Motion Simulator System for Rendezvous and Docking Based on RTX

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Abstract. Motion simulator system for rendezvous and docking needs high precision and high real-time capacity. The main structure, crucial indexes and control system structure are introduced at first. Software demand is also analyzed, software is modular designed, makes use of fine interface of Windows, use real-time processing ability of RTX and high precision of control algorithm. The experimental results show that the motion simulator system for rendezvous and docking based on RTX have the high precision and dynamic real-time capacity, which can satisfies the demand of application.

1. Introduction
Space rendezvous and docking technology is a key technology for deep space development of human beings. Complete space rendezvous and docking is a very large project, involving many key technologies such as guidance, navigation, control, and docking separation [1-3]. Therefore, it is very necessary to carry out sufficient ground simulation verification tests to ensure the success of space rendezvous and docking [4].

The rendezvous and docking motion simulation system is used as a physical carrier for the simulation test of the space intersection grounding simulation. It is used to simulate the relative motion process of two docked space crafts from a certain distance to each other before collision. The dynamic accuracy and steady-state accuracy directly affect the test. [5-6].

ESA and German Space Academy established a semi-physical simulation laboratory at the German Space Operation Center in 1984. The motion simulator uses a gantry crane with a target table rotation accuracy of 0.01° and a low speed. The motion simulation system of the Japan Space Center for Waves uses a retractable 6-bar mechanism. The linear motion stroke is only 7m, the attitude angle range is 20°, and the movement speed is low. There is no requirement for dynamic accuracy. China's research on this system also has the disadvantages of low positioning accuracy, slow speed, and low dynamic accuracy [7].

According to the requirements of the project, the rendezvous and docking movement simulation system proposes higher indicators, including the requirements of rotational positioning accuracy, linear positioning accuracy and high dynamic response, which imposes higher requirements on engineering practice.
2. Motion Simulator Introduction
The rendezvous and docking motion simulation system is a special device for simulating the relative pose motion of the target and the tracker. The system composition is shown in figure. 1.

The target consists of a three-freedom turntable with a yaw, pitch, and roll function and a vertical (z-direction) horizontal platform. The tracker's three-degree-of-freedom turntable is similar to the target but is flipped and contains two translational degrees of freedom, horizontal (x-direction) and vertical (y-direction).

There are nine degrees of freedom for the entire system. Targets and cameras are fixed on the tracking and target table's load plate, which can simulate all aspects of rendezvous and docking in space, including dynamic simulation and static calibration.

Figure 1. Practicality of the simulation system

2.1. Control system induction
The control system is the key to the motion performance of the system. Nine axis position feedbacks adopt high-precision grating imported from Germany. The hardware of the control system adopts German imported drive unit, high-performance industrial computer and control board, including I/O board, analog board card, grating feedback card and fiber reflection memory Card, in strict accordance with the process standards for the connection and installation of electrical equipment, to fully shield the interference source, and the system's signal ground and protective ground to connect and test.

2.2. System key indicators

| Table 1. Main technical indexes |
|--------------------------------|
|                             | Rotating part                                      | Linear motion part                      |
| Steady-state accuracy        | Position control accuracy: ± 0.001°;               | Control absolute error: 0.05mm;          |
| Dynamic accuracy             | (1) Input sinusoidal signal frequency: 0.5 Hz; amplitude : 0.5°. output signal phase shift: less than 1°. amplitude variation : less than 2%. (2) Input sinusoidal signal frequency: 1 Hz; amplitude : 0.5°. output signal phase shift: less than 2°. amplitude variation : less than 3%. | (1) Input signal frequency: 0.1 Hz; amplitude : 0.03mm. output signal phase shift: less than 1°. amplitude variation : less than 2%. (2) Input signal frequency: 0.2 Hz; amplitude :120mm. output signal phase shift: less than2°. amplitude variation : less than 3%. |
3. Control software requirements

3.1. Performance requirements analysis

1) Real-time requirements: computer needs to communicate with multiple boards. Due to the high dynamic response of the position motion, the control period must be controlled within 1 millisecond, and the multiple data transmission and collection must be processed in parallel.

2) Steady-state performance requirements: The software system is required to have reliable reliability and stability during operation. When the driver or control board fails, the communication is interrupted, or the system accidentally moves, the control software should take reliable manner to ensure the stability and security.

3) Extensibility requirements: As the test progresses, the software system may need to be modified and improved, such as changing hardware and software data communication protocols, adding or deleting software functions, etc. Therefore, software design needs to consider expanding as much as possible.

3.2. System control software architecture

In order to meet the higher control frequency, the control software of rendezvous and docking motion simulation system adopts "Win32+RTX" platform. The software environment of the control system mainly includes Win32 and RTSS. RTX is a real-time extension subsystem from Ardence. It provides an additional real-time kernel module that works with the Windows kernel by modifying and extending the Windows Hardware Abstraction Layer (HAL). Matching the Windows operating system with the RTX operating system, the timing accuracy can reach 100ns, which not only meets the real-time and high-precision requirements of the control system, but also has good human-computer interaction.

RTX is developing a real-time subsystem, the RTSS subsystem, on the physical extension layer of Windows. RTSS has its own operating environment and API to implement its own corresponding functions. For reading and writing of board cards, high-precision control algorithms, watchdogs, etc. all run in the RTSS environment, the operation of the buttons, the status detection of the board, the system status, the display drawing curve, etc. are all run in the Win32 environment. Data communication and exchange between the Win32 and the RTSS are performed through the shared memory area [8-9].

