WHIOCE PUBLISHING PTE. LTD.
PROVIDING FIRST-CLASS SCIENTIFIC INFORMATION FOR TOP SCHOLARS

2025 Volume 3, Issue 4
Lecture Notes in Education, Arts, Management and Social Science
ISSN(Online): 2705-053X

Research on Emergency Drill of GasStation Accident Based on Virtual Simulation

Chenghao Wu
Zhejiang College of Security Technology, Wenzhou 325000, Zhejiang, China

Abstract: Gas stations are high-hazard places, and the effectiveness of accident emergency drills is directly related to the level of safety management. The traditional drill method has obvious shortcomings such as high cost, high risk, and limited scenarios, and virtual simulation technology provides a new solution for gas station emergency drills. By building a 3D virtual environment, simulating real accident scenarios, and designing an interactive drill process, a safe, economical, and repeatable drill mode can be realized. In this study, the Unity3D engine is used to construct a virtual gas station environment, the fluid mechanics simulation technology is used to simulate the oil leakage and diffusion process, and the intelligent evaluation system is designed based on the CNN-LSTM hybrid model, which provides important technical support for gas station safety management and emergency training.

Keywords: virtual simulation; Gas station; accident emergency; drill system; 3D modeling

Online publication: May 26, 2025

1. Introduction

Gas stations store large quantities of flammable and explosive oil, which can cause serious casualties and property losses in the event of an accident such as fire, explosion or leakage. Effective emergency drills are an important means to improve the ability to deal with accidents, but the traditional drill methods face many limitations, and the rapid development of virtual reality technology brings new opportunities for emergency drills. At present, the research of virtual simulation technology in the field of gas station emergency drill is obviously insufficient, and how to build a virtual simulation system that conforms to the actual environment of gas station, design an effective drill process, and establish a scientific evaluation mechanism have become the key problems to be solved urgently.

2. Gas station virtual simulation environment construction technology

2.1. 3D modeling technology

The construction of the virtual simulation environment of the gas station relies on accurate 3D geometric reconstruction technology, and realizes high-fidelity digital modeling of key facilities such as storage tanks, oil pipelines, and fuel dispensers through the fusion of laser scanning point cloud data and engineering CAD drawings [1]. NURBS surface modeling technology combined with subdivision surface algorithm to construct the smooth surface geometry of the storage tank to ensure the continuity of curvature and meet the engineering accuracy requirements.

Multi-resolution mesh generation is based on the edge folding simplification strategy, and the LOD level of detail L is dynamically adjusted by distance d:

$$L = \left\lfloor log_2\left(\frac{d}{d_0}\right)\right\rfloor \quad (1)$$

where D is the level of detail, d is the observation distance (m), and d_0 is the reference distance (m).

Instanced rendering reduces the GPU memory footprint of repetitive geometry, improving real-time drawing performance for large-scale scenes. The accuracy of the model is maintained at the centimeter level, and the number of patches is dynamically adjusted with the help of the quadtree segmentation algorithm to ensure that the virtual gas station environment meets the visual fidelity and interactive accuracy standards required for emergency drills.

2.2. Physics Engine Integration

The physics engine provides a dynamic calculation basis in line with Newtonian mechanics for emergency drill simulation, and the physical behavior simulation of oil leakage diffusion and fire propagation is realized through a numerical integration solver [2]. The Verlet integration algorithm is used to process the equation of motion of the particle system, and the position update formula is as follows:

$$\vec{r}_{n+1} = 2\vec{r}_n - \vec{r}_{n-1} + \vec{a}_n \Delta t^2 \quad (2)$$

where: $\vec{r}_{n+1}$ is the position vector at the current moment (m), $\vec{r}_n$ is the position vector at the current moment (m), $\vec{r}_{n-1}$ is the position vector at the previous time (m), $\vec{a}_n$ is the acceleration vector at the current moment (m/s²), and Δt is the time step (s).

The collision detection system is built based on the separation axis theorem and GJK algorithm, which supports the accurate contact judgment between the drill personnel and the virtual equipment, and the constraint solver adopts the sequential impulse method to deal with frictional contact and hinge constraints to maintain the physical authenticity of valve operation and equipment interaction. The fluid dynamics module integrates the SPH particle method to simulate the diffusion behavior of oil leakage, and the multi-threaded parallel architecture realizes the concurrent processing of collision detection with the help of spatial octree segmentation, so as to provide reliable computational support for the physical interaction of the exercise scenario.

