Fire Evacuation and Management Model Based on Building Information Modeling and Virtual Reality

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Abstract –

Fire management is a key aspect of building management. During a fire, the primary reason why evacuees cannot evacuate in time and causalities occur is their lack of familiarity with the evacuation route. In practice, two dimensional images or videos are used as aids for firefighting educational training. However, they can only display a partial view of an evacuation route (not a 360° panorama) and thus have limited effectiveness in helping evacuees to understand the evacuation route. We proposed a fire evacuation management model that combines building information modeling (BIM) and virtual reality (VR) to support fire evacuation. The model is divided into two modules, namely (1) the evacuation route, and (2) educational training modules. The evacuation route module is used to analyze the shortest evacuation route from a room (where evacuees are located) to an exit and to estimate the shortest evacuation time. To verify whether the simulated route generated by the VR fire management system is applicable to evacuations, we further calculated the allowable evacuation time with the empirical equation provided in the Building Fire Refuge Safety Verification Technique Manual. The VR-based educational training module helps evacuees to evacuate from a building by providing a first-person perspective simulation. The immersive characteristic of a VR environment allows people to view an evacuation route from a 360° perspective, which deepened their impression of an environment. In this study, the proposed model was introduced and tested in a case study, which verified its ability to assist management units with fire management assessments and support fire evacuation training for users of buildings.

Keywords –

Fire evacuation; Building information modeling (BIM); Virtual reality (VR)

1 Introduction

In recent years, the frequency of fires in Taiwan has increased. According to the statistics released by the National Fire Agency, Ministry of the Interior, 17,319 fires occurred from January to September, 2021, causing 110 deaths and NT$252,881,000 in property damage [1]. Therefore, tragedies can be reduced by implementing disaster prevention measures.

Studies on fire escapes have indicated that in fire education and training for the public, fire evacuation knowledge can only be conveyed through text, posters, or videos. However, to improve the efficiency of fire education as well as equipment maintenance and management, virtual reality (VR) technology can be incorporated to support evacuation training for the public, and building information modeling (BIM) can be employed in setting the parameters for firefighting equipment models and achieving the informatization of equipment maintenance and management.

In the present study, we incorporated optimal evacuation route guidance into a VR system to effectively guide personnel who are unfamiliar with a building to avoid dangerous areas safely and easily and reduce accidents caused by prolonged evacuation time. We also used VR to simulate the emergency stress that personnel cannot experience when they are performing an evacuation drill in a safe environment to improve their emergency response to actual disasters and increase the effectiveness of such drills.

2 Literature Review

2.1 Incorporation of BIM into firefighting management

Studies on disaster prevention management have mostly verified whether the structural design of a building is appropriate or whether an evacuation route is safe. Few studies have comprehensively evaluated personnel safety by examining both indoor structures and evacuation routes. Therefore, Shih established a disaster prevention management model on the basis of BIM to implement disaster prevention measures before disasters occur, increase emergency response efficiency, and reduce casualty rates and property loss, thereby achieving the goals of disaster prevention management [2].

When building fires occur, information about dangerous factors is crucial for emergency responders, equipment management personnel, and rescue teams. Inadequate management limits the accuracy and speed of fire rescue operations. In addition, relying solely on the experience of emergency responders may have a negative effect on fire response operations. BIM can support disaster prevention by providing information on the locations of key elements and enabling effective decision-making. However, the integration of the life cycle information of buildings is a challenging task. In particular, information about building fires should be retrieved through BIM software because it mostly has spatial characteristics. Suhyun et al proposed the Building Fire Information Management System, which provides reliable fire-related information through computerized and systematic methods and BIM tools. This system enables emergency responders to intuitively identify the location of indoor facilities by referring to information that is presented in a three-dimensional format. Through scene-based application, the system was proven to accelerate access to relevant information [3].

2.2 VR evacuation simulation

When a fire occurs in a building, the timely evacuation of residents from the building is the key to protecting the safety of residents and property. In a literature review, Chiu et al. examined the fire-related regulations in Taiwan, process through which fires occur, methods for calculating evacuation time, and fire simulation software that were commonly used. A fire simulation model was built using the Unity software, and variables (e.g., size and location of the rescue opening and number and age of victims) were adjusted to estimate the time required for evacuation under varying conditions. The final simulation result was consistent with the results obtained by other researchers who used other fire simulation software. This indicated that the Unity software can be used in disaster prevention simulation. This software can also output fire simulation models in a mobile platform mode that is compatible with mobile phones or tablets, such that onsite furniture layouts can be considered when conducting an evacuation simulation [4].

Wang et al. employed a BIM-based virtual environment and a game engine to solve the key challenges in building emergency management, which include the provision of timely two-way information updates and enhanced emergency response awareness training [5]. They reported on how real-time fire evacuation guidance can be provided by adopting BIM to provide comprehensive building information and combining BIM with VR technology to create applicable and immersive game environments.