In the control system software program design, data variables and parameter variables are mainly defined in the shared memory area. Therefore, variables defined in the shared memory area can be implemented in Win32 and RTSS environments. Once a certain task is executed in Win32, a variable in the shared memory area is changed. In the RTSS environment, the change of the shared memory area is immediately detected, and the control board carries out the corresponding operation to control the drive of the drive motor. The software structure of the rendezvous and docking motion simulation system is shown in Figure 2.
4. Software design

In order to facilitate the design modification of the program and increase the extensibility, the control system of the rendezvous and docking movement simulation adopts a modular design, and the main body is divided into three parts: a functional module, an algorithm module and a security module. According to the design requirements, the functional module includes three parts: data transmission module, data recording module and state synchronization display module; the algorithm module is used to implement user operation, high-precision control algorithm etc. The security module contains a series of security protection measures. The overall design is shown in Figure 3.

4.1. Functional module design

1) Data transmission module: For the system have 10 axes to control, the control system shares two 8-channel analog cards, two 32-bit digital cards, and three 4-channel high-speed data acquisition cards in the PCI slot of the IPC. Communication with the IPC is through the PCI bus.

2) Data record module: According to the design requirements, the system must record the position of each axis in real time in the process of starting and stopping according to the instruction. The recording period is 0.5 milliseconds. Since the opening and closing of the file is time consuming, the
file is kept open during the recording process. The state is automatically closed at the end of the movement.

3) Data record module: In the operation interface, the target position and actual position information should be observed and compared. The software should display in real time. Each control cycle writes the target position and actual position to the shared memory area, and reads from the shared memory area in the WIN32 process. Take the position information and display on the interface according to the frequency of 50 ms.

4.2. Formatting the text

Because the AC servo system needs to realize position, velocity and current closed loop, the AC servo system is a third-order system, which can be understood as a second-order system plus an integrator $1/s$. The model of the system is

$$G(s)_{motor} = \frac{k}{s(T_1s + 1)(T_2s + 1)}$$

The work needed to identify the $k$, $T_1$, and $T_2$ parameters based on the identification principle.

The pseudo-random sequence is used: the inverse M sequence is used as the input of the system sweep frequency, and the inverse M sequence has no DC component with respect to the M sequence. It has better application in eliminating polynomial-type drift interference, periodic interference and nonlinear influence, and is used as the input signal can be identified to obtain more reliable data. The IPC sends an analog signal to the driver to record the change of the position of the detected axis in real time. System is identified by MATLAB.

According to the identification of the system model, the advanced compensation control algorithm is added to improve the system’s steady-state characteristics and dynamic characteristics. The system bode diagram after adding the lead compensator is shown in Figure 4.

![Figure 4. Bode diagram of transfer function for compensation](image)

The blue dotted line in the figure indicates the transfer function before correction, and the solid green line indicates the corrected transfer function. It can be seen that the phase margin of the compensated system is increased to 33.1deg to meet the stability requirements of the system, and the cut-off frequency is increased to 111 rad/sec, which increases the fast response of the system and increases the margin to 10.1db increases the closed-loop stability of the system [10].

5. Test results and analysis

The main control indicators of the turntable include two parts: position control error and dynamic response.
5.1. Positioning accuracy

The self-collimator is used to coordinate with the twenty-three prisms to measure the steady-state positioning accuracy within the rotating range. The linear-axis positioning accuracy measuring instrument is laser tracker. The drive motor moves and holds at a fixed distance. It is measured in both positive and negative directions. The data is read and recorded. One-half of the difference between the maximum and minimum readings of the autocollimator at each measurement position is the steady-state positioning accuracy. The measurement results are shown in Table 2.

Table 2. Control errors of motion

| Rotary axis | Positioning accuracy/(') | Linear axis | Positioning accuracy/(mm) |
|-------------|--------------------------|-------------|--------------------------|
| scroll axis | 1.1                      | X axis      | 0.035                    |
| pitch axis  | 2.0                      | Y axis      | 0.02                     |
| yaw axis    | 1.9                      | Z axis      | 0.04                     |

5.2. Dynamic response

The system software records the target position (standard sinusoidal curve) and the actual position of the rotary axis in real time. The actual following position is measured by a high-precision grating and form a test text file. The data is read and processed by the software and two curves are plotted and compared [11].

The phase shift is the delay at the phase angle of 0°, and the amplitude shift is the amplitude variation at the phase angle of 90°. Take the tracker pitch axis input sine signal frequency 0.5 Hz, amplitude 0.5° curve as an example, the delay Δt1 is required ≤1°/360°×2s=0.0056s, amplitude shift ΔA1≤2%×0.5°=0.01° meets requirements. Using Matlab for graphical analysis, the results are shown in Figures 5 and 6. It can be seen from the figure that the amplitude shift is 0.0053° and the time delay is 0.003s, which meets the requirements of the indicator. After the overall test, the remaining axes also meet the requirements.

![Figure 5. Amplitude offset check of tracker on pitch axes](image-url)
6. Conclusion

Based on the RTX real-time environment rendezvous and docking motion simulation system control software, good experimental results are obtained in both the positioning accuracy index and the dynamic corresponding index.

Due to the RTX real-time development platform, the hardware structure of the system is greatly simplified, all software development is only required to be developed on the Windows operating system, and no special real-time operating system is required, and the human-computer interaction is friendly, and the scalability is stronger and the stability is higher. State-accuracy and dynamic-accuracy equipment development provides technical solutions and implementation methods.

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