

Research on the Application of Virtual Simulation Technology in the Safety Management of Coal Mining

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Abstract: Safety is paramount in coal mining as it affects efficiency. Thus, it is essential to enhance the management of coal mine safety. With the ongoing advancement of modern technologies, more innovative solutions are being integrated into the safety management of coal mining, including virtual simulation technology. This paper focuses on analyzing and researching the application of virtual simulation technology in the safety management of coal mining, providing insights for reference.

Keywords: Virtual simulation technology; Coal mine safety management; Application

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1. Introduction

With the continuous development of China's economy, the energy demand is also increasing. As coal mining is a cornerstone of the national energy supply, ensuring its stable operation is crucial for the healthy and sustainable development of China's national economy. However, coal mining operations are affected by complex and variable geological structures and uncertain natural factors, leading to a high risk of safety accidents that can result in significant loss of life and property^[1]. Therefore, strengthening the management of coal mine production safety has become an urgent issue for the industry. In the information age, the emergence and application of virtual simulation technology have transformed traditional coal mine safety management. This technology plays an important role in coal mining as it significantly reduces the likelihood of safety accidents while enhancing work efficiency and reducing production costs.

2. Overview and analysis of virtual simulation technology

Virtual simulation technology enables the creation of realistic environments by integrating various technical means, such as real-time image display, multimedia, and tracking and positioning technologies^[2]. With this technology, users can interact with virtual environments through a variety of sensing equipment, gaining a

realistic perception of these environments. Its main characteristics are immersion and interactivity.

Immersion, a key feature, involves creating highly realistic virtual scenes through data modeling and placing users in these scenes with sensing equipment, providing a rich, multi-sensory experience that includes visual and auditory elements. Interactivity refers to the exchange of information between the user and computer data, allowing users to perform actions within the virtual world using sensor devices. For instance, users can navigate and explore the virtual environment by using the directional keys on a controller, achieving human-computer interaction.

3. Types and characteristics of coal mine accidents

3.1. Types of coal mine accidents

Coal mine accidents are sudden incidents that occur during coal mining that endanger the miners. These accidents can be divided into different categories based on their factors and nature.

One major type is the coal dust explosion accident, which is the most serious in coal mine production. Coal dust, a common combustible particulate matter in mines, can easily explode under certain concentrations and temperatures when exposed to an external fire source such as an open flame or electric arc. These explosions are typically violent and rapid and can trigger chain reactions, posing a significant threat to the safety of miners and their property.

Another type is the coal outburst accident, which involves the high-speed movement and collapse of underground coal and rock. This phenomenon, often accompanied by a huge impact force and loud collapse sounds, poses a severe threat to miners' safety. Coal outbursts are generally caused by factors such as insufficient coal seam fixing force, the geological structure of the rock mass, and the internal mechanical properties of coal and rock.

Third, coal and gas outburst accidents occur when gas and coal suddenly erupt into the mine due to a broken coal seam or mine pressure. These accidents are highly destructive, release energy rapidly, and have a wide impact, typically occurring in mines with large amounts of gas and coal coexistence^[3].

The fourth type is fire accidents. Coal's flammability, combined with the mine's closed environment and poor ventilation, leads to frequent fire accidents, usually due to coal seam spontaneous combustion, gas explosions, or electrical equipment failures. These fires pose serious threats to miners and production equipment.

The fifth type is mine flooding, involving the influx and accumulation of water in the mine. Causes include high groundwater content, accidental breaches in the coal wall or roof, and geological structure ruptures. Flooding can damage mine equipment and may lead to secondary accidents such as gas explosions and geological disasters.

3.2. Characteristics of coal mine accidents

Coal mine accidents are characterized by their diversity, high risk, and preventability. These incidents can include coal dust explosions, coal outbursts, fires, coal and gas outbursts, and mine flooding. When they occur, they are often accompanied by significant dangers, such as violent explosions, huge impact forces, and sudden eruptions, which severely threaten the safety of miners. While the occurrence of coal mine accidents may be inevitable, effective prevention and reduction are possible through strengthened safety management, improved safety awareness, and enhanced skills among miners.

4. Current application of virtual simulation technology in coal mine safety management

Virtual simulation has been adopted in coal mining operations relatively early in Western countries. This technology not only simulates the process of coal mine production planning and disaster management but is also used in training for safety systems ^[4]. For example, the University of Pennsylvania developed a virtual reality miner training system that allows comprehensive training and simulation of miners' work. This includes basic inspection tasks and simulations of fault problem responses, enabling miners to practice necessary measures in case of issues. Similarly, JCDecaux De Montfort University (DMU), with the support of modern technical means, developed a mine decision simulation system. This information system, designed for teaching mining majors in colleges and universities, enhances students' management and decision-making abilities through scene simulations ^[6].

In China, the application of virtual simulation technology in coal mine safety management has been relatively late and is still in the preliminary exploration stage. Most applications are focused on investigating coal mine safety accidents. For instance, during the collection process of a gas explosion incident in a coal mine in Shaanxi Province, relevant experts utilized virtual simulation technology to recreate the accident scene, quickly identifying its cause. By simulating various management decisions, they developed a virtual reality system for coal mine gas explosion and fire accidents, providing valuable experience and a basic guarantee for future coal mine safety work ^[7]. Despite lagging behind foreign countries in the scope and depth of application, China is actively exploring more uses of virtual simulation technology in coal mining. For instance, China University of Mining and Technology has partnered with JCDecaux DMU to explore specific applications of mine simulation decision-making systems in practical scenarios.