Because of the high-risk environment and complex superstructures of offshore oil and gas platforms (OOGPs), accidents on OOGPs typically result in severe casualties and economic loss. Accordingly, Cheng et al. developed an OOGP simulation model in which evacuation plans are evaluated through BIM to improve evacuation technology and achieve an enhanced agent-based model. To increase their simulation performance, they developed and input environment perception and dynamic evacuation routing functions into the agent [6].

2.3 Navigation function of Unity

The navigation function of the Unity game engine can be used to create characters that move intelligently within a virtual world. It can create a navigation mesh that serves as the moving area of the agent on the basis of geometry. The agent then simulates movement behavior and controls a character to cause it to move toward a target. [7]

The factors that should be considered in the navigation function are speed, angular speed, acceleration, and stopping distance. The setting for each parameter is determined based on the needs of the navigation process. [8]

3 BIM-VR Based Fire Evacuation and Management Model

In this section, we demonstrate a BIM–VR-based fire evacuation and management model (Fig. 1) in which a BIM model was integrated into a VR environment. To increase drill effectiveness, immersive VR technology was applied to induce in users the emergency stress that they cannot experience through conventional fire drills and educational animations.

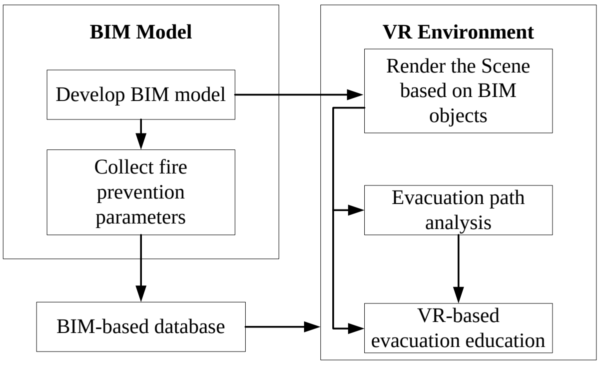

Fig. 1. BIM–VR-based fire evacuation and management model.

3.1 BIM module

Before the integration of VR software, BIM was conducted. The case model contained basic elements, such as columns, beams, slabs, and walls. Because a discussion on the maintenance and management of firefighting equipment was required, the relevant data about the elements of firefighting equipment were input into a database that was subsequently linked to the VR software.

3.2 VR environment

The VR system was divided into three modules, which are as follows.

3.2.1 Evacuation route module

Through the use of the navigation function of the Unity game development engine, we created a bake mesh map in the building information model. Parameters were added in accordance with the settings for the game agent. The script function was used to move the agent to the safe area. The information of each room in the model was substituted into the building refuge safety recommendation equation (provided in the Building Fire Refuge Safety Verification Technique Manual) to calculate the required evacuation time, which was calculated by summing the start time of an evacuation (e.g. the period after the fire occur and before the evacuees start to escape, t_{start}), travel time to the ground (t_{travel}), and the time required to move pass the ground exit (t_{queue}). The floor area in a space was required to estimate the start time of an evacuation (t_{start}), the distance from a room to an exit was required to estimate the travel time to the ground (t_{travel}), and the floor area and exit width were required to estimate the time required to move pass the ground exit (t_{queue}). The aforementioned information could be obtained through BIM. The empirical equation is displayed in Eq. (1).

$$Tescape = t_{start} + t_{travel} + t_{queue} = ((\sqrt{\Sigma A})/30+3) + \max li/v + (\Sigma \rho A)/\Sigma NeffBd \tag{1}$$

Subsequently, the estimated evacuation time for an entire building was compared with the descent time of a smoke layer to determine whether the residents of the building had enough time to evacuate. The calculation of the required time for smoke in each room to descend to the threshold height is performed using Eq. (2).

$$t_s = \frac{A_{room} \times (H_{room} - H_{lim})}{max(V_s - V_e, 0.01)} \tag{2}$$

Where, Aroom = floor area of the room (m^2), Hroom = height from the floor to the ceiling of the room (m), Hlim = height of smoke boundary (m), Vs = smoke volume (m^3/min) , and Ve = effective smoke exhaust volume (m^3/min).

Finally, we verified whether the evacuation times calculated using the empirical equation and the evacuation route set using Unity had allowable values to determine whether the residents could evacuate safely in time. In our model, the simulated building was treated as a fire-resistant structure. The fire-resistant properties of the building (e.g., situation in which the building collapses because of a prolonged fire) were not considered. Furthermore, the physical and mental factors associated with dangerous situations (e.g., panic, and coma) were not considered in the parameter setting for the agent.

