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Research on Control Strategy of Manipulator Based on Simulation

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Abstract. The force supple control method of robotic arm has been widely researched internationally for many years, and its specific use varies according to the structure of the robotic arm, the location of the sensor, the working space environment, and other factors. Based on the force control principle and control method of the space robot arm, this paper adopts the position-based Cartesian spatial impedance control and proposes an effective force-smoothing control method after pre-processing the feedback signal of the six-dimensional force sensor installed at the end of the space robot arm with the coordinate system conversion. In addition, the proposed position-based Cartesian spatial impedance control method is modeled and simulated to analyze the effect of each control element on the force-following control effect, to find out the control conditions that can optimize the force-position control effect, and finally to optimize the impedance parameters. This study aims to promote the rapid development of the field of robotic arm control.

1. Introduction

Space robotic arms are an indispensable component in the construction, maintenance and use of space stations, and have been used successfully on both the Space Shuttle and Space Station since the 1970s. Space robotic arms play an important role in cargo handling, spacecraft docking, astronaut extravehicular activities and so on. Along with the development of China's space industry, China's space station construction plan is also underway, and the development and design of China's space robotic arm is also being carried out in an orderly manner [1]. The seven-degree-of-freedom symmetrical redundant space robotic arm developed by 805 Institute of Spaceflight, 149 Factory and Harbin Institute of Technology is based on the advanced experience at home and abroad. Based on the advanced experience at home and abroad, the space robotic arm is designed to be able to realize the function of moving freely on the outer wall of the space station by using the docking transposition between the end effector and the ground adapter [2]. The process of docking the end effector of the space robot arm with the ground adapter is divided into three steps: capturing, tensioning and locking. In the process of docking the end effector and the ground adapter, there is inevitably a certain amount of attitude error in the space robotic arm, which may result in a large contact force between the end effector and the ground adapter during the docking process. Although the high deflection of the space robotic arm in some degrees of freedom can provide a certain passive softening effect, there is still a possibility of damage in other rigid degrees of freedom [3]. In order to avoid such risk, the contact force between the end effector and the ground adapter must be force actively controlled and force servo controlled by the force signal feedback from the six-dimensional force sensor installed at the connection between the end effector and the robotic arm, so as to ensure that the contact force between

the effector and the adapter is within the allowable range and avoid accidental damage to the robotic arm.

2. Impedance control of space robotic arm

2.1. Impedance control principle
The force-impedance control of a robotic arm was proposed by Hogan in 1985, who assumed that the interaction of a physical system with its surroundings under the control of a controller must conform to the general properties of a physical system, and on this basis he took into account the work done by the contact force between the robotic arm and the environment and thus proposed the impedance control, which gives the important elements of the desired feedback of a purely physical system: desired inertia, desired damping, and Desired stiffness [4]. This desired relationship, called the "target impedance", determines the performance of the system and gives a unified framework for flexible control in both free and constrained spaces.
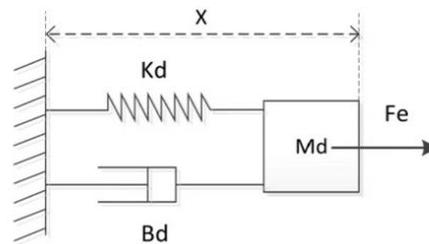

Figure 1. Sketch of spring damping system.

In traditional impedance control theory, a spring-damped system is used to describe the action of the arm on the environment, as shown in Figure 1, and the mathematical model can be described by the following differential equation:

$$M_d(\ddot{X} - \ddot{X}_r) + B_d(\dot{X} - \dot{X}_r) + K_d(X - X_r) = E_f \tag{1}$$

Where M_d, B_d, and K_d are semi-positive definite matrices representing the desired inertia, desired damping, and desired stiffness of the impedance system in different directions in the workspace. X is the actual position of the robot arm in the workspace, X_r is the desired trajectory of the robot arm in the workspace that generates the desired contact force F_r, F_e is the actual contact force between the robot arm and the environment, and E_f denotes the deviation between the spatial robot arm in the environment E_f represents the deviation between the contact force and the desired contact force. When the space arm stops the active motion and follows the traction by the uniform traction force, if F_r=0, then the desired position is coincident with the traction point position, so we have X_r=X_e.

