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Research on the Construction of Immersive Education Systems for Fire Safety in University Laboratories Using VR/AR in Hazardous Chemical Scenarios

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Abstract: With the rapid development of virtual reality (VR) and augmented reality (AR) technologies, their application potential in the field of education has become increasingly significant. For a long time, fire safety education in university laboratories has faced numerous challenges, and traditional teaching methods have been insufficiently effective, with high-risk scenarios difficult to realistically recreate. Especially in special scenarios involving hazardous chemicals, conventional training methods struggle to enable learners to achieve deep understanding and behavioral formation. This study systematically integrates immersive technology theory with safety education needs, providing a replicable technical solution for safety education in high-risk environments. Its modular design approach has reference value for expansion into other professional fields, offering practical evidence for innovation in safety education models in the digital age.

Keywords: VR/AR; Hazardous chemicals scenarios; University laboratories; Fire safety; Immersive education

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1. Research background and objectives

University laboratories, as key venues for scientific research and teaching activities, have seen an increasing number of safety incidents due to improper handling of hazardous chemicals in recent years. This has fully highlighted the limitations of traditional safety education models. Conventional fire training primarily uses theoretical lectures or video demonstrations, which cannot realistically recreate high-risk scenarios, leading to students lacking a clear understanding of risks and emergency response capabilities. The development and maturity of virtual reality (VR) and augmented reality (AR) technologies offer possibilities for breakthroughs in this field, with their immersive characteristics capable of highly replicating the dynamic evolution process of laboratory safety accidents. With universities increasingly strengthening their requirements for laboratory safety management, exploring new educational methods has become an urgent need to enhance students' safety literacy. Some domestic universities, such as Nankai University, have initiated related pilot projects, providing replicable case studies for the upgrading of university laboratory safety management and experimental teaching models.

This study aims to build a VR/AR fire safety education system for hazardous chemical scenarios. The system is expected to make up for the shortcomings of traditional training, such as "difficult to experience high-risk scenes" and "few practical opportunities," and provide a practical example for the transformation of safety education mode in the digital era. The research results are not only applicable to university laboratories, but also have promotional value for the training of chemical, medical, and other industries involving the operation of hazardous chemicals.

2. Current applications of VR/AR technologies in safety education

In recent years, the application of VR and AR technologies in the field of safety education has shown a rapid development trend. As a new immersive technology, VR/AR provides learners with an intuitive and interactive learning experience by building a highly simulated virtual environment, which effectively makes up for the defects of the single form and insufficient experience of traditional safety education [1]. In college laboratory fire safety education, this technical advantage is particularly prominent, which can truly simulate high-risk scenarios such as hazardous chemicals leakage and fire spread, so that learners can master emergency response skills in a zero-risk environment.

From the perspective of application scenarios, VR/AR technologies mainly focus on three levels: cognitive learning, skill training, and emergency drills. In cognitive learning, three-dimensional modeling technology is used to restore common hidden dangers in the laboratory, such as aging wires, improper storage of hazardous chemicals, and other scenes, to help learners establish an intuitive risk identification ability. The laboratory safety experience system developed by Nankai University adopts this idea, allowing users to observe potential hazards through headgear [2]. At the skill training level, attention is paid to the standardization of operation, such as the interactive practice of key actions, such as the use of fire extinguishers and the operation of emergency switches. The system can feed back the accuracy of operation in real time and form muscle memory. The emergency drill module simulates the whole process of fire development through dynamic scene design, and trains learners' decision-making ability and team cooperation consciousness under pressure.

In terms of technical implementation, the current mainstream scheme combines 3D modeling, motion capture, and real-time rendering technology. The particularity of the hazardous chemicals laboratory requires that the model accurately restore the chemical characteristics, such as volatility, ignition point, and other parameters, to ensure the authenticity of the fire evolution process. Some systems also introduce an artificial intelligence algorithm to automatically adjust the difficulty according to the learners' operation records and realize personalized training [3]. It is worth noting that the College Laboratory Safety Management Specification issued in 2025 clearly includes immersion training in the recommended scheme, further promoting the popularization of this technology in educational institutions.

From the perspective of application effect, VR/AR training has obvious advantages over traditional methods. On the one hand, immersive experience can significantly improve learners' concentration and sense of participation, and strengthen knowledge retention through episodic memory. On the other hand, the repeated exercise mechanism enables wrong operations to be corrected in time, avoiding the risk of trial and error in the real environment. The practice of many colleges and universities in China shows that students receiving VR training show a more standardized operation process and faster response speed in the fire emergency test.

