Space dual-arm compliant capture control technology based on force/contact fusion

Zuan Li[a], Guopeng Wang*[a], Hailei Wu[a], Yuchao Yan[a] and Fengrui Liu[a]
[a]Shanghai Aerospace Control Technology Institute, Shanghai 201109, China

ABSTRACT

Robot system is the key technology for the development of space on-orbit service technology. In view of the relative movement between the manipulator and the target during the capture process, the force sensor is used to obtain the interaction force and torque information between the gripper and the docking ring, and the manipulator opens the zero force control to adjust the pose. At the same time, according to the contact force information between the gripper and the docking ring obtained by the tactile sensor, whether the dual-arm gripper is closed is judged. In this paper, the system modeling and zero force acquisition control of space manipulator are studied under the research background of space failed satellite acquisition mission. Based on the ground microgravity air flotation simulation system, the experimental results show that the space dual-arm zero force capture control system based on force/contact fusion is feasible and it has excellent performance.

Keywords: Force/contact fusion, zero force control, space manipulator, ground microgravity test

1. INTRODUCTION

As a branch of space robotics, space manipulator has become a hot topic in the field of aerospace research[1]. Capturing space targets is an important application of space manipulators in space tasks, which mainly includes the following main stages: tracking and obtaining the target stage, approaching the target stage, grasping stage, and hybrid control stage after grasping[2]. Among them, the grabbing stage is crucial to the whole capture process. The specific capture process is shown in Figure 1.

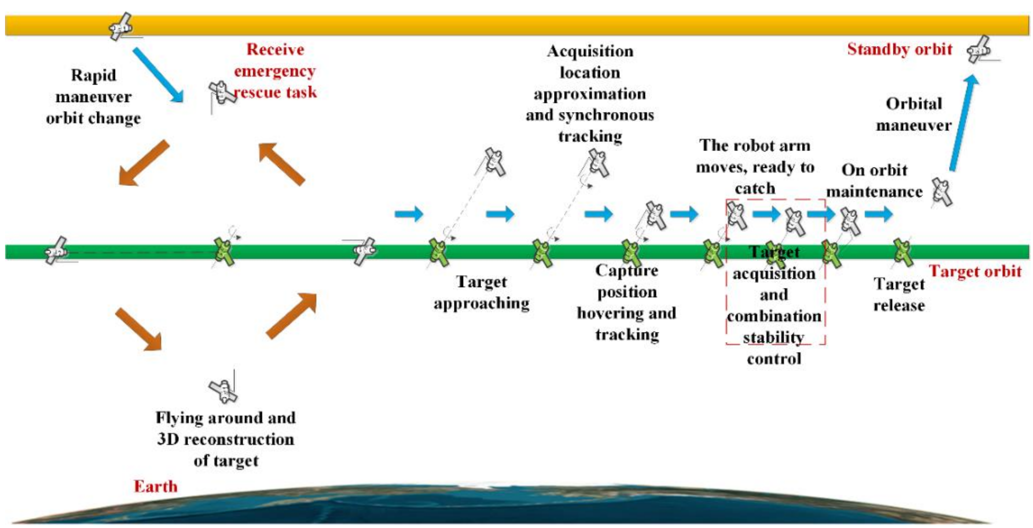

Figure 1. Space manipulator system captures the target process.

For the grasping stage, Wang proposed a visual servoing control method for manipulator based on velocity feedforward[3]. The integral control method was introduced to compensate the predicted velocity, which overcomes the influence of the

*guopwang@163.com; phone 19921845396

International Conference on Optics, Electronics, and Communication Engineering (OECE 2024), edited by Yang Yue, Proc. of SPIE Vol. 13395, 133950G · © 2024 SPIE · 0277-786X · Published under a Creative Commons Attribution CC-BY 3.0 License · doi: 10.1117/12.3048693

motion of the end coordinate system in the discrete system on the target prediction; Javier presents an optimal control approach to guiding the free-floating satellite-mounted robot, using visual information and considering the optimization of the motor commands with respect to a specified metric along with chaos compensation[4]; In our previous work[5], we proposed an autonomous motion planning method for a dual-arm space robot to capture a failed satellite. These methods all ideally assume that the end effector of the manipulator will be fixed on the target and the system is a stable rigid body system during the acquisition and control process of the manipulator. However, in the actual acquisition task, due to visual measurement and external interference, it is not guaranteed that the manipulator will firmly grasp the target, that is, in the subsequent system control process, the manipulator and the target may move relative to each other[6], and the specific analysis is shown in Figure 2.