2.2. Pre-processing of force feedback signals
Because the six-dimensional force sensor installed on the end effector of the space robot arm is located at the connection between the end effector and the seventh joint, and there is a certain distance between the end effector and the ground adapter contact point, so the feedback signal of the force sensor reflects only the force situation at the connection between the seventh joint of the space robot arm and the end effector, and we need the docking contact point at the wire rope force exists there is a There is a certain gap. Therefore, before designing the impedance control method, we need to pre-process the force signals from the six-dimensional force sensors to more accurately describe the actual contact force at the contact point.

$$F_e = T(t) * F_c \tag{2}$$

Where F_e and F_c represent the actual contact force in the contact force coordinate system {O-xyz} and the sensor force feedback in the sensor coordinate system {Oc-$x_c y_c z_c$}. T(t) is the transformation

matrix from the sensor coordinate system to the contact force coordinate system, which is related to the time since the start of the tensioning process.

2.3. Position-based impedance control in Cartesian space

After obtaining the impedance control method between the end effector of the space robot arm and the environment we can design the impedance control method for the space robot arm in Cartesian space. Where F_r is the desired contact force with the environment, Fe is the actual contact force between the end effector and the ground adapter, F_a is the force feedback from the sensor, and F_d is the zero point deviation of the sensor [5]. After the contact force is collected, the contact force error E_f is obtained by subtracting from the desired contact force, and the position correction δ_X is obtained by the impedance controller to correct the desired trajectory X_d so as to obtain the trajectory control quantity X_c, and the joint trajectory control quantity is obtained by the inverse kinematic $R^T(X)$ to control the position of the robot arm position control inner loop.

2.4. Docking process impedance control model analysis

After determining the framework of the impedance control system, we now model the process of the space robotic arm being subjected to uniform traction motion in the case of stopping active motion, so as to simulate the uniform traction process of the wire rope on the end effector during the docking process, and mathematically analyze the dynamic change process of the contact force error and position error in it. We take the initial position of the end of the robot arm as the origin, and take the direction of follower traction as the positive direction to establish the model coordinate system. The desired position X_d of the space arm is 0. If the control delay of the inner loop of the arm position is ignored, the actual position X can be equated to δ_X. The final simplified model is shown in Figure 2:
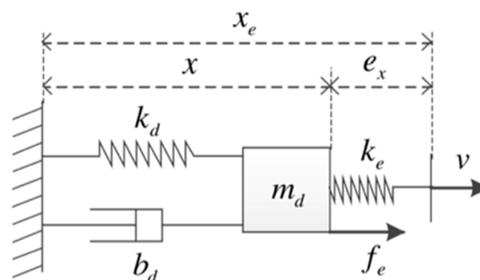
Figure 2. Simplified model of impedance controlled follower at the end of the robot arm.

3. Simulation of impedance control

3.1. Impedance control simulation modeling of tensioning process

In order to accurately control the contact force and position deviation during the docking process, and to ensure that the contact force is adjusted to a safe and appropriate range, we must first understand the impact of each target impedance parameter on the docking process of the space robot arm, especially on the force tracking process of the uniform pull-down process during the tensioning process, which will help us to reasonably select the target impedance parameters. The main reasons for this are:

- The Z-axis has the largest position error to be eliminated in the tensioning process.
- The end effector has the worst flexibility in the Z-axis direction due to the hanging system.
- The tensioning process takes the longest time in the docking process.

Matlab/Simulink was used to simulate the tensioning process, and its simulation diagram is shown in Figure 3-4 :

Figure 3. Impedance controller model diagram.

