Research on the Applicability of Virtual Reality Technology in Nuclear Accident Emergency Training

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Abstract. Traditional nuclear accident emergency training has limitations such as high risk, high cost, and limited scenarios. In contrast, virtual reality technology, with its immersive, interactive, and imaginative features, offers innovative solutions for nuclear accident emergency training. This article systematically elaborates on the specific applications of virtual reality technology in various training scenarios, analyzes the current technical challenges, proposes corresponding solutions, and looks forward to future development trends.

Keywords: Virtual reality technology, nuclear accident emergency, education and training, applicability

1 Introduction

Traditional nuclear accident emergency training mainly relies on classroom lectures, field exercises, and simulation operations, which have obvious limitations. Real nuclear accident environments are difficult to replicate, limiting the effectiveness of training, and field training may expose participants to radiation risks, posing significant safety concerns. In addition, large-scale field exercises are costly and complex to organize, making frequent implementation difficult. These factors all restrict the effective improvement of nuclear accident emergency training outcomes.

Virtual reality technology, as an innovative simulation tool, creates a realistic virtual environment that allows participants to immerse themselves and interact within it, providing a new solution for nuclear accident emergency training[1]. Especially in recent years, the improvement of virtual reality hardware performance and advancements in software development have enabled its application in nuclear accident emergency response and simulation, medical rescue training, and safety education and hazard inspection training to move from concept to practice[2]. This paper explores the advantages of applying virtual reality technology to nuclear accident emergency training, specific application scenarios, technical challenges faced, and future development trends, providing reference and guidance for nuclear emergency training practice.

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2 Analysis of the Advantages of Applying Virtual Reality Technology in Nuclear Accident Emergency Training

Virtual reality technology, with its unique technical characteristics, demonstrates significant advantages over traditional training methods in the field of nuclear accident emergency training in terms of safety, realism, cost structure, training frequency, and flexibility. It not only addresses the inherent shortcomings of traditional training methods but also opens up new possibilities for training models, as shown in Table 1.

Table 1. Comparison between Traditional Training Methods and Training Methods Enhanced by VR Technology.

Comparison Imension	Traditional Training Methods	VR Training Methods
Safety	Risk of radiation exposure, complex safety measures	Absolutely safe, zero radiation exposure
Veracity	Limited by actual conditions, limited scenarios	Highly realistic, can simulate various accident scenarios
Cost Structure	Investment needed for each training session, high variable costs	High initial investment, low marginal cost

2.1 Safety and Risk Control

The core dilemma of nuclear accident emergency training lies in the fact that the scenarios that require training the most are precisely those with the highest risk and the least feasible real-world training environment. Virtual reality technology effectively addresses this problem through fully digital simulations.

The application of virtual reality technology can serve as a substitute for hazardous environments. Virtual reality can simulate extremely dangerous settings such as high-intensity radiation fields, nuclear material leaks, and equipment failures, without exposing trainees to any real radiation risks. For example, in nuclear radiation reconnaissance simulation training, virtual hazard environment units are used to simulate radiation scenarios, replacing the traditional training conducted in low-radiation real environments.

The application of virtual reality technology can recreate the process of accidents. Virtual reality systems can simulate the entire evolution of a nuclear accident, including the initiation of leakage, spread, contamination, and other stages, allowing trainees to comprehensively understand the development patterns of accidents without being exposed to any actual hazardous materials.

The application of virtual reality technology can allow for safe tolerance of mistakes. In a virtual environment, trainees can safely make errors and learn from them, such as improperly wearing protective equipment or mistakes in handling procedures. Errors that could cause serious harm in real-life situations become valuable learning experiences in virtual reality.

2.2 Realism and Situational Immersion

Compared with the abstract tabletop exercises and limited field drills in traditional nuclear emergency training, the realism and immersive advantages brought by virtual reality technology are revolutionary, fundamentally reconstructing the training experience on sensory, cognitive, and psychological levels.

