Simulation study on dynamics model of two kinds of on-orbit soft-contact mechanism

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Abstract. Aiming at the problem that the operating conditions of the space manipulator is harsh and the space manipulator could not bear the large collision momentum, this paper presents a new concept and technical method, namely soft contact technology. Based on ADAMS dynamics software, this paper compares and simulates the mechanism model of on-orbit soft-contact mechanism based on the bionic model and the integrated double joint model. The main purpose is to verify the path planning ability and the momentum buffering ability based on the different design concept mechanism. The simulation results show that both the two mechanism models have the path planning function before the space target contact, and also has the momentum buffer and controllability during the space target contact process.

1. Introduction

With the development and maturity of space technology, the on-orbit servicing and guarantee is becoming an important means to save cost and restore losses. Its main mission is to enhance the control and support capability of space environment by finishing the on-orbit maintenance, guarantee and service task through enhancing the space environment control and support capability through a variety of space operations. The space contact technology is the basic aspect of the on-orbit servicing and guarantee. [1,2] Currently, the world's major space powers have already realized the space contact technology on-orbit tests, such as NASA's “Orbital Express” [3] and Japan's ETS-VII [4]. But these tests basically adopt "hard-contact technology", that is, directly contacting with rigid components in orbit capture technology. This technology’s space target operating condition is very harsh. The DART launched by the US in 2005 is a classic example of the dangers of hard-contact technology. This satellite started to rendezvous and dock with a communications satellite after entering into the orbit. However, during this process, the DART broke down and collided with the target satellite. Finally, this mission was failed because the impulsive momentum generated by the collision made the orbit height of the target satellite increasing about 3 km. [5] The main reason is that the main spacecraft’s space contacting device is generally composed of a single rigid arm or multi-rigid arm cascade, and the space target relative attitude requires keeping highly stability during operating. This requires that any abnormal disturbance should not happen when the main spacecraft and space targets are contacting with each other. This greatly limits the space contact technology to improve on-orbit operational capacity and the range of applications of space target.

To resolve the on-orbit hard-contact technology problem, it is necessary to find a new technical method controlling and buffering the collision momentum generated during the collision moment.
This paper proposes a new concept, which is called soft-contact technology. Its core idea is to build up the soft-contact mechanism model and rigid-flexible complex control methods to achieve transformation from stepped collision momentum to harmonic attenuation momentum, and the key parameters, such as harmonic amplitude, phase and convergence time, can be controlled according to the desired function. [6] This idea can make collision momentum controlled buffering and unloading come true. According to the literature, it is found that robots based on modular joints and bionics are excellent in rigid-flexible compound control. For example, the movement of the German Powercube modular robots is very simple, the flexibility of its modular joints is for the path planning, refers to the flexibility of the harmonics reducer of the flexible wheel. [7] Fujita developed a reconfigurable robot platform, which is based on the SONY company OPEN-R standard to build a variety of software and hardware modules, and through these modules composed a variety of different robot structure. [8] Shigeo Hirose of Tokyo Institute of Technology in Japan completed the world's first bionic arm structure in 1972 and proposed a "serpentine curve" to simulate the movement of the biological snake. [9] In 2000, the German National Laboratory developed a flexible snake robot GMD, which can be bent in the vertical and horizontal direction, mainly for underwater detection operations. [10]

As the flexible robot of modular joint and snake-like robot have great flexibility and controllability, the paper proposed two design schemes of space manipulator based on bionics and based on integrated double joint to explore solutions of controlled movement limitation issues of the current space manipulator. Firstly, the joint configuration of space manipulator based on bionics is designed. Secondly, the kinematic equation of the manipulator is built up. Finally, the manipulator rigid and flexible characteristics are simulated in order to assess whether the soft-contact technology could meet the design idea under the space environment or not.

