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.

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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...
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 to 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.

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 \( t = 0 \) and \( t = k T \). \( k T \) 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.
$Y_j(t)$ is defined as the displacement of the simulators in one of the six DOFs, where $j = 1...6$. Then $\dot{Y}_j(t), \ddot{Y}_j(t)$ represents the velocity and acceleration respectively. The motion equations are shown as follows.

$$
Y_j(t) = a_j t^5 + b_j t^4 + c_j t^3 + d_j t^2 + e_j t + f_j \\
\dot{Y}_j(t) = 5a_j t^4 + 4b_j t^3 + 3c_j t^2 + 2d_j t + e_j \\
\ddot{Y}_j(t) = 20a_j t^3 + 12b_j t^2 + 6c_j t + 2d_j
$$

Taking the boundary conditions where $t=0$ and $t=T_k$ into account, we could get the exact value of these parameters. The results are shown as follows.

$$
\begin{align*}
    a_j &= \frac{-3T_k^2 Y_j(T_k)}{Y_k^2} + 6Y_j(T_k) \\
    b_j &= \frac{7T_k Y_j(T_k) - 15Y_j(T_k)}{4} \\
    c_j &= \frac{-4T_k^3 Y_j(T_k) - 10Y_j(T_k)}{3} \\
    d_j &= e_j = f_j = 0
\end{align*}
$$

According to the analysis above, we could see that the key of this problem is to know the constraints that the DOFs have on the displacement, velocity and acceleration, and according to the difference of the initial conditions the proper $T_k$ that this simulation platform system’s ability allows could be given. The total time $T$ of the simulators’ motion would be determined after considering all these problems, and all the six DOFs would be controlled to satisfy the initial condition.

4. THE POSE CONTROL METHOD OF THE AIR-BEARING PLATFORM SYSTEM BASED ON OPTIMIZED SLIDING MODE CONTROL

Because of the limited structure space and the special requirements of this experimental table, the pose control system needs to have a high-precision real-time control on the low-velocity simulators, while the inertia is very big. So improving the robustness of the system to boost anti-jamming is extremely important. This pose control system could be divided into several servo control systems of single degree of freedom.

4.1 The Dynamic Model of the Servo Control System for Single DOF

The differential equation of the servo control system is as follows:

$$
J \ddot{\theta} + \beta \dot{\theta} = T_L - T_M = K_I I
$$

Where $\theta$ is the angular displacement, $J$ is the rotational inertia, $\beta$ is the friction coefficient, $T_L$ is the load torque, $T_M$ is the magnetic torque, $K_I$ is the torque constant, $I$ is the phase current. $\theta_{\text{ref}}$ is set as the input reference angular displacement while $G_c$ is the controller. The structure diagram of this servo control system is as figure 3 shows.

The system state variable $X$ is defined as

$$
X = [x_1, x_2]^T
$$

With the control variable $U_c = I$, the state equation is as follows:

$$
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} = \begin{bmatrix}
0 & 1 \\
0 & -a_j
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} + \begin{bmatrix}
0 \\
b
\end{bmatrix} U_c - \begin{bmatrix}
0 \\
c
\end{bmatrix}
$$

4.2 The Quadratic Regulator Optimal Control of the Pose

The state equation of the air-bearing platform system is:

$$
\dot{X}(t) = AX(t) + BU_c(t) + W(X,t)
$$

Where $W(X,t)$ is the uncertain term which includes the internal and external disturbance of the parameters.

We will assume the following.

1. $\text{rank}(B) = m$, and there exists the unknown function vector $\mathbf{W}(X(t),t)$ which satisfies $W(X(t),t) = B\mathbf{W}(X(t),t)$.

2. With the known constants $\rho_0$ and $\rho_1$, $\mathbf{W}(X(t),t)$ satisfies the inequality:

$$
\mathbf{W}(X(t),t) \leq \rho_0 + \rho_1 \|X\|
$$

Taking the nominal system into account ($W(X,t) = 0$), the quadratic cost function is:

Fig. 3. The structure diagram of this servo control system.
\[
J = \frac{1}{2} \int_0^\infty [X(t)^T Q X(t) + U_c^T R U_c(t)] dt \tag{10}
\]

Where the weight matrix Q is \( n \times n \) non-negative definite matrix and R is an \( m \times m \) positive definite matrix.

The feedback control law that minimize the response time of (9) is the following.

\[
U^*(t) = -K_c X(t) = -R^{-1} B^T P X(t) \tag{11}
\]

Where \( K_c = R^{-1} B^T P \) is the \( m \times n \) feedback gain matrix; The \( n \times n \) non-negative matrix \( P \) is the solution of the parametrized differential matrix Riccati. The Riccati equation we use is as follows.

\[
P B^T P - PA - A^T P - Q = 0 \tag{12}
\]

And the dynamic equation of the closed loop control is the following.

\[
\dot{X}(t) = (A - B K_c) X(t) \tag{13}
\]

The closed loop system is asymptotically stable according to the optimal control theory, so the solution of the equation above is the best motion track of the air-bearing platform system. While when this system faces up with all the uncertainties, the performance of the optimal control system based on the nominal system would deviate from the optimal value and even become unstable.

4.3 The Design of the Pose Sliding Mode Controller

In order to make the whole dynamic process of the air-bearing platform system have the sliding mode and to make the ideal sliding mode have the optimal motion track based on the nominal system, the control with integral compensation is introduced on the basis of the optimal control theory. Thus the optimal controller is robust.

