Design of a Semi-physical Simulation and Testing system for Space Robot Operating platform

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Abstract. In view of the importance and complexity of the control and execution tasks of the space robot, the development of a real test environment has the risks of high cost and long cycle. Therefore, a semi-physical simulation and testing system is designed for the space robot operating platform. The system is composed of a robotic arm console, a central control system, a fusion system, a position tracking system, etc., to realize the verification of the hardware electrical interface, software algorithm logic and task operation process of the robotic operating platform. Through the realization of 3D animation demonstration of the robot operation, motion tracking and other simulations, the semi-physical simulation and testing system has a higher visualization and a stronger sense of experience, and can simulate the complex operating conditions of the system on orbit. At present, the simulation and testing system has been successfully applied to the ground test of the space robot operating platform, and its reliability and simulation verification effect are better.

1. Introduction

The space robot has integrated space perception, manoeuvring and operation capabilities. It can complete the on-orbit assembly, observation and inspection, replacement of faulty modules, and on-orbit refuelling of the spacecraft through on-orbit operation, ground teleoperation or autonomous operation, consumable load replacement and replenishment, track cleaning, track transfer, etc. Therefore, the robot becomes an indispensable part of spacecraft to complete on-orbit maintenance and special tasks, and one of the indispensable key equipment in the construction, operation, maintenance and expansion of the Chinese space station.

The space robot has a strong carrying capacity, and can complete tasks such as large load handling, large-scale transfer, cabin transposition and docking, and can also complete fine operation tasks such as load installation. In order to improve the flexibility and manoeuvrability of the space robot and reduce the working pressure of the astronauts, the astronauts realize the operation of the space robot through the on-orbit and ground operations for the space robot operating platform. In addition, in order to improve the proficiency of astronauts in operating the space robot and reduce the risk of operation, astronauts can complete the simulation operation of the space robot through the on-orbit training mode.

The space robot operating platform plays a vital role in the process of completing the tasks of the space robot. In order to improve the reliability of the space robot operating platform, it is necessary to fully test and verify its operation tasks. Therefore, this paper designs a semi-physical simulation and testing system for space robot operating platform. The system can simulate a variety of complex
operating conditions of the robot on-orbit operation, complete the simulation verification of the function and performance of the space robot operating platform, and has high reliability and versatility.

2. Test system design

2.1. Overview of the test system
The semi-physical simulation and testing system for the space robot operating platform verify the functions and performance of the space robot operating platform by semi-physical simulation combined with virtual reality technology, and realize motion operations such as multi-joint linkage, big-arm linear planning, single-joint motion, and simulation tasks such as robotic arm crawling outside the cabin and spacecraft body grabbing and docking by 3D animation demonstration, motion tracking and robot simulation technology, and establish a virtual reality simulation environment to enhance the operator’s immersive experience and the system’s real-time interaction capabilities.

The test system mainly includes a central control system, a fusion system, a position tracking system, a robot operating platform and auxiliary equipment. Its composition is shown in Figure 1.

![Figure 1. The composition of the test system](image)

2.2. Design of the test system
The semi-physical simulation and testing system for the space robot operating platform is a simulation test system that the operator realizes the simulation operation of the space robot by operating the display touch screen, buttons, joysticks, etc. on the robot operating platform. The robot operating platform collects the operator’s motion signal, converts it into an agreed protocol format, and sends it to the workstation through a dedicated bus to analyse and process action instructions. The workstation maps the corresponding action instructions to the action state of the robot in the scene, completes the effective combination from the operating platform to the virtual control object, and realizes the virtual reality simulation operation of the robot. The design scheme of the test system is shown in Figure 2.
The semi-physical simulation and testing system for the space robot operating platform mainly realizes the following functions:

1) Physical on-orbit operation mode

In the physical on-orbit operation mode, the action signal is processed by the test system and displayed on the visual screen to achieve an immersive experience. The operation of the virtual digital arm and the operation simulation of the virtual digital arm work task are completed according to the instructions of the robot operating platform, combined with the digital helmet, digital gloves, positioning system to complete the astronaut cabin and outside maintenance tasks.

