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Capturing a Space Target Using a Flexible Space Robot

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Abstract: Capturing space targets by space robots is significant for on-orbit service and is a challenging research topic nowadays. This paper focuses on the dynamics and control of capturing a non-cooperative space target by a space robot with a long flexible manipulator. Firstly, the dynamic equation of the flexible space robot is given. The Hertz contact model is used to describe the contact force between the robot and the target. Secondly, an active compliance controller is designed to reduce the capture impact on the robot. Finally, the capture impact on the whole system is analyzed in detail in four scenarios: the combination of two kinds of movement forms and two kinds of relative positions of the robot and the target before capturing. Simulation results indicate that the capturing operation may cause complicated dynamic behaviors such as the vibration of elastic links and the continuous collision of the target. Moreover, the results show that the control method effectively offsets the capture impact on the space robot system. In general, this work lays a theoretical foundation for further study of the dynamic phenomena of the capture process.

Keywords: flexible space robot; space target; capture; impact; control

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1. Introduction

With the development of science and technology, human explorations of space have been growing quickly. A number of space launches have been carried out in recent years to meet the demands of communication, weather monitoring, and the military. However, human space exploration activities have tremendously affected the space environment, leaving a large amount of space debris such as failure satellites, upper rocket stages, and collision derivatives, which bring a significant threat to human space activities. To ensure the security of spacecrafts, some active debris removal (ADR) schemes were proposed, such as lowering the orbit of near-earth target debris and burning them down in the atmosphere, lifting the debris on the geostationary Earth orbit to a graveyard orbit. In all of these schemes, capturing space debris on-orbit is necessary. Since most space debris are non-cooperative and information about them, for instance, mass, centroid location, geometric shape, and motion state, is unknown, the capturing operation is a difficult task to realize.

To date, some capture methods have already been proposed, such as manipulator, net, and hook. Among them, the research of manipulator-based capturing technology is a significant direction [1,2]. Related works include those of McDonald Dettwiler Space and Advanced Robotics Ltd. (MDSAR) who developed a simulation tool to analyze the dynamic behavior between robot and target during contact [3]. Wee and Walker [4] studied the contact between a free-flying space robot and a non-cooperative target. They developed an algorithm to minimize the contact impulse by planning the robot trajectory tracking and impulse minimization. In Cyril and Jaar's research [5,6], post-capture dynamics of a flexible spacecraft manipulator were studied deeply. Yoshida et al. [7–12] carried out extensive studies on the operation of capturing a free-flying/free-floating object by a rigid space robot, including impact dynamics modeling, impulse minimizing, and impedance control. Shibli

and Su [13,14] studied the dynamic modeling and control of the capture of a satellite by a rigid space robot. To reduce the difficulty of the capturing operation, Matunaga et al. [15] proposed a contact/push-based control method for reducing the angular momentum of an uncontrolled target satellite. For the same reason, Uyama and Nakanishi [16,17] utilized a controllable compliant wrist installed on a rigid robot to offset the impact of the target satellite. Thai et al. [18] used a Magneto-Rheological (MR) damper to offset the impact from the target satellite too. Xu et al. [19,20] studied the captures of a non-cooperative object and a larger flexible spacecraft by a rigid space robot, respectively. Liu et al. [21] and Yu et al. [22] conducted a series of studies on the dynamics and control of capturing a floating rigid body by a rigid space robot. Nishida et al. [23–26] studied the dynamics of capturing space debris by a rigid space robot, and some research results about capturing strategy were achieved. Liu et al. [27], Liu et al. [28,29], and Stolfi et al. [30,31] studied the control problem of the capture of a larger tumbling object by multi rigid robot arms. Zarafshan et al. [32,33] studied the control problem of cooperative object manipulation by a rigid-flexible arm. From the studies above, we can see that the capture of space objects using space robots has gained much attention, and there are many research results. However, there still are some problems remaining for further study. For example, in most existing studies, the capture missions are conducted by a rigid space robot. The flexible space robot has a longer manipulator, so the flexible space robot has a larger working space than the rigid space robot. Thus, a flexible space robot could finish the capture mission in a relatively safe position. However, the flexibility brought by the longer manipulator will cause more complex dynamics behaviors of the system during capturing. Such behaviors could make the capture a failure. To date, the research on the capturing operations realized by flexible space robots is insufficient but essential [1]. Therefore, it is essential and meaningful to research the dynamics and control of capturing a non-cooperative target by a flexible space robot.