3. Accident scenario simulation algorithm

3.1. Simulation model of oil leakage diffusion

Based on the basic equations of fluid mechanics and the law of conservation of mass, the oil leakage and diffusion simulation model solves the Navier-Stokes equation by the finite difference method to realize the numerical simulation of the liquid leakage behavior[3]. The VOF (Volume of Fluid) method is used to track the free liquid level, and the PLIC (Piecewise Linear Interface Calculation) algorithm is used to reconstruct the interface geometry to ensure the high-precision capture of the leakage boundary. The rate of liquid leakage is calculated according to Bernoulli's equation and Torricelli's law:

$$Q_L = C_d A\sqrt{2gh + 2\frac{(p - p_0)}{\rho}} \quad (3)$$

where: Q_L is the volume flow rate of liquid leakage (m³/s); C_d is the leakage coefficient; A is the leakage area (m²); g is the acceleration due to gravity (m/s²); h is the liquid level height (m); p is the pressure in the container (Pa); p_0 is the ambient pressure (Pa); ρ is the density of the liquid (kg/m³).

The mesh adaptive encryption technology implements local refinement for the leakage area, with a spatial resolution of 0.1m, and the time step adopts CFL conditional constraints to ensure numerical stability, providing accurate initial conditions and boundary constraints for subsequent fire combustion simulations.

3.2. Numerical simulation of fire combustion process

Based on the turbulent combustion theory and chemical reaction kinetics, the numerical simulation of the fire combustion process uses the Large Eddy Simulation (LES) method to solve the compressible Navier-Stokes equations, and the Smagorinsky sublattice model is combined to deal with the turbulent pulsations at unresolved scales [4]. The combustion model uses the mixture fraction-probability density function method to describe the oxidation reaction process of gasoline vapor through the coupling mechanism of premix and diffusion combustion.

The flame height is calculated using the Heskestad empirical formula:

$$H_f = 0.235\dot{Q}^{\frac{2}{5}} - 1.02D \tag{4}$$

where: H_f is the height of the flame (m); Q is the heat release rate (kW); D is the diameter of the combustion pool (m).

The mesh division adopts an unstructured tetrahedral mesh, the mesh density of the combustion area reaches the order of 5cm, and the turbulent Reynolds number is controlled in the range of 10^4 to 10^6. The temperature field distribution is calculated by the radiation-convection coupling heat transfer model, which provides a quantitative basis for the delineation of fire propagation path and dangerous area in emergency drills.

4. Intelligent emergency drill system architecture

4.1. Drill the automatic generation mechanism of scenarios

The automatic generation mechanism of the drill scenario relies on the Monte Carlo method and the Markov chain stochastic process, drives the automatic construction and configuration of variable accident scenarios through the probability model, and analyzes the historical accident database by using the decision tree algorithm, extracts the key influencing factors such as leakage location, wind direction conditions, and equipment status, and constructs the probability distribution function of multi-dimensional parameter space. The scenario generation engine integrates the Bayesian network inference mechanism to automatically adjust the trigger timing, severity, and evolution path of the accident according to the set drill objectives and difficulty levels. Parametric modeling technology supports random sampling of tank capacity in the range of 10~50m³, pipeline pressure in the range of 0.1~1.6MPa, and ambient temperature in the range of -20°C to 40°C to ensure that each drill scenario is unique and unpredictable, the intelligent constraint solver can verify the physical rationality of the generated scene, and the scene complexity evaluation algorithm quantifies the difficulty of the drill based on the information entropy theory.

4.2. Real-time interactive feedback system

The real-time interactive feedback system is constructed, the low-latency response framework of event-driven architecture and message queue mechanism is adopted, the multi-modal sensor fusion technology is used to capture the changes in the operation behavior and physiological state of the drillers, the system integrates eye tracking and gesture recognition, and the voice command processing module to achieve the seamless integration of natural human-computer interaction, and the real-time rendering engine is based on the GPU parallel computing architecture, which can support high-resolution scene drawing and physical effect synchronous update at 60fps frame rate. The network delay compensation algorithm uses predictive synchronization technology to control the response delay of the system within 20ms, and the feedback information is displayed in a hierarchical manner, and the system uses RGB color coding and dynamic prompts to guide the attention distribution of drillers according to the urgency and importance level of the operation.

