U}^{iy}$ (m)	$\rho_{C_U}^{iz}$ (m)	$J_{O_U}^{ixx}$ (kg·m ²)	$J_{O_U}^{ixy}$ (kg·m ²)	$J_{O_U}^{ixy}$ (kg·m ²)	$J_{O_U}^{iyy}$ (kg·m ²)	$J_{O_U}^{iyz}$ (kg·m ²)	$J_{O_U}^{izz}$ (kg·m ²)
1	Real value	500	-0.4	0.5	0.5	325	125	125	325	-125	325
	Estimation	500.052	-0.39995	0.50009	0.50008	324.9415	125.0188	124.9900	324.9568	-125.02	325.0585
	Error rate	0.0104%	0.0125%	0.018%	0.0161%	0.0182%	0.0153%	0.0082%	0.0133%	0.0167%	0.0182%
2	Real value	1000	-0.5	0.5	0.5	650	250	250	650	-250	650
	Estimation	999.863	0.50006	0.50007	0.49992	650.0533	250.0343	249.9570	649.9018	250.2300	649.9324
	Error rate	0.0137%	0.0128%	0.0143%	0.0154%	0.0082%	0.0137%	0.0172%	0.0151%	0.0092%	0.0104%
3	Real value	5000	-0.5	0.5	0.6	3250	1250	1250	3250	-1250	3250
	Estimation	5000.412	0.49993	0.49992	0.60007	3250.4842	1250.1187	1249.8537	3249.5905	1249.8075	3250.5427
	Error rate	0.00824%	0.0124%	0.0158%	0.0132%	0.0149%	0.0095%	0.0117%	0.0126%	0.0154%	0.0167%

verified the effectiveness of the control method presented here but also demonstrated that the proposed scheme can obtain a high-precision parameter estimation result.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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