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Analysis on Modeling and Motion Simulation Based on Manipulator End Executor of Small Satellite during the Grasping Process

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Abstract

This paper introduces the components and functions of institution aiming at docking capture link of the small satellite manipulator end executor. Putting forward to Euler method and quaternion as the theoretical basis, kinetics of grasping institution the relative position and attitude are modeling and analyzed. The axial tilt grab conditions of the simulation analysis are finished by the ADAMS software. The results of the simulation analysis for the relative position and velocity and the hand-grasp collision force are concluded.

Keywords: *End executor institution, Kinematics analysis, Movement modeling, Simulation analysis*

1. Introduction

Since the twenty-first century, the development of the world aerospace industry is changing so rapidly that the human explore the space deeper and deeper. Currently a large number of the man-made satellites have been launched. It is widely used for communication, meteorological, reconnaissance, navigation, geodesy, volley and so on. So the man-made satellite space on-orbit service technology, such as capture recovery, on-orbit assembly repair, science payload care, becomes more and more important. On-orbit capture technology is a key technology in the premise and guarantee among the on-orbit service technology [1]. The space agency of foreign developed countries attaches great importance to on orbit capture technology application development, such as the United States "Orbital Express Program", Russian classic "cone-rod" docking mechanism and Japan's ETS-VII end executor mechanism ERA and ARH etc[2].In China, many universities have gradually carried out research on the on-orbit capture technology.

The realization of small satellites grasping basic conditions is to ensure that in the approximation actuator the end executors' active part and passive part cannot collide each other at the grab-connect process. Therefore, to obtain and control the pose parameters of the two parts have become the key success to grasp. In a word, only to determine the position and attitude of the target satellite capture range which is the designed the end executors' active part can successfully capture.

2. The Components and Functions of Grasping Institution

The end executor grasping mechanism's active part is connected mainly through hinge type three claw mechanisms. The three supporting beams are uniformly distributed between the upper and lower plate in the active parts which realize fixed and connected function. Each lock claw has the chute, the upper thread lifting plate's three extending end is provided with a pin shaft which passes through the lock claw. Through the relative sliding, they make completely opening and closing movement. The pin shaft respectively

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hinged the three lock claw's lower parts and three extending end of the plate. The guide rod respectively passes through the upper and the lower screw lifting plate, the plate is fixedly connected with the pull between the active parts of the upper and lowers two plates, which plays a guiding and positioning role. Through the bearing positioning, double rotating threaded rod is fixedly connected with the passive gear through the active part of the axis and the lower part of the extending shaft. The pressure sensor is arranged on the contact surface of the active plate, using stepper motor driver, the transmission part mainly apply for the connecting rod mechanism, screw mechanism, gear mechanism etc. In addition, there are three elastic buffers (both location and transfer function), a signal contact switch and body etc. The passive part is composed of a frame body, a guiding side, passive buffering locator electrical signal contacts, etc. The structure of the end executor is shown in Figure 1.

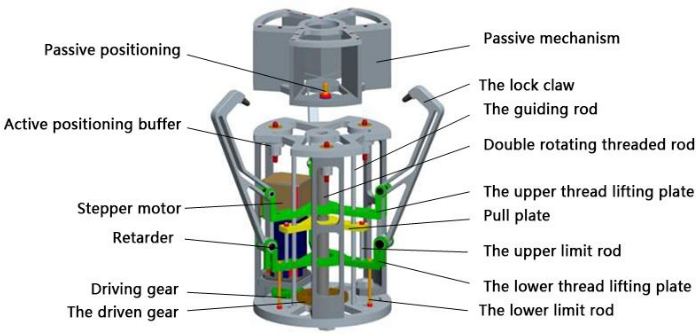


Figure 1. Structure of the End Executor

3. The Relative Position and Attitude Determine of the Grasping Mechanism and Establishment of the Kinematics Model

When on orbit service object as the cooperative targets, the target satellite is usually in near circular orbit, the relative motion model of the inter satellite is relative motion model in rendezvous and docking. But when the service object is non-cooperative target, the target satellite orbit and attitude information cannot be obtained directly. Here the model of relative movement among the elliptical orbit satellite must be adopted in order to complete the theoretical analysis and the method of design of flight trajectory. This paper relates to the service target goals for cooperation, so target satellite lies in a nearly circular orbit [3].

