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Key Technologies for an Augmented Reality Safety Education System Based on Real Railway Incident Cases

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Abstract:

This project is an augmented reality (AR) and virtual reality (VR) construction safety education and training system. The purpose of the system design is to allow users to experience the real construction scene, learn the correct construction process, and handle emergencies and safety rescue operations through VR immersive interaction, so as to achieve the purpose of safety training. The system involves different construction scenes. The key technology includes scene reconstruction and interaction, case-driven scenario simulation, and multisensory interaction technology. Through user interface and voice prompts, users are guided to learn construction precautions and complete construction operations. This system is developed in the Unity3D engine and finally displayed on the AR and VR device.

Keywords:

Virtual reality
Immersive interactive experience
Safe construction
Education and training
Unity3D

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1. Introduction

In life, the safety issues in the construction process should be emphasized, such as tunnel water leakage, high-altitude work, slope collapse, and so on. The construction personnel need to have rich experience and safety awareness. Therefore, safety education and training is critical. With the development of virtual reality (VR) technology, immersive training through VR has gradually replaced the traditional way of learning and training. Through the immersive interactive experience of this system, users can achieve the same training purpose and improve safety awareness under low-cost and safe conditions. The functional modularity of this system is also unified and standardized, including the user interface (UI) system, scene model and material design, animation system, photorealistic rendering technology, particle effects, and so on. It provides technical support for the design and development of future related virtual reality systems [1-3].

With the rapid development of the railway transportation industry, safety issues have increasingly become a focal point. Traditional safety training methods are no longer sufficient to meet actual needs, and technologies like VR and augmented reality (AR) are gradually being introduced to enhance training effectiveness. This paper designs and implements an AR safety education system based on real railway incident cases (**Figure 1**). The system utilizes AR technology to recreate accident scenes with 3D reconstruction and interactive simulations, allowing employees to learn safety knowledge and procedures through immersive experiences [4-6].

The key technologies include:

(1) 3D scene reconstruction and interaction: AR technology is used to model and reconstruct real railway accident scenes in 3D, enabling users to interact with different incident scenarios and safety hazards.

(2) Case-driven scenario simulation: Based on actual railway safety incidents, the system incorporates multiple accident cases to generate various danger scenarios and provide real-time feedback, helping trainees master emergency response skills.

(3) Multisensory interaction technology: Voice recognition, gesture control, and visual enhancement are employed to enhance user engagement and the effectiveness of the training.

(4) Cross-platform adaptability and application: The system supports multiple terminal devices, including mobile devices and AR glasses, ensuring flexibility and wide applicability.

This system effectively enhances railway employees' safety awareness and emergency response capabilities, offering great potential for widespread adoption in the railway transportation industry.

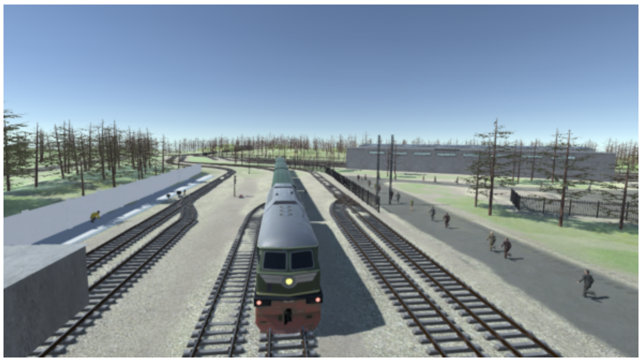

Figure 1. Scene of the system

2. 3D scene reconstruction and interaction

2.1. Based on construction scene

This system is based on the construction scene development and design, including ten different scenes. Through a comprehensive training experience, users can learn construction operations and safety awareness. The design of the scene refers to the real construction scene (**Figure 2**). In the aspect of 3D scene reconstruction and interaction, we adopted real-world scenarios as references and utilized advanced 3D animation modeling technology to create highly realistic virtual animation scenes [7,8]. The detailed technical implementation is described as follows.