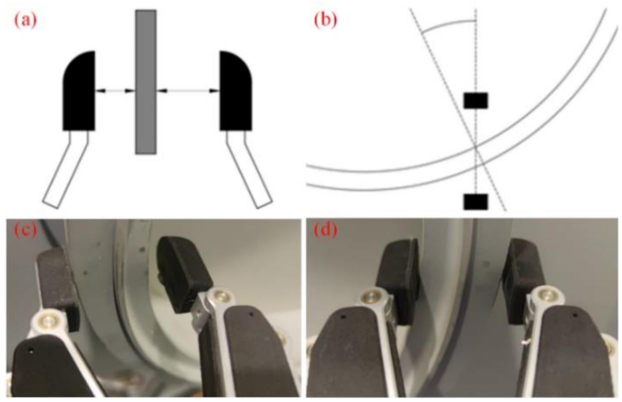

Figure 2. Schematic of the grasping process. (a\c) The distance between the left and right of the gripper and the docking ring is different; (b\d) Deviation of gripper closure from the normal direction of the contact surface.

In view of the relative motion between the manipulator and the target in the grasping process, this paper uses a force sensor to obtain the interaction force and moment information between the gripper and the butt ring, and adjusts the posture of the manipulator by adopting zero-force control. At the same time, according to the contact force information between the gripper and the butt ring obtained by the tactile sensor, whether the double-arm gripper is closed or not is judged. In the second section of this paper, the dynamic model of the space manipulator is established. In the third section, a zero-force control scheme of the target capture with two manipulator arms is proposed. In the fourth section, the experiment of capturing a failure simulation satellite is based on this scheme.

1.1 Method

The key link of target capture using space manipulator is the grasping stage. Due to the influence of the space environment, the collision in space capture is significantly different from the ground situation. The main difference is that in the case of space, the collision has a strong impact on the manipulator system, which will affect the configuration of the manipulator system. In particular, the attitude of the base will change, which will also affect the momentum of the system [7]. For the analysis of the collision process, the main purpose is how to avoid, reduce and control the impact of the collision force on the system. The impact of the collision force on the system is manifested in the change of the momentum of each part of the system, which mainly includes the momentum of the control system such as the base, manipulator and reaction flywheel [8]. Using the conservation relationship between linear momentum and angular momentum, the momentum of the space manipulator system is expressed as the sum of the above parts and the conservation relationship between linear momentum P and angular momentum L of the system is as follows:

$$\begin{bmatrix} P \\ L \end{bmatrix} = H_B \begin{bmatrix} v_0 \\ \omega_0 \end{bmatrix} + H_c \dot{\theta} + \begin{bmatrix} 0 \\ r_0 \times P \end{bmatrix} \tag{1}$$

where, $H_B \in R^{6\times6}$ represents the inertia matrix associated with the platform base, v_0, ω_0 and r_0 represent the linear velocity, angular velocity and centroid position vector of the base; H_c represents the base-manipulator Jacobian matrix; $\dot{\theta}$ represents the manipulator joint angular velocity vector.

2. DUAL-ARM ZERO-FORCE CONTROL SCHEME FOR SPACE FAILED SATELLITE ACQUISITION

2.1 Flow of dual-arm zero force control algorithm for failed satellite acquisition

The acquisition of space failed satellites requires space robots to have autonomous planning and decision-making ability, and to work normally in unknown environments. Firstly, the failed satellite is in rolling motion, and the position and orientation information of the capture point is obtained through real-time measurement by the hand-eye camera installed at the end of the manipulator. However, due to the deviation of the image measurement results, and the disturbance of the base caused by the movement of the robot, the gripper cannot firmly capture the docking ring. Therefore, it is necessary to obtain the interaction force and torque information between the gripper and the docking ring by the force sensor to realize zero force control, and determine whether the capture is completed by the tactile sensor on the gripper finger.