5. Application of virtual simulation technology in the safety management of coal mining

5.1. Mine development simulation

Coal mining is the fundamental and most hazardous task in coal production, serving as the frontline of coal mine safety management and a critical link susceptible to accidents ^[8]. Within mine operations, safety hazards such as roof collapses, fires, and coal dust explosions often arise due to poor safety conditions, equipment concentration, operator errors, and limited workspace ^[9]. By integrating virtual simulation technology into coal mining practices, it becomes possible to accurately replicate the mine's environmental conditions, including the roof, roadways, and ground. Furthermore, factors such as shearer and boring machine operations can be incorporated into the virtual environment. Miners can enter this virtual world to observe their surroundings and consider potential problems and their solutions comprehensively. This approach allows miners to conduct coal mining operations more efficiently while also reducing the occurrence of safety accidents.

5.2. Coal mine equipment manufacture simulation

In traditional coal mine equipment manufacturing processes, measuring the underground environment typically precedes prototype design. Prototypes are then tested in the mine, with detailed records kept of any issues encountered during testing. These findings inform iterative modifications to the prototype, gradually refining it to better suit coal mine use ^[10]. However, this approach requires significant manpower, financial resources, and time, with frequent modifications hindering equipment utilization rates. Conversely, virtual simulation technology applied in coal mine equipment manufacturing allows for the simulation of actual underground environments and equipment designs. By inputting equipment attributes into computers, digital instructions can

simulate equipment operation in the mine, streamlining the manufacturing process and reducing reliance on physical prototypes.

5.3. Mine accident simulation

Mine accidents are a primary focus of coal mine safety management, and virtual simulation technology plays a crucial role in understanding their causes ^[11]. This technology enables the reproduction of accident scenes and processes, facilitating comprehensive analysis. Furthermore, the continuous advancement of modern technical means has led to the development of electronic information networks for underground ventilation systems. These networks allow for digital presentation and management of ventilation networks, enhancing safety measures. In the event of a ventilation safety accident, the system can swiftly analyze data to identify the optimal ventilation route, control airflow, and guide underground staff to safety. To address this, researchers at the Association of International Marathons and Distance Races have developed a mine fire virtual reality technology system, utilizing real case data to simulate accident scenes. This approach holds significant importance for the study and prevention of mine accidents ^[12].

5.4. Coal mine water control simulation

In underground mining, the destruction of underground aquifers can lead to mine flooding accidents, necessitating a thorough understanding of the distribution and thickness of underground water layers by coal mine personnel to effectively prevent and control floods ^[13]. Traditional coal mine water prevention and control methods typically involve two-dimensional plane analysis, which offers limited perspective and lacks intuitive display and comprehensive analysis, often leading to incorrect judgments. However, virtual simulation technology allows for the input of water system parameters to obtain an overall view of the water layer. Through three-dimensional dynamic presentation, including characteristics such as flow direction, velocity, and storage status of underground water layers, this technology provides valuable data support for the development of coal mine water control measures, enhancing accuracy and effectiveness.

5.5. Simulation of technical training scenarios for coal mine personnel

Technical training for coal mine personnel plays a vital role in ensuring the safety of coal production ^[14]. However, traditional training methods often have limitations such as limited effectiveness and practice environments, making it challenging to guarantee training outcomes. By implementing virtual simulation technology in technical training management, coal mine personnel can be provided with realistic work scenarios and simulate various potentially hazardous situations without the need to be physically present at the site. This approach helps reduce the occurrence of underground accidents and enhances the quality of coal mine technicians. For instance, simulating coal mine explosion, collapse, and gas outburst scenarios enables miners to confront emergencies in a virtual environment. They can operate virtual characters' actions using sensor equipment to ensure safety, effectively training relevant technical skills for coal mine personnel.

5.6. Emergency rescue drill simulation

Virtual simulation technology can also be applied to the emergency rescue drill work in coal mine safety management. For example, in the coal mine rescue drill, due to the limitations of realistic scenes, it is difficult to truly simulate the complex environment when the accident occurs, and it is impossible to effectively carry out actual combat. Through virtual simulation technology, a virtual scene of the real coal mine environment can be built, including underground roadway, underground working area, etc., and a variety of accident scenes can be simulated, such as fire, gas explosion, collapse, etc., so that rescue workers can carry out real skills exercises in the

simulation environment, such as rope down the well, the use of fire extinguishers, first-aid skills and so on.^[15]

6. Conclusion

Virtual simulation technology, as an emerging modern technical tool, holds significant importance in various fields including China's military, security, and public safety. It has become an essential component in the construction and development of modern society. Its application in modern coal mine safety management is of paramount significance. Specifically, virtual simulation technology can be utilized in mine development, coal mine equipment manufacturing, handling mine accidents, coal mine water prevention, technical training for coal mine personnel, emergency rescue drills, and many other simulation scenarios. Its integration can effectively elevate the standards of modern coal mine safety production management, contributing to safer working environments and improved operational efficiency.

Disclosure statement

The authors declare no conflict of interest.

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