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Experimental Research on Trajectory Planning and Control of Space Robot Target Capture

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Abstract: With the continuous deepening of human space exploration activities, space robot service technology occupies an important position in ensuring the reliable and efficient operation of satellites and space stations. Target capture involves the process of trajectory planning before capture, approaching the target to be captured, capturing and controlling the target. Based on this, this paper conducts experimental research on the trajectory planning and control of space robot target capture. This article first analyzes the capture mechanism of the space robot based on the friction elimination theory. In order to plan the path of target capture more accurately, this paper proposes a target motion prediction algorithm under the state of a uniform velocity model to design the impedance control of the robot arm joint space. Finally, an experimental study was carried out to verify the characteristics of the trajectory planning method proposed in this paper. The experimental results show that during the entire target acquisition process, the maximum tracking errors of the attitude control system's X-axis, Y-axis, and Z-axis are 0.003m, 0.002m, and 0.004m. In addition, although the target movement speed is high and the movement direction changes frequently, the tracking accuracy of the robot arm end to the target is still very good.

1. Introduction

In recent years, the research on space exploration activities has gradually deepened, and the tasks that need to be performed in outer space have become more difficult and diverse [1-2]. The application of space robot technology provides an important guarantee for logistics service tasks [3-4]. Space robots can complete tasks such as docking, docking, fuel filling, maintenance, transfer, rescue, and space station construction, which significantly improves efficiency and the quality of task completion [5-6]. Therefore, planning and implementing more accurate control of the trajectory of space robots during target capture has been extensively studied by the academic community and the industry.

Regarding the research of robot trajectory planning, many scholars have conducted multi-angle discussion on it. For example, Vidakovic J studied accelerated robot trajectory planning [7]; Liu J researched on the topic of robot trajectory optimization based on space offset curves [8]; Wang W made optimal planning and design for the robot trajectory by improving the cuckoo search algorithm [9]. It can be seen that in order to improve the accuracy and speed of robot target capture, it is of great practical significance to study the problem of trajectory planning and control.

This paper takes the trajectory planning and control of space robot target capture as the research object, and proposes a prediction algorithm for target motion parameters in the capture process. Then in order to reduce the impact force of the manipulator, the impedance control of the joint space of the manipulator is analyzed, and finally the target capture trajectory of the space robot is optimized. Finally, a space robot manipulator target capture and control experiment are designed, and the characteristics of the trajectory planning method proposed in this paper are analyzed.

2. Trajectory Planning and Control of Space Robot Target Capture

2.1 Principle and Analysis of Target Capture

Based on the concept of friction derotation, the spin axis of the out-of-control target and the rotation axis of the derotation mechanism of the robotic arm must be linear. Considering factors such as different targets, unspecified positions and shapes, and microgravity environment, the robotic arm approaches the capture target during the process, there can be no collision between the hand grasping and the captured target, otherwise it will cause the target to fly away from the captured position [10-11].

The size of the capture range is determined by the envelope range of the space robot manipulator's capture mechanism and the position of the buffer guide mechanism, and the accuracy of the capture is also determined by the envelope range. Therefore, the design of the capture mechanism for space robot target capture needs to meet the following three points:

(1) The capture mechanism has a large grasping range and strong flexibility. If there is a certain angle and displacement deviation between the axis of the capture mechanism and the axis of the target to be captured, it can still ensure that the capture mechanism captures the target and completes the docking;

(2) It should be ensured that capture agencies can capture different and multiple types of targets;

(3) During the capture process, the mechanical arm joint buffer mechanism should have a strong buffer impact load, and should have the performance of autonomously adjusting the deviation from the target to be captured as much as possible, so that the radial direction of the nozzle of the space robot is consistent with the axis of the front section of the mechanical arm. High performance, so that the stability of the target capture process control is high, and the target capture can be completed reliably to prevent damage to both.

2.2 Trajectory Planning and Control of Space Robot Target Capture

2.2.1 Target motion parameter prediction

When the robotic arm moves in the planned trajectory, the pose and speed of the target to be captured will still change, which reduces the tracking accuracy of the captured target. If the movement state of the target can be accurately predicted, and the intersection point between the end point of the robotic arm and the target is selected, the trajectory captured by the space robot target can be planned better and more accurately, and the tracking accuracy of the capture can be improved. Therefore, the Kalman filter method is used to predict the motion state of the target at the end of each trajectory planning cycle of the manipulator through the motion information of the target to be captured obtained by the measurement system, and apply the predicted value to the manipulator trajectory planning. Reduce the occurrence of the problem of target tracking decline caused by target motion [12].

