Development of Compliant Control Technology in Space Capture

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Abstract. Based on the background of compliance control, this paper first introduces compliance control's significance, then analyzes the advantages and limitations of the current mainstream compliance control, including Impedance control, Force/position hybrid control, Modern, compliant control, Intelligent, compliant control. Moreover, this paper puts forward the limitations and the possible development direction of these schemes.

Keywords: Compliance control, On-orbit service, Space docking, Space capture technology.

1. Introduction

With the development of space technology, space docking has developed from cooperative target docking to non-cooperative target docking. Non-cooperative target docking technology can be used to realize docking between any spacecraft in space and expand the scope of space activities, such as space garbage cleaning, satellite recovery, fuel supply, parts replacement, system upgrade, and other space activities. Non-cooperative target docking technology has high application value and military significance, and the world's space powers are actively researching and testing it. Therefore, it is urgent to speed up the research on docking technology for space non-cooperative targets. In the non-cooperative target docking technology, capturing space targets is an important part of the space manipulator system to perform tasks, which inevitably leads to a collision. A collision could cause damage to equipment or even fail a capture mission. Therefore, measures must be taken to suppress the collision in capturing the target, the compliant control method.

2. Background

In performing fine control tasks, the end of the space manipulator is in contact with the target, and contact forces will be generated. Excessive contact force may spring the target apart and make the contact part of the target bear an excellent impact load, which will cause local deformation and structural damage to the target and the manipulator itself.

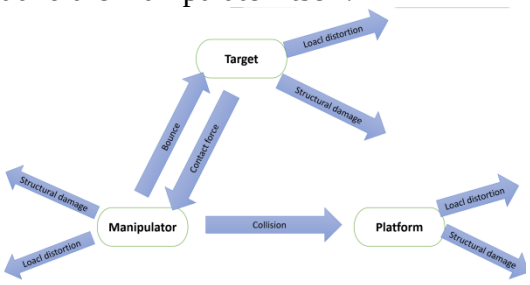


Figure 1. Technical background

Therefore, a compliant control strategy must be adopted. From the initial position to the reserve position, the Dobby system needs to avoid collisions between the mechanical arm, roadblocks, and dobby. It avoids dobby pose error produced in the target ontology appears more considerable difference, the power of the manipulation of the vehicle at the same time, target motion state and the space environment, such as light dynamic change, increased the difficulty of accurate motion planning. On the other hand, the contact operation in the process of the multi-arm task requires the accuracy of pose and force/moment, as well as the mutual pose and interaction force between multi-

arm. In the controller design, it is necessary to consider the task precision requirement, the real-time performance of online calculation, the accuracy of target modeling, and other factors.

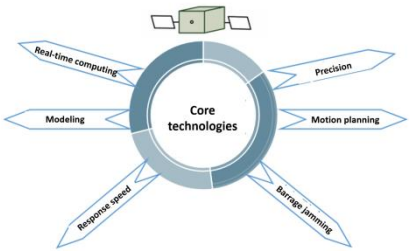


Figure 2. Core technologies

3. Research significance

In the non-cooperative target docking technology, capturing space targets is an important part of the space manipulator system to perform tasks, which inevitably leads to collisions. A collision could cause damage to equipment or even fail a capture mission. Therefore, measures must be taken to suppress the collision in capturing the target. By studying the path planning, optimal configuration, and non-contact impedance control of the space manipulator in the non-cooperative target docking technology, the reasonable path planning of the space manipulator can ensure the stability of the system base posture during operation. By studying the optimal collision configuration of the space manipulator, the impact of the collision force on the angular momentum of the system is minimized. The safe and stable capture of non-cooperative targets can be achieved by the non-contact impedance control of the manipulator, and the impact force can be controlled within the acceptable range.

4. Technical Scheme

4.1. Impedance control:

Impedance control realizes force control indirectly by adjusting reference position and can be divided into position impedance control and force impedance control. Working condition of practical application, it is difficult to measure and forecast. Even the smaller measurement error will lead to a big error output and, therefore, LASKY, etc., put forward the inner and outer loop control strategy. . By establishing the quadratic performance index of force error, the correction rate of the reference position of the outer loop is obtained, and the dynamic uncertainty is compensated in the position control of the inner loop. Dong Xiaoxing used the force compliance impedance control method based on position to realize the compliant control of the space manipulator. SALISBURY defines the linear relationship between end-effector force and position. It selects the stiffness matrix to define the end-compliance of the manipulator in the constraint direction to realize the compliant control, but this method ignores the dynamic global stability. YAO et al. introduced sliding mode control into impedance control. An ideal impedance relationship is included in sliding mode, but its accurate tracking control of force requires accurate modeling of the environment, which has obvious defects. In impedance control, virtual impedance has been widely used in control methods to meet the application requirements of modern robots. NAKABO proposed the concept of visual impedance based on virtual impedance, which combined visual feedback information with impedance control to realize impedance control of robot end-effector.

4.2. Force/position hybrid control:

The core of force/position hybrid control is to use force control in some degrees of freedom and position control in the rest of the system to achieve the goal of comprehensive control. In the force/position hybrid control process, the control mode can be changed according to whether the system is in contact with the external environment. The contact force can be controlled to change

with the expected value, but the controller structure should be determined according to the system's dynamic characteristics and environment. The classic force/position hybrid controller is shown in Figure 3.