3.1. Definition the Coordinate System of the Grasping Mechanism

In order to describe how the tracking satellite is relative to the target satellite on relative position and attitude motion, we define the following coordinate system, $Ox_1y_1z_1$ is geocentric inertial coordinate system. $Oxyz, Ox_f y_f z_f$ respectively represent of body coordinate system of the target satellite (spacecraft) and tracking satellite (spacecraft). The X axis of the target satellite outward direction along the geocentric vector, the Z axis along the track of normal direction, and meet the right-hand rule as shown in Figure 2.

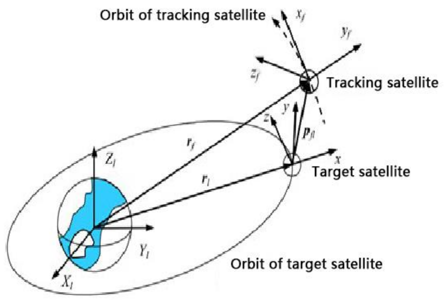


Figure 2. Definition of Coordinate System

3.2. The Introduction and Transformation Attitude Parameters

In the description of attitude motion of the small satellite grasping mechanism, the establishment of grasping mechanism the attitude kinematics equations is based on Euler method and quaternion [4]. Using the Euler method to describe the attitude motion of small satellites have been more mature, but Euler angle will appear singular point when only be used. To avoid this situation, quaternion can be used instead of the Euler method in the kinematics equation [5].

3.2.1. Euler Method and Euler Kinematic Equation: Definition that tracking satellite coordinate system $O_f x_f y_f z_f$ relative to the target satellite coordinate system *Oxyz* pitch angle, yaw angle, roll angle is φ, θ, ψ . Two coordinates system are in accordance with ψ - θ - φ sequential rotation. According to Euler's theorem, the displacement of rigid body around the fixed point can also be synthesized several finite rotation around the point [6]. The relation between Euler angle rate of change and the angular velocity is Euler kinematic equation [7].

$$\dot{\varphi} = \left(\omega_y sin\,\psi + \omega_z cos\psi\right) sec\,\theta \tag{1}$$

$$\dot{\theta} = \omega_y cos\psi - \omega_z sin\,\psi \tag{2}$$

$$\dot{\psi} = \omega_x + \left(\omega_y sin\,\psi + \omega_z cos\psi\right) tan\,\theta \tag{3}$$

On the above formulas, the nonlinear equations in the $\theta = \pm\pi/2$ presence of singularities, so the Euler method has certain limitation which describe the approach stage of two satellite attitude.

3.3.2. Quaternion and Quaternion Kinematics Equation: Quaternion invented by Hamilton is a complex which is the promotion in the four-dimensional space of real numbers [8]. Quaternion can be expressed as *q=[s, v]*, Where *s* is a scalar, *V* is for a three element vector. Quaternion instead of Euler angle in the equations of motion

$$q_0 = q_1 i + q_2 j + q_3 k = [q \quad q_3] \tag{4}$$

The i, j, k is the imaginary unit.

The unit's standardization of quaternion is the quaternion of $q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1$. Assuming three axis angular stars of velocity is $\omega = \lfloor \omega_x \omega_y \omega_z \rfloor$, Get the attitude of quaternion equations motion. That is:

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_z & -\omega_y & -\omega_z \\ \omega_x & 0 & \omega_z & -\omega_y \\ \omega_y & -\omega_z & 0 & \omega_z \\ \omega_z & \omega_y & -\omega_x & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \tag{5}$$

Which can be abbreviated as?

$$\dot{q} = \Omega（\omega）q/2 \tag{6}$$

This equation is a linear differential equation, no trigonometric function is contained, no singularity problems and easy calculation.