Assuming that the movement of the target is a uniform movement, and at the same time, set the position and speed of the target at a moment before the movement to be $\mathrm{x}(k-1,k-1)$ and

$\mathrm{v}(k-1,k-1)$, respectively, and the speed state noise of the target is W. Then the motion model of the target is shown in formula (1):

$$\begin{bmatrix} \mathrm{x}(k,k) \\ V(k.k) \end{bmatrix} = \begin{bmatrix} 1,t_f \\ 0,1 \end{bmatrix} \begin{bmatrix} \mathrm{x}(k-1,k-1) \\ V(k-1.k-1) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} W \tag{1}$$

It can be seen that the state transition equation of the uniform velocity model is shown in equation (2):

$$A = \begin{bmatrix} 1 & t_f \\ 0 & 1 \end{bmatrix} \tag{2}$$

In formula (2), t_f represents the planning cycle.

2.2.2 Impedance control in the joint space of the robotic arm

In the process of space robot target capture, the impedance control of the robot arm joint space is generally used for the robot arm to avoid obstacles. For example, during human-computer interaction, the robot arm is subject to an external collision. If it does not dodge, the robot arms the joints will be impacted. Therefore, it is necessary to take reasonable measures for the control strategy of each joint of the manipulator, so that when the manipulator is in contact with the target to be captured, the movement of the base will not be affected by a large impact.

For a space manipulator, not only the end of the manipulator can be equivalent to a mass-spring-damping system, but the joint layer can also be equivalent to a mass-spring-damping system. The joint impedance control is shown in formula (3):

$$M_{jd}\Theta + D_{\mathrm{jd}}\Theta + K_{\mathrm{jd}}\triangle\Theta + \tau^* = \tau_{\mathrm{e}} = J^T F_e + \sum_{i=1}^{\mathrm{n}} J_{fi}^T f_i \tag{3}$$

In formula (3), $\tau^* = D_{\mathrm{jd}}\Theta + K_{\mathrm{jd}}\triangle\Theta$. M_{jd}, D_{jd}, K_{jd} represent the expected inertia, damping, and stiffness of the $\mathrm{n}\times\mathrm{n}$ dimensional joint impedance; τ_e represents the equivalent external moment of the joint layer; J_{fi} represents the Jacobian matrix related to the external force at the joint; f_i represents The external force received at each joint of the robotic arm.

2.2.3 Trajectory planning for target capture

The trajectory planning of the robotic arm to capture the moving target needs to pay attention to controlling the robotic arm's end capture mechanism to track the moving target at the desired speed, and reaching a very small range of the moving target is regarded as a successful capture. The capture process satisfies the angle, the joint angular velocity is within a given range and other constraints.

Assuming that the position of the moving target is $p_m(\mathrm{t})$, the position of the grasping mechanism at the end of the robotic arm is p_e, and the speed is v_e, the description of the trajectory planning of the moving target captured by the robotic arm is as follows: It is known that the position of the grasping mechanism at the t end at the current time is $p_e(\mathrm{t})$ speed It is $\dot{p}_e(\mathrm{t})$, and the position of the moving target at the current time is $p_m(\mathrm{t})$ and the speed is $\dot{p}_m(\mathrm{t})$. The condition for successful capture is that the distance between the capture mechanism and the target is less than ε, then the joint path calculation method is shown in equation (4):

$$\theta(\mathrm{t}) = f(p_e, \dot{p}_e, p_m, \dot{p}_m) \tag{4}$$

So that at some point in the future t_g, meets $\left\| p_e(\mathrm{t}_g) - p_m(\mathrm{t}_g) \right\| \prec \varepsilon$.

Suppose the minimum joint angle is limited to $\theta_{\min}$, and the maximum value is limited to $\theta_{\max}$. In the same way, the angular velocity is limited to between $\dot{\theta}_{\min}$ and $\dot{\theta}_{\max}$, and the angular acceleration is limited to between $\ddot{\theta}_{\min}$ and $\ddot{\theta}_{\max}$. The trajectory planning process needs to meet the requirements of the robotic arm as shown in the formula (5) Shown:

$$\begin{cases} \theta_{\min} \le \theta \le \theta_{\max} \\ \dot{\theta}_{\min} \le \dot{\theta} \le \dot{\theta}_{\max} \\ \ddot{\theta}_{\min} \le \ddot{\theta} \le \ddot{\theta}_{\max} \end{cases} \tag{5}$$

It can be seen from the formula (5) that the main indicators to measure the performance of the trajectory planning algorithm are the amount of time t_g used by the end-of-manipulator capture mechanism to track the moving target, and the smoothness of the end-of-manipulator motion trajectory.

3. Trajectory Planning and Control Experiment Design for Space Robot Target Capture

3.1 Space Robot Motion Simulator

The experiment uses the robotic arm hardware-in-the-loop space robotic arm ground verification system. The attitude simulator that captures the target through continuous dynamic simulation of the absolute attitude of the target on the X-axis, Y-axis, and Z-axis, the target simulator's attitude control accuracy is within ±0.002 °, and the three-axis attitude angle maintains accuracy within ±0.001 °.

