Dynamics Investigate on Capture Process of rope end Mechanism of Space Manipulator

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Abstract. The rope end mechanism of large space manipulator satisfies the characteristics of large tolerance and soft acquisition, and is an ideal actuator for space acquisition operation. Based on the discretization method, the dynamic model of wire rope is obtained by flexible spring connection. By introducing the non-linear contact force and friction model between the rope and the target, the capture dynamics model of the end mechanism is obtained. The model is used to simulate and analyze the two acquisition strategies of uniform speed acquisition and FA-SC-VT acquisition. It is found that the collision force is uncontrollable and the target is easy to escape during the acquisition process. To solve the above problems, a motion synchronization acquisition strategy is proposed. The simulation results of the three acquisition strategies are compared and verified by the dynamic model. It is found that the motion synchronization acquisition strategy can effectively reduce the collision force between the rope and the target and improve the acquisition capability compared with the uniform acquisition strategy and FA-SC-VT acquisition strategy. It is of great significance to the dynamics study of the acquisition process of large space manipulator.

1. Introduction

With the development of space technology, the future spacecraft will develop in the direction of large-scale, complex and long life. On-orbit service technology has become a research hotspot in the field of aerospace high technology. In order to accomplish on-orbit assembly of large-scale systems such as space stations, on-orbit maintenance of faulty satellites and fuel replenishment of spacecraft, successful capture of target loads is one of the key tasks of space manipulators. In the process of capturing target loads, there will be a great impact between the end-effector and target loads. The cable capture mechanism satisfies the characteristics of large tolerance and soft capture, and is an ideal end-effector. The flexible wire rope capture mechanism has been successfully applied on the Canadian arm (SRMS) [1].

Dynamic modeling of large deformation cable structures has always been a research hotspot of scholars at home and abroad. Danilin AN [2] and NakayaK [3] use lumped mass model to simulate the cable. Kamman J [4] separates the rope into a chain structure consisting of many rigid bodies. The rigid bodies are connected by spherical hinges. The bending deformation between the ropes can be considered, but the axial tension deformation is neglected. Steiner W [5] and Williams P [6] used spring models to study the deployment and recovery of tethered satellites. Yang Qin et al. [7] Using the lumped mass spring damping model, the optimization of launch angle and equivalent cable
damping of space rope net system is studied. Tan Yisong [8] proposed a plane bending flexible wire rope model based on torsional damper spring, and used this model to study the dynamics of flexible wire rope in the process of capturing load chamber. However, this model assumes that the cable only moves in plane and only considers torsional bending deformation. In 1996, Shabana AA proposed the absolute nodal coordinate method [9] for the first time based on the theory of finite element and continuum mechanics, which can truly reflect the dynamic behavior of large deformation flexible bodies. Based on this method, the dynamic models of beam element, plate element and shell element are established by Shabana AA [10-11]. The dynamics of large deformation flexible body based on absolute nodal coordinate method is a hot topic at home and abroad at present. Sopanen JT [12], SugiyamaH [13], Tianqiang [14], etc. are all studied in this aspect. But at present, the absolute node coordinate method can only solve the dynamic modeling of simple structures, and it is difficult to model the rigid-flexible coupling multi-body system of complex mechanisms.

There are two main difficulties in the research of the capture dynamics of rope end effector: first, it is difficult to model the dynamics of rope structure with large flexibility and large deformation characteristics, especially in the space microgravity environment, the internal tension of rope may be very small during the movement, and it is easy to relax, which further increases the difficulty of modeling; [15-19] Second, in the process of capturing the target, There are complex contact collisions between rope and target acquisition rod, end and target adapter. The instantaneous non-linear contact collision force is difficult to measure and calculate, and has a great impact on the safety and stability of the acquisition process [19-21].

In this paper, a large End Effector (LEE), developed by Robot Research Institute of Harbin University of Technology, is used as the research object. The dynamic model of wire rope is obtained by using discretization method and flexible spring connection. By introducing the non-linear contact force and friction model between the rope and the target, the capture dynamics model of the end mechanism is obtained. The capture process was analyzed dynamically. The strategy of motion synchronization acquisition is proposed, which can effectively reduce the collision force between the end mechanism and the target load, and improve the acquisition ability of the mechanism. It is of great significance to the dynamics study of the acquisition process of large space manipulator.