2. design of Joint conceptual model
On the one hand, joint conceptual model design should meet the requirement of path planning in dexterity, work space and complexity. On the other hand, it should have the ability to reduce disturbed momentum of the satellite platform in buffering control process, and transforms the pulsed pass to harmonic pass to meet the need of on-orbit mission through synergistic control. Therefore, the joint conceptual model must contain two functional modules: a rigid drive unit and a flexible damping unit. This model is built by ADAMS in three-dimension. The space soft-contact mechanism general design is shown as Figure 1.

![Figure 1. Model of the space soft-contact mechanism](image)

1. Base Body No.1, 2. Base Body No.2, 3. Rotating Shell, 4. Connecting rod No.2, 5. Connecting rod No.1, 6. Bracket No.1, 7. Buffer Shaft, 8. Bracket No.2, 9. Drive Shaft

The rigid transmission unit uses motor as the drive. In consideration of the complexity of the space environment, the deceleration mechanism uses planetary gear. Rotation between base body and cross shaft is driven by mutual meshing motion between the gears, so as to realize the rotation between two manipulators and to complete pitch (X direction) or the yaw (Y direction) movement. The construction of the flexible controllable damping unit needs to follow the three principles below. Firstly, the flexible controllable damping unit is built on the base of the rigid transmission unit. So it could not destroy the function of the rigid transmission unit, while must keeping the flexible characteristics. Secondly, in order to buffer and unload the disturbance momentum received by the satellite platform during the on-orbit contact, the flexible controllable damping unit should possess the momentum unloading capacity of six degrees of freedom. Thirdly, the damping force generated by the flexible controllable damping unit should be controlled damping force, for the flexible damping unit can
transfer the impulsive disturbance momentum into the harmonic disturbance momentum after the satellite platform being touched by the target. So that the disturbance momentum of the satellite platform can be reduced.

The space soft-contact mechanism based on the integrated double joints general design is shown as Figure 2.

1. motion block 1, 2. static block 1, 3. static block 2, 4. motion block 2, 5. Connecting rod, 6. Rotating Shell

Figure 2. Model of the space soft-contact mechanism

The drive transmission mechanism of rigid drive unit uses motor as the drive and the harmonic reducer is used as reduction mechanism. When the motor works, it drives the rotor drive shaft, then makes the wave generator start to rotate for reduction, while outputting by the rigid wheel and driving torque sensors and motion block rotation, to complete the pitch direction (X direction) or the yaw direction (Y direction) movement. Flexible damping unit is built up according to the following three strategies. Firstly, momentum of axial direction can be buffered by constructing a flexible controlled linear damper of axial direction. The substrate is divided into two parts. These two parts can slide relatively by nested with each other, so that the momentum can be applied to the damper and buffer. Secondly, the rotating flexible controllable dampers of the pitch and yaw direction should be constructed. When the joint is collided by the target satellite from pitch (and yaw) direction of rotation, the angular motion transfers directly to the spindle, at this moment the collision torque can be transmitted to the flexible linear controllable damper, by using bevel gears and pinion mechanism. Thirdly, the rotating flexible controllable damper of axial direction should be constructed. When the joint is collided by the revolving target satellite from axis direction, the angular motion transfers directly to the substrate. The rotation momentum of axis direction can be buffered by the rotating flexible controllable damper between substrates. [6]

3. The establishment of the kinematic equation

Kinematic parameters are shown in Figure 3 [11]. The study of this paper is carried out in the free-floating mode.

Figure 3. Manipulator kinematic parameters

In Figure 3, $\Sigma_i$, $\Sigma_a$, $\Sigma_r$ represent the inertial coordinate system, the coordinate system of the base, and manipulator coordinate system, respectively. $a_i \in \mathbb{R}^3$ represents the position vector from the joint $i$ to the manipulator $i$’s centroid. $b_j, b \in \mathbb{R}^3$ respectively represent the position vector from base centroid to joint 1 and the position vector from the arm centroid to joint. And then $r, r, r_i \in \mathbb{R}^3$ respectively represent the position vector of the base centroid, the position vector of manipulator $i$’s centroid, and
the position vector of multibody system’s centroid. \( \mathbf{p}, \mathbf{p} \in \mathbb{R}^3 \) respectively represents the position vector of joint \( i \) and the position vector the actuator end of manipulator.

