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Design and Realization of Proprioceptive Simulator for Construction Machinery

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Abstract: As one of the important guarantee forces in emergency rescue, the drivers of construction machinery must have high-level operating capabilities and be able to complete the operation tasks safely and efficiently under harsh and complex working conditions. In order to improve task proficiency, drivers usually use simulators for long-term training before performing tasks. However, most construction machinery simulators used for special operation training currently lack real proprioceptive feedback, and the control proprioceptive and authenticity are inconsistent with the actual equipments, which makes it easy for accidents to occur during the actual operation. In response to the above problems, this paper designs a construction machinery proprioceptive simulator based on a multi-degree-of-freedom platform. During the training process, trainees can feel the movement state of the construction machinery in real time, which effectively improves the proprioceptive authenticity of the control and can reduce the safety risks of actual training.

Keywords: Construction Machinery; Simulator; Proprioceptive Simulation.

1. Introduction

Construction machinery can be operated quickly, safely and efficiently in complex and dangerous environments. They are an important guarantee for emergency disaster rescue. The operating results and speed of the construction machinery equipment will directly affect the completion of the task [1-2]. However, the operating effect and speed depend not only on the parameter indicators of the construction machinery itself, but also on the driver's reasonable planning of the operating process and the operating proficiency. Therefore, the troops of various countries mostly focus on improving the driving and operating skills of drivers. In recent years, with the development of virtual simulation technology, the training method of construction machinery is gradually changing from practical training to simulation training. Using simulation software to build virtual training grounds and construction machinery equipment models according to actual operating scenarios, and conducting skill training in a virtual environment by controlling peripherals, it can effectively improve training efficiency and reduce training costs [3].

However, most current construction machinery simulators are unable to simulate the various motion produced during training, resulting in a lack of real physical feedback in the training process. The control feel and authenticity are inconsistent with the actual machinery, which weakens the training effect of the simulator. It may even cause the driver to be unable to correctly perceive the motion state of the equipment and control it due to not adapting to the actual operation feeling, resulting in safety accidents during the actual operation.

In response to the above problems, this paper designs a proprioceptive simulator for construction machinery equipment based on a multi-degree-of-freedom platform. The simulator consists of a proprioceptive feedback device, a control device, and training software. The proprioceptive feedback device is mainly used to simulate various motion states of the equipment. The control component restores the actual installation layout and control feedback feeling to the greatest extent, reducing the difference with the actual equipment; the training software is developed using Unity, 3Ds Max, etc. [4]. The simulator combines computer simulation technology and proprioceptive feedback devices, so that trainees can feel the various motion states of the construction machinery through the proprioceptive feedback device when operating the construction machinery for operation training, effectively improving the proprioceptive authenticity of the control during training and reducing the safety risks of actual equipment training [5].

2. Overall Design

2.1. Component Functions

The proprioceptive simulator for construction machinery equipment uses control devices to operate a digital model of the equipment. The movement of the digital model drives the proprioceptive feedback system, simulating the functions and operational experience of the machinery, and creating virtual training conditions [6]. The simulator consists of training software, control devices, and proprioceptive feedback equipment. The system structure is shown in the figure below.

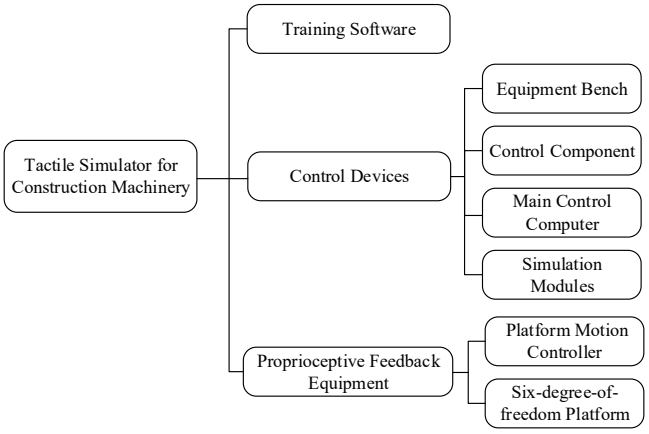


Fig 1. The Composition of the Simulator

The training software can configure various training scenarios and content based on the training requirements. The control devices include a simulation module, construction machinery control components, a master control computer, and an equipment platform. These components are mainly used to capture the operator's control commands and transmit them to the simulation training software, providing control feedback consistent with the actual equipment.