The tracker consists of four parts: three-axis mechanical turntable, vertical position motion simulation mechanism, air-floating base and swing arm mechanism. In the experiment, it can continuously and dynamically simulate the physical movement of the tracker in the absolute posture of the X-axis, Y-axis, and Z-axis and the relative position of the X-axis, Y-axis, and Z-axis between the tracker and the target simulator. The tracker's X, Y, Z axis attitude angle control accuracy is within ±0.001 °, the vertical position control accuracy is ±0.1mm, and the lateral rotation angle control accuracy is ±0.01 °.

3.2 Experimental Program

The experimental plan adopted in this experiment is: the target to be captured floats on the air bearing table, and it is almost free from external force in the horizontal direction, in a free state, and the movement direction and speed are uncontrolled and random, so as to simulate the space. The environment of the robot target capture experiment.

The target to be captured is placed at the end of the robotic arm, and the system measures the pose information of the free-floating target through a trinocular camera, and plans the movement of the robotic arm to achieve target tracking. Through the joint angle information returned by the joint sensor, the end point pose and the target pose curve of the robot arm are obtained through the positive kinematics solution. When other conditions are the same, the characteristics of the trajectory planning method can be analyzed by comparing the tracking error between the end pose and the target pose.

3.3 Experimental Process

The experiment process is as follows:

First, the trinocular camera obtains the image information of the target to be captured, and then the vision processing computer obtains the pose of the target to be captured relative to the end coordinate system of the robotic arm. Finally, the posture of the captured target is transmitted to the control computer, and the control computer sends the visual data and other control information to the PCI card to realize the control of the robotic arm. The PCI card can realize the complex calculation of the algorithm proposed in this paper, which is helpful for the calculation of the planned trajectory.

The FPGA on the control card is used as the bus communication chip, and the feedback loop signal is obtained from the FPGA of the bottom motor drive layer through the PPSeCo serial bus, and the corresponding instructions are transmitted. The PCI card can be programmed to realize the trajectory planning of the space robot to capture the target and generate the control information of the manipulator joints to control the joint movement of the manipulator through the joint controller.

4. Experimental Analysis of Trajectory Planning and Control of Space Robot Target Capture

4.1 Target Acquisition Trajectory Planning Control Test

In the experiment, the machine first predicts the target motion state, programmable trajectory planning in the PCI card, and controls the manipulator movement according to the planned path. The experimental results of the end of the manipulator and the target motion pose are shown in Table 1:

Table 1: Experimental results of trajectory planning (unit: m)

Time(s)	Y direction end point	Y direction target position	End point in X direction	X direction target position
2	0.47	0.39	0.66	0.48
4	0.40	0.40	0.65	0.65
6	0.37	0.37	0.73	0.74
8	0.38	0.39	0.65	0.67
10	0.36	0.36	0.68	0.68
12	0.40	0.40	0.69	0.70
14	0.34	0.34	0.71	0.71
16	0.35	0.35	0.80	0.81
18	0.36	0.37	0.77	0.77

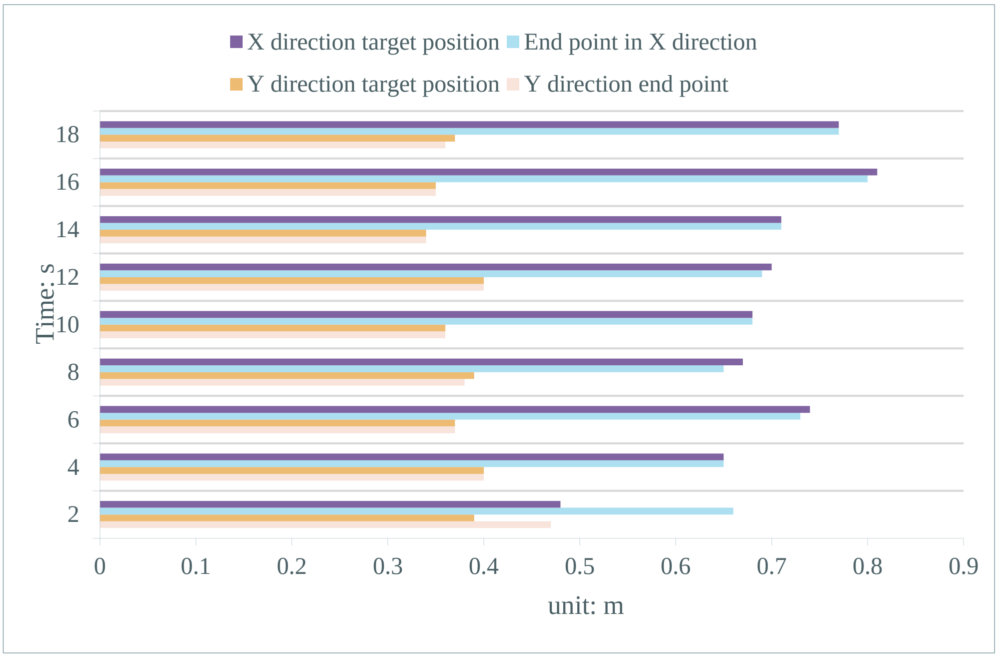

Figure 1: Experimental results of trajectory planning (unit: m)