In this paper, Jourdain's velocity variation principle is adopted to build the dynamics of a flexible space robot, and the Hertz contact theory is used to describe the contact force between the end-effecters of the manipulator and the target. Moreover, an active controller is designed to reduce the capture impact on the robot system. In the numerical simulation section, we analyze the complex dynamic behaviors in the capture process. Meanwhile, this section verifies the validity of the controller. This paper is organized as follows. Section 2 briefly presents the expression of the dynamic model of the flexible space robot. The contact model between the robot and the captured object is presented in Section 3. Section 4 provides the controller design process. Section 5 provides numerical simulations. Finally, Section 6 gives a concluding remark.

2. Dynamic Model of Space Robot

This paper uses a simplified flexible space robot and a target (shown in Figure 1) to study capturing operation. The space robot is composed of a spacecraft base (the body B_1), a manipulator (the bodies B_2 – B_5), and an end effector (the bodies B_6 and B_7). The manipulator consists of two flexible links (the bodies B_2 and B_3) and two rigid links (the bodies B_4 and B_5) and has six degrees of freedom (Axes 1–6). The body B_2 can rotate around Axes 1 and 2, B_3 around Axis 3, B_4 around Axis 4, and the body B_5 around Axes 5 and 6. The end effector is composed of three same cylinder-shaped hands, two of which form B_6 , while the other one forms B_7 . The body B_8 is the space target to capture, denoted by a rigid cylinder that simulates the handle of a captured spacecraft. The space robot shown in Figure 1a is like the Shuttle Remote Manipulator System (SRMS) designed by the Canadian Space Agency (CSA).

Based on the Jourdain's velocity variation principle, the dynamic equation of the robot system can be expressed as [34]

Figure 1. Space robot and the object to be captured: (a) the total diagram of the robot system, and (b) enlarged drawing of the end effector.

$$\sum_{i=1}^n \Delta v_i^T (-M_i \dot{v}_i - f_i^w - f_i^u + f_i^p) + \Delta P = 0 \quad (1)$$

where v_i is the vector of configuration velocity of the i -th body, $M_i \dot{v}_i$ denotes the acceleration-dependent inertia force acting on the i -th body, f_i^w is the velocity-dependent inertia force acting on the i -th body, f_i^p is the external force of the system acting on the i -th body, f_i^u is the elastic force acting on the i -th body (if the i -th body is a rigid body, f_i^u will be a zero vector), and ΔP is the sum of virtual power of the inner forces of the system. $n = 7$ in Equation (1) since the robot system shown in Figure 1 is composed of seven bodies.

By the assumed mode method, the elastic force f_i^u can be expressed as [34].

$$f_i^u = [0^T \quad 0^T \quad (C_{a_i} \dot{a}_i + K_{a_i} a_i)^T]^T \in \mathbb{R}^{(6+s) \times 1} \quad (2)$$

where a_i is the modal coordinate vector of the i -th body, $C_{a_i} \in \mathbb{R}^{s \times s}$ and $K_{a_i} \in \mathbb{R}^{s \times s}$ are the modal damping and stiffness matrices of the i -th body, s denotes the highest order of the mode chosen. For the robot system given in Figure 1, the bodies B_2 and B_3 are flexible, so only these two bodies have elastic force. In the simulations, the first six modes of B_2 and B_3 are both chosen, so $s = 6$ in this paper.

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

$$\Delta v^T (-M \dot{v} - f^w - f^u + f^p) + \Delta P = 0 \quad (3)$$

where $v = [v_1^T, \dots, v_n^T]^T$ is the configuration velocity of the system, $M = \text{diag}[M_1, \dots, M_n]$ is the mass matrix, $f^u = [f_1^{uT}, \dots, f_n^{uT}]^T$, $f^w = [f_1^{wT}, \dots, f_n^{wT}]^T$, and $f^p = [f_1^p, \dots, f_n^p]^T$ are the elastic force, the velocity-dependent inertia force, and the external force, respectively.