The flow of dual-arm zero force control algorithm is shown in Figure 3, and the main steps are as follows:

(1) Set the capture threshold $F_{\lim}, N_{\max}$ (respectively, the contact force threshold of the gripper, the maximum number of times to meet the contact force threshold) and the maximum allowable time $t_{\max}$;

(2) Move both arms to the capture point according to the measurement data of the hand-eye camera, and the gripper is closed;

(3) Read the six-dimensional force/contact force data, if $N \geq N_{\max}$, consider that the capture end algorithm has been completed, otherwise proceed to the next step;

(4) Determine the gripper contact force Fi, if $\forall F_i \geq F_{\lim}, i = 1, \cdots, 4$, $N++$, otherwise $N = 0$;

(5) The zero-force position controller calculates the desired joint angle under external force according to the six-dimensional force and joint angle information;

(6) The joint controller takes the desired angle as input, generates the joint control torque, and controls the joint movement according to the desired value;

(7) If $t \leq t_{\max}$, let $t = t + \Delta t$ and go to step (3); Otherwise, it is considered that both arms cannot capture the target within the maximum admissible time and the algorithm stops.

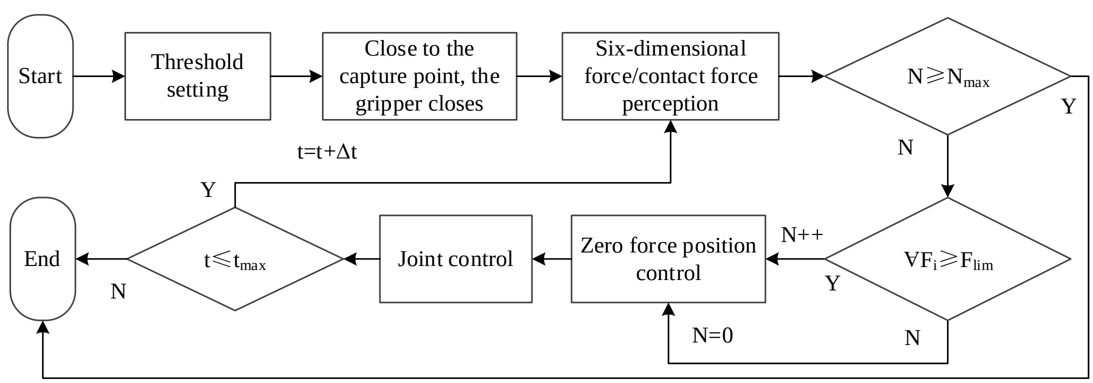

Figure 3. Flow chart of autonomous motion planning and control algorithm for manipulator

2.2 Zero force control based on position control

The zero-force control method based on position control is to sense the external force magnitude and direction of the docking ring on the manipulator through the six-dimensional force sensor, introduce the gravity and friction compensation of the manipulator in the ground test, and then the zero-force position controller calculates the resultant force to obtain the desired joint angle of the manipulator and sends it to the manipulator driver. The actuator controls the joint motor to realize the action control of the joint and feedback the current position and angle of the joint. The control system of the zero force control technique based on position control is shown in Figure 4.

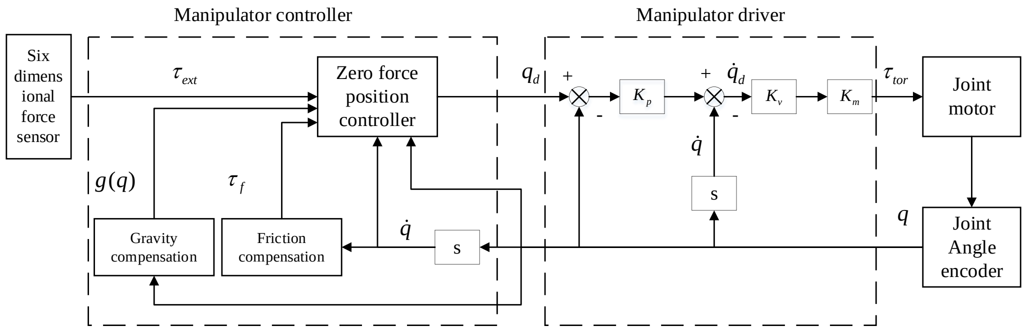

Figure 4. Diagram of zero force control system based on six-dimensional force sensor.