2) Virtual on-orbit operation mode

In the virtual on-orbit operation mode, the action signal is processed by the test system and displayed on the visual screen to achieve an immersive experience. The operation of the virtual digital arm and the operation simulation of the virtual digital arm work task are completed according to the instructions of the robot operating platform, combined with the digital helmet, digital gloves, positioning system to complete the astronaut cabin and outside maintenance tasks.

3) Training mode

In this mode, the user can input data to the system, but does not need to be visualized and displayed on the screen simultaneously. The operation of the virtual digital arm and the operation simulation of the virtual digital arm work task are completed according to the instructions of the robot operating platform, combined with the digital helmet, digital gloves, positioning system to complete the astronaut cabin and outside maintenance tasks.

4) Virtual reality environment

In the virtual reality environment, the three-dimensional equipment of the virtual reality is in contact with the object, so that the user can perceive the objects in the virtual environment immersivity, thus realizing human-computer interaction.

5) Robot operating platform verification
The testing system can be used to verify the functions and performance of the robot operating platform, as well as the precision of manual operations by astronauts, and verify the safety and reliability of mission tasks.

6) Offline playback demo
Play the recorded data offline to demonstrate. The recorded data is saved in xml format, and the relevant file can be directly called when playing back.

3. Hardware design
The hardware design of the semi-physical simulation and testing system for the space robot operating platform, as shown in Figure 3.

1) System architecture: It is mainly composed of 3 hosts, 2 stereo projectors, 3 displays, digital helmet, position tracking system, hand capture, LAN router and physical on-track operation platform.
The function of the digital helmet, position tracking system, hand capture, display, and physical on-orbit operation platform is to display the astronaut's perspective picture and capture the astronaut's body movements and grasping movements.
The function of a host computer and two screens is to display the virtual exterior panorama and different camera views, and monitor various parts of the space station.
One host and two stereo projectors form a ring screen $\geq 120^\circ$. The entire display environment is a seamless splicing projection system with edge hardware fusion, displaying a three-dimensional panorama outside the cabin, and can be switched to other camera images including the astronaut's perspective.

2) The visual software accepts the operating instructions of the physical on-orbit operating platform, and drives the virtual robot dynamic model according to the instructions to generate corresponding actions. According to different incoming operation instructions, it is divided into the following two situations.
The operation command is the angle of rotation of each joint of the robotic arm. Each joint of the dynamic model of the virtual robot rotates according to the value in the operation instruction, and sends the angle data after the action to the visual computer;

3) Provide external virtual visual environment, including: space station, spacecraft, astronaut, foot stopper, robotic arm, projection lighting system, ORU and other components, auxiliary tools, space background, star effect model.

4) Provide a virtual visual environment in the cabin, including: astronauts, auxiliary tools, virtual on-orbit operation platform and platform operation area environment simulation, and reserve digital interfaces for rebuilding the virtual environment in other parts of the cabin.

5) According to the instructions of the on-orbit operating platform, complete the robot crawling, the combined operation of the large and small arms, the transposition of the cabin, and the grasping and docking of the spacecraft body.

6) Through the digital helmet, position tracking system and hand capture system, the movement of the astronaut's head and hands are collected. Through the inverse IK calculation, the positions and angles of the astronaut's arms, elbows, shoulders and other joints are calculated. Display the three-dimensional picture of the astronaut from the first-person perspective in the digital helmet.

7) The astronauts complete the movement in the cabin, the walk outside the cabin, the maintenance outside the cabin, and the maintenance and replacement of the on-orbit operation platform in the cabin.

8) Data storage: including operating data, instructions and feedback data related to the operating platform. Save data with time stamp information for offline analysis.

9) Three high-definition displays are used to display the virtual exterior panorama and different camera views, superimpose the virtual status information of the digital arm, and monitor the entire scene and the operation of the astronaut.
4. Software design
The software cooperates with the semi-physical simulation and testing system for the robot operating platform to complete the construction of the virtual simulation environment for the operating objects of the robotic arm console, including digital arms, space stations, and astronauts, and complete the operation of the virtual digital arm and the operation simulation of the task of the virtual digital arm according to the operating instructions of the manipulator console, and complete the astronaut's in-vehicle and out-of-vehicle maintenance tasks by digital helmets, digital gloves, and positioning systems.