Figure 2. Real scene

We first gathered real railway accident site data through field surveys, photography, and video recording. These materials provided accurate references for scene reconstruction, ensuring that the layout, structure, and details of the virtual scene closely match the real-world settings as shown in **Figure 2**. Additionally, technologies such as laser scanning and drone aerial photography were employed to generate high-precision point cloud data, serving as the foundation for 3D modeling.

Based on the collected real-world data, we used 3D modeling software (such as Maya, Blender, etc.) to build detailed scene models. To ensure the realism of the models, every object in the scene was carefully modeled, considering the geometric shapes, size proportions, and material properties of railway facilities [9]. For texture processing, high-resolution texture mapping techniques were used, combined with PBR (Physically Based

Rendering) materials, to provide realistic lighting, reflections, and shadow effects. This technique allows users to experience a visual effect within the AR system that closely resembles being in a real-world environment as shown in **Figure 3**.

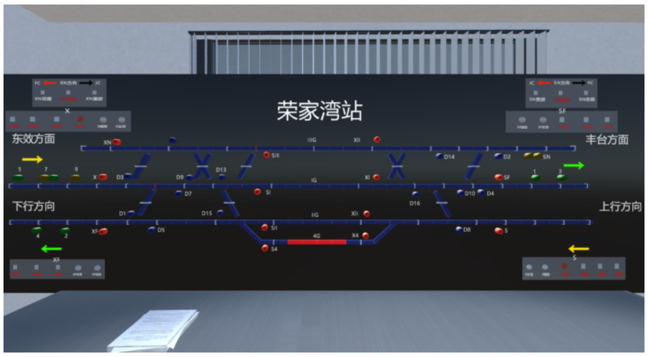

Figure 3. The scene of Rongjiawan station

2.2. Unified scene interaction

The ten construction scenes maintain the same interactive experience logic design and process to prevent ambiguity caused by different operations in different scenes as shown in **Figures 4** and **5**.

To enhance immersion, dynamic accident reconstructions and environmental interactions were added to the scene. For example, animations simulating train movements, track malfunctions, and changes in traffic signals were incorporated, creating realistic visual changes. We used 3D animation technology to recreate accident processes and employed skeletal animation and particle systems (such as fire, explosions, and smoke effects) to simulate real-world emergencies. These dynamic scene presentations enable users to fully immerse themselves in dangerous scenarios, reinforcing their safety awareness.

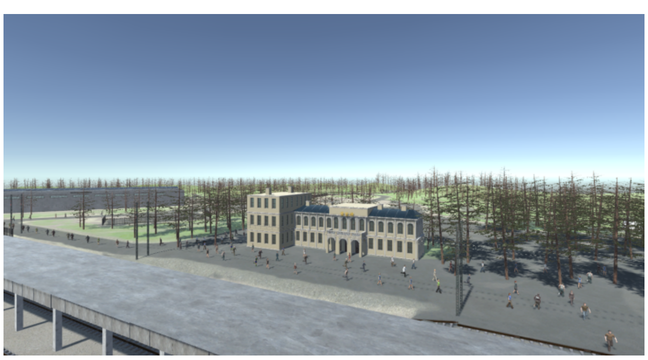

Figure 4. The railway station

Figure 5. The railway station

2.3. Based on realistic rendering

The models in the scene are rendered based on physics, which improves the rendering quality of the objects, makes the models look more realistic, and enhances the user experience. To provide a more realistic user interaction experience, the system integrates a physics engine (such as Unity or Unreal Engine), allowing users to interact with virtual scene objects in various ways. For instance, users can use gestures or control devices to interact with objects in the virtual scene, simulating real-world accident response operations. The physics engine ensures that the forces exerted by the users and the movement trajectories of objects comply with physical rules, enhancing the authenticity of the interaction and overall experience [10,11].

In combination with AR devices, users can experience the accident scene from a first-person perspective. Using mobile device cameras or AR glasses, users can see virtual scenes superimposed onto the real world and interact with them. The system also provides real-time feedback mechanisms, offering tips or warning messages during the user's operation, further enhancing the effectiveness of the training.