Joint motor output driving moment is:

$$\tau_{tor} = K_m K_v [K_p (q_d - q) - \dot{q}] \tag{2}$$

where, K_p , K_v and K_m respectively represent the position gain, velocity gain and motor torque sensitivity of the joint controller, q_d , q and $\dot{q}$ denote the desired angle, current angle, and current angular velocity of the manipulator.

The desired angle value of each joint is as follows:

$$q_d = K_p^{-1} [K_v^{-1} K_m^{-1} \times (g(q) + \tau_{ext} + \tau_f) + \dot{q}] + q \tag{3}$$

where, $g(q)$, τ_{ext} and τ_f represent the gravity compensation value, external force and friction compensation value respectively.

3. EXPERIMENTS AND RESULTS

3.1 Experiment setup

The scenario of this test is shown in Figure 5, and the hardware configuration is as follows: 3-DOF air flotation simulator for serving/failed satellite; The space manipulator is UR5; Gripper is RG6; The six-dimensional force sensor is HEX-E; The contact force sensor is a film pressure sensor. Control and measurement computer; The measurement system is the OptiTrack Motive system, which is used for absolute measurement and can calculate the centroid position and attitude of the simulator.

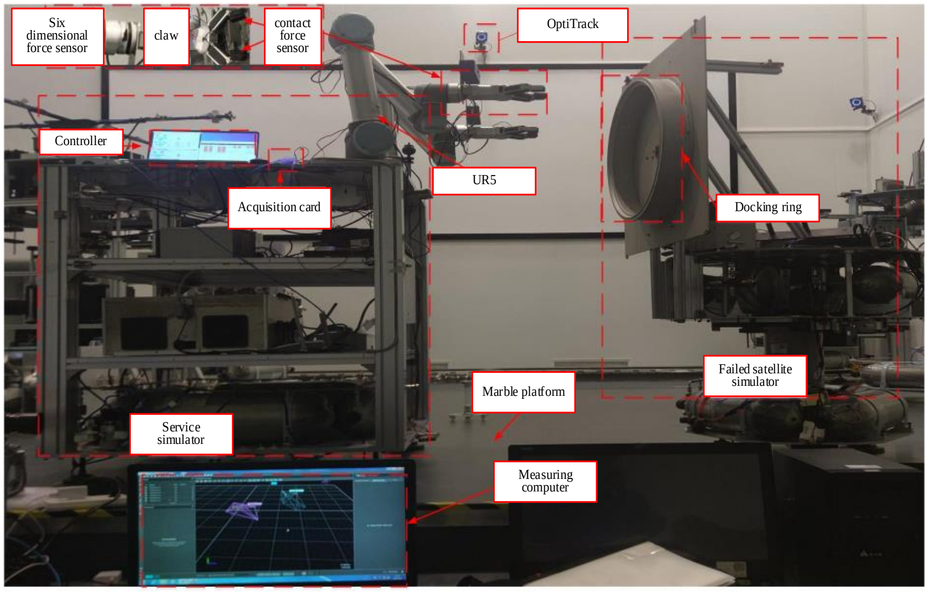

Figure 5. Schematic diagram of dual-arm compliant capture docking loop system.

