RESEARCH ARTICLE

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Designing and Evaluating a 3D Fire Escape Educational System for Enhancing Safety Skills in Children

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Abstract

This research presents a novel 3D fire escape educational system for children, addressing the urgent need for more engaging and interactive fire safety training methods. Traditional approaches to fire safety education fall short in capturing the attention of primary and middle school students, who are crucial yet less responsive audiences for such critical knowledge. Leveraging 3D modeling and human-computer interaction technologies, our system offers an immersive learning experience that allows children to actively participate in self-rescue drills. Through autonomous navigation within a simulated environment, learners are empowered to make decisions during fire scenarios, including choosing escape routes or attempting fire extinguishment based on situational prompts. This hands-on approach not only aims to enhance the understanding of fire safety principles but also to improve the learners' ability to react appropriately in real-life emergencies. The system encompasses environmental simulations for realistic scenarios, interactive tasks tailored to provoke thoughtful responses, and educational content including videos and quizzes to consolidate the learned principles. Initial evaluations indicate that this interactive system significantly improves engagement and the acquisition of self-rescue skills among young learners, marking a significant advancement in fire safety education.

Keywords: 3DS Max, 3D modeling, fire escape, unity3D.

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1 Introduction

Fire has played a critical role in human development, offering convenience and utility while posing significant risks to life and property. The absence of adequate firefighting knowledge and experience can exacerbate the consequences of fire incidents, particularly for children, who often lack the cognitive and experiential capacity to respond appropriately during emergencies. Therefore, educating children on fire safety is of paramount importance. However, due to their limited cognitive development compared to adults, effectively imparting this essential knowledge presents unique challenges. Traditional fire safety education methods, such as direct instruction, provide foundational self-rescue skills but often fail to fully engage children in an era characterized by increasing aesthetic expectations and immersive technologies like virtual reality (VR) [1]. Moreover, while practical fire evacuation drills are effective, their high costs and the expertise required for their organization limit their scalability and accessibility [2].

The challenges faced in fire safety education bear

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similarities to those encountered in the dissemination of scientific knowledge, such as the initial translation of One Two Three… Infinity into Chinese, which was constrained by the technological and societal limitations of the era [6]. Similarly, current fire safety training methods in China often struggle to meet the practical demands of modern learners due to temporal and developmental constraints. However, advances in artificial intelligence (AI), virtual simulation, and 3D visualization technologies present a transformative opportunity to address these limitations [3–5]. By leveraging these technologies, it is possible to create sustainable, engaging, and realistic training environments that allow for repetitive practice and enhance the overall effectiveness of fire safety education [6].

AI technologies, including natural language processing (NLP), computer vision, and machine learning, have the potential to revolutionize fire safety training. AI can be integrated into virtual simulation systems to create personalized and adaptive learning experiences tailored to individual users, especially children [7–9]. These systems can dynamically adjust difficulty levels, simulate diverse fire scenarios, and provide instant feedback, ensuring that learners acquire not only practical survival skills but also a deeper understanding of fire safety principles. Furthermore, AI-powered analytics can evaluate learning outcomes and identify knowledge gaps, enabling continuous improvement of training programs.

International efforts to enhance educational outcomes using virtual simulation technologies highlight the potential for similar advancements in China. For instance, the Civil Defense Disaster Prevention Science Research Institute in Shanghai has pioneered the use of augmented reality (AR) in disaster prevention education, demonstrating the viability and effectiveness of immersive technologies in this domain. Inspired by these global trends, this study proposes a novel AI-driven simulated fire escape teaching system designed to make fire safety education more engaging, accessible, and effective for children. By combining the immersive capabilities of virtual simulation with the adaptive and analytical power of AI, the proposed system aims to equip children with the knowledge and skills needed to respond confidently and competently in fire emergencies [10].

This approach not only addresses the limitations of traditional fire safety education but also aligns with broader efforts to integrate cutting-edge technologies into educational practices, ultimately enhancing the preparedness of future generations.