From imagination to firsthand experience, the senses are truly engaged. In traditional training, radiation fields, casualties, and hazardous environments are all conveyed through verbal descriptions or warning signs, requiring trainees to rely on experience and imagination to construct the scenes. Virtual reality technology, however, employs panoramic 3D modeling, spatial sound effects, and realistic visual feedback to directly present crumbling ruins, flashing alarms, and pervasive smoke. It can even visualize invisible radiation fields through colors and particle effects, turning abstract high-dose zones into immediate, moving threats, compelling trainees to react under highly realistic visual and auditory stimuli.

Realizing dynamic scenarios and complex interactions enhances the realism of cognition. Traditional exercises feature linear and preset plots, whereas virtual reality technology can simulate highly dynamic and unpredictable accident evolutions. For instance, a radiation cloud can spread in real-time, following the wind direction, and equipment may suddenly malfunction. This breaks the limitations of traditional exercises, which follow a scripted approach, requiring trainees to continuously assess changes and adjust strategies flexibly, just as they would in a real disaster. At the same time, the physical interaction mechanisms in virtual reality technology ensure the operational authenticity of skill training, far surpassing simulations that merely mimic actions in the air.

The core advantage of virtual reality technology is decision-making honed under pressure. Traditional training methods often fail to replicate the psychological stress of a nuclear accident scenario. In contrast, virtual reality effectively triggers stress responses in trainees by creating an isolated and helpless environment, continuous time pressure, resource scarcity, and a sense of responsibility for virtual lives. Within this highly tense and immersive atmosphere, participants' decision-making skills, teamwork, and psychological resilience are thoroughly enhanced, achieving training outcomes that surpass those possible in safe, detached traditional classrooms.

2.3 Cost-effectiveness and Accessibility

Compared with traditional training methods, virtual reality training shows clear economic advantages in long-term operations. The application of VR technology allows for a one-time investment that can be used repeatedly, saving resources and improving efficiency. Although the initial development cost of a VR training system is high, once completed, it can be used indefinitely without continuously consuming materials and human resources as on-site exercises do. This eliminates substantial costs for each training session, such as venue rental, equipment wear and tear, protective materials, and waste disposal, significantly reducing the marginal cost of training. VR training can be conducted anytime and anywhere, without the need to coordinate multiple

departments and production schedules, greatly enhancing the flexibility and frequency of the training.

3 Specific Application Scenarios of Virtual Reality Technology in Nuclear Accident Emergency Training

The application of virtual reality technology in nuclear accident emergency training has evolved from single-scenario simulations to a comprehensive, multi-level training system, covering various aspects from on-site operations to command decision-making.

3.1 Radiation Monitoring and Reconnaissance Training

Radiation monitoring is a primary component of nuclear emergency response, directly affecting the scientific validity and effectiveness of subsequent decision-making. Virtual reality technology plays an irreplaceable role in this field. Through virtual simulation systems, trainees can repeatedly practice operating various radiation monitoring instruments, including surface contamination detectors, gamma dose rate meters, and nuclide identifiers. The nuclear and radiation emergency monitoring virtual simulation training system can conduct learning and training at three levels: instrument simulation operation, skills simulation training, and comprehensive simulation training[3]. This type of virtual training not only avoids the risk of damaging expensive instruments but also ensures the correct mastery of operational skills. In the virtual environment, trainees can learn to formulate radiation reconnaissance plans, including monitoring point layout, monitoring route planning, and data quality control. The portable nuclear radiation reconnaissance simulation training system uses a Gaussian Plume Model for hazard field distribution calculation, capable of simulating complex accident dispersion scenarios, allowing trainees to develop reconnaissance strategy skills under near-real conditions. The virtual system can simulate the characteristics of radiation field distribution under different nuclides and dispersion conditions, training trainees to correctly interpret monitoring data, and assess the degree and scope of contamination. This capability is crucial in actual incidents for rapidly determining contamination boundaries and implementing protective measures.