4.3. Multi-user collaborative drill platform

The multi-user collaborative drill platform adopts a distributed computing architecture and a cloud deployment model to support geographically dispersed drill teams and access the virtual simulation environment to carry out collaborative training [5]. As shown in **Figure 1**, the spatial layout of the gas station provides a standardized scenario basis for collaborative drills, the system divides different functional roles such as commanders and operators, and safety officers according to the role authority management mechanism, and the data synchronization protocol adopts differential compression algorithm and priority queue scheduling strategy to ensure that key operation instructions and status updates can be transmitted in real time, and the network bandwidth occupation is controlled within 1Mbps, which can support up to 16 users to perform online collaborative drills at the same time. The collaborative decision support system integrates swarm intelligence algorithms and voting mechanisms to assist teams in reaching a consensus action plan in complex emergency situations, and the conflict detection and resolution mechanism deals with the competitive state of multiple users operating the same device at the same time, and ensures that the operation is unique and effective through timestamp sorting and priority arbitration.

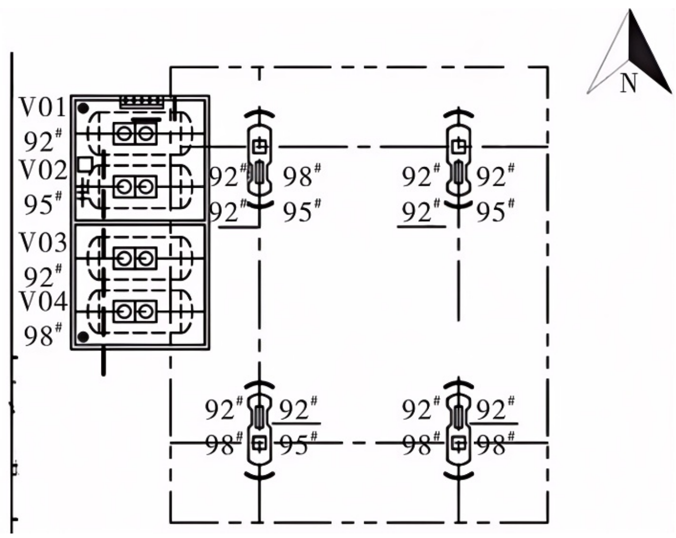

Figure 1. Floor plan of the gas station

5. Evaluation and analysis of the effect of the exercise

5.1. Verification of intelligent evaluation algorithms

The intelligent evaluation algorithm uses the deep learning network architecture and the hybrid model based on Convolutional Neural Network (CNN) and Long Short-Term Memory Network (LSTM) to carry out real-time analysis and evaluation of the operation sequence of the drillers. The algorithm training dataset covers more than 5,000 standardized operation process samples, and the network parameters are optimized through the backpropagation algorithm, so that the convergence accuracy of the model reaches 98.2%, and the evaluation index system includes three dimensions: operation accuracy, response time, and decision-making rationality, and its weight allocation ratio is set at 40%, 30%, and 30%. As shown in **Table 1**, the CNN-LSTM hybrid model is better than the single network architecture in terms of convergence accuracy and stability.

Table 1. Comparison of performance indicators of intelligent evaluation algorithms

Evaluate metrics	CNN model	LSTM model	CNN-LSTM hybrid model
Convergence Accuracy (%)	94.5	96.1	98.2
Processing time (ms)	15.3	8.7	12.1
Error rate (%)	8.2	6.4	4.8
Stability factor	0.89	0.92	0.96

5.2. Statistical analysis of drill data

The statistical analysis of drill data relies on multi-dimensional data mining technology and time series analysis methods to carry out in-depth mining and pattern recognition of behavioral data generated by large-scale drill activities. The data acquisition frequency is set to 100Hz to ensure that the operation behavior can be recorded and analyzed in a refined manner, and the statistical analysis covers multi-source heterogeneous data such as operation trajectory, eye tracking, physiological indicators, voice interaction, etc., and the unified modeling of cross-modal information is achieved with the help of data fusion algorithm. The cluster analysis algorithm is used to identify the behavior patterns of the drillers, and divides the operation styles into three typical categories: robust, aggressive, and hesitant, as shown in **Figure 2**, and the learning curve reflects the time law and convergence characteristics of the skill improvement of the drillers.