It can be seen from Figure 1 that in the process of the robot arm tracking the target, although the target movement speed is high and the movement direction changes frequently, the tracking accuracy of the target at the end of the robot arm is still very good. At the same time, the joint impedance control is used to effectively buffer the force impact of the joint, and further reduce the disturbance force impact between the robot arm and the base.

4.2 Target Tracking Error

During the entire target capture process, the three-axis tracking error results of the attitude control system are shown in Table 2 (negative numbers indicate the opposite direction): the maximum error of the X axis is 0.003m, the maximum error of the Y axis is 0.002m, and the maximum error of the X axis at 0.004m..

Table 2: Three-axis tracking error results (unit: deg)

Time(s)	X axis	Y axis	Z axis
0	0.001	0.001	0.000
10	0.000	0.000	-0.002
20	0.002	0.001	0.004
30	0.003	0.002	0.001
40	0.000	-0.001	-0.001
50	0.001	0.001	0.000
60	-0.002	0.002	0.002

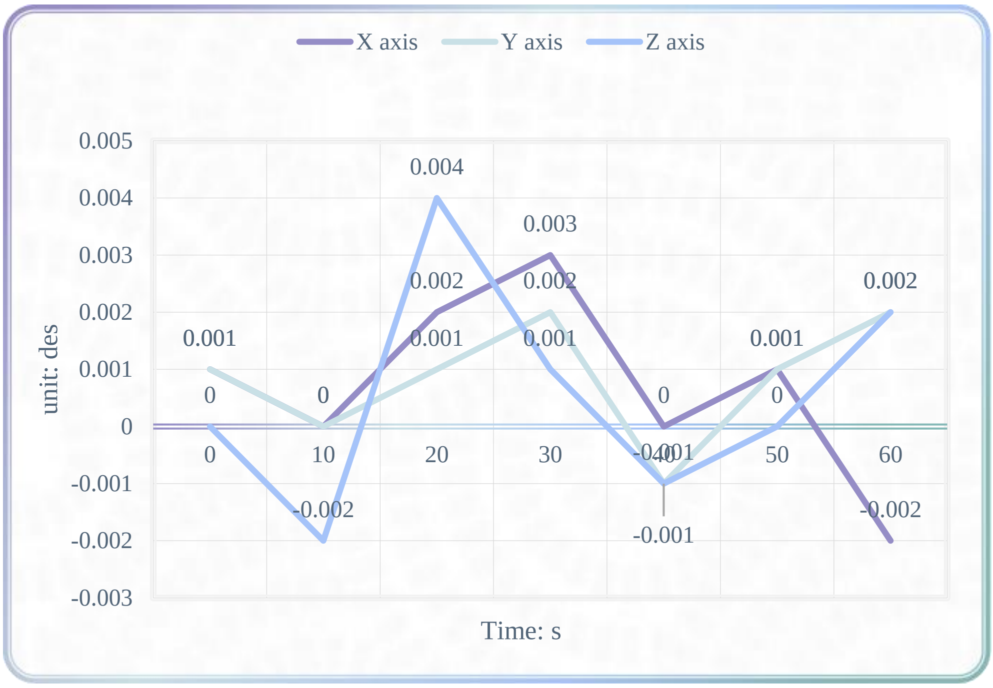

Figure 2: Three-axis tracking error results (unit: deg)

It can be found from Figure 2 that the error of the three-axis tracking is within a relatively small range, which indicates that during this process, the position and posture of the base are controlled so that the pose of the space robot is consistent with the target pose. It can be seen that the target trajectory planning method in the target acquisition control proposed in this paper can ensure that the space robot can track the target trajectory while reducing the base disturbance torque, thereby reducing the load of the base attitude control system in the base maneuvering mode.

5. Conclusions

At present, various countries in the world are conducting research on space robots for different purposes to varying degrees. my country has also invested a lot of energy in important space technologies such as space robots. With the advancement of intelligent robotics disciplines and advanced manufacturing equipment capabilities, the research on trajectory planning and control of space robot target capture has also made considerable progress. This paper mainly studies the trajectory planning and control of space robot target capture, proposes a prediction algorithm for capturing target motion parameters, analyzes the impedance control method of the manipulator joint space, and finally optimizes the target capture trajectory of the space robot to verify the trajectory planning Advantages of the method.

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