2. Capture Principle of Rope End Actuator
The terminal executor (LEE) consists of three parts: capture module, drag module and lock module. This paper mainly studies capture module. The capture module is realized by driving component and acquisition mechanism. It is composed of rotating ring, fixing ring, wire rope, driving component and so on. The physical figure of the end effector is shown in Figure 1.

![Figure1. Physical diagram of end-effector.](image-url)
The actuator of the flexible capturing mechanism is a flexible capturing ring composed of three wire ropes with greater flexibility. The output shaft of servo motor drives the rotating ring to rotate after deceleration by harmonic reducer and internal gear set. One end of the flexible wire rope is fixed on the fixed ring, the other end is fixed on the rotating ring by hinges. The two ends of the three wire ropes are evenly distributed on the fixed ring and the rotating ring, and the head and the tail are connected, forming a closed ring, i.e. the capture ring. The wire rope is gradually contracted by rotating the rotating ring to complete the target load. The process of charge capture is shown in Figure 2.

3. Modeling of flexible rope
The cable structure can withstand larger tension, but its flexural capacity is weak and has greater flexibility. In the process of capturing the target load, the flexible rope of the end effector has contact collision with the target matching rod, and the force is complex. In addition to stretching, when the rope winding the matching rod, bending stress will also occur in the rope. In order to reflect the movement and dynamic response of the cable structure in the capture process more truly, the tension, shear, torsion and bending of the cable structure must be considered comprehensively. Especially in the space microgravity environment, the cable structure is prone to relaxation and complex deformation can not be ignored.

In this paper, by dividing the rope into several rigid bars, the shape and mass of the rigid bars are consistent with the rope structure of the same size. The rigid bars are connected by a six-dimensional force/moment spring. The tension, shearing, bending and torsion of the rope can be considered. When the discrete section of the rope is infinite, it will be completely identical with the rope continuum, but the increase of the number of discrete bodies will make the design possible. The calculation time is greatly increased. The simplified cable structure is a typical tree-like multi-body system. The schematic diagram is shown below.

![Figure 2. Capture theory of the rope.](image)

![Figure 3. Discretization model of rope systems.](image)
In Figure 3, each rigid rod represents a discrete segment of wire rope. Six components $F_x, F_y, F_z, T_x, T_y, T_z$ of force and moment are defined. A flexible force is applied between the two components to simulate the large deformation characteristics of the wire rope.

The formula for calculating the flexible force between two bodies is as follows:

$$
\begin{pmatrix}
F_x \\
F_y \\
F_z \\
T_x \\
T_y \\
T_z
\end{pmatrix} = \begin{bmatrix}
k_{11} & 0 & 0 & 0 & 0 & 0 \\
0 & k_{11} & 0 & 0 & 0 & 0 \\
0 & 0 & k_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & k_{11} & 0 & 0 \\
0 & 0 & 0 & 0 & k_{11} & 0 \\
0 & 0 & 0 & 0 & 0 & k_{11}
\end{bmatrix}
\begin{bmatrix}
R_x \\
R_y \\
R_z \\
\theta_x \\
\theta_y \\
\theta_z
\end{bmatrix} - \begin{bmatrix}
c_{11} & 0 & 0 & 0 & 0 & 0 \\
c_{11} & 0 & 0 & 0 & 0 & 0 \\
0 & c_{11} & 0 & 0 & 0 & 0 \\
0 & 0 & c_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & c_{11} & 0 & 0 \\
0 & 0 & 0 & 0 & c_{11} & 0
\end{bmatrix}
\begin{bmatrix}
V_x \\
V_y \\
V_z \\
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix}
\begin{pmatrix}
F_{x0} \\
F_{y0} \\
F_{z0} \\
T_{x0} \\
T_{y0} \\
T_{z0}
\end{pmatrix}

(1)

In the formula, $F, T$ are force and moment, $k$ and $c$ are stiffness coefficient and damping coefficient, $R$ and $\theta$ are relative linear displacement and angular displacement, $V_i$ and $\omega_i$ are relative linear velocity and angular velocity, $F_{i0}$ and $T_{i0}$ are initial force load and moment load respectively.