3.2 Results

During the whole capture operation, the external force and torque of the manipulator, the contact force of the gripper, the relative distance of the simulator and the rotation angle are as follows (since the position and orientation of the left and right arms are basically the same during the capture process, the data of the left arm are used in this paper for display):

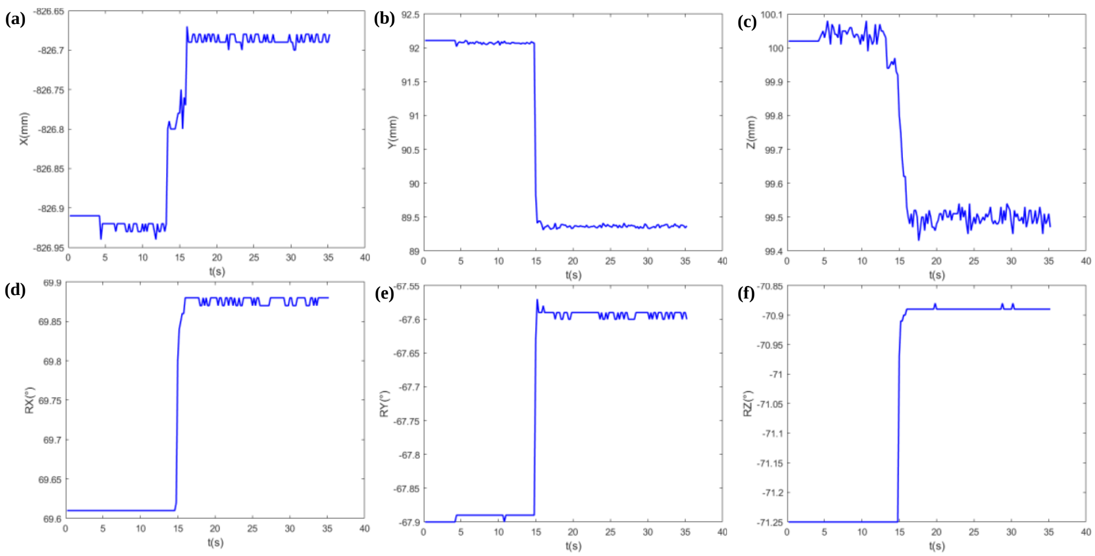

Figure 6. Curve of left arm pose versus time during docking loop capture

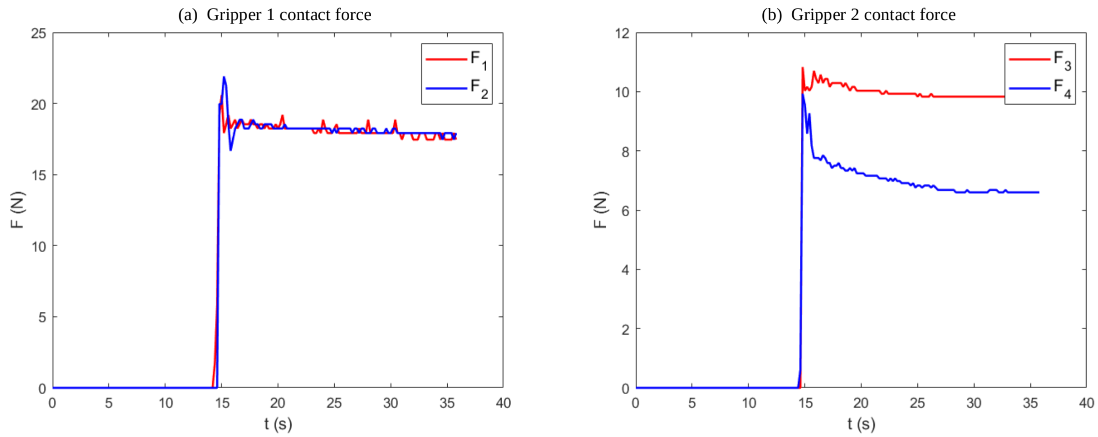

Figure 7. Curve of the gripper contact force with time during the capture of the docking ring

