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Research on Optimal Sliding Mode Pose Control for a Six-DOF Air-Bearing Simulation Platform System

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Abstract: According to the requirements of the ground experiment table which is designed to simulate the lunar orbiter's docking and the sample transferring processes for the 3rd step of China's Lunar Exploration Program, a 6-DOF air-bearing simulation platform system is designed. We also proposed an optimal pose control method which method combines the sliding mode control with the optimal control theory in this paper. By introducing an integral compensation term, the optimal regulator is robust and the reaching mode of the sliding mode control is eliminated. This control methods could also eliminate the influence that the big load inertia ratio and the uncertain factors of the air-bearing pose control system had on the control precision. The experimental results indicate that the control accuracy of the system meets the task requirements and the correctness and feasibility of this scheme are verified.

Keywords: six-DOF air-bearing platform system, optimal sliding mode pose control, lunar orbiter, full-physics simulation docking mechanism.

1. INTRODUCTION

China's Lunar Exploration Program has three steps, which are orbiting, landing, and finally returning. Now the third step of China's Lunar Exploration Program has started successfully. The key of this step is the lunar orbiter' s docking, unmanned sample collecting and returning. Of all these techniques the docking is the first key issue and is realized by the docking mechanisms between the lunar orbiter and ascender. The difficulty of this technique comes from the big mass difference between these two spacecrafts and some other relative influences. An irrational design of the docking mechanism might cause safety threats and even structural damage to the spacecrafts, which would make immeasurable loss. The physical environment of the outer space is another reason why the study is difficult. Because of the weightlessness, there are 12 DOFs as a whole of these two spacecrafts. So a simulation experiment must be conducted on ground to accurately simulate the docking process in order to improve the reliability of the docking mechanism. The dynamics of the contact and impact of the docking could be studied in the simulation experiment, and the actual whole process should be simulated to test the docking mechanisms' functions.

According to the simulation method, the experimental tables could be divided into three types: mathematical simulation, half-physics simulation, and full-physics simulation. Compared with the other two kinds, the full-physics simulation uses the practical model with the true scale to simulate the docking process and thus the difficulty of building accuracy mathematical model for some complex parts could be avoided. The fidelity of the full-physics simulation is as high as the practical docking process, so the experimental results of this have the highest reliability. In China, a full-physics docking simulation table with 10 DOFs has already been developed. This simulation platform system is composed of two air-bearing simulators, and each of them could simulate the tracing spacecraft or the target spacecraft. Due to the structural reason, this simulation platform system could not accurately simulate the vertical acting force of the docking mechanism, so it could only simulate 5 DOFs.

This paper developed an air-bearing simulation platform system with 6 DOFs according to the requirements of the China's three-step lunar program. With this system we could make a full-physics simulation of the spacecraft's weightless motion state in all the 6 DOFs. And thus the study on lunar orbiter's docking and the sample's transferring could be conducted on ground. This simulation system could simulate the processes of the docking, holding, separating, and the sample transferring. And this is a typical multi-input multi-output system, which has the characteristics of nonlinearity, time varying and pose kinematic coupling. The added DOF to this 6-DOF air-bearing simulation platform system than the former one makes its axes' coupling property better. But as there is one more DOF, there are more uncertainties due to the disturbances such as the side interference force and the moment of this force. So the pose control system needs to have stronger robustness to the external disturbance and the uncertainty of the dynamic model. Besides it is demanded to

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truly simulate the mass and the inertia of the two spacecrafts, so there are more requirements for the servo system's installation size and the weight, which would lead to the big inertia ratio.

We proposed an optimal sliding mode pose control strategy by combining the sliding mode control with the optimal control theory in this paper. A robust compensating control law is proposed based on the optimal control theory with an integral compensation item introduced. This control law would make the sliding mode exist and would make the system arrive at the sliding mode surface in limited time. Then the pose control system would have the strong robustness to the parametric perturbation and the external disturbance. The influence that the big inertia ratio and the uncertainty have on the control precision would also be eliminated. This laboratory table realizes the full-physics weightless simulation of the space orbiter, and the accurate experimental data from this could be used to evaluate and improve the docking mechanism.