The stiffness and damping coefficients are obtained according to the properties of wire rope materials.

$$
k_{11} = \frac{EA}{L} \quad \text{is the coefficient of tensile stiffness.}
$$

$$
k_{22} = k_{33} = \frac{GA}{L} \quad \text{is shear stiffness coefficient.}
$$

$$
k_{44} = \frac{G\pi d^4}{32L} \quad \text{is the torsional stiffness coefficient.}
$$

$$
k_{55} = k_{66} = \frac{E\pi d^4}{64L} \quad \text{is the coefficient of bending stiffness.}
$$

In the formula, $E$ and $G$ are the tensile modulus and shear modulus of the material, and $d$ and $L$ are the diameter and length of each small cylinder.

From the calculation formula of flexible force, it can be seen that if the stiffness and damping coefficients of the flexible connection force are controlled according to the actual selection of the wire rope, the deformation, physical and dynamic properties of the cable model can be in accordance with the actual performance of the cable.

4. Capture dynamics model

According to the discrete rope model, the collision relationship between each small rope segment and the target is determined by judging the minimum distance between them, and the contact collision detection is realized. When there is no contact between the rope and the target, there is no restraint relationship between them. The target moves freely. When the two contact, the target is restrained by the rope. By introducing the force restraint of the contact force instead of the geometric restraint, the contact dynamics model of the capture process is realized. In this paper, the normal contact force
between the wire rope and the adapter is calculated by using Hertz contact theory model [14]. The model equates the collision process of the object in practice to a non-linear spring-damper model based on penetration depth, which converts the contact non-linearity problem into material non-linearity problem.

Normal contact force based on Hertz theory:

\[ F_n = K \delta^2 + C \dot{\delta} \quad (1.5 < e < 2) \]  

(2)

\[ K = \frac{4}{3\pi(\sigma_1 + \sigma_2)} \left[ \frac{R_i R_j}{R_i + R_j} \right]^{1/2} \]  

(3)

\[ \sigma_i = \frac{1 - \nu_i^2}{\pi E_i} (i = 1, 2) \]  

(4)

In the formula, \( R \) is the contact radius, \( K \) and \( C \) are the contact stiffness and damping coefficients between the wire rope and the target adapter, which are related to the material characteristics of the contact pair. \( \delta \) is the embedding depth between the two bodies and \( \dot{\delta} \) is the normal relative velocity at the contact point. In this paper, the equivalent contact stiffness and damping are determined according to the material properties and geometric characteristics of the wire rope and the capture rod.

In addition to the normal contact force, tangential friction exists when the wire rope contacts the target adapter. The modified Coulomb friction model is used to calculate the tangential friction force.

Tangential friction model:

\[ F_t = -\mu_d c_d F_n \frac{V}{v} \]  

(5)

In the formula, \( \mu_d \) is the sliding friction coefficient, \( c_d \) is the dynamic correction coefficient and \( V_t \) is the relative tangential velocity.

According to the flexible wire rope model and the contact dynamic model of the capture process, the first kind of Lagrange method is used to establish the dynamic model of the multi-body system of the end-effector capture process.

![Figure 4. Sketch of Capturing dynamic mode of LEE.](image-url)
The Cartesian coordinate $\mathbf{R}=[x, y, z]^T$ of the center of mass of each rigid body and the Euler angle $\gamma=[\psi, \theta, \phi]^T$ reflecting the orientation of the rigid body in Figure 8 are defined as generalized coordinates, i.e. $q=[x, y, z, \psi, \theta, \phi]^T$.

Then the kinetic energy of each body can be expressed as:

$$T^i = \frac{1}{2} \dot{q}^T M^i \dot{q}^i$$  \hspace{1cm} (6)

The Lagrange method shows that:

$$\frac{d}{dt} \frac{\partial T}{\partial \dot{q}^i} + \frac{\partial T}{\partial \dot{q}^i} = Q^i$$ \hspace{1cm} (7)

By substituting formula (4) into formula (9), the dynamic equation of each body in free state can be obtained. The equation is as follows:

$$M^i \ddot{q}^i + K^i q^i = Q^i_F + Q^i_V$$ \hspace{1cm} (8)

In the formula: $n$ is the total number of entities in the system.