4. Dynamic Modeling and Analysis of Grasping Mechanism the Relative Position and Attitude

4.1. Dynamic Modeling and Analysis of Grasping Mechanism the Relative Position

In the Hill coordinate system position vector P that racking satellite centroid relative to target satellite centroid can be described as $\rho_L = [x \quad y \quad z]^T$, in the Hill coordinate system acceleration control which acted on tracking satellites can be described as $a_L = [a_x \quad a_y \quad a_z]^T$ without considering the orbit perturbation [9].

In Hill coordinate system dynamics model of the relative position which target satellite relative to tracking satellites can be described as:

$$x = 2\theta y + \theta y + \theta^2 x - \frac{\mu(R_T + x)}{\left[(R_T + x)^2 + y^2 + z^2\right]^{3/2}} + \frac{\mu}{R_T} + a_x \tag{7}$$

$$\ddot{y} = -2\dot{\theta}\dot{y} - \dot{\theta}\dot{y} + \dot{\theta}^2 y - \frac{\mu y}{\left[(R_T + x)^2 + y^2 + z^2\right]^{3/2}} + a_y \tag{8}$$

$$\ddot{z} = -\frac{\mu z}{\left[(R_T + x)^2 + y^2 + z^2\right]^{3/2}} + a_z \tag{9}$$

In the formulas, μ is the earth's gravitational constant; R_T is position vector model of target satellite centroid in inertial coordinate system; θ is real near angle of point target satellite.

4.2. Dynamic Modeling and Analysis of Grasping Mechanism Attitude

Without considering the disturbance torque, attitude dynamics model of the target satellite in free-tumble space is:

$$\dot{q}_t = \frac{1}{2} q_t \otimes \begin{bmatrix} c \\ \omega_t \end{bmatrix} \tag{10}$$

$$I_t \omega_t + \dot{\omega}_t (I_t \omega_t) = 0 \tag{11}$$

Where, q_t and ω_t are respectively attitude quaternion and attitude angular velocity of the target satellite; $\otimes$ is quaternion multiplication; I_t is inertia matrix of the target satellite.

The attitude dynamics model for tracking satellite:

$$\dot{q}_s = \frac{1}{2} q_s \otimes \begin{bmatrix} 0 \\ \omega_s \end{bmatrix} \tag{12}$$

$$I_s \dot{\omega}_s + \omega_s \times (I_s \omega_s) = T_c + \sigma \tag{13}$$

Where q_s and ω_s are respectively attitude quaternion and attitude angular velocity of the tracking satellite; I_s is inertia matrix of the tracking satellite. T_c is control torque of tracking satellite ; σ is the disturbance torques acting on the tracking satellite.

Attitude dynamics equation which the tracking satellite relative to the target satellite:

$$\dot{\omega} = -\mathrm{I}_s^{-1}\{(\omega + \mathrm{A}_{st}\omega_t) \times [\mathrm{I}_s(\omega + \mathrm{A}_{st}\omega_t)]\} + \omega \times \mathrm{A}_{st}\omega_t + \mathrm{A}_{st}\mathrm{I}_t^{-1}[\omega_t \times (\mathrm{I}_t\omega_t)] + \mathrm{I}_s^{-1}(\mathrm{T}_c + \delta) \tag{14}$$

Formula above mainly gives the relative position and attitude dynamics model of grasping mechanism, but there is no mutual coupling between the relative position and attitude because its dynamics and kinematics are independent of each other.

