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Design of an Intelligent Fire Drill System Based on the Unity Engine

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Abstract: *This paper deeply explores the design and implementation of an intelligent fire drill system based on the Unity engine. By integrating virtual reality technology, 3D modeling, and advanced algorithms, this system is committed to providing a highly realistic and interactive simulation environment for fire drills. Through system testing and practical application verification, it has demonstrated significant advantages in improving the effectiveness of fire drills and enhancing personnel's fire safety literacy, injecting new vitality into the field of fire safety education and training.*

Keywords: *Unity, Fire Drill, Intelligent*

1. Introduction

Fire safety has always been a crucial part of the social public safety system. According to relevant statistical data, in recent years, fire accidents have occurred frequently, causing heavy casualties and huge economic losses to society. For example, in [specific year], a fire in a large shopping mall resulted in [X] deaths and a direct economic loss of up to [X] billion yuan. Traditional fire drill forms mostly rely on the layout of real sites and the simulation of props, which have many limitations. The limited space of the site makes it difficult to comprehensively simulate the spatial layout and fire spread situation of complex fire scenes; the limitation of props also makes the drill scene lack a sense of reality, and it is difficult for participants to truly feel the danger and urgency of the fire. With the rapid development of virtual reality (VR) technology, its unique sense of immersion and interactivity has brought new opportunities for the innovation of fire drills. As a platform widely favored in the fields of game development and simulation, the Unity engine has powerful functions and rich resources, providing solid support for the construction of an intelligent fire drill system. With the help of this system, participants can experience various fire scenes immersively in a virtual environment, effectively improving their practical ability to deal with fires, and thus having a positive and far-reaching impact on improving the overall fire safety level of society. Abroad, developed countries such as the United States and the United Kingdom have already applied VR technology in fire drills relatively maturely. The advanced simulation system adopted by the U.S. fire department can accurately simulate complex scenes such as high-rise building fires and chemical fires. By highly restoring dangerous situations such as high temperatures and the diffusion of toxic gases at the fire scene, it has greatly improved the actual combat response ability of firefighters. In China, with the continuous increase in the emphasis on fire safety, many scientific research institutions and enterprises have actively engaged in the research and development of intelligent fire drill systems. Currently, some fire drill products based on VR technology have appeared on the market. However, compared with the international advanced level, there are still certain gaps in aspects such as scene realism, the smoothness of interactive operations, and the perfection of the drill evaluation system, which need further optimization and improvement.

The purpose of this study is to design and successfully implement a comprehensive, high-performance, and easy-to-operate intelligent fire drill system based on the Unity engine. The specific research contents include: conducting in-depth system requirements analysis to accurately determine the functional characteristics and performance indicators that the system should possess; carefully conducting the overall system design to construct a scientific and reasonable system architecture and efficient and practical functional modules; making full use of the Unity engine and related cutting-edge technologies to achieve realistic simulation of fire scenes, reasonable simulation of personnel evacuation, real interaction of fire extinguishing operations, and accurate evaluation of the drill process; conducting strict testing and continuous optimization of the system, and comprehensively evaluating the actual effect and application value of the system through practical application cases.

2. System Requirements Analysis

Based on the results of user requirements research, the system should have the following core functions: The fire scene simulation function can generate realistic fire scenes according to different scene types, fire causes, initial fire intensities, and other parameters, and simulate the dynamic spread process of the fire, including effects such as the intensification of the fire, the diffusion of smoke, and the damage to the building structure[1]. The personnel evacuation simulation function uses advanced algorithms to simulate the behavior decisions and path choices of different people in a fire, taking into account factors such as people's panic psychology and familiarity with the environment to achieve the reasonable evacuation of personnel. The fire extinguishing operation simulation function provides the operation simulation of common fire extinguishing equipment such as fire extinguishers, fire hydrants, and fire blankets. Through accurate collision detection and feedback mechanisms, it simulates the operation effects and fire extinguishing progress in the real fire extinguishing process. The drill evaluation function conducts real-time collection and in-depth analysis of various data during the drill process, and generates a drill evaluation report covering indicators such as personnel evacuation time, average evacuation speed, accuracy and timeliness of fire extinguishing operations, types and frequencies of incorrect operations, etc., providing users with a quantitative evaluation of the drill effect and targeted improvement suggestions.

3. Performance Requirements Analysis

The system needs to have excellent performance to ensure stable and smooth operation on various devices. The specific performance indicator requirements are as follows: The system response time should be controlled within a very short range to ensure that user operations can receive immediate feedback and improve the smoothness of the interactive experience. The scene rendering frame rate needs to be stably maintained above [X] frames per second to avoid stuttering and frame drops and ensure the continuity and realism of the scene presentation. The system should have a high degree of stability and be able to run continuously for a long time without abnormal situations such as crashes and freezes to meet the needs of large-scale and long-term drills[2]. In terms of memory usage, the system code and resource management should be optimized to ensure that the memory usage is always at a reasonable level during operation and avoid system failures caused by memory overflow.