2. THE OVERALL DESIGN OF THE 6-DOF AIR-BEARING SIMULATION PLATFORM SYSTEM

The 6-DOFs air-bearing simulation platform system is the full-physics simulation system to simulate the weightless kinestate of spacecrafts. This equipment could methodically test the parameters such as the force, the moment, the pose, the velocity, and the acceleration of the motion processes. And the processes such as approaching, contacting, catching, locking, tensioning, and sample transferring could be simulated on ground once the initial docking condition is satisfied. All the experimental data could be used to study the real docking process. The schematic of this ground simulation platform system is shown in figure 1. It can be seen that this full-physics simulation platform system is composed of two 6-DOFs air-bearing simulators, so there are 12 DOFs as a whole. The left part in figure 1 is the active simulator, which is used to simulate the lunar orbiter, while the right part is the passive end which is used to simulate the lunar ascender. It is known that the mass of the orbiter and the lunar ascender is 3066 kg and 509 kg, respectively.

The 6-DOF air-bearing simulation platform system is composed of pose simulator, main axis, inertia simulator, air-bearing granite platform, and the docking mechanism. The pose simulator could realize the rolling and pitching movement. When the laboratory table works, the air film is formed between the supporting circle air feet and the granite platform. This air film could help to simulate the weightless movements of three DOFs, including the two dimensional motion in the horizontal plane and the yawing motion. The method we use to simulate the weightlessness in the Z-direction is as follows. Firstly, a balance weight is used to balance the weight of the simulator, and air bearings are used eliminate the rolling friction; then the air-floating guiding pillars are mounted to guide the movement in Z-direction; the principle of equivalent mass is also introduced to balance the weight and reduce the total mass of the simulator. The mass and the inertia systems are designed to match the mass and the inertia of the spacecrafts. The structure of the passive simulator is shown in figure 2.

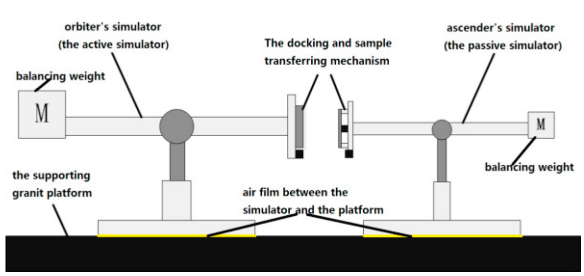

Fig.1. The schematic of the ground simulation platform system.

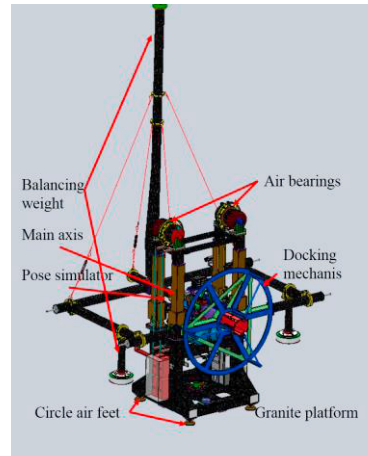

Fig.2. The structure of the passive simulator.

The experimental table uses two real-time controllers to control the active and the passive simulators respectively. The far-end ground console using PXI system could control the 6-DOFs motion of the two simulators. The EtherCAT real-time bus is used to help the real-time controller and the servo system of the lower computer to communicate. All the operation tasks use mutual exclusion semaphores of the VxWorks real-time system to ensure the synchronization between the tasks.

3. THE ESTABLISHING OF THE INITIAL DOCKING CONDITIONS

Both of the active and passive simulators we designed have 6 DOFs. We have t as the variable of moving time. And in order to make sure that all the DOFs have the specified displacements, required velocities and smooth movement at the initial docking moment, the path planning method has been used on analyzing the motion to satisfy the boundary conditions where t is zero and t equals T_k . T_k is the time when the simulators begin to contact. The quintic polynomials of time t in the Cartesian coordinate have been presented to calculate both of the two simulators' motion paths in all the six DOFs. When the simulators contact after moving in the calculated path from the beginning position, the relative movement of the two simulators is used as the initial docking condition.