4.1. 3D animation model
The 3D animation model is used to realize the visual experience of the controlled object and the environment, to ensure the immersion of the operator during the simulation test process, and the calculation results of the mathematical model are vividly presented to the user through three-dimensional animation.
1) Space background animation
   The space background has a three-dimensional effect, which can truly reflect the distance of the viewing angle, the size of the object, the image of the earth under sunlight and the image without sunlight, with reasonable illumination and light and dark texture. And the starry sky images truly reflect the positions of the sun and the moon and the distribution of stars.
2) Space station animation
   The components of the space station animation are clearly visible, including the cabin composition, solar panels, robotic arms on the cabin, antennas, attitude motorized nozzles, and foot stopper positions.
3) Astronaut animation
   The astronaut animation mainly includes the astronaut's crawling process in the cabin and the crawling process outside the cabin. The astronaut’s perspective is displayed in the VR glasses. The perspective image changes with the astronaut’s crawling and head movement, which can show the collision of other parts when the astronaut moves and the astronaut’s use of gloves to complete the crawling process.

4.2. Robotic arm model
Robotic arm model can be considered that the linkage of the robotic arm is rigid. The posture of the robotic arm is described by the reference point of the rigid body and the posture of the rigid body. The description methods mainly include homogeneous transformation method, vector method, spinor method and quaternion method. This design uses the homogeneous transformation method, and its advantage is that it links motion, transformation and mapping with matrix operations.
   The boom adopts a pivot connection, the root shoulder and the end wrist have three degrees of freedom of rotation, yaw and pitch, and the elbow joint has one degree of freedom of pitch. The
replacement of the shoulder and wrist of the robot can realize the walking of the space robot. The arm connection method is shown in Figure 4.

![Figure 4. Diagram of the arm connection](image)

4.3. Virtual reality software
Virtual reality software is used to manage the entire simulation process, complete system configuration, data loading and so on.

The software provides space station, spacecraft, astronaut, foot stopper, projection lighting system, ORU components, auxiliary tools, space background, star effect model, and provides cabin astronaut, auxiliary tools, on-orbit operation platform and platform operation area Environment simulation, digital interface reserved for virtual environment reconstruction.

The software provides a database for saving key data of the simulation process, which can be played back offline. The database operation requires stable and reliable operation and can store data for at least one year.

5. Test verification
At present, the semi-physical simulation and testing system for the space robot operating platform has been successfully applied to the ground test of the space station robot operating platform. Taking the robot operating platform to complete the crawling and grasping of the robot arm as an example, the semi-physical simulation and testing system can record the path planning and joint rotation angle of the robot arm, as shown in Figure 5. The virtual view in the cabin is shown in Figure 7, which can provide intuitive feedback on the condition of some equipment in the cabin during the execution of the task.

![Figure 5. Result of the normal temperature](image)

![Figure 6. Result of the high temperature](image)
The system can better derive the whole process of the robot performing space tasks, and provide better support for the functional verification of the robot operating platform. Experiments have proved that the semi-physical simulation and testing system for the robot operating platform can better verify the hardware electrical interface, software algorithm logic and task operation process of the robot operating platform, and its reliability and simulation verification effect are better.

6. Conclusion
In the paper, a semi-physical simulation and testing system is designed which can complete the complex working conditions of the space robot on orbit, according to the characteristics of the robotic arm performing space tasks. This article introduces the semi-physical simulation and testing system from the aspects of its scheme, hardware and software design, and conducts experimental verification on the semi-physical simulation test system. The verification results show that the application of virtual/augmented reality technology in the semi-physical simulation and testing system gives users more realistic sensory effects, enhances the user’s sense of immersion in operation, and makes the entire operation process more intuitive and transparent. The system can quickly and conveniently complete the verification of the hardware electrical interface, software algorithm logic, and task operation process of the robot operating platform, improve the reliability of the equipment on orbit, and provide astronauts with more realistic sensory effects, which is convenient for astronauts quickly to familiarize with the entire process of performing tasks on the space robot.

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