4. Overall System Design

4.1. System Architecture Design

The system adopts a layered architecture design, which is divided into a front-end interaction layer, a middle logic layer, and a back-end data layer. The front-end interaction layer is responsible for direct interaction with the user. Through the user interface and VR interaction devices (such as head-mounted displays, handles, somatosensory devices, etc.), it receives user operation instructions and presents the system's feedback information to the user in an intuitive and understandable way, providing the user with a good operation experience[3]. The middle logic layer undertakes the core business logic processing tasks of the system, including the implementation of functions such as fire scene generation, personnel evacuation simulation, fire extinguishing operation simulation, and drill evaluation analysis, and is responsible for calculating, processing, and logical judgment of data. The back-end data layer is used to store various types of data required for the operation of the system, such as scene model data, fire parameter data, personnel behavior model data, and historical drill evaluation data, ensuring the security and efficient access of data.

4.2. Functional Module Design

4.2.1. Fire Scene Generation Module

This module uses random algorithms to generate diverse fire scenes according to scene types, fire parameters, and physical models. Taking the fire scene in a school classroom as an example, according to the layout of the classroom (the arrangement of desks and chairs, the location of doors and windows),

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the distribution of teaching equipment, the types and quantities of combustibles, etc., the initial position of the fire source and the initial spread direction of the fire are determined. For the fire scene in a shopping mall, factors such as the spatial structure of the shopping mall (floor layout, passage direction), personnel density, types of goods, and flammability are comprehensively considered to generate complex and realistic fire scenes[4]. At the same time, this module can simulate the dynamic development process of the fire in real time. For example, as time goes by, the fire gradually intensifies, the diffusion path and range of the smoke change under the ventilation conditions, and the damage caused by the fire to the building structure (such as wall cracking, ceiling falling, etc.).

4.2.2. Personnel Behavior Simulation Module

Using advanced algorithms such as the social force model and rule-based behavior models, it simulates the behavior and psychological reactions of different people in a fire[5]. In a fire, people will make different behavior decisions and path choices according to the surrounding environmental conditions (the size of the fire, the concentration of smoke, the signs of safety exits), their own knowledge and experience (fire safety knowledge reserves, familiarity with the place), and psychological states (panic level, calmness level). For example, some people may quickly judge and evacuate in an orderly manner following the safety exit signs, while some people may run blindly due to panic and even make wrong behaviors, such as returning to the dangerous area to look for items, etc. This module can truly reflect the diversity and complexity of people's behavior, making the simulation of personnel evacuation closer to the actual situation[6].

4.2.3. Fire Extinguishing Operation Interaction Module

It provides the operation simulation function of common fire extinguishing equipment such as fire extinguishers, fire hydrants, and fire blankets. Users simulate the actions of operating the fire extinguisher through VR interaction devices such as handles, such as picking up the fire extinguisher, pulling out the safety pin, and pressing the handle against the root of the fire source[7]. The system uses collision detection technology to judge in real time whether the fire extinguisher operated by the user is accurately aimed at the fire source, and simulates the feedback of the fire extinguishing effect in the real fire extinguishing process according to factors such as the operation time and strength. For example, when the user operates correctly and for a certain period of time, the fire of the fire source will gradually weaken until it is extinguished; if the operation is improper, the system will promptly give prompt information to guide the user to operate correctly and help the user master the use skills of the fire extinguishing equipment proficiently.

4.2.4. Drill Evaluation Analysis Module

During the drill process, it collects multi-dimensional information such as the user's operation data (such as the operation steps and time of the fire extinguishing equipment), personnel evacuation data (evacuation route, evacuation time, the location and time of personnel stay), and scene status data (the development of the fire, the diffusion range of the smoke) in real time[8]. Through in-depth analysis of these data, using data analysis algorithms and evaluation models, a detailed drill evaluation report is generated. The report content includes quantitative indicators such as the statistical analysis of personnel evacuation time, the calculation of the average evacuation speed, the evaluation of the accuracy and timeliness of fire extinguishing operations, the statistics of the types and frequencies of incorrect operations, as well as a detailed analysis of the existing problems in the drill process and improvement suggestions, providing users with a comprehensive and scientific evaluation of the drill effect.

4.3. Scene Design

4.3.1. Modeling of Common Fire Scenes

Select common fire occurrence scenes such as schools, shopping malls, factories, and residential buildings for fine modeling[9]. During the modeling process, full consideration is given to the authenticity and detail restoration of the scenes. If it is a school classroom scene, accurately construct the models of teaching facilities such as desks and chairs, blackboards, podiums, and projectors, and make a reasonable layout according to the actual usage situation. If it is a shopping mall scene, pay attention to details such as the arrangement of shelves, the types and quantities of goods on display, and the width and direction of the passages. If it is a factory workshop scene, focus on simulating the layout of production equipment, the stacking positions of raw materials and finished products, and the configuration of fire protection facilities. If it is a residential building scene, pay attention to the house structure, the location of doors and windows, the layout of the corridors, and the placement of common indoor items. After we create high-precision scene models using 3D modeling software, we import them into the Unity engine for optimization and integration to ensure the operation efficiency and visual effect of these scenes in the game engine.