3. System architecture

The system has ten scenes such as tunnel water leakage, road collapse, falling objects, fire accidents, bad weather, slope collapse, high-altitude work, no helmet, vehicle injury, and electric shock accidents. For each scene, after entering the scene, the system will introduce the construction scene, and then conduct a correct construction simulation experience through the guidance of UI and voice. When the wrong operation occurs, there will be corresponding accidents, risk prompts, and emergency rescue prompts. Subsequently, the user will complete the training under the correct operating instructions [12,13]. Finally, the system will summarize and review the construction scene to help users review. The system composition is shown in **Figure 6**.

Through these technical approaches, the system successfully constructs a 3D scene based on real-world cases and provides a highly immersive and interactive experience, offering more effective safety training for railway employees. This system aims to use VR and AR technologies to construct multiple highly realistic railway safety training scenes, including key areas such as the pre-departure personnel meeting room, vehicle dispatch room, and indoor and outdoor views of railway stations. By recreating real-world classic accident cases and using a narrative approach, the system vividly re-enacts the events, causes, and responses, aiming to enhance trainees' operational and emergency response skills. Below is the detailed technical solution [14,15].

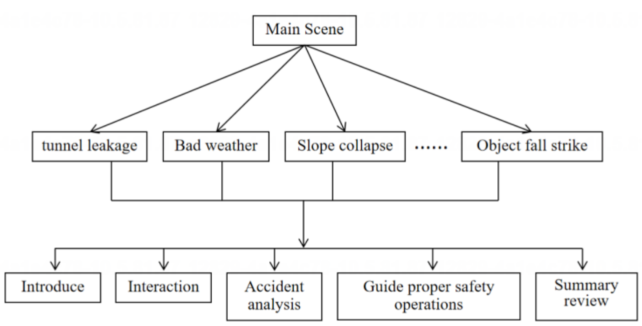

Figure 6. Construction system structure

4. Technical highlights

The system is divided into three parts, including the interactive module, the operation instruction module, and safety rescue training. The key technologies are as follows.

4.1. Interactive module

The system includes several scenes covering critical operations and decision-making points in railway operations, ensuring that trainees can engage in comprehensive learning and practice in the AR environment. The main scenes include the following:

Pre-departure personnel meeting room: This scene displays the process of a pre-departure personnel dispatch meeting. Trainees can observe virtual characters' dialogues to learn about train schedules, safety instructions, and procedures for pre-departure safety checks and personnel assignments.

Vehicle dispatch room: The dispatch room is the central hub for train operation management. The system simulates the real-time data and workflow of train dispatching. Trainees can participate in key stages of dispatching, including train arrival and departure planning, signal system control, and emergency response. AR technology provides interactive experiences with dispatch equipment, allowing trainees to virtually operate devices and simulate real-world scenarios.

Indoor and outdoor views of the train station: Using virtual modeling, the system recreates station interiors (waiting rooms, platforms, ticket gates) as well as exterior areas (tracks and parking zones). Trainees can experience different job roles, such as guiding passengers, ticket inspection, and managing crowd control. Outdoor scenes simulate potential safety hazards during train arrival and departure, such as equipment failures or train overspeed. The interaction with objects is shown in **Figures 7** and **8**.

Figure 7. Interact with objects in the scene

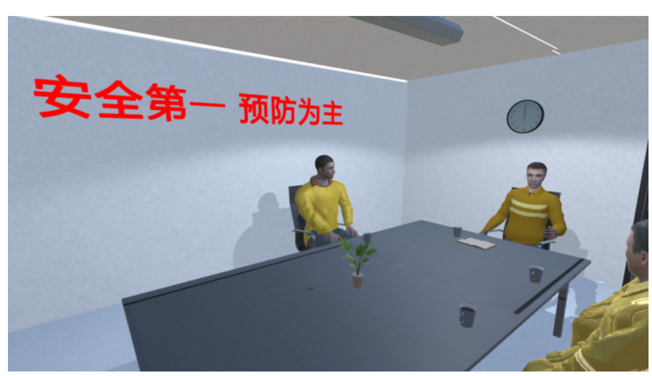

Figure 8. The staff office

4.2. Operation instruction module

This system can not only achieve the simulation of the construction process, but also achieve the correct operation guidance, and the final review of the construction process. Instructions for operation are shown in **Figure 9**. For safety education, the system is based on real-world classic railway safety cases and uses a narrative approach to fully recreate events. Case reconstruction is divided into several phases as follows.