3.2 Medical Emergency Rescue Training

Medical rescue in nuclear accidents is characterized by high professionalism, complex procedures, and strong time sensitivity. Virtual reality technology provides powerful support for training in this field. Through a nuclear accident medical emergency rescue simulation training system, participants can learn to quickly triage casualties, assess the degree of radiation injuries, and implement emergency treatment capabilities within a virtual environment. The system can simulate the characteristics of different injuries, such as symptoms of acute radiation syndrome and complex injury manifestations, enhancing medical personnel's ability to recognize and handle special conditions in

nuclear incidents[4]. Participants can practice the full process of decontaminating injured individuals in a virtual environment, learning the correct use of decontamination equipment and methods to avoid cross-contamination[5]. In a VR-based nuclear emergency medical rescue simulation platform, devices such as single-soldier decontamination simulators provide highly realistic training conditions for such operations[6]. Medical rescue in nuclear accidents requires collaboration across multiple departments and specialties. Virtual reality platforms can simulate this complex collaborative environment. For example, different participants can assume roles such as triage officers, decontamination personnel, and treating doctors in the same virtual scenario, coordinating to complete rescue tasks and cultivating team collaboration skills.

The nuclear emergency medical rescue platform built with virtual reality technology plays the role of a collaborative catalyst and a decision pressure tester in coordinated training. It can place various departments into the same scenario and, through carefully designed task flows, information barriers, and resource constraints, compel personnel from different professional backgrounds to follow the same procedures and collaborate efficiently to achieve the goal of saving lives. By repeatedly rehearsing in a virtual reality environment, relevant departments can solidify collaboration processes, refine communication mechanisms, and build trust, so that when a real nuclear disaster occurs, seamless coordination can be achieved, greatly enhancing overall rescue efficiency and success rate.

3.3 Emergency Command and Decision-Making Training

Nuclear accident emergency response requires not only on-site operational skills but also scientific command and decision-making abilities. Virtual reality technology provides a powerful tool for this high-level training. Through a nuclear emergency simulation training system driven by 3D digital technology, commanders can learn to quickly and accurately assess the accident situation, including radiation levels, impact scope, and potential hazards[7]. The system can dynamically simulate the accident development process, helping commanders grasp key elements and methods for situational assessment. In virtual scenarios, commanders need to allocate emergency resources reasonably according to the accident situation, including personnel, equipment, and materials, and learn how to optimize resource utilization efficiency to improve emergency response effectiveness. Nuclear accident emergency response requires coordination and communication across multiple departments and levels. The virtual reality system can simulate this complex communication environment, training commanders in communication and coordination skills as well as information transmission efficiency.

4 Technical Challenges and Solution Strategies for Virtual Reality Technology in Nuclear Accident Emergency Training

Despite the significant potential of virtual reality technology in nuclear accident emergency training, it still encounters numerous technical challenges in practical applications, necessitating effective solution strategies.

4.1 Challenges and Improvements in Hardware Devices

Virtual reality is directly impacted by hardware performance limitations such as constraints of display devices, adaptability of interaction devices, and mobility and wireless capabilities, which in turn affect the training experience and effectiveness.

VR headsets commonly face issues such as insufficient resolution, limited field of view, and low refresh rates, which can lead to visual fatigue and reduced immersion. To address these challenges, it is necessary to develop professional-grade VR equipment specifically for nuclear emergency training, providing higher resolution, wider field of view, and higher refresh rates, while also considering device comfort to ensure feasibility for prolonged training sessions. Nuclear emergency training involves operating a variety of specialized tools and equipment, which generic VR controllers cannot accurately replicate. The solution is to develop specialized simulation controllers, such as dedicated interaction devices for simulating the use of radiation detectors, sampling tools, and other specialized equipment, enhancing the realism and accuracy of operational training. Wired VR devices restrict movement, whereas wireless devices face latency and stability issues. For emergency training scenarios that require extensive mobility, high-performance wireless transmission technology combined with inside-out tracking technology should be used to achieve a VR training experience that is both unrestricted and high-performance.

In response to the above three core issues, Figure 1 constructs a complete set of solutions.