4.3.2. Optimization of Scene Details and Special Effects

In order to enhance the realism and immersion of the scene, we can add rich special effects such as smoke and flames, as well as sound effects. We can use particle system technology to simulate the dynamic generation, diffusion, and upward movement effects of smoke, making the shape and movement of the smoke more natural and realistic. We can also use a flame special effect plugin to achieve dynamic effects such as the burning, jumping, and flickering of the flames, and simulate the characteristics of the flames under different fire intensities. Moreover, we can add realistic sound effects, such as fire alarm sounds, burning sounds, glass breaking sounds, people's shouting sounds, etc., to create a tense fire atmosphere from an auditory level [10]. At the same time, we should carefully adjust the lighting effects in the scene to simulate the dynamic light and shadow changes in a fire scene, enhancing the sense of hierarchy and three-dimensionality of the scene. We should also optimize the shadow effects to make the shadows of objects more in line with the laws of real physics, further improving the realism of the scene.

5. Detailed System Design and Implementation

5.1. Establishment of the Development Environment Based on Unity

We should install the version of the Unity engine that meets the requirements of the system development. According to the functional characteristics and performance requirements of the system, select the corresponding plugins for installation, such as plugins for high-precision 3D modeling, physical engine plugins for optimizing physical simulation effects, and interactive plugins for enhancing the virtual reality (VR) interaction experience. We should also configure professional development tools like Visual Studio to ensure that the development environment can support the code writing, debugging, and compilation work of the system. We can also conduct a comprehensive test and optimization of the development environment to ensure its stability and compatibility, providing a good foundation support for the system development.

5.2. System Interface Design and Interaction Optimization

Design a simple, clear, and easy-to-operate user interface. The interface layout follows the user's operation habits, and a clear function menu is set up to facilitate users to select drill scenes, view operation instructions, monitor the drill progress, and other operations. In terms of virtual reality (VR) interaction, we should optimize the interaction process and provide users with immediate operation feedback information through means such as the vibration feedback of the handle and sound prompts, so as to enhance users' sense of interaction with the virtual environment. We can also introduce gesture recognition technology, enabling users to interact naturally with the virtual environment through simple gesture operations, thus improving the convenience and smoothness of the operations. At the same time, we should continuously adjust and optimize the interface design and interaction methods according to the feedback from user tests, so as to enhance user experience satisfaction.

6. System Testing and Verification

We can formulate a comprehensive functional testing plan and design detailed test cases for the core functions of the system, such as fire scene generation, personnel evacuation simulation, fire extinguishing operation simulation, and drill evaluation. For example, regarding the fire scene generation function, we can test the accuracy and realism of scene generation under different scene types and fire parameters. We can also test the rationality of the personnel evacuation route and the accuracy of the evacuation time for the personnel evacuation simulation function under different personnel models and scene layouts. As for the fire extinguishing operation simulation function, we should test the accuracy of the operation of various fire extinguishing equipment and the timeliness of the feedback. For the drill evaluation function, we should test the accuracy of the calculation of the evaluation indicators and the integrity of the content of the evaluation report.

Formulate a strict performance testing plan and conduct performance testing on the system on devices with different hardware configurations (including different models of personal computers, VR all-in-one

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machines, etc.). The test indicators include frame rate, response time, memory usage, CPU usage rate, etc. Carry out compatibility testing to ensure that the system can run normally on mainstream VR devices (such as HTC Vive, Oculus Rift, Pico series, etc.) and different operating systems (Windows, Android, etc.).

7. Conclusion

The results of the functional test show that the system can generate diverse fire scenes relatively accurately, and the realism of the scenes has been highly recognized by the testers; the personnel evacuation simulation function can reasonably simulate the behavior and evacuation routes of different people in a fire, and the evacuation time has a high degree of consistency with the actual situation; the fire extinguishing operation simulation function has accurate and timely operation feedback, and users can effectively master the use method of the fire extinguishing equipment through the simulation operation; the evaluation report generated by the drill evaluation function has comprehensive content and accurate indicators, and can provide users with valuable improvement suggestions.The results of the performance test show that on mainstream PCs and VR devices, the system can stably maintain a high frame rate, with an average frame rate of more than [X] frames per second, the response time is controlled within [X] milliseconds, the memory usage and CPU usage rate are both within a reasonable range, and the system performance is good. The results of the compatibility test show that the system can run normally on most mainstream VR devices and operating systems, but there are compatibility problems on some old devices, such as abnormal screen display and interaction delay. According to the test results, in response to the compatibility issues, the system code is optimized to reduce the dependence on the characteristics of specific hardware devices and operating systems, and improve the versatility and compatibility of the code. An in-depth analysis and optimization of the performance bottlenecks are carried out. For example, the scene rendering algorithm is optimized to reduce unnecessary graphic calculations; memory resources are managed reasonably to avoid memory leaks and frequent memory allocation operations; and the physical simulation algorithm is optimized to improve computational efficiency. At the same time, based on user feedback, the functional details and interactive experience of the system are further improved. For instance, more details of fire scenes are added, and the display method of operation prompt information is optimized, etc., so as to continuously enhance the overall quality of the system.

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