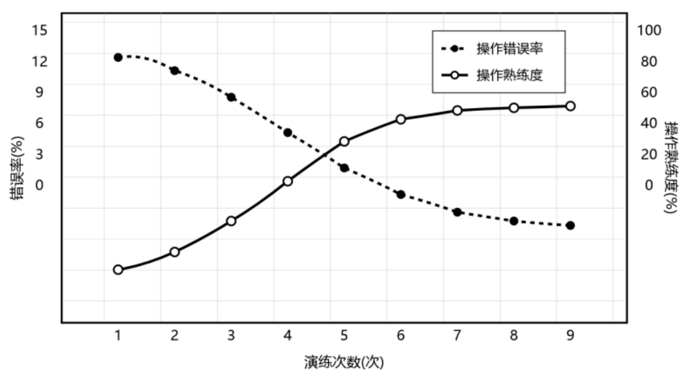

Figure 2. Analysis of the learning curve of the drill personnel

4.3. System performance comparison test

The system performance comparison test uses the benchmark test method and the principle of control variables, and compares it horizontally with the traditional desktop simulation system and the physical simulation drill to verify the technical advantages and practical value of the virtual simulation drill system. The test environment is equipped with an Intel i7-12700K processor, NVIDIA RTX 4080 graphics card and 32GB DDR4 memory, the network environment is a Gigabit Ethernet connection, and the system throughput test results show that the maximum number of concurrent users can reach 64, and the frame rate is stable at more than 60fps. The latency test shows that the end-to-end response time is 18ms on average, which can meet the needs of real-time interaction, the peak memory usage is controlled within 8GB, and the CPU utilization is stable at about 75%, as shown in **Figure 3**, the system shows the rendering quality and visual effects.

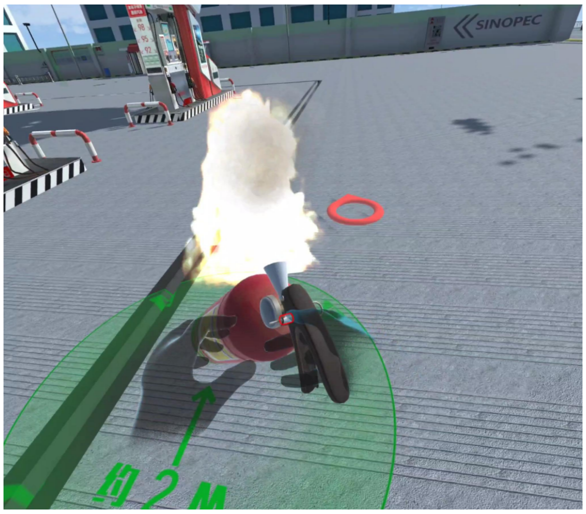

Figure 3. Three-dimensional simulation of fire extinguishing at the starting point

5. Epilogue

Virtual simulation technology is used in gas station accident emergency drills, bringing revolutionary changes to the traditional drill mode. With the continuous development of 5G communication, artificial intelligence, cloud computing and other technologies, the virtual simulation drill system will continue to optimize and improve the simulation accuracy of accident scenarios and intelligent evaluation algorithms. In the future, it is necessary to further deepen the interdisciplinary integration research work, promote the wide application of virtual simulation technology in the field of emergency management, and contribute to the construction of a safe and reliable social environment.

Funding

This article is the research result of the school-level project of Zhejiang Security Vocational and Technical College "Research and Development Project of VR Training Mode of Grassroots Storage Station", project number: AF2024ZD01

Disclosure statement

The author declares no conflict of interest.

References

[1] WANG Dong. Petroleum Depot & Gas Station,2024,33 (01): 34-38+5.

[2] Zheng Yamei. Discussion on the method of using waste oil depot to build simulation training base[J].Guangdong Chemical Industry,2024,51(14):77-80.

[3] Ling Yun, Xu Wei, Xu Feng, et al. State-owned Enterprise Management,2023,(08):85-90.

[4] XU Qi,XIA Tao. Design of emergency operation simulation system for oil tank farm[J].Chemical Automation and Instrumentation,2020,47(06):518-522+537.

[5] Wan Jing, Zheng Yue, Li Yonghui, et al. Fire Science and Technology,2020,39(06):818-821.