The proprioceptive feedback system includes a six-degree-of-freedom platform and a platform motion controller. Its primary function is to provide real-time feedback on the motion state of the construction machinery within the simulation system, replicating the actual equipment's motion. This ensures that the operator's experience during the simulation training matches the actual equipment's behavior.

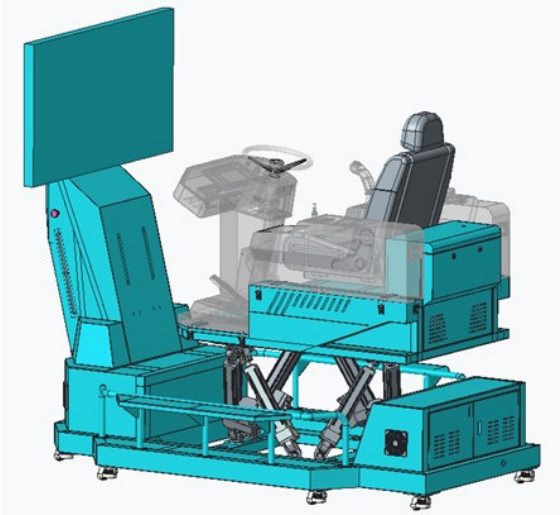


Fig 2. Proprioceptive Simulator for Construction Machinery

2.2. Working Principle

During the simulation training, the operator controls the digital model of the construction machinery within the software using the simulator's control devices. The digital model moves and operates in the virtual environment, with real-time calculations for motion and collisions. The software processes the images, sound effects, and motion information generated by the digital model and transmits this data to the simulation modules and proprioceptive feedback system.

The image simulation module receives data from the virtual camera within the software and displays real-time image information on the visual display unit.

The audio simulation module integrates real-time sound effects by utilizing various sound resources and generates audio signals to drive the sound system, simulating effects such as distance and direction of sounds.

The proprioceptive feedback system receives displacement information transmitted by the software, simulating the movement of the construction machinery. This ensures that the operator's proprioceptive experience is consistent with the digital model's motion.

Through the combined input of visual, auditory, and proprioceptive feedback, the operator controls the digital model of the construction machinery to perform driving and operational tasks, creating a closed-loop simulation system. The working principle of the system is illustrated in the diagram below.

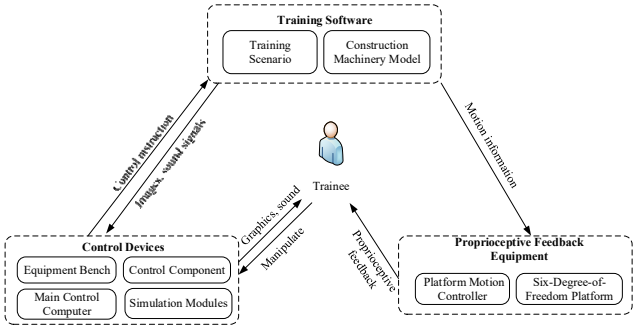


Fig 3. Interaction Diagram

3. Proprioceptive Feedback System

The proprioceptive feedback system is a crucial component of this simulator, significantly enhancing the realism of the construction machinery simulation training. It is a key differentiator from common simulators. Therefore, this section provides a detailed explanation of the design of the proprioceptive feedback system.

The system is primarily composed of a six-degree-of-freedom platform and a platform motion controller, allowing for movement in multiple directions within space. This enables the operator not only to observe the vehicle's posture changes through the visual display unit but also to experience corresponding displacement, rotational angles, and acceleration, resulting in a more immersive and realistic driving simulation experience.

3.1. Six-Degree-of-Freedom Platform Structure

Construction machinery operations typically involve large displacements and high speeds. Thus, the six-degree-of-freedom platform adopts a Stewart parallel structure, which is characterized by long travel distance, fast response, and stable operation. This structure consists of four main components: the upper moving platform, Hooke joints, retractable electric cylinders, and the lower static platform. The expansion and contraction of the retractable electric cylinders allow for motion in six degrees of freedom, effectively simulating the motion posture of construction machinery. The structure of the six-degree-of-freedom platform is shown in the figure below.