2 Requirement analysis and system making

2.1 Requirement analysis and system design

In this system, the construction of 3D models and indoor scenes is pivotal [11]. The integration of scaffolding and animation fulfills not only the requirements of scene functionality but also supports corresponding interactive capabilities [12]. Additionally, ensuring the accuracy and professionalism of the guidance, along with appropriate UI settings and other functionalities, is crucial. Moreover, the system incorporates hints and judgments, facilitating a simplified evaluation process through selectable response options. This system's foundational feature offers users a simulation of emergency situations during a fire, including the generation of flame and smoke particles to create a realistic scenario. It enables the switching of action roles, providing practical guidance post-fire outbreak, along with choices that elucidate the underlying reasons and tips. The inclusion of fire escape educational videos enhances the learning experience, coupled with engaging tests to reinforce the educational content.

2.2 Project Design

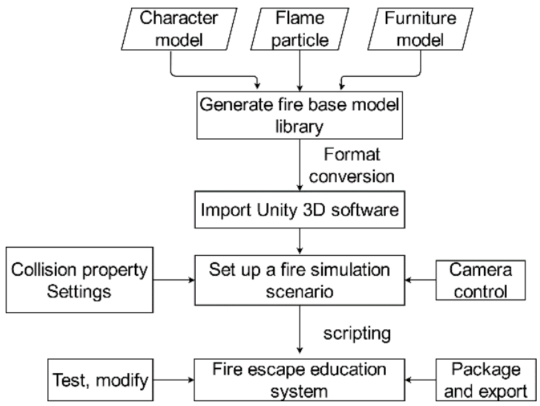

Figure 1. System Production process.

As shown in Figure 1. The system comprises several essential modules, each contributing to its comprehensive functionality. These include:

- **Scene Module**: This module forms the core of the simulation environment, featuring a variety of settings such as the kitchen, living room, bedroom, bathroom, indoor corridor, and safety passage. These scenes provide the backdrop for the simulated fire scenarios.

- **Interaction Module**: Facilitating user engagement, this module allows for interactions within the simulation through the provision of hints and selectable options. This interaction is crucial for educational purposes, enabling users to navigate through the simulation based on their decisions.
- **Action Module**: It simulates realistic human actions within the emergency scenarios, including characters walking and bending. This addition aims to enhance the realism of the simulation, allowing users to understand and practice the physical maneuvers required during a fire.
- **Sound Module**: This module augments the immersive experience of the simulation with auditory elements. It includes background music, the sound of fire burning, alarm bells, and prompts for questions from the question bank, thereby enriching the user's sensory experience and aiding in the learning process.
- **Other Modules**: Comprising additional functionalities, these modules include a progress bar, countdown timer, video playback for educational content, and a test question bank. These features are designed to further the educational goals of the simulation, offering users a comprehensive learning experience that includes knowledge assessment and reinforcement.

2.3 Build models and scenarios

The dissemination of fire escape knowledge is paramount to public safety, necessitating both accuracy and a comprehensive grasp of self-rescue principles and specifics. Information on fire causes and evacuation precautions primarily derives from the official Weibo account of the China Fire Protection service. The acquisition of related imagery predominantly utilizes internet resources, with adjustments via Photoshop software as required.

In the creation of 3D models, adherence to established standards is critical. Attention must also be given to the arrangement of indoor scenes and furnishings to ensure object sizes are realistic and contribute to the overall authenticity of the simulation. The construction of scenes should follow a "whole before part" principle, maintaining stylistic consistency throughout. Regarding the incorporation of indoor objects, all models in 3DS Max are mapped, and the process is completed upon their attachment and grouping.

Character importation involves integrating a third-person resource package into the Unity3D engine, replacing exported characters from 3DS Max, and including corresponding animations. Scene construction within Unity 3D is essential, with lighting arrangements enhancing realism post-setup. The Unity3D software's point, directional, and area lighting sources are utilized. Basic character movement is facilitated by embedding a third-person character player from Unity3D's resource package [13]. Following scene establishment, flame and smoke particles are employed to simulate fire effects, with dynamic changes in flame and smoke achieved through ongoing image updates. Selected model examples are illustrated in Figures 2, 3, and 4:

Figure 2. The sitting room.

Figure 3. Character model.

Figure 4. Flame effect.

3 System function realization

3.1 Page design

The system's user interface is primarily developed using the Unity3D UGUI plugin. The page design workflow is outlined as follows: initiate a new scene within the system dedicated to page layout, right-click to select New UI, and opt to create a new Image under Canvas. An appropriate image is then assigned as the background. In the Inspector's Texture Type field, the format is altered from Default to Sprite (2D and UI). Applying these settings enables the image for UI utilization.