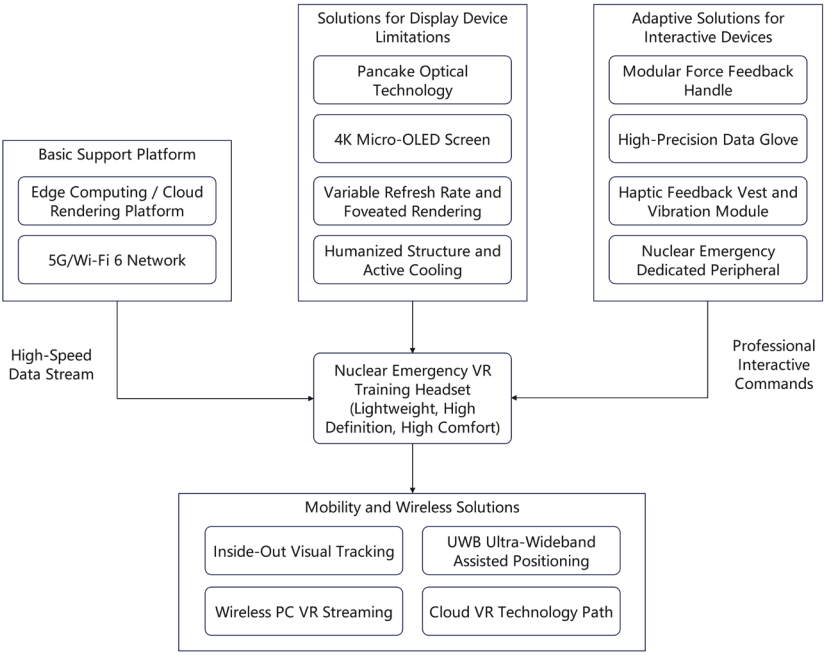

Fig. 1. Solutions for hardware devices.

4.2 Challenges in Software Systems and Modeling

The realism and accuracy of virtual reality training software directly determine the effectiveness of the training.

In terms of physical process modeling, nuclear accident emergency training involves multiple complex physical processes such as radiation transport, contamination dispersion, and equipment response. Accurately modeling these processes is a significant challenge. It is necessary to develop high-precision physical models based on first principles and experimental data, such as using the Monte Carlo method to simulate radiation transport and computational fluid dynamics methods to simulate contamination dispersion, ensuring that the virtual environment is consistent with real physical processes.

In terms of system integration and interoperability, comprehensive nuclear accident emergency training requires the coordinated operation of multiple subsystems, and there are technical challenges in integrating and achieving interoperability between different systems. This can be addressed by establishing unified interface standards and data formats, adopting a modular design approach, and constructing an open VR training platform architecture, facilitating the integration and expansion of different functional modules.

In terms of scene reuse and rapid construction, emergency training for different types of nuclear facilities requires specific virtual scenarios, but building these scenes from scratch is costly and time-consuming. This can be mitigated by establishing

libraries of nuclear facility components and scene templates, developing intelligent scene generation tools, and combining real-world scanning and modeling technologies, significantly improving the efficiency and quality of virtual scene construction.

To address the above three core issues, Figure 2 presents a complete solution set.

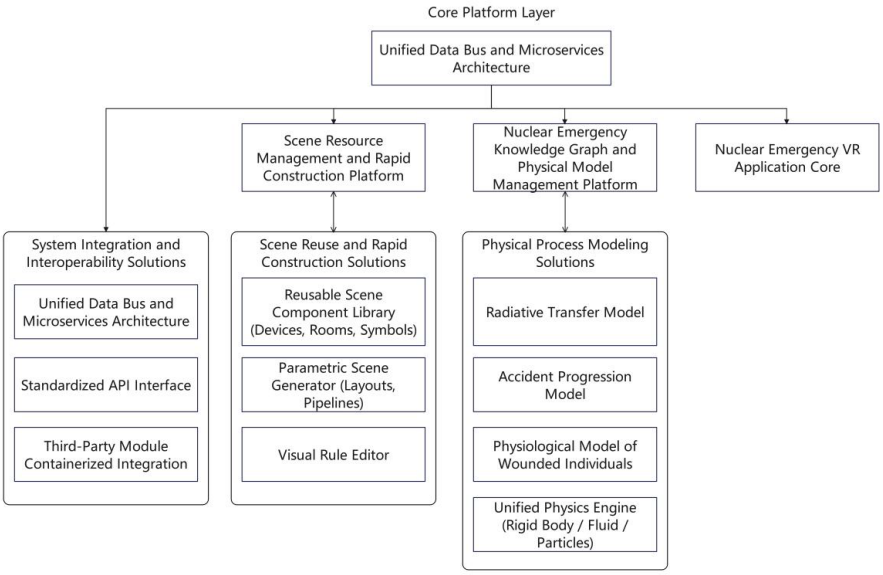

Fig. 2. Solutions for software systems and modelings.