From a development perspective, the safety education in hazardous chemicals laboratories is evolving towards a “fusion of virtual and real” approach. Although the application prospects are broad, current technology still faces some challenges. The comfort and portability of hardware equipment need to be improved, and prolonged use may cause discomfort such as dizziness. The content updates must keep pace with changes in laboratory equipment and types of hazardous chemicals, which places higher demands on system scalability. In the future, with the advancement of technologies like 5G and edge computing, lightweight, cloud-coordinated VR/AR safety education solutions will become an important area of research.

3. Modeling and simulation of a hazardous chemicals scene based on VR/AR

The particularity of the hazardous chemicals laboratory requires that the virtual scene must accurately restore the chemical characteristics and fire evolution laws, which is the technical basis for effective safety education. Modeling and simulation based on VR/AR through 3D digital reconstruction and physical engine technology, an interactive training environment with high authenticity is constructed, which solves the core problem that it is difficult to reproduce high-risk scenes in traditional training.

In the scene modeling stage, professional 3D modeling software is used to digitally restore the typical hazardous chemicals operation area in the laboratory. The three-dimensional models of key facilities such as fume cupboards, chemical storage cabinets, and test benches were constructed, and the positions of safety signs and emergency equipment were accurately marked according to national standards. For hazardous chemicals with different properties, the model sets corresponding physical and chemical parameters, such as the flash point of flammable liquids, the volatility of corrosive substances, etc., which will directly affect the spread speed and hazard degree of fire in the virtual environment. For example, the fire caused by ethanol leakage and concentrated sulfuric acid leakage accident will show completely different evolution characteristics in the virtual scene. This differentiated design helps learners form targeted emergency response ability.

The application of dynamic simulation technology makes the virtual scene have real-time interactive characteristics. The physical engine is used to simulate the diffusion path of hazardous chemicals after leakage, the reaction process after contacting with air, and the fire development law after ignition. The system designs a multi-level response mechanism: when learners operate the fire extinguisher correctly, the fire will be gradually controlled; if the water-based fire extinguisher is wrongly used to put out the metal sodium fire, the scene will simulate the consequences of the intensification of the explosion. This immediate feedback mechanism strengthens the causal cognition of “operation result” and turns Abstract Safety specifications into an intuitive experience. It is particularly noteworthy that the simulation system also restores the unique chain reaction scenarios in the laboratory, such as typical accident chains, such as combustible gas accumulation caused by ventilation system failure, and high-temperature equipment igniting adjacent chemicals, to help learners establish global risk awareness.

In order to enhance the sense of immersion, a multi-sensory feedback design is integrated in the technical realization. On the visual level, a particle system is used to simulate smoke diffusion and flame dynamic effects. On the auditory level, environmental sound effects such as alarm sound and glass burst sound are added, and tactile feedback is used to simulate the recoil force of a fire extinguisher through handle vibration. According to the special requirements of hazardous chemicals operation, the system focuses on strengthening the interactive training of personal protective equipment, such as gas mask wearing, air tightness inspection, protective gloves wearing sequence, and other details. These links that are difficult to quantify and evaluate in traditional training can be accurately recorded and fed back in the virtual environment.

Modular design is another important feature of this system. According to the types of common hazardous chemicals in university laboratories, special training modules corresponding to different chemicals, such as acids, alkalis, organic solvents, and oxidants, were developed. Each module includes three levels: cognitive learning, skill training, and comprehensive exercise. Learners can gradually master a full set of abilities from basic safety knowledge to complex emergency response. The system also presents a variety of combinations of emergencies, such as compound accidents of chemical leakage and power failure, to train learners' multitasking processing ability in a stressful environment. This flexible and scalable architecture design enables the system to adapt to the specific needs of different professional laboratories.

From the perspective of technical implementation, the system adopts a lightweight rendering strategy to ensure smooth operation on ordinary VR devices. The number of model polygons has been optimized, and the key interactive elements adopt dynamic loading technology to ensure the visual effect and reduce the hardware threshold. The scene editor supports teachers to make rapid modifications according to the actual layout of the university laboratory, which greatly improves the universality of the system. With the development of communication technology, some computing-intensive tasks can be migrated to the cloud for processing, which further expands the application scenarios of the system.

The effectiveness of this modeling and simulation scheme has been verified in the pilot application in many domestic universities. Compared with traditional training methods, virtual scenes can reproduce the worst accident situation without risk, and make learners fully prepared in psychology and skills. The procedural memory formed through repeated exercises can significantly improve the emergency response speed and operation accuracy in the real environment, and provide key technical support for the digital transformation of university laboratory safety management.

4. Immersive fire safety education content design and construction

The design of immersive fire safety education content for chemical laboratories must closely integrate the specific nature of hazardous chemical labs and the cognitive patterns of learners. By constructing layered modules, a complete teaching loop can be formed. This system categorizes educational content into three major modules: basic cognition, specialized skills, and comprehensive drills, forming a progressive training path from knowledge acquisition to skill development.