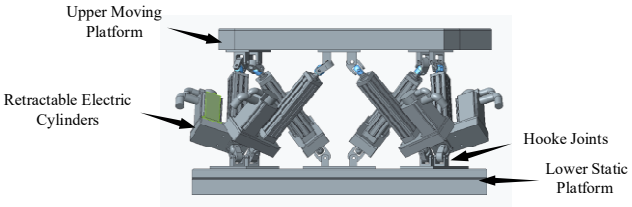


Fig 4. Structure of the Six-degree-of-freedom Platform

3.2. Control of the Six-degree-of-freedom Platform

The six-degree-of-freedom platform used in this simulator is configured with basic parameters within the platform motion controller, along with a posture inverse kinematics algorithm. When the controller receives real-time posture data from the digital model of the construction machinery within the training software, it calculates the required extension length of each electric cylinder. The servo drivers then control the extension and retraction movements of the cylinders, ensuring synchronization with the real-time posture of the digital model. The platform motion controller communicates

with the simulation training software via the UDP protocol to ensure seamless data exchange [8].

3.3. Motion Range of the Six-degree-of-freedom Platform

The motion limits of the six-degree-of-freedom platform designed for this simulator are specified in the table below. The simulated motion range of the platform is illustrated in the accompanying figure.

Table 1. Six Degrees of Freedom Platform Motion Parameters

No.	Name	Parameter
1	Displacement of X	±250mm
2	Displacement of Y	±250mm
3	Displacement of Z	250mm
4	Angle of roll	±8°
5	Angle of pitch	±9°
6	Angle of yaw	±10°