4.3 Challenges in Realism and Immersion

High levels of realism and immersion are prerequisites for effective training. Currently, virtual reality systems still face problems such as insufficient multi-sensory feedback, unnatural human-computer interaction, and unrealistic environmental responses. Virtual reality systems mostly focus on visual and auditory senses, while multi-sensory feedback such as tactile, force, and temperature sensations is relatively weak. Developing multifunctional haptic feedback devices, temperature simulation devices, and force feedback devices can enrich sensory feedback channels, enhancing the realism and immersion of training. Human-computer interaction methods in virtual environments differ from those in the real world, affecting operational intuitiveness. Gesture recognition, motion capture, and natural language interaction technologies need improvement so that trainees can interact with the virtual environment more naturally, reducing learning costs and increasing training efficiency. The realism of the virtual environment's response to user actions directly impacts training outcomes. Strengthening the physics engine and accurately simulating interactions with tools and equipment, such as collision detection and material deformation, can ensure that virtual environment responses meet trainees' real-world expectations.

In response to the above three core issues, Figure 3 constructs a complete set of solutions.

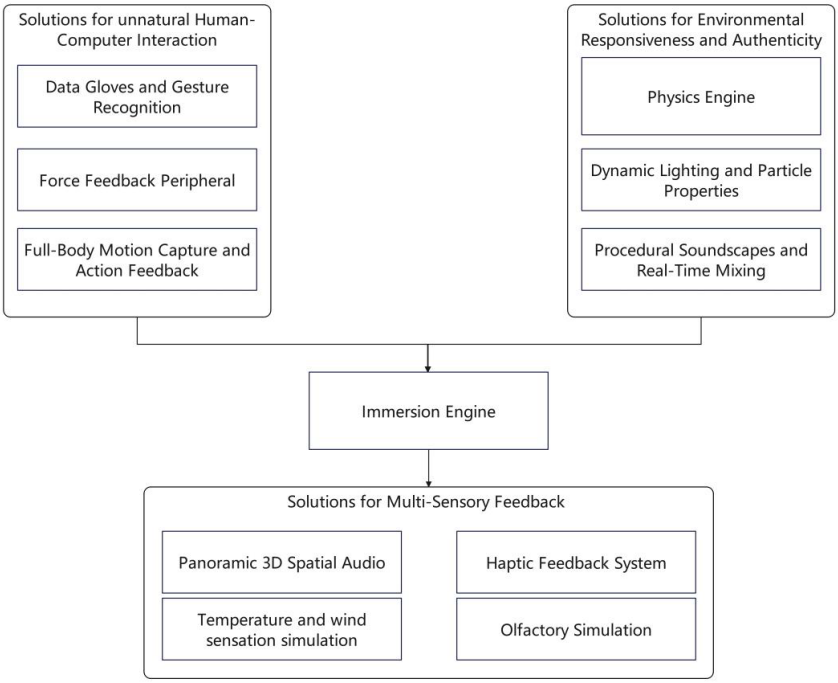

Fig. 3. Solutions for software systems and modelings.

5 Conclusion

Virtual reality technology exhibits a broad applicability and unique value in nuclear accident emergency training. By generating highly realistic yet completely safe virtual environments, it effectively surmounts the inherent limitations of traditional training methods. However, there are still a series of technical challenges in terms of hardware devices, software modeling, realism, and performance evaluation, which need to be addressed through technological innovation and system optimization[8].With the deep integration of technologies such as artificial intelligence, digital twins, and 5G communication with virtual reality, virtual reality technology is bound to play a more important role in ensuring nuclear energy safety and promoting the sustainable development of nuclear energy.

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