5. The Simulation Results of the End Executor Grasping Mechanism during the Grasping Process

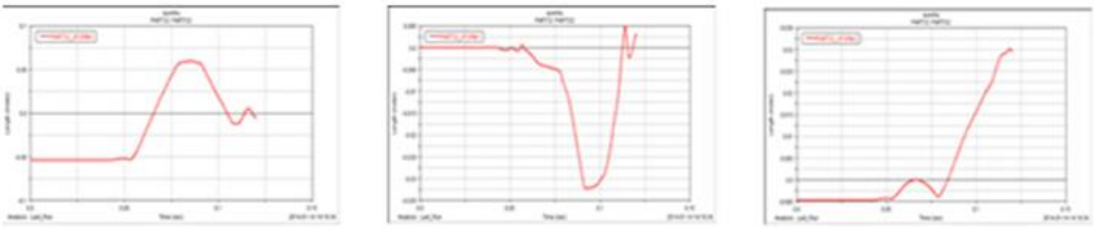
A new end executor grasping mechanism has compact layout, high reliability, complete function etc. A new grasping mechanism which based on 3D solid model has been established by Pro/E, import it into ADAMS further. The kinetic model of grasping mechanism is established during the grasping process, and the grasping mechanism carries out simulation test.

This is grasping test status for the axial tilt grab. The Z direction distance is 30mm and tilt angle is 10°. The simulation time is 0.15s, step is 0.001s. The simulation results during the grasping process as follows. The grasping process shown in Figure 3.

a) Initial state **b) Grasping process** **c) End of grasping**

Figure 3. Process Simulation of Grasping

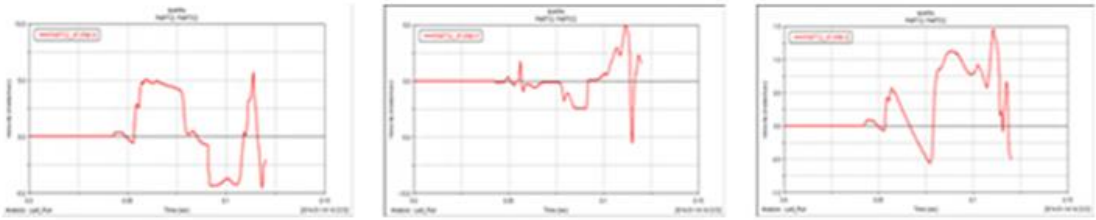
During the grasping process, target relative position changes as shown in Figure 4.



a) X-axis **b) Y-axis** **c) Z-axis**

Figure 4. The Relative Position Change

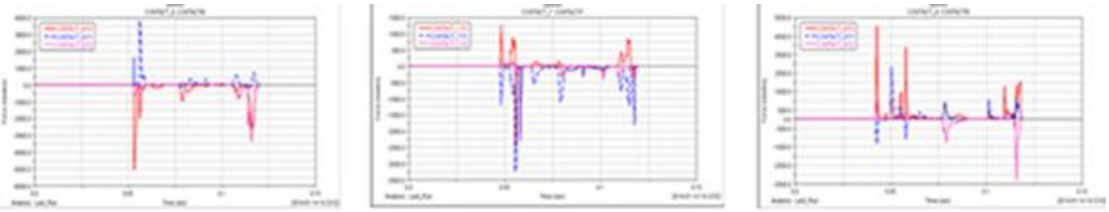
During the grasping process, target relative velocity changes as shown in Figure 5.



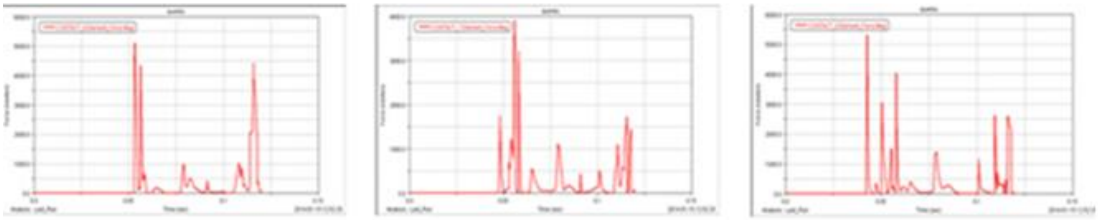
a) X-axis b) Y-axis c) Z-axis

Figure 5. The Relative Velocity Change

During grasping process of simulation, the hand-grasp collision force and the con-collision force as shown in Figure 6.