Based on the single direction recursive construction method, we can write the configuration velocity of the system as [34]

$$\dot{v} = G\dot{y}, \ddot{v} = G\ddot{y} + \hat{g}I_N \quad (4)$$

where $y \in \mathbb{R}^N$ is the independent generalized coordinate vector of the robot system, composed of the generalized coordinates of the robot base (B_1), the joint coordinates of the manipulator, the modal coordinates of the flexible links B_2 and B_3 , and the generalized coordinates of B_6 and B_7 . The generalized coordinates of the robot base contain three translational ones and three rotational ones, eight joint coordinates of the manipulator, six modal coordinates of B_2 , and six modal coordinates of B_3 . Therefore, the number of independent generalized coordinates of the robot system is twenty-six, namely $N = 26$. The parameters G , g , and $\hat{I}_N$ in Equation (4) are all constant matrices or vectors, and their expressions can be found in Ref. [30].

Using Equations (3) and (4), Equation (3) can be written as

$$\Delta\dot{y}^T[-Z\ddot{y} - z + h + f^{ey}] = 0 \quad (5)$$

where $Z = G^T M G$, $z = G^T(f^\omega + f^u + M g \hat{I}_N)$ and $h = G^T f^p$, and f^{ey} is the vector of the generalized force of the system.

Since all the elements of y are independent, Equation (5) becomes

$$-Z\ddot{y} - z + h + f^{ey} = 0 \quad (6)$$

This formula is the dynamic equation of the flexible space robot system. We have established the dynamic model for this system, for details please see Ref. [34].

3. Contact Model

This section presents the contact model between the robot and the target. Today there are two main methods to analyze impact and contact between contact objects. One is the momentum method. In this method, impact impulse is used instead of contact force in impact analysis. The contact process is considered as a discontinuous process divided into two phases: pre-contact and post-contact. Comparatively, in the other method, the contact process is considered as a continuous process, and contact force acts on the contact objects until they separate. Compared with the first method, the second method gives a better description of the real contact behavior. More importantly, the second method can be applied to complex contact problems such as multi-object contact. The Hertz contact theory is a typical example of the second method and has had many applications in practice [35].

In this paper, the Hertz contact theory is used to model the contact dynamics of the robot system, and computer graphics are employed to detect the interference between the end effector and the target object. For simplicity of description, the target object is modeled as a rigid cylinder, as shown in Figure 1, it may simulate the handle of a target spacecraft or other structures with a similar shape which are captured.

3.1. Contact Force

In the research on contact mechanics, some contact force models have been proposed, such as the linear Hertz model, the linear Hook model, and the nonlinear Hertz model. The linear Hertz model is the most classical of these models, and it has been successfully used to deal with small deformation contact problems. For the problem of target capture by space robots, considerable contact deformation is harmful to the capturing operation, so the material of the end effector and the contact point of the captured target both have high stiffness. Therefore, the linear Hertz theory can describe the contact behavior of the

robot capture. In the linear Hertz theory, the contact force is a non-linear power function of penetration depth and can be written as [35]

$$F_c = \frac{4}{3} E^* R^{1/2} \hat{d}^e \quad (7)$$

where R is the radius of the cylinder, $\hat{d}$ is the penetration depth, e is an exponent, $e = 1.5$ is taken in this paper, and E^* is the material stiffness that is given by

$$(E^*)^{-1} = (1 - \nu_1^2)/E_1 + (1 - \nu_2^2)/E_2 \quad (8)$$

where E_1 and E_2 are the elastic modulus, and ν_1 and ν_2 are the Poisson's ratios of the two contact objects, respectively.

3.2. Contact Detection and Penetration Depth Calculating

It can be seen from Figure 1 that the end effector is composed of three cylinders, and the target object is a cylinder too. Thus, the contact between the end effector and the target can be converted to the contact among the cylinders. The target object B_8 is assumed to be inside the two hands B_6 and B_7 during the capturing process, so the point contact is the only existing form of contact between B_8 and the two hands. The contact detection is introduced below.

Figure 2 shows the contact of the target object B_8 with one hand of B_6 , where HJ and EF are the cylinder axes of Hand 1-1, and the two cylinders of Hand 1-1 have the same radius and are represented by r_1 ; XI is the axis of B_8 and its radius is r_2 . To detect the distance between two axes, we need to calculate the closest point of the two axes first. Let the axes HJ and XI be specified parametrically by the points H, I, X and J , given by [36].