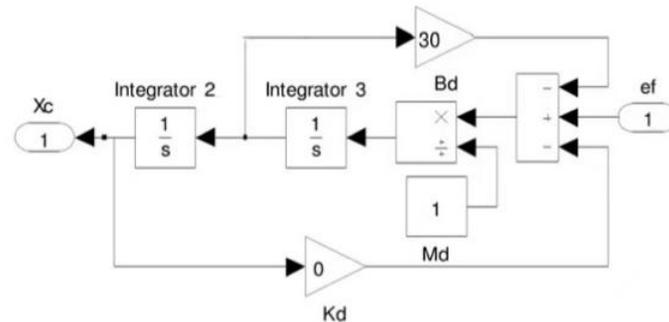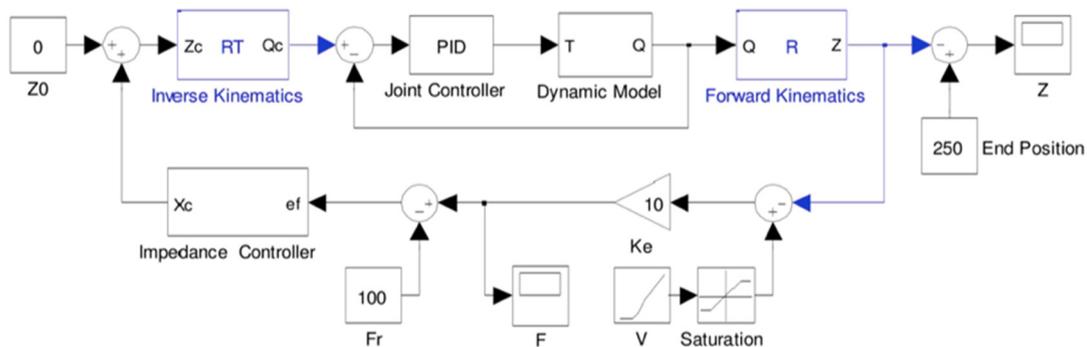Figure 4. Simulation model of impedance control of tensioning process.

In order to improve the simulation speed of the model so that we can conduct comparison experiments for several different parameter ratios, we use a second-order linear transfer function instead of the inner loop of the position control of the robot arm to represent the relationship between the position command Z_c and the actual position Z of the robot arm.

Where J_m is the mechanical inertia of the robot arm position control, B_m is the mechanical damping of the position control, and K_m is the mechanical stiffness of the position control. This simplified system can better take into account the delay factor in the robot arm position control process, and can also better characterize the dynamics of the position control inner loop.

After the measurement in the experimental environment, it can be seen that there is a delay of nearly 4s between the mechanical and communication of the space robot arm, mainly due to the holding of the hanging system in the vertical ground direction, which makes the robot arm not able to respond to the position command immediately [6]. Although there is no delay in the hanging system in the real space environment, the communication delay is significant due to the possible space-ground communication delay. Therefore, we still keep a delay time of 4s in the simulation to ensure that our force-following control can operate in the space environment, so we take a=4, b=1 for the delay time of 4s.

3.2. M_d, B_d, K_d parameter characteristics simulation

The impedance controller has three variable control variables, namely, the desired inertia M_d small, the desired damping B_d, and the desired stiffness Kg. In the above section, we have obtained the influence of these variables on the contact force deviation and position deviation during the tensioning process through mathematical analysis, and now we will do a more intuitive qualitative analysis of their control characteristics through simulation experiments. In the simulation process, different impedance control parameters M_d, B_d, K_d ratios are used to observe the effect of each parameter on the contact force and position deviation changes in the tensioning process, and the ratios are:

- Fix B_d, K_d, and select different M_d for simulation;

- Fix M_d, K_d, and choose different B_d for simulation;
- Fix M_d, B_d, and choose different K_d for simulation;

Experiment 1 is a plot of the simulation results obtained by increasing M_d from 0 to 200 kg with a fixed B_d = 55Ns/m and K_s = 0N/m in a span of 50 kg. It can be found that the amplitude of oscillation and overshoot in the tensioning process intensifies with increasing M_d. In the process of increasing M_d from 0 to 200, the oscillation amplitude of the contact force deviation in the vertical direction increases continuously, and the maximum value increases from 340N to 470N. It can be seen that increasing M_d increases the maximum value of contact force and increases the adjustment time, which are both unfavorable to the tensioning process. However, considering the instability of the tensioning speed and other possible disturbances during the tensioning process, M_d cannot be taken as 0, but as a small value to ensure stability while controlling the contact force and position deviation.

Experiment 2 is a graph of simulation results obtained by increasing B_d from 35Ns/m to 100Ns/m with a fixed M_d = 0.5kg and K_d = 0N/m in a span of 10Ns/m. It can be seen that B_d has an important influence on the stable value of contact force error, and it can be seen that the stable value of contact force and position deviation at K_d = 0N/m is proportional to B_d. However, the decrease of B_d also increases the amplitude of contact force oscillation, which increases the adjustment time and prolongs the contact force oscillation time, which is unfavorable for the tensioning process. It can be seen that B_d has both positive and negative impressions on the contact force of force-following control, and the above two relationships need to be considered. The B_d can be chosen to be about 45Ns/m.