Pre-event scenario recreation: The system first demonstrates normal operations before the accident, helping trainees understand the working state before the incident. For example, the normal operation of the dispatch room or passenger activity on the platform.

Incident triggering: Through virtual animation technology, the system simulates the occurrence of accidents, such as a dispatcher's command error leading to a train collision or equipment malfunction causing an emergency brake. The system highlights key moments and triggers to help trainees recognize potential risks.

Emergency response and aftermath handling: After the accident, trainees can simulate different emergency response measures using the AR system, learning how to handle emergencies quickly and effectively. Through repeated interaction exercises, trainees master emergency skills such as passenger evacuation, equipment repair, and dispatch adjustments, enhancing their crisis management capabilities.

Figure 9. Operation instruction

4.3. Safety rescue training

When accidents happen in the process of construction, such as electric shock, students can learn the rescue measures that should be taken in an emergency. This topic will also cover the knowledge of emergency rescue. Safety rescue is shown in **Figure 10**. The system not only presents the course of accidents but also provides various operational tasks that allow trainees to improve their practical skills through hands-on simulation. The specific technical implementations include the following.

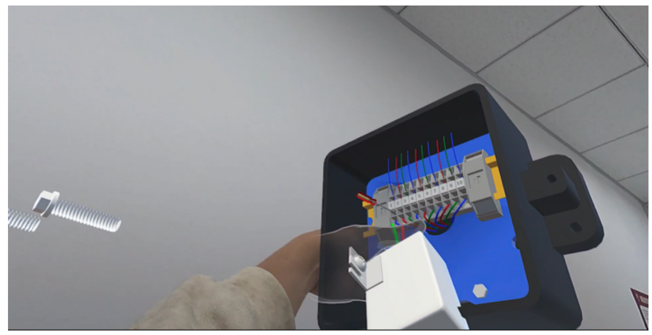

Figure 10. Equipment maintenance experiment

Virtual interactive devices: Using gesture recognition and touch controls, trainees can interact with virtual devices within the AR scenes. For instance, in the dispatch room, they can operate control panels, ticketing machines, and signal lights, allowing them to simulate the actual controls needed for various equipment.

Task-driven learning mode: The system sets multiple learning tasks, guiding trainees through procedures such as issuing dispatch orders or handling emergencies. Each task provides immediate feedback on operational steps, such as error prompts or rewards for correct operations, helping trainees continuously refine their skills.

Emergency response drills: Based on real accident cases, the AR scenarios allow trainees to simulate emergency response procedures. The system dynamically adjusts the difficulty of incidents through a stress-testing mechanism, testing trainees' decision-making and response speeds under pressure.

4.4. Narrative-driven learning experience

The system adopts a narrative-driven educational approach, embedding the safety training process into a series of complete storylines to enhance continuity and engagement in learning. Specific features include the following.

Event causes and progression display: Through virtual character dialogues and animated demonstrations, the system presents the background, causes, and development of each accident. For instance, dispatcher miscommunication or equipment aging leading to failures, helping trainees understand the origins of safety hazards in a storyline format as shown in **Figures 11** and **12**.