Figure 2. Schematic diagram of contact detection.

$$L_1(s) = H + sd_1, \quad d_1 = J - H \quad (9a)$$

$$L_2(t) = X + qd_2, \quad d_2 = I - X \quad (9b)$$

For some pairs of values, for example, for s and q , $L_1(s)$ and $L_2(q)$ correspond to the points on the lines, and $v(s, q) = L_1(s) - L_2(q)$ describes a vector between them. When the segments L_1 and L_2 do not intersect each other, if $v(s, q)$ is perpendicular to both lines L_1 and L_2 , the points $L_1(s)$ and $L_2(q)$ are the closest points on the lines. For nonparallel lines, $v(s, q)$ is unique. Based on the definition of perpendicularity constraints, we can obtain

$$d_1 \cdot v(s, q) = 0, \quad d_2 \cdot v(s, q) = 0 \quad (10)$$

Considering Equation (9) and the parametric equation of $v(s, q)$, we can get

$$d_1 \cdot (L_1(s) - L_2(q)) = d_1 \cdot ((H - J) + sd_1 - qd_2) = 0 \quad (11a)$$

$$d_2 \cdot (L_1(s) - L_2(q)) = d_2 \cdot ((H - J) + sd_1 - qd_2) = 0 \quad (11b)$$

This can be expressed as the 2×2 system of linear equations

$$(d_1 \cdot d_1)s - (d_1 \cdot d_2)q = -d_1 \cdot (H - J) \quad (12a)$$

$$(d_2 \cdot d_1)s - (d_2 \cdot d_2)q = -d_2 \cdot (H - J) \quad (12b)$$

Solving Equation (12), we can get s and q . Substituting them into Equation (9), we can obtain $L_1(s)$ and $L_2(q)$. Regarding d as the distance between $L_1(s)$ and $L_2(q)$, if $d < r_1 + r_2$, the two cylinders have contacted, and the penetration depth is $\hat{d} = r_1 + r_2 - d$.

4. Controller Design for the Manipulator

In capturing process, big impacts between the robot and the non-cooperative target may result in the damage of the manipulator or disorder of the robot attitude. In this paper, an active compliance controller is designed to eliminate the impact of collision. Next, the derivation process of the controller is given as follows.

The dynamic equation of the space robot system (Equation (6)) involving the capturing operation can be written as

$$Z\ddot{y} + z = F_c + u \quad (13)$$

where $u = f^y$ is the vector of control force that is generated by electrical motors installed on the joints, and $F_c = h$ is the vector of contact force on the end effector. It is reasonable to predict that, in the case $F_c \neq 0$, the desired coordinates y_d of the robot system are no longer ensured. Inspired by the passive compliance control method, the system equation can be written as

$$Z\ddot{y} + D(\dot{y} - \dot{y}_d) + K(y - y_d) = F_c \quad (14)$$

where K and D are the active stiffness weighting and active damping weighting, respectively. To obtain Equation (14), the controller should be

$$u = z - D(\dot{y} - \dot{y}_d) - K(y - y_d) \quad (15)$$

From Equations (14) and (15) we can find that the response of the robot system to the contact force depends not only on the inertia parameters (Z) of the robot system but also on the compliance parameters (K and D) of the controller. Therefore, the system response can be lowered by choosing suitable compliance parameters of the controller. Thus, the influence of impact is reduced.

5. Numerical Simulations

This section will carry out simulations to demonstrate the effectiveness of theoretical studies. As shown in Figure 1, the robot base is assumed to be a big rigid cylinder, of which

the length is 24 m, and the radius is 1 m. The lengths of the four links (B_2 , B_3 , B_4 , and B_5) of the manipulator are 6.4 m, 7 m, 0.5 m, and 0.6 m, respectively. The first six modes of the flexible links B_2 and B_3 are considered in this paper, and the free-pinned beam's modal functions are both used. The first six natural frequencies of B_2 are 5.9076 Hz, 25.8648 Hz, 368,781 Hz, 834,175 Hz, 1,026,270 Hz, and 172,7682 Hz, respectively, and those of B_3 are 54,859 Hz, 240,087 Hz, 342,174 Hz, 773,491 Hz, 951,008 Hz, and 1,599,500 Hz. The space object is also assumed to be a rigid cylinder and its radius is $R = 0.05$ m. It is used to simulate the handle of a target spacecraft or other structures with a similar shape to be captured. The end effectors and the targets are steel, so Young's modulus and Poisson's ratio in Equations (7) and (8) are $E_1 = E_2 = 2.06 \times 10^{11}$ and $\nu_1 = \nu_2 = 0.3$. The other physical parameters of the robot system are given in Table 1. The space robot shown in Figure 1a is like the Shuttle Remote Manipulator System (SRMS) designed by the Canadian Space Agency (CSA).