Considering the uncertain terms of this air-bearing platform system, the integral sliding mode surface is designed as follows.

\[
s(t) = G[X(t) - X(0)] - \int_0^t (A - BK_c) X(\tau) d\tau \tag{14}
\]

Where \( G \) is \( m \times n \) matrix of full rank. When the system comes into the sliding mode, we will have \( s(t) = 0 \), \( s(t) \neq 0 \).

So there is the following equation.

\[
\dot{s}(t) = G \dot{X}(t) - G (A - BK_c) X(t) = 0 \tag{15}
\]

And the equivalent control model is the following.

\[
U_{EQ} = -R^{-1} B^T P X(t) - \dot{\mathcal{X}}(X,t) \tag{16}
\]

Then we will get the ideal sliding mode motion equation of the air-bearing platform system after applying (16) into (8).

\[
\dot{\mathcal{X}}(t) = (A - BK_c) X(t) \tag{17}
\]

As (17) and (13) are the same, we can conclude that the ideal sliding mode track and the optimal track based on the nominal system agree completely. It also shows that the optimal sliding mode has strong robustness to the parametric perturbation and the external disturbance.

The optimal sliding mode control law of the air-bearing platform system is the following.

\[
U_c = U^* + U_s \tag{18}
\]

Where \( U^* \) is the optimal sliding mode control law based on the nominal system, \( U_s = (GB)^{-1}(\eta + \rho_0 \|GB\| + \rho_1 \|GB\| X \| X \| sgn(s) + GB \dot{\mathcal{Y}})\) is the integral sliding mode control law which can improve the robustness of the controller, \( \eta \) is a proper positive constant.

The Lyapunov function we use is as follows.

\[
V(t) = \frac{1}{2} s^T (t) s(t), \quad s \neq 0 \tag{19}
\]

\[
\frac{d}{dt} V = s^T (t) s(t) \leq -\eta s^T s + \rho_0 \|GB\| s + \rho_1 \|GB\| X \| X \| \| s \| \tag{20}
\]

It can be seen from (19) that the sliding mode process could be finished in limited time. So the track of the air-bearing platform system under this control law above will reach the sliding mode surface in limited time and maintain in the surface all the time after its arriving. This pose control system has optimal robustness to the quadratic index of the whole dynamic process and the uncertainties that satisfy the matching conditions.

5. THE EXPERIMENT

In order to verify the effectiveness of the optimal pose control strategy we proposed, an experiment is conducted. And through the experiment, we could also study the allowed docking time. This experiment takes the rolling DOF of the passive simulator as the object, and the actual mass and inertia of the ascender is given to this simulator.
This equipment which is like a windmill has only one DOF. There are two mutually perpendicular rolling shafts. The inertia and the mass is simulated by these two shafts. The balancing weight could be moved on the shafts to adjust the mass and inertia of the equipment. The driving force comes from the motor and the experimental data is gotten from the sensor.

The load inertia of this experimental roller is 173 kgm$^2$, and the mass of it is 190 kg. Because of the strict requirements of the mounting size for the experimental motor, the main parameters of the selected motor are set as the follows. The moment of inertia is $J = 28.5$ kgcm$^2$, and the torque coefficient is $K_T = 2.31$ N·m/A. The ratio between the load inertia and the motor inertia is $K_{J,M} = 60701.75$, and the friction resistance moment is 0.1 Nm. We use (9) to evaluate the quadratic performance indicators. Where $Q = \begin{bmatrix} 4 & 2 \\ 2 & 1 \end{bmatrix}$, $R = [0.01]$. 

5.1 The motion control of the normal pose

With the initial docking condition satisfied, the planned rolling angle and the rolling angular velocity are as figure 5 shows. The motion process is to rotate in reverse for a while and then accelerate in the positive direction. The specified maximum angular velocity $0.1^\circ$/s is reached when the roller goes back to the initial pose and then the roller moves with this constant velocity. The planned motion time is 60 seconds.

The motion of this experimental equipment is controlled as the moving track mentioned above. The errors of the angle and angular velocity between the experimental and the planned track are shown in figure 6. We could conclude that although the motor’s load inertia ratio is about 60,000, with the control strategy in this paper, the pointing accuracy is within $0.004^\circ$ and the angular velocity precision is within $0.01^\circ$/s. The precision meets the requirements.

5.2 The dynamic control of the big rolling angle pose

The big rolling angle pose control is necessary because the lunar ascender needs to rotate an angle from one stable state to another during the docking process. With the initial docking condition satisfied, the planned rolling angle and the rolling angular velocity of this pose are as figure 7 shows.

The specified maximum angular velocity is $0.1^\circ$/s and the planned moving time is 110 seconds.
Fig.8. The error of the angle and the angular velocity between the experimental track and the planned track.

The errors of the angle and angular velocity between the experimental and the planned track are shown in figure 8. We could see from the figure that with the big angle dynamic control, the pointing accuracy of this air-bearing system is within 0.012° and the angular velocity precision is within 0.01°/s. So the accuracy requirements would be satisfied.

6. CONCLUSION

We designed a ground air-bearing simulation table with 6 DOFs for the study of the lunar orbiter’s docking and sample transferring processes. An optimal sliding mode pose control method by combing sliding mode control with the optimal control theory is proposed in this paper. With this control method, the whole dynamic process of the simulation system would have strong robustness to the parametric perturbation and the external disturbance. The experimental results show the effectiveness of this control strategy. This simulation platform system could simulate the whole docking process in space and the precision could meet the requirements. So this simulation platform system could provide lots of accurate experiment data for the further study on lunar orbiter’s docking process and even the space science.

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