Figure 11. Hand interaction in AR

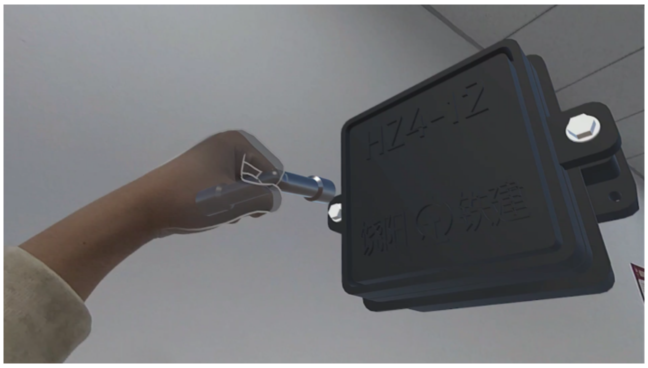

Figure 12. Hand operation

Multi-angle role participation: Trainees can take on various roles such as dispatcher, train attendant, or ticket inspector. By experiencing accidents from different perspectives, they gain a comprehensive understanding of the responsibilities and responses required in each role during an incident.

Scenario narration and feedback: The system provides dynamic story feedback based on trainee operations. For example, correct emergency operations lead to a positive storyline progression, while incorrect actions result in more complex accident developments, enhancing the interactivity and challenge of the learning experience as shown in **Figure 13**.

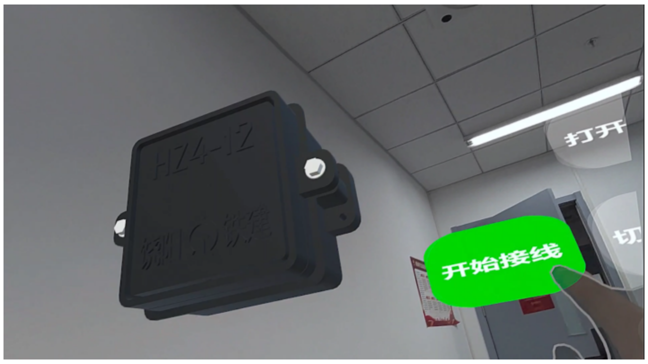

Figure 13. System design

4.5. System optimization and expansion

Cross-platform support: The system supports various device terminals, including AR glasses, smartphones, and tablets, ensuring trainees can use the system in different environments. It also features cloud synchronization, enabling real-time uploading of trainee progress and operational data for course management and evaluation.

Modular design: The system is designed modularly, allowing for easy expansion with new cases and scenarios in the future. For example, additional content on high-speed rail operation safety management or freight train dispatch can be incorporated, further enriching the training material.

With the above technical solution, this system realizes comprehensive virtual simulation of railway safety training. Through AR technology, trainees can experience realistic safety operations and emergency handling (**Figure 14**), significantly improving the effectiveness of training and practical skills.

Figure 14. Safety rescue

5. Conclusion and future work

This system successfully creates an immersive railway safety training experience through the construction of multi-scene, case-based AR environments. It covers key operational scenes such as pre-departure meeting rooms, vehicle dispatch rooms, and both indoor and outdoor areas of train stations, simulating real accidents and their responses. The narrative-driven learning approach enables trainees to deeply understand the causes, development, and emergency handling of incidents. Meanwhile, AR technology's interactive capabilities allow trainees to practice operations using virtual equipment and improve their emergency response and operational skills within simulated accident scenarios. The system's cross-platform design and modular architecture offer great flexibility and scalability, providing robust technical support for future railway safety education and training.

As AR and VR technologies continue to evolve, this system is expected to see broader applications and functional upgrades. In the future, artificial intelligence could be integrated to automatically analyze trainee behavior and offer personalized feedback and improvement suggestions. Additionally, more railway operation scenarios and emerging safety cases, such as those involving high-speed rail and smart railways, can be incorporated into the system to address the latest developments and safety requirements. With cloud-based platform support, the system could enable large-scale remote training, allowing trainees from different regions to participate in high-quality safety education anytime and anywhere. Through continuous optimization of technical features and training content, this system is poised to become a core tool for standardized and intelligent railway safety training, significantly contributing to enhancing the industry's overall safety standards.

Disclosure statement

The authors declare no conflict of interest.

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