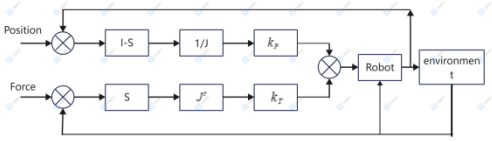


Figure 3. Classical R-C controller structure diagram

Both the position control loop and the force control loop are completed independently in their respective constraint Spaces. In the hybrid control, it is necessary to constantly switch back and forth between the two Spaces, which has high computational complexity. Meanwhile, the coupling effect of the end force and position of the manipulator is not considered in this method, so the system stability is poor. ZHANG et al. proposed to directly control the joints of the manipulator by transforming the expectation of position into the expected angle of each joint. Based on the classical R-C controller, Qin Haiqiang introduced the gradient projection method, finally designed and realized the mixed control method of force/position based on the gradient projection method, and verified the method's feasibility through simulation. The mixed control method of force/position has been widely used in industrial production.

4.3. Modern, compliant control:

The space manipulator system is highly nonlinear, and many unknown disturbances affect the system. It is challenging to apply the classical control theory when executing the capture task because of the uncertainty of model parameters, external disturbance, and non-cooperative target capture parameters. Therefore, compliant control combined with the intelligent algorithm is also a major development direction of space manipulator control methods. Ma Xiaoliang introduced the adaptive algorithm into the impedance controller and designed the adaptive impedance controller, which indirectly adjusted the target impedance parameters and improved the adaptability and anti-interference ability of the system to the environment. Gao Daoxiang et al. introduced an adaptive algorithm to solve the problem that the force/position hybrid controller was vulnerable to external interference and unstable. The system could adjust the system parameters by itself in response to external environmental interference, thus improving the robustness of the system. OSYPIUK et al. improved the model tracking control algorithm according to the mixed control requirements of mechanical arm force/position, adding model output, controlled object, and model feedback to realize contact force control and increase the robustness of the system. SONG et al. added a sliding mode structure with a smooth, robust compensator into the control system, which enhanced the anti-interference capability of the system. onsidering the contact stiffness of the unknown environment under the condition of force/position control, CHIAVERINI, parallel with the expected force feedforward inverse dynamics equation, is adopted to form the controller. Moreover, he designed an adaptive update algorithm driven by an error of force to implementation constraints on the direction of force control and no constraint on the direction of motion control. Its model is too complex to be solved in the actual problem. Therefore, its application has limitations.

4.4. Intelligent, compliant control:

Some researchers have applied the artificial intelligence method to the intelligent control of manipulators. Zhang Qingli et al. combined the fuzzy adaptive method with compliant control to achieve compliant grasping control of a three-finger space robot and achieved satisfactory experimental results. CONNOLLY et al. combined the multi-layer forward feedback neural network and force/position hybrid control in the control of the manipulator. The feedforward neural network was used to identify the uncertain model parameters in the manipulator system and was successfully applied to the simulation control of the 2-DOF manipulator. JEON et al. successfully applied the machine learning algorithm combined with force/position hybrid control to the control of the

manipulator and found that the force and position errors in each operation were corrected, showing asymptotic stable characteristics. JUNG et al. applied the neural network algorithm to the impedance force control. The neural network algorithm was used to compensate for the uncertainty of the robot model in control, and the impedance controller for the driving torque and position of the robot increased the robustness of the system. TANAKA et al. used the online learning method based on the neural network to adjust the impedance control parameters and applied them to the impedance control of the manipulator. By adjusting the end position, speed, force, and environmental identification parameters of the mechanical arm, the control system had good robustness. XU proposed a combination of active compliance and passive compliance. For the designed mechanical wrist, fuzzy control was used to carry out the jack experiment. YANG et al. used fuzzy rules and language variables to set neural network parameters and optimized the system through neural network optimization so that the system has an adaptive ability to compensate for interference. Zhou Xiaodong et al. combined the particle swarm optimization algorithm with the impedance control model to optimize the impedance control parameters, and the simulation experiment proved that the control method has good robustness.

5. Problems need to be solved

(1) Space manipulator system has the characteristics of high nonlinear and strong coupling. Traditional control methods (such as PID control) treat the space manipulator system approximately linearly, making the control model unable to reflect the dynamic characteristics of the space manipulator well. Therefore, traditional control methods make it challenging to achieve compliant control of the space manipulator.

(2) In the traditional impedance control, the contradiction between stiffness and flexibility of the system makes its application has certain limitations and needs to be optimized.

(3) It is difficult to determine the control matrix parameters of the hybrid force/position control method when the environment is unknown; Due to the different requirements of force and position on system stiffness, it is difficult to make changes according to the task requirements in actual control.

(4) Modern compliance control theory has many shortcomings, such as a complex control model and small application range, so its theory is mostly verified in a computer simulation. Therefore, it still needs to be improved to apply modern compliance control methods in practical systems.

(5) The combination of intelligent algorithms and traditional control algorithms, such as fuzzy theory, impedance control theory, and neural network learning algorithm, is only in the adjustment stage of control parameters. There is an extensive application space to be explored.

6. Development Direction

The compliant capture technology of the space manipulator is combined with main artificial intelligence algorithms, such as deep learning and machine learning, to achieve the space manipulator for the target object without the operation of astronauts.

Autonomous space catcher. The end of the arm system needs to be equipped with a universal end-effector, which can not only meet cooperative targets but also achieve the capture of non-cooperative targets with certain specifications.

In in-orbit operations, the cooperative operation of the dual-arm or multi-arm system is another development direction for the space manipulator to implement the compliant capture operation. The tolerance performance of the multi-arm system for target capture will be greatly improved, and the success rate of capture will be higher than that of the single-arm system. The multi-arm system also suggests that space robots will entirely replace astronauts' extravehicular activity.

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