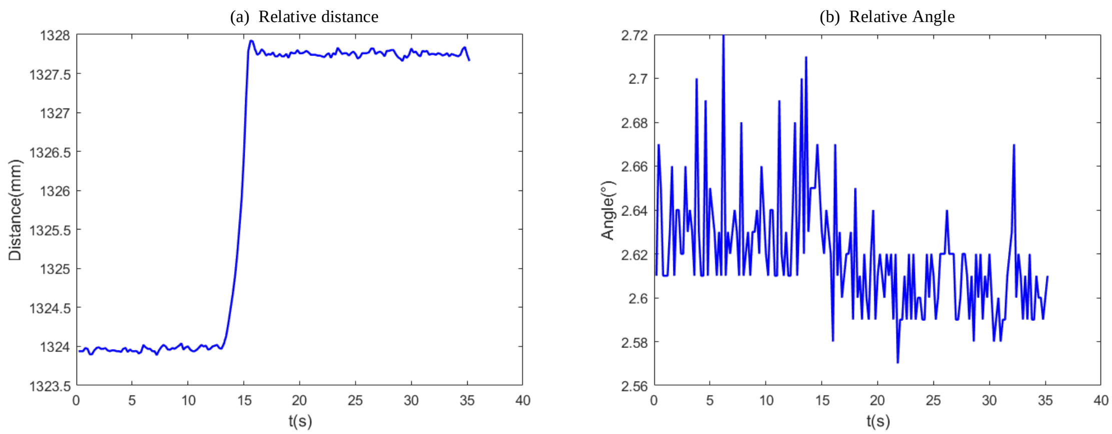

Figure 8. Curve of relative distance and angle change between service simulator and target simulator of docking loop capture process

As can be seen from Figures 6-8, during the capture process, the pose of the left arm was adjusted under the action of external force/torque (0.21 mm, 2.72 mm, 0.48 mm, 0.27 °, 0.32 °, 0.36 °). The tactile sensors at the end of the capture have contact force information, and the relative distance and rotation angle between the service simulator and the target simulator are changed in the range of 0.17mm and 0.07 °, respectively.

4. CONCLUSIONS

Capturing space failed satellites has important application value in new space missions in the future, which has been widely concerned and studied. In this paper, a dual-arm zero force acquisition control technology based on force/contact fusion is designed for this mission background. In the closing process of the gripper, the data of the force/torque of the manipulator end and the contact force of the finger are collected, and the zero force capture control is opened to realize the fixed connection between the space manipulator and the docking ring. Finally, the method is verified by experiments based on the ground microgravity air flotation simulation system. The results show that the relative distance between the service simulator and the target simulator is 0.17mm and the relative angle is 0.07 °after the acquisition. Considering the measurement noise, the two simulators can be considered as fixed connection.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 12102248, 62204151, 12102253), the Advance Research Projects (Grant No. D030309).

REFERENCES

[1] Flores-Abad, A., Ma, O., Pham, K., et al., "A review of space robotics technologies for on-orbit servicing," Progress in Aerospace Sciences, (68), 1-26 (2014).

[2] Cheng, W., Tianxi, L. and Yang, Z., "Grasping strategy in space robot capturing floating target," Chinese Journal of Aeronautics, (5), 591-598 (2010).

[3] Wang, R., Liang, C., Pan, D., et al., "Research on a visual servo method of a manipulator based on velocity feedforward," Space: Science & Technology, (2021).

[4] Alepuz, J. P., Emami, M. R. and Pomares, J., "Direct image-based visual servoing of free-floating space manipulators". Aerospace Science and Technology, (55), 1-9 (2016).

[5] Wang, G., Wu, H., Cao, S., Han, F., Di, X. and Shen, S., "An autonomous motion planning method of a dual-arm space robotic system for capturing failed satellites," ICGNC, (2022).

[6] Xie, Y. and Wang, Y., "Adaptive recursive control of space service Robot," Flight Control and Detection, (1), 63-70 (2018).

[7] Flores-Abad, A., Zhang, L., Wei, Z., et al., "Optimal capture of a tumbling object in orbit using a space manipulator," Journal of Intelligent & Robotic Systems, (2), 199-211 (2017).

[8] Qiao, G., Gao, H., et al., "Ground demonstration system based on in-orbit assembly oriented manipulator flexible force control," High Technology Letters, (03), 271-278 (2017).