And in order to the kinematic equation of this manipulator, this paper defines some parameters, such as \( E \in \mathbb{R}^{3 \times 3} \) represents a unit matrix. \( m \) represents manipulator \( i \)'s quality. \( M \) represents the total mass of the multibody system. \( Z \in \mathbb{R}^3 \) represents the joint \( i \)'s rotation axis unit vector. \( I \in \mathbb{R}^{3 \times 3} \) represents the inertia of the manipulator relative to its centroid. \( \Theta \in \mathbb{R}^3 \) represents the joint angle vector in the joint space of manipulator. \( v, \omega \in \mathbb{R}^3 \) represent linear velocity and angular velocity of multibody system of base. \( v, \omega \in \mathbb{R}^3 \) represent linear velocity and angular velocity of the actuator end of manipulator. According to the kinematics parameters of manipulator in Figure. 3 and the space manipulator energy conservation law under free-floating mode, the generalized Jacobian matrix between the base and each joint angular velocity is established as below. [7]

\[
\begin{bmatrix}
v_v \\
\omega_v
\end{bmatrix} = 
\begin{bmatrix}
-\hat{r}_v H^{-1} H_\Theta - J_{v \Theta} \\
-H^{-1} H_\Theta
\end{bmatrix} \hat{\Theta} = J_w \hat{\Theta}
\]

(1)

\( J_{bm} \) is the base-manipulator Jacobian matrix, and disturbances of the base generated by the movement of the manipulator can be obtained by this matrix. and then

\[
\begin{bmatrix}
H_v \\
H_\Theta
\end{bmatrix} = \begin{bmatrix}
(\hat{r}_v H + H_v) \\
(\hat{r}_v H - H_\Theta)
\end{bmatrix}
\]

(2)

\( H_v \) and \( H_\Theta \) in (2) are as below.

\[
H_v = \sum_{i=1}^{n} \left(I_i + m_i \hat{r}_i \hat{p}_i \right) + I_0, \quad H_\Theta = \sum_{i=1}^{n} \left(I_i \hat{r}_i + m_i \hat{r}_i \hat{J}_i \right)
\]

(3)

And also \( J_{Ri} \) and \( J_{Ti} \) in (3) are as below.

\[
\begin{bmatrix}
J_\rho \\
J_{\theta}
\end{bmatrix} = [Z_1, Z_2, \ldots, Z_n, 0, \ldots, 0]
\]

(4)

At the same time, the generalized Jacobian matrix between velocity of the actuator end of manipulator and the angular velocity of each joint is built up as (5).

\[
\begin{bmatrix}
v_v \\
\omega_v
\end{bmatrix} = \begin{bmatrix}
J_{w} + J_{w_{act}}
\end{bmatrix} \hat{\Theta} = J_s \hat{\Theta}
\]

(5)

Where \( J_s \) is the generalized Jacobian matrix which describes the relationship between velocity of the actuator end of manipulator and the angular velocity of joints. And then

\[
J_s = \begin{bmatrix}
Z_1 \times (p_p - p_i) & Z_2 \times (p_p - p_i) & \ldots & Z_n \times (p_p - p_i)
\end{bmatrix}, \quad J_w = \begin{bmatrix}
E_i & -(\hat{r}_v)
\end{bmatrix}
\]

(6)