To enhance the presentation, upon initial scene access, the system displays the page's location on-screen. To avoid obstructing the user's view during operation, the system is designed to display pages automatically upon detecting interaction, anchoring them to the screen's upper right corner. This is achieved by setting the anchor point in the specified corner. The visual effect following these adjustments is depicted in Figure 5:

Figure 5. The start page.

In order to make the system run smoothly, a simple progress bar is designed to connect and segment scenes. Part of the effect is shown in Figure 6:

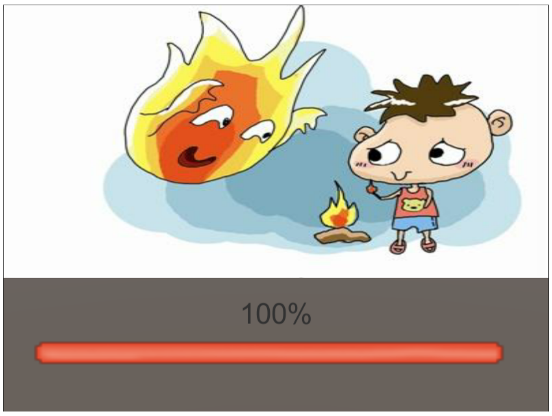

Figure 6. Loading progress bar.

3.2 Realization of countdown function

The teaching mode implemented by this system allows users to freely explore indoor environments. Subsequently, a fire scenario is triggered after a set duration, enabling users to familiarize themselves with their surroundings. This setup provides users with a more authentic experience during the simulated escape and firefighting activities. The transition to this emergency scenario is managed through C# scripting, specifically using coroutines to handle the countdown function. Coroutines run outside the main program thread, allowing the code within them to execute without disrupting the main program's operations. This approach ensures that users can continue to interact normally with the system during the countdown period, effectively simulating an unexpected fire situation and enhancing the realism and educational value of the experience.

3.3 Navigation function realization

To assist users unfamiliar with the indoor scene layout and design, the system introduces a guidance line feature. This feature is implemented by scripting a navigation bar control, which is activated when the user's character interacts with specific colliders within the scene. The guidance is primarily achieved through dynamically changing the background arrow image, creating a visual cue with a blinking arrow that directs and propels the user forward. The scene employs a Plane as the backdrop for this purpose, onto which a material arrow is created and an arrow texture ball is attached. This Plane is strategically positioned on the floor to guide the user. During development, the imagery is programmed to update every 0.04 seconds per frame, with the sequence resetting upon reaching the final image. This visual guidance mechanism is illustrated in Figure 7.

Figure 7. Display of arrows.

3.4 Implementation of highlighting function

To enhance realism within the virtual indoor scenes, this system incorporates an array of tangible models, such as fruits, kitchenware, potted plants, and lamps, to enrich the setting with lifelike details. Users are required to interact with certain items within this environment, such as switches, mobile phones, and towels. Given the impracticality and inefficiency of expecting users to locate specific models without guidance, the system utilizes highlighting techniques to facilitate model visibility.

The Highlighting Plugin, controlled through C# scripts, enables the highlighting and blinking of objects under specific conditions. Within the control panel, parameters such as brightness color, blinking range, and frequency can be adjusted. Upon detecting user interaction with an object, the script activates, emphasizing the object's location—like making a phone in the bedroom easily noticeable, allowing users to swiftly identify and select it. The visual effect manifests as an outlined, blinking highlight around the object, as depicted in Figure 8.

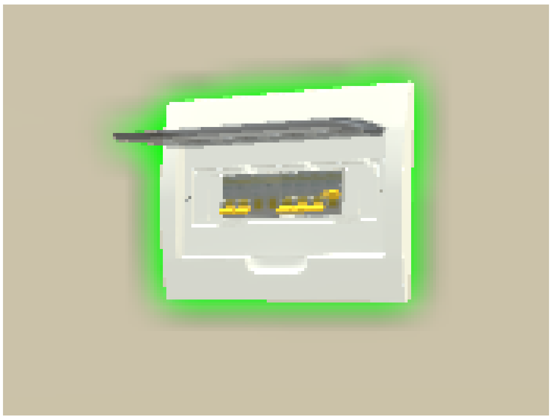

Figure 8. Item highlight effect.