Table 1. Physical parameters of the space robot.

Body	Mass (kg)	I_{xx} (kg·m ²)	I_{yy} (kg·m ²)	I_{zz} (kg·m ²)	EI (N·m ²)	GJ (N·m ²)	EA (N)
B_1	1.0179×10^5	5.0894×10^6	4.9113×10^6	4.9113×10^6			
B_2	138	0.399	471.82	471.82	4.04×10^6	2.040×10^6	2.8×10^9
B_3	85.06	0.4	348.01	348.01	2.81×10^6	1.417×10^6	1.2×10^9
B_4	8	0.2	0.76	0.76			
B_5	41	0.2	5.02	5.02			
B_6	12.25	0.163	0.136	0.2759			
B_7	6.125	0.082	0.0068	0.0767			
B_8	480.35	1.18	0.7	0.7			

As shown in Figure 1, frame O - XYZ is an absolute reference frame; frame O_1 - $X_1Y_1Z_1$ paralleling to the frame O - XYZ fixes on the robot base B_1 and the origin O_1 is on the mass center of B_1 . Floating frames O_2 - $X_2Y_2Z_2$ and O_3 - $X_3Y_3Z_3$ fix on the two links B_2 and B_3 , respectively, and the origins O_2 and O_3 are on the mass centers of the two links. Furthermore, frames O_6 - $X_6Y_6Z_6$ and O_7 - $X_7Y_7Z_7$ fixed on the body B_5 are used to describe the relative rotational motion of the two hands of the end effector with respect to the body B_5 . In the simulations, the initial joint angles of B_2 - B_5 are chosen as ($^\circ$ 30° −57.2041° 27.2038° 0° 0°), where the axes of B_4 and B_5 are both parallel to the Y axis. The space robot is in the O - YZ plane before capturing. The initial and final positions of B_6 and B_7 are shown in Figure 3. The robot base is free-floating during capturing, while only the robot manipulator and the end-effector are controlled. The desired angular velocities of the manipulator (B_2 - B_5) are all zero.

Figure 3. Positions of the two hands and the captured object: (a) initial position, (b) final position, and (c) grasped position of B_8 .

The effectiveness of the active controller designed in Section 4 is verified firstly. The relative position of mass center of the target cylinder B_8 in the $O_1-X_1Y_1Z_1$ frame is (0 m, 25.05 m, 1 m) and the cylinder axis parallels the X_1 axis. The absolute angular velocity and the absolute translation velocity of the target cylinder B_8 are (0, 0, 0) and (0, -0.05 m/s (-0.1 m/s), 0), respectively, namely B_8 moves toward the space robot at 0.05 m/s and 0.1 m/s along the Y direction. Since the robot is at rest before impact, the absolute velocity of B_8 is the relative one. The robot will grasp the middle position of B_8 , as shown in Figure 3c. The following two control cases are considered in the simulations:

Case 1: the six joints of the manipulator are locked and the manipulator can be regarded as one body. The two hands B_6 and B_7 of the end effector are only controlled in the capture of the target. In controller design, the matrices K and D in Equation (15) are both 26×26 matrices, and all elements of K and D are chosen to be zeros except $K_{25,25} = K_{26,26} = 200$ and $D_{25,25} = D_{26,26} = 50$. $K_{25,25}$, $K_{26,26}$, $D_{25,25}$, and $D_{26,26}$ correspond to the control weightings of B_6 and B_7 . The desired rotational velocities of B_6 and B_7 are both 0.1 rad/s.

Case 2: the six joints of the manipulator and the two hands B_6 and B_7 are all controlled in capturing the target. For this case, active compliance controls are applied on the six joints of the manipulator to offset the capture of the robot. In controller design, all elements of K are chosen to be zeros except $K_{25,25} = K_{26,26} = 200$, and D is chosen as $D = \text{diag} [0_{1 \times 6} \ 100 \ 100 \ 0_{1 \times 6} \ 100 \ 0_{1 \times 6} \ 100 \ 100 \ 100 \ 50 \ 50]$. The first $0_{1 \times 6}$ in D is the control weighting of the robot base, the second and third $0_{1 \times 6}$ are the control weightings of modal coordinates of the two flexible links B_2 and B_3 , respectively; and the six 100 are the control weightings of six joint coordinates of the manipulator. The desired rotational velocities of B_6 and B_7 are both 0.1 rad/s too.