Experiment 3 is to increase K_d from 0 to 1N/m for a fixed M_d = 0.5kg and B_d = 55Ns/m . The graph of the simulation results obtained. It can be seen that K_d has a significant effect on the stability error of the contact force, and K_d can make the contact force stability error increase continuously with the tensioning process, and the rate of increase is proportional to the size of K_d.

In summary, M_d has no effect on the stable value of the contact force, but it will intensify the oscillation of the contact force and lead to the increase of the peak contact force. B_d has an effect on the stability of the contact force and also on the oscillation of the contact force, according to the simulation results in the figure, B_d should be taken as 45~55Ns/m. K_d has a direct effect on the stability of the contact force, if K_d is not 0, the contact force will continue to increase during the tensioning process. Therefore, K_d is taken as 0N/m.

We can use the above rules to select different target parameters for the control requirements of different directions in not many stages of space robotic arm docking process. For example, force control is required in the horizontal plane and position control in the vertical direction during the capture process. For example, force control is required in the horizontal plane and position control is required in the vertical direction, so that a small K_d and a large M_d, B_d can be taken in the horizontal direction of freedom.

4. Optimization of impedance control parameters

After coarse selection of a set of optimization parameters, we continue to have optimization algorithms for further selection and optimization of parameters. Genetic algorithm is an optimization algorithm that simulates the process of biological genetic evolution. The basic optimization process is to select a certain number of individuals through a random process, evaluate and compare each individual using an evaluation function, and select the winners in a way that the winners replace the losers for random reproduction [7]. At the same time, randomly varying individuals are introduced to ensure the emergence of possible superior individuals, so that the results are optimized in a continuous cycle until the final end condition is met [8]. The end condition can be that a specific number of cycles is reached, or that the difference between two adjacent optimization results is less than a specific value. To optimize the impedance control parameters of a space robot arm by genetic algorithm, it is necessary to first determine the optimization objective and determine the optimization objective function, and then program the objective function to facilitate the optimization algorithm.

4.1. Optimization objective and objective function establishment

Considering that the optimization objectives of the tensioning process can be roughly divided into two, one is that the maximum contact force Fmax needs to be minimized, and the other is that the stability of the contact force needs to be enhanced as much as possible, we choose a unified optimization objective to make this part of the area characterize the oscillation amplitude of the contact force error.
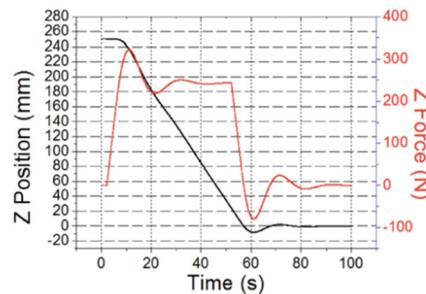
4.2. Genetic algorithm optimization

Figure 5. Simulation diagram of optimized tensioning process position and contact force.

Genetic algorithm is a series of cyclic processes such as evaluation, selection, crossover, and variation to optimize the parameters similar to the biological evolution process, which is shown in Figure 5. In Matlab, the genetic algorithm in the optimization toolbox was used to further optimize the parameters of the tensioning process. The parameters of Md of 1 kg, Bd of 50 Ns/m, and Kd of 0 were selected for the optimization, The final optimization result is [0.751 48.8060]. The simulation results are shown in Figure 5. The maximum contact force is 323 N, which is in accordance with the design requirements and the degree of oscillation is small.

5. Conclusion

In this paper, we design a position-based impedance control method for the docking process of space robotic arm, and carry out a series of modeling analysis and simulation for the docking process to obtain the influence characteristics of parameters Mg, Bj and Kg on the contact force error and position error in the impedance controller, so as to obtain the parameter ratios that can meet the requirements, and further optimize the parameters by using genetic algorithm. The method has some guiding significance for the control of spatial resistance of robotic arm, and it is hoped that more scholars will continue to study this field method in depth in future development and contribute advanced power to this field.

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