4. Rigid-flexible characteristic simulation comparison of single-joint manipulator

4.1. Simulation of Single Joint Rigid Drive Unit

As to the space soft-contact mechanism based on the bionics, Soft-contact mechanism should have the ability of path planning like the traditional multi-rigid manipulator, in order to achieve its large-scale movement. So its single joint must have rigid transmission function. By adding the motor drive, while combining function and script control, joint range of motion can be simulated. Yaw motor drive function of the simulation is “if(time>10:9d.0, if(time>20:-9d.0, if(time>30:9d.0,0)), and the step is 300. The status of simulation of single joint space soft contact mechanism is shown as Figure 4. Figure 4 shows that, in the ADAMS’s simulation, the single joint’s degree of freedom can range up to -90°~ + 90°. As to the space soft-contact mechanism based on the integrated double joint, it should have the ability of path planning like the traditional multi-rigid manipulator, in order to achieve its large-scale movement. So its single joint must have rigid transmission function. According to the structure and transmission principle, all the damping buffer mechanisms lose efficacy when the manipulator start moving, and the electromagnetic brake and the positioning mechanism are activated. The system is in
the rigid structure state. By adding the motor drive, while combining function and script control, joint range of motion can be simulated. Yaw motor drive function of the simulation is “if(time-10:9d,0,if(time-20:9d,0,if(time-30:9d,0,0)))”, and the step is 300. The simulation result is shown as Figure 5. Figure 5 shows that, in the ADAMS simulation, the single joint’s degree of freedom can range up to 0° ~ 360°.

The simulation commonality of the two kinds of joint mechanism model of the drive structure is adding the drive to the motor shaft, and the drive function type is the same. But the values of the drive according to the design of the scope of rotation are a slight different. The simulation results of two kinds of joint mechanism model show that the rigid motion design structure can meet the requirement of large range of motion characteristics of soft-contact mechanism.

Figure 4. Rotation angle change of rigid simulation of the joint around the X and Y axis

Figure 5. Rotation angle change of rigid simulation of the joint around the X and Y axis

4.2. Simulation of single joint flexible controllable unit

For the specific momentum collision at the end of a single joint, the simulation can be verified according to the application background of the following three typical space targets: ① Adding the instantaneous axial force to the end of Z axis to verify the working mechanism of the linear motion flexible controllable unit; ② Adding the instantaneous axial force and instantaneous torque to the end of Z-axis to verify the working mechanism of angular motion flexible control unit; ③ Adding instantaneous force and instantaneous torque with 45° to the end in each X / Y / Z axis to verify the working mechanism of the Z-axis linear motion flexible control unit and X / Y / Z axes three angular motion flexible control units. Because of the limit of paper length, we only present the simulation of compound flexible controllable unit. That is the third application background above. The results of the other two simulations are the same as the third one.

We carry out simulation verification on the third application background of space target control, that is, the working mechanism of the angular motion flexible control unit. Then adding instantaneous force and torque to the end of 45° to the X/Y/Z axes to simulate the Z-axis Linear motion and X/Y/Z axes angular motion composite flexible control mechanism. The initial conditions are shown in Table 1.

| Table 1. Composite flexible controllable unit initial condition |
|---------------------------------------------------------------|
| **instantaneous force** |
| Driving function: if(time-0.1:20N,0,0), 45° to the X/Y/Z axis |


According to the initial conditions given in Table 4, the simulation results of the composite flexible control of the on-orbit soft contact mechanism based on different mechanism models can be obtained by simulating the collision process of space targets with both linear motion and angular motion. The results are shown in Figure 6.

The dynamic parameters of the two mechanism models in flexible controllable mode were compared and analysed in detail. The simulation results show that both the two mechanism models can achieve the expected goal, but the mechanism model based on bionics is slightly better in the comprehensive performance.
5. conclusion

In this paper, the dynamic characteristics of two different single joint soft-contact mechanisms are simulated. On the one hand, the simulation results and evaluation analysis of the rigid transmission unit in the path planning of the soft-contact mechanism are given based on both the bionic model and the integrated double joint model. On the other hand, the mechanism model simulation of the single joint flexible controllable unit is carried out, and the comparison results of the control dynamics under the three typical space target control applications are given. The simulation results show that both the two mechanism models have the path planning function before the space target contact, and also has the momentum buffering and controllability during the space target contact process. However, the bionic model is slightly better in the comprehensive performance.

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