Figure 4 depicts the state of the space robot in the pre-capture and post-capture phases. Figures 5–8 present the simulation results for Cases 1 and 2, where Figures 5 and 7 are the time histories of the attitude of the robot base, and Figures 6 and 8 are those of the rotation angle of the hands B_6 and B_7 ; the solid line represents the results of Case 1 and the dotted line Case 2. From Figures 5 and 7, it can be observed that capturing operation only causes the plane motion of the robot system and does not produce rotational motions in the Y and Z directions. This is because the space robot is initially in the O - YZ plane, and the middle position of the target is grasped. The change in rotational angle of the robot base around the X -axis using an active compliance controller is smaller than that without using the controller, which demonstrates the effectiveness of the controller in reducing the capture impact on the robot. From Figures 6 and 8, we can observe that the target can finally be firmly grasped for the two cases.

Figure 4. State of the space robot in the process of capturing: (a) pre-capture, and (b) post-capture.

Figure 5. Time histories of angular displacement of the robot base B_1 with and without active compliance control of the manipulator (0.05m/s): (a) the X axis, (b) the Y axis, and (c) the Z axis.

Figure 6. Time histories of rotation angle of the two hands B_6 and B_7 with and without active compliance control of the manipulator (0.05 m/s): (a) B_6 , and (b) B_7 .

Figure 7. Time histories of angular displacement of the robot base B_1 with and without active compliance control of the manipulator (0.1 m/s): (a) the X axis, (b) the Y axis, and (c) the Z axis.

Figure 8. Time histories of rotation angle of the two hands B_6 and B_7 with and without active compliance control of the manipulator (0.1 m/s): (a) B_6 , and (b) B_7 .

The results above indicate that the active compliance control of the manipulator could effectively reduce the capture impact on the robot. Next, extensive simulations are conducted to further demonstrate the influence of impact. The four impact cases shown in Figure 9 are considered. In these cases, the Y_1 and Z_1 positions of the mass center of the target cylinder B_8 in the O_1 - $X_1Y_1Z_1$ frame are 25.05 m and 1 m, respectively, and the cylinder axis parallels the X_1 axis. For the first and second impact cases (Figures 8b and 9a), the relative position of the mass center of the target cylinder in the X_1 direction is 0 m, and the impact is central impact, and for the third and fourth impact cases (Figures 8d and 9c), the relative position is 0.05 m, and the impact is eccentric impact. In these two cases, the tumbling motion of B_8 caused by the capturing operation will appear. Assume that v is the relative velocity between the target cylinder B_8 and the end effector. Two different relative velocities, $v = 0.05$ m/s and $v = 0.1$ m/s, are considered in the simulations. The absolute angular velocity of the target cylinder B_8 is (0, 0, 0) and the absolute translation velocity of

the target cylinder B_8 is $(0, v \text{ m/s}, 0)$ for the first and third impact cases (Figure 9a,c), and they are $(0, 0, 0)$ and $(0, -v \text{ m/s}, 0)$ for the second and fourth impact cases (Figure 9b,d). In other words, the target cylinder B_8 moves at a constant speed $v \text{ m/s}$ along the Y direction with no rotation towards or away from the robot. The six joints of the manipulator and the two hands B_6 and B_7 are all controlled in the capturing process. In controller design, K and D are chosen as the same as those in Case 2, namely all elements of K are chosen to be zeros except $K_{25,25} = K_{26,26} = 200$, and $D = \text{diag} [0_{1 \times 6} \ 100 \ 100 \ 0_{1 \times 6} \ 100 \ 0_{1 \times 6} \ 100 \ 100 \ 100 \ 50 \ 50]$. The desired rotational velocities of B_6 and B_7 are both also 0.1 rad/s . The simulation results are given in Figures 10–19, where Figures 10 and 14 are the attitude change of the robot base B_1 for $v = 0.05 \text{ m/s}$ and $v = 0.1 \text{ m/s}$, respectively. Figures 11 and 15 are the angular displacement change of the six joints of the robot manipulator, Figures 12 and 16 are the rotation angle change of the two hands of the end effector, Figures 13 and 17 are the tip responses of the flexible links B_2 and B_3 in the floating frames $O_2\text{--}X_2Y_2Z_2$ and $O_3\text{--}X_3Y_3Z_3$. Figures 18 and 19 are the attitude change of the target B_8 . The conclusions drawn from Figures 10–19 are:

Figure 9. Four impact cases.