3.5 Audio function realization

To authentically simulate the ambiance of a fire emergency, the system employs alarms to cultivate a heightened sense of urgency associated with sudden fire incidents [14]. The importation of audio and video elements is facilitated through Unity plugins, specifically utilizing the Avapro Video plugin within Unity3D for video integration. The process involves initially importing the plugin, followed by designating a suitable user interface (UI) location for interactive elements such as play, pause, next, a progress bar, and a volume control button [15]. UI management and control are executed through a dedicated script, UI Manager, wherein audio control variables are designated as public. This approach permits rapid substitution of audio components directly from the panel, significantly streamlining the content update process.

3.6 Test question bank function realization

To enhance the learning impact and reinforce users' retention of fire-escape knowledge, incorporating a question bank assessment upon completion of simulated instruction is crucial. Thus, the system includes quizzes to evaluate learning outcomes. The questions derive from critical tips shared during the fire escape process. To accommodate users of all ages, including children who may not have typing skills, the quiz predominantly features multiple-choice questions. Users can select the correct answer using the mouse, allowing for a swift assessment of their learning progress.

The functionality is implemented by creating a new text document listing 10 questions and their corresponding options sequentially, with the correct answer indicated for each. This document serves as the foundation for developing the feature. It is imported into the project folder, and a C# script is developed to navigate the question bank array, capture user inputs, compare them with the correct answers, and update the accuracy rate accordingly. After determining whether the responses are correct, a voice prompt provides feedback. Examples of these questions are illustrated in Figure 9.

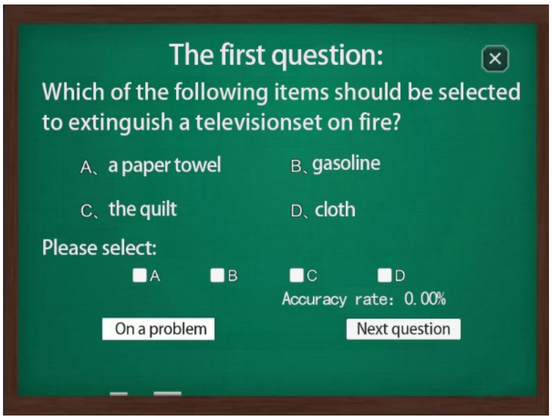

Figure 9. Quiz interface.

3.7 The system test

After completing the development of the whole system, we also need to test each module of the system. System testing is the prerequisite to ensure the normal operation of software, which can help find hidden errors and loopholes in the system, so that the whole system becomes more perfect. Before starting to test the system, first determine the software and hardware environment for the test; Then the software is tested globally and module by module, including function test and performance test. Finally, summarize the test results, complete the test result record form, system test log and comprehensive system test summary report, for the convenience of testing and improving the system in the future. The objectives of software testing are as follows :(1) to find out the system errors and vulnerabilities not found in the development process. (2) The system can run stably without stalling or crashing. (3) The software meets the actual needs of users in functions and efficiency. After testing, the system meets the requirements.

4 Conclusions

Upon the completion of the system's development, comprehensive testing of each module is crucial to ensure its functionality and reliability. System testing represents a fundamental step in verifying the seamless operation of the software, enabling the identification of latent errors and vulnerabilities that enhance the system's overall robustness. Before initiating the testing phase, it is essential to establish suitable software and hardware environments to facilitate the process. The adopted testing strategy encompasses a holistic examination of the software at both the global and modular levels, with a focus on functionality and performance evaluations. Detailed documentation of the testing process—including test outcome records, system testing logs, and a comprehensive system test summary report—serves as a critical resource for future refinements and improvements. The primary objectives of the testing phase are threefold: (1) to uncover system errors and weaknesses overlooked during development, (2) to ensure stable and crash-free operation, and (3) to validate that the software aligns with user requirements in terms of functionality and efficiency. After rigorous testing, the system has been confirmed to meet these objectives.

Looking forward, the integration of artificial intelligence (AI) technologies presents a promising direction for future research and system enhancement. AI-driven tools such as automated testing frameworks, anomaly detection algorithms, and predictive analytics could significantly augment the testing process [16–18]. For instance, AI-powered test case generation can increase coverage and efficiency by identifying critical edge cases and scenarios that may be overlooked in traditional testing approaches. Additionally, machine learning models can analyze historical test data to predict potential system vulnerabilities and optimize the testing strategy accordingly.

Conflicts of Interest

The authors declare no conflicts of interest.

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