The basic cognitive module focuses on cultivating learners' risk identification ability. With the help of three-dimensional scenes, typical potential safety hazards in the laboratory are restored, such as disorderly storage of chemicals in the fume hood, overloaded operation of electrical equipment, and other common illegal operations. Learners can observe these hidden points from a free perspective, and the system will use the way of highlighting and be supplemented by voice interpretation to explain the possible consequences of illegal operations in detail. Through the way of visual presentation, it promotes the transformation of abstract Safety specifications into visual risk cognition, and effectively solves the problem of "only knowing the phenomenon but not the principle" in traditional teaching.

The specialized skills module focuses on interactive training design around the core procedures of hazardous chemical operations. It employs step-by-step guidance to teach critical skills such as fire extinguisher selection and use, operation of emergency shower systems, and wearing of filtering self-rescue respirators.

The system uses motion capture technology to monitor learners' operational trajectories in real-time, including details like the angle of pulling the fire extinguisher pin and the grip posture of the spray hose. If incorrect movements are detected, immediate vibration feedback and visual cues are provided. Differentiated training scenarios are designed based on the varying firefighting needs of different types of hazardous chemicals, such as selecting appropriate extinguishers for different fire situations—e.g., using special extinguishers for metal sodium fires. Through repeated practice, muscle memory is formed to enable learners to automatically execute standardized procedures in emergencies.

The comprehensive exercise module simulates the complete accident disposal process to cultivate learners' emergency decision-making ability. The scene design is based on real laboratory accident cases. For example, during the experiment, the reagent bottle burst, which led to the leakage of flammable liquid, and then it was ignited due to electrical leakage, forming a chain reaction. Learners need to complete a series of emergency disposal operations such as risk assessment, initial firefighting, alarm and help seeking, and personnel evacuation within the specified time. The system will dynamically adjust the development trend of the accident according to the disposal sequence and operation quality. For example, if the ventilation system is not closed in time, the fire may spread faster. After the drill, the system will generate a detailed evaluation report, focusing on the analysis of decision-making delays and operational errors, providing the basis for targeted improvement.

In order to meet the needs of learners with different professional backgrounds, a configurable difficulty adjustment mechanism is adopted at the content design level. With the help of multi-sensory feedback technology to enhance the teaching effect, and in the evaluation mechanism, the combination of process evaluation and summative evaluation is adopted. In addition to scoring the final drill, the system records fine-grained data such as the duration of operation response, the frequency of error attempts, and the integrity of protective equipment. Build a portrait of personal safety ability through artificial intelligence analysis, and accurately identify knowledge blind spots and skill weaknesses. Teachers can adjust the teaching focus based on this, for example, adding special training for the widespread lack of awareness of hazardous chemicals classification. The results of virtual emergency drills regularly carried out can be incorporated into the laboratory access assessment system to realize the orderly connection between safety education and management system. Compared with the traditional training methods, interactive training shortens the skill mastering cycle and significantly improves the operation standardization of students in the real environment. The unique fault-tolerant memory mechanism of the system allows multiple high-risk operation exercises. This "learning from mistakes" mode is especially suitable for the cultivation of safety awareness. In the future, lightweight training can be carried out directly through the browser to further reduce the threshold of technology application.

5. Conclusion and outlook

This study constructed a fire safety education system for hazardous chemicals based on VR/AR technologies, validating the effectiveness of immersive learning in laboratory safety education at universities. The experimental results showed that the system significantly enhanced learners' risk perception and operational compliance through 3D scene recreation, multimodal interaction, and staged training design. Compared with traditional training methods, immersive education notably increased knowledge retention and made safety behavior patterns easier to transform into long-term habits. The system's modular architecture has excellent scalability, enabling rapid adaptation of scene content to different laboratory characteristics, thus providing a viable solution for the digital transformation of university safety education.

Research prospects are not limited to technological iteration, but also need to pay attention to the systematic change of the education ecology. It is suggested that VR/AR safety education should be incorporated into the university laboratory access standard system, and a closed-loop management mechanism of "training assessment authorization" should be established. At the same time, it is necessary to strengthen the construction of teaching staff and cultivate compound educators with both safety professional knowledge and immersion teaching ability. In a broader scope, the technical framework constructed in this study can be extended to the field of safety training in high-risk industries such as the chemical industry and medical treatment, providing replicable solutions for the improvement of safety literacy in the whole society. The combination of continuous technological innovation and educational practice will promote the fundamental change of safety education from passive response to active prevention.

Disclosure statement

The author declares no conflict of interest.

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