Figure 10. Time histories of angular displacements of the robot base B_1 ($v = 0.05 \text{ m/s}$): (a) the X axis, (b) the Y axis, and (c) the Z axis.

Figure 11. Time histories of angular displacements of the manipulator ($v = 0.05$ m/s): (a) Axis 1, (b) Axis 2, (c) Axis 3, (d) Axis 4, (e) Axis 5, and (f) Axis 6.

Figure 12. Time histories of the rotation angles of the two hands ($v = 0.05$ m/s): (a) B_6 , (b) B_7 .

Figure 13. Tip displacements of the flexible links B_2 and B_3 ($v = 0.05$ m/s): (a) B_2 in the Y_2 direction, (b) B_2 in the Z_2 direction, (c) B_3 in the Y_3 direction, and (d) B_3 in the Z_3 direction.

Figure 14. Time histories of angular displacements of the robot base B_1 ($v = 0.1$ m/s): (a) the X axis, (b) the Y axis, and (c) the Z axis.

Figure 15. Time histories of angular displacements of the manipulator ($v = 0.1$ m/s): (a) Axis 1, (b) Axis 2, (c) Axis 3, (d) Axis 4, (e) Axis 5, and (f) Axis 6.

Figure 16. Time histories of the rotation angles of the two hands ($v = 0.1$ m/s): (a) B_6 , and (b) B_7 .

Figure 17. Tip displacements of the flexible links B_2 and B_3 ($v = 0.1$ m/s): (a) B_2 in the Y_2 direction, (b) B_2 in the Z_2 direction, (c) B_3 in the Y_3 direction, and (d) B_3 in the Z_3 direction.

Figure 18. Time histories of angular displacements of the target B_8 : (a) $v = 0.05$ m/s, (b) $v = 0.05$ m/s, (c) $v = -0.05$ m/s, and (d) $v = -0.05$ m/s.

Figure 19. Time histories of angular displacements of the target B_8 : (a) $v = 0.1$ m/s, (b) $v = 0.1$ m/s, (c) $v = -0.1$ m/s, and (d) $v = -0.1$ m/s.

- (1) From Figures 10 and 14, we can observe that central impact only causes the attitude change of the robot base B_1 in the X direction, but the eccentric impact could cause the attitude change in all directions.
- (2) From Figures 11 and 15, we can observe that the controller designed in this paper can stabilize the motion of joint angles of the manipulator. It is observed from Figure 11a,e,f and Figure 15a,e,f that eccentric impact could cause the joint angle change of the manipulator in the Axis 1, Axis 5, and Axis 6 directions, while central impact could not.
- (3) It is observed from Figures 12 and 16 that the end effector can successfully capture the target for the four cases.
- (4) From Figures 13 and 17, we can observe that central impact and eccentric impact can both lead to the deformation of the flexible links B_2 and B_3 in the Y_2 and Y_3 directions, but only the eccentric impact can lead to the deformation of B_2 and B_3 in the Z_2 and Z_3 directions.
- (5) As depicted in Figures 18 and 19, we can observe that eccentric impact causes obvious attitude change of B_8 , meaning B_8 is tumbling, but central impact cannot. Meanwhile, it is observed that the attitude evolution trend is changed several times in eccentric impact cases, which shows that there are multiple instances of contact during capturing. Moreover, it demonstrates that the tumbling motion of the target object makes the capturing operation complicated.
- (6) Figures 10–19 show the impact on the robot system caused by capturing when the target cylinder moves towards the manipulator are more significant than those when the target moves away from the manipulator.

6. Concluding Remark

In this paper, the process of capturing a space target using a flexible robot is studied in detail. First, the capture dynamics model is established based on the multi-body dynamics and Hertz contact theories. Then, an active compliance controller is designed to reduce the capture impact on the robot system. We found the presence of dynamic behaviors when using a flexible space robot to capture a non-cooperative target by numerical simulation. The capture impact causes attitude change of the space robot and leads to the deformation of the flexible robotic arm. Comparing different capturing scenarios, the scenario of eccentric

impact with negative relative velocity may cause more complex dynamic behavior of the robot than others. So, to reduce the risk, that scenario should be avoided. Furthermore, when the proposed active compliance controller is considered, the capture impact on the robot can be effectively offset.

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