By assembling the dynamic equations of $n$ individuals in the system with constraints, the dynamic equations of the end-effector multi-body system can be obtained. The equation is as follows:

$$M \ddot{q} + C \dot{q} + Q^T \lambda = Q_F + Q_V$$ \hspace{1cm} (9)

The corresponding constraint equation is:

$$C(q, \dot{q}, t) = 0$$ \hspace{1cm} (10)

In the formula, $q$, $M$, $K$, $\lambda$, $C$, $Q_F$ and $Q_V$ are respectively generalized coordinate array, generalized mass matrix, stiffness matrix, Lagrange multiplier array, Jacobian matrix of constraint equation, generalized force and generalized velocity quadratic term matrix.

5. Simulation analysis

In order to reduce the complexity of the control system and improve the reliability and efficiency of load capture, considering the influence of residual vibration on the operation process of the end-effector during the operation of a large manipulator, during the process of load capture, the joints of the manipulator are locked, that is, when the manipulator locates the end-effector to a position that meets the requirements of the tolerance range of the end-effector capture, the manipulator is locked. Joint braking, the capturing operation of load is completed independently by the end effector. It is assumed that the acquisition process has little effect on the position and posture of the manipulator or that the position and posture of the manipulator are maintained during the acquisition process. Therefore, in the simulation process, the end effector is fixed and the load is floating freely. The parameters used in the modeling are shown in the following table 1.

| Name                          | Numerical value | Name                          | Numerical value |
|-------------------------------|-----------------|-------------------------------|-----------------|
| Rope length                   | 300mm           | Target quality                | 200kg           |
| Cable diameter                | 5mm             | Contact stiffness             | 1e5N/mm         |
| Tensile modulus of rope       | 206GPa          | Contact Damping               | 50Ns/mm         |
| Shear modulus of rope         | 80GPa           | Friction coefficient          | 0.25            |

The traditional uniform acquisition strategy and FA-SC-VT acquisition strategy are simulated and analyzed by using the acquisition dynamics model. The simulation results are as follows:
The simulation results show that the collision force will be greater when the target is captured by the traditional uniform capture strategy. The collision force produced by FA-SC-VT capture strategy is much smaller. But there are some problems in these two capture strategies, such as uncontrollable collision force and easy escape of target.

Aiming at these problems, a motion synchronization acquisition strategy is proposed, which uses visual system to lock the target, shrink the rope and adjust the shrinkage speed of each rope to ensure that the distance between each rope and the target is equal in the process of shrinkage until the target is finally captured. The strategy flow chart is shown in Figure 6 below.

![Figure 6. Motion synchronization capture strategy.](image)

The capture dynamics model is used to simulate and analyze the synchronous capture strategy, and the change diagram of collision force during the end-of-rope capture process is obtained. As shown in the following figure:
From Figure 7, it can be seen that compared with the traditional uniform acquisition strategy and FA-SC-VT acquisition strategy, the motion synchronization acquisition strategy can greatly reduce the number of collisions in the acquisition process, effectively reduce the collision force between the rope and the target, improve the acquisition capability, and avoid the escaping phenomenon of the moving target in the acquisition process. It is very important to study the dynamics of the capture process of large space manipulator.

6. conclusion
The dynamic model can be used to simulate the process of space rope capture. It provides an effective way to solve the difficulty of large space target acquisition. The problems of uncontrollable collision force and easy escape of target are found in the traditional uniform velocity acquisition strategy and FA-SC-VT acquisition strategy by simulation. To solve these problems, a motion synchronization acquisition strategy is proposed. The simulation results are also given. It is found that compared with the uniform velocity acquisition strategy and FA-SC-VT acquisition strategy, the motion synchronization acquisition strategy can effectively reduce the collision force between the rope and the target and improve the acquisition ability, which is of great significance to the research on the dynamics of large space manipulator acquisition process.

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