a) Hand-grasp1 collision force b) Hand-grasp2 collision force c) Hand-grasp3 collision force



d)The con-collision force 1 e)The con-collision force 2 f)The con-collision force 3

Figure 6. The Hand-Grasp Collision Force

From the simulation test, in the initial grasping stage, the target position and attitude change greatly caused by the impact, and it is prone to volatility. Then hand-grasp in contact with passive mechanism, and finally the target is captured. When $0<t<0.05s$, the relative position, relative velocity and the hand-grasp collision force is mean, the end of contact mechanism is not contact with grasping target at present. When $0.05s<t<0.125s$, the relative position and velocity curves of X, Y, Z direction position began to change, the lock claw firstly folded and then began to closer to grasp the target; When $0.125s<t<0.15s$, the relative position and velocity, the hand- grasps collision force with the time prolonged amplitude decreases, finally tends to be stable to catch the captured target.

6. Conclusion

In this paper, the relative position and attitude dynamics modeling are established at the grasping process of the end executor of small satellite. Using ADAMS software to simulate and analyses the change of the relative position and velocity and the hand-grasp collision force in the complex inclined grasp condition.

(1)Grasping mechanism has the certain captured range. The design of the lock claw and sideway one system can to meet the fast acquisition requirements for adapting to the target better ability of the grasping mechanism.

(2)With Euler method and quaternion as the theoretical basis, dynamics model of the relative position and attitude can be given at the final approach stage in order to provide the theoretical basis for model with the end executor in later capture simulation control system.

(3)In the inclined grasp condition, the relative distance and angle of radial and axial deviation reduce to zero gradually because of interaction of the passive frame body and buffer. The hand-grasp collision force can be obtained allowable collision force. At the same time, it can be seen from the heoretical analysis and simulation results tests that the higher the initial docking accuracy, the smaller vibration, and the less stable time in the process of docking.

Acknowledgments

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References

[1] Z. Yuan, W. Yingying, S. Yan and Z. Lili, "Kinematics analysis and simulation of small satellite docking mechanism end executor", Mechanical Structures and Smart Materials, **(2013)**, pp. 460-464.
[2] Z. Dan, "Research on the simulation of the collision between the class of rod - cone docking mechanism", Harbin Institute of Technology, vol. 8, **(2008)**, pp.25-30.
[3] W. Feng, "Research on dynamics and control of the process for on orbit servicing spacecraft to approach", Harbin Institute of Technology, vol. 10, **(2009)**, pp.132-135.
[4] Z. Yuan, S. Lili, H. Naiweng and W. Jian, "Dynamic analysis of small satellite vertical docking test platform", Journal of Harbin University of Science and Technology, vol. 19, no.2 **(2014)**, pp.7-9.
[5] L. Qiang, H. Yiyong, C. Xiaoqian and Z. Yong, "Modeling and Simulating of Independent On-orbit Servicing Spacecrafts' Docking Process", Computer Simulation, **(2011)**, pp. 57-61.
[6] Z. Junqing, "Method and satellite attitude determination based on quaternion", Nanjing University of Aeronautics and Astronautics, vol. 4, **(2008)**, pp.72-76.
[7] J. Boyan, H. Qinglei and S. Zhong, "To control the relative attitude coupling of rendezvous and docking near distance and free target rolling", Harbin Institute of Technology, **(2014)**, pp.125-130.
[8] Z. Yuan, S. Lili, W. Jian and L. Xin, "New six-degree of freedom motion simulator and performance test", Journal of Harbin University of Science and Technology, vol. 19, no. 4, **(2014)**, pp. 40-42.
[9] L. Wei, G. Yunhai, C. Xueqin and W. Feng, "Coupled Control of Relative Position and Attitude for On-orbit Servicing Spacecraft with Respect to Target", Acta Aeronautica et Astronautica Sinic, vol. 7, **(2011)**, pp.56-60.