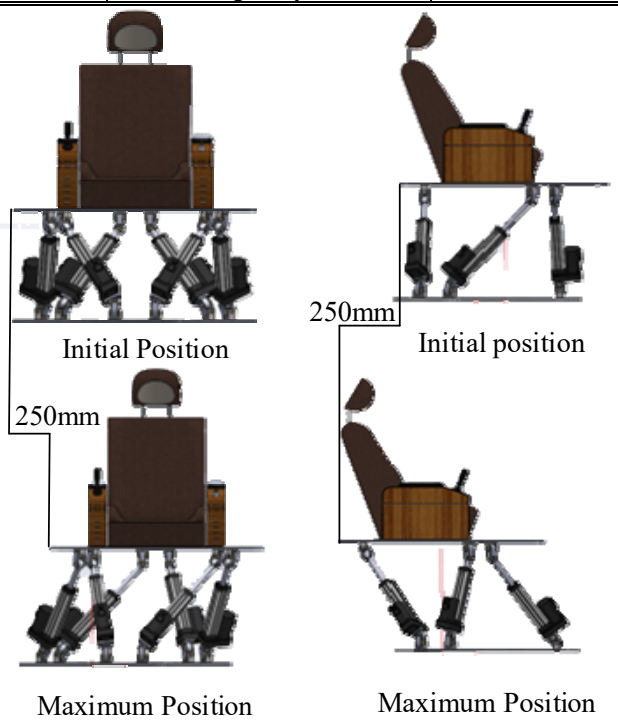


Fig 5. Displacement of X Y

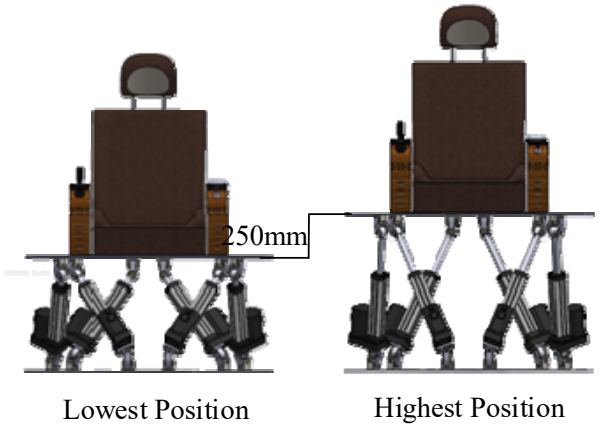


Fig 6. Displacement of Z

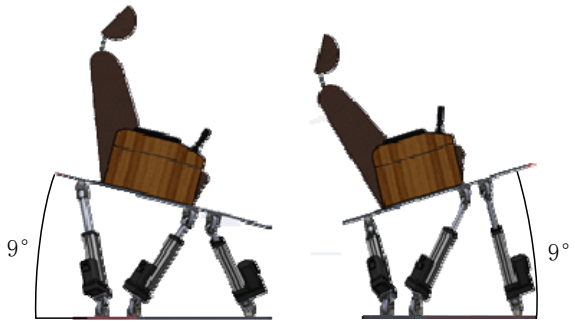


Fig 7. Angle of pitch



Fig 8. Angle of roll

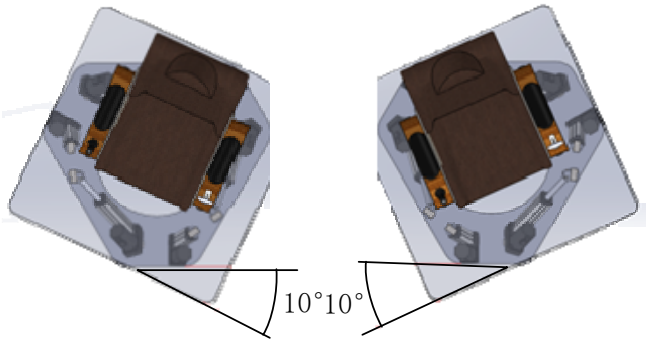


Fig 9. Angle of yaw

4. Simulator Testing and Results Analysis

To evaluate the training effectiveness of the simulator, testing was conducted after the development of the proprioceptive simulator for construction machinery equipment. The developed training software was deployed on the main control computer, which was configured as follows:

Table 2. Configuration of the Computer

No.	Name	Parameter
1	OS Version	Windows 10 64-bit
2	RAM	16GB(2×8GB)
3	CPU	Intel CORE i5-13400
4	CPU Speeds	Turbo 3.80GHz
5	Video Card	GeForce RTX 2080
6	Hard Disk	500GB

After the software deployment was completed, the proprioceptive simulator for construction machinery equipment was launched. The training software was initiated, and simulations for various types of construction machinery operations were conducted to test the effectiveness of the simulated training. The results of the simulation testing are as follows:



Fig 10. Proprioceptive Simulator for Construction Machinery



Fig 11. Jolting Effect

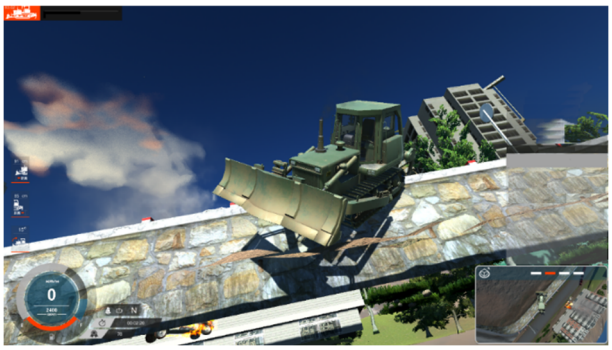


Fig 12. Effect of Overturning



Fig 13. Effect of Roll Over

The test results indicate that the construction machinery simulation trainer developed in this study can effectively display the movement posture of the equipment. The proprioceptive feedback module is able to maintain real-time synchronization with the posture of the digital model. The operator can control the movements of the construction machinery in the software through the control components, and receive real-time visual, auditory, and proprioceptive feedback via the visual display unit, audio system, and proprioceptive devices. This enables the simulation of construction machinery operation exercises.

5. Conclusion

Construction machinery as a rescue and disaster relief in the important protection force, its importance is increasingly prominent. Currently, the training of construction machinery is gradually changing from hands-on training to simulation training, however, most of the current simulators are unable to simulate the training process of construction machinery in a variety of sports, resulting in a lack of real proprioceptive feedback of the training process. In this regard, this paper based on the six-degree-of-freedom platform designed a construction machinery proprioceptive simulation trainer and related tests. Test results show that through the combination of computer simulation technology and proprioceptive feedback device, proprioceptive simulator can make the trainee in the engineering machinery operation training at the same time feel its various motions, effectively improve the training of the manipulation of proprioceptive authenticity, reduce the safety risks of the actual training, has a broad application prospect.

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