3.2.2 Educational training module

After comparing the evacuation time that was estimated based on the evacuation route (set using Unity) with that obtained through the empirical equation, we discovered that the evacuation time estimated based on the Unity-derived evacuation route was within limits of the allowable evacuation time. Therefore, VR educational training is a feasible means for guiding users on the use of an evacuation route to reach a safe area. Moreover, we added evacuation route guidance to the educational training module, which enabled users to clearly identify evacuation routes. The particle system of the Unity software was used to simulate the flow of smoke during an actual fire; this increased the feelings of tension and stress experienced by users, giving them an experience that conventional fire drills and educational animations cannot provide.

4 Case Study

The case in this study was a 4-story duplex. We combined the building information model of the duplex with a fire management and maintenance VR system. The test process is described in the following subsections.

4.1 BIM module

The case model had basic elements, such as columns, beams, slabs, walls, a firefighting system, and firefighting equipment. In addition, to import the maintenance and management module into the VR system, firefighting equipment maintenance information was added to the model parameters.

4.2 VR environment

When a building information model is imported into Unity as an FBX file, texture loss tends to occur. Therefore, we re-rendered the model and added light and shadow through Unity (Fig. 2) by making a shader with the more realistic texture maps provided by the Unity developer. We then added the shader to the model elements for reattachment and set the lighting effect to increase shadow detail. With the Unity lightmap function, the realism of scenes can be enhanced. After a scene was rendered, and light and shadow settings were adjusted, the setting of the module function could be conducted.

Fig. 2. Rendered model with light and shadow added through Unity.

4.2.1 Evacuation route module

The navigation function in Unity was applied for mesh map baking (Fig. 3). According to the Building Fire Refuge Safety Verification Technique Manual, the average and stair-descent walking speeds of an evacuee are 60 and 36 m/min, respectively. Hence, the waking speeds of the agent was set accordingly. The agent would move to the safe area according to the script function, and the system would record the overall time they spent to move to the safe area. Subsequently, the relevant evacuation information (e.g., building sections, building areas, and width measurements; Table 1) was exported by using the schedule export function in the building information model. We estimated the allowable evacuation time by applying the empirical equation provided in the Building Fire Refuge Safety Verification Technique Manual and verified whether the actual evacuation time of the agent was within the limits of the allowable evacuation time calculated using the empirical equation. During the test, the agent was placed in the second-floor bedroom in Flat B, and the ignition was set to occur in the second-floor dressing room. The actual evacuation time of the agent in the VR system was 129 s, and the estimated allowable evacuation time obtained using the empirical equation was 360 s. The actual evacuation time calculated using the VR system was shorter than the estimated allowable evacuation time. Therefore, the optimal evacuation route produced by the VR system (Fig. 4) can assist the agent to evacuate safely.

Fig. 3. Mesh map baking.

Fig. 4. Evacuation route of agent.

Table 1. the evacuation information retrieved from BIM model.

Floor	1	2
Flat	Flat B	Flat B
Section	Living room	Master bedroom
Agent	Agent 01	Agent 01
Minimum average ceiling height	2.8 m	2.1 m
Area	13.6 m2	13.43 m2
Effective smoke exhaust level	0 m3/min	0 m3/min
Exit width	1.2 m	1 m

4.2.2 Educational training module

Conventional fire-related education training is conducted through actual drills or educational videos. However, actual drills tend to require additional cost and time (e.g., creation of props and dispatch of training personnel), and the content in educational videos are easily forgotten. After comparing the actual evacuation time of the agent in the VR system with the allowable evacuation time estimated using the empirical equation, we verified that the evacuation route recommended by the VR system was a feasible route. On the basis of this finding, we created a navigation agent (Fig. 5) that guides users to evacuate to a safe area. In addition, the Unity particle system was employed to simulate an actual fire scene and increase users' feelings of tension and stress.

Fig. 5 Navigation agent.

5 Conclusion

In the present study, we proposed a BIM–VR-based fire evacuation and management model. Through the integration of the building information model and VR technology and the use of the navigation and script functions of Unity, the game agent was able to move to a safe area by taking the shortest evacuation route. We estimated the allowable evacuation time by using the empirical equation provided in the Building Fire Refuge Safety Verification Technique Manual and verified that the agent in the VR system could evacuate to the safe area through the shortest evacuation route within the estimated allowable time. In addition, the navigation agent was set to guide users to evacuate to the safe area through the verified evacuation route and assist users in identifying an evacuation route during a fire. We used the Unity particle system to simulate smoke to increase users' sense of tension and stress during a simulated fire scene; we also employed the Unity script function and an SQL Server to enable access to the firefighting equipment information of the building information model in the VR system, enabling users to understand information about firefighting equipment maintenance.

The case model was a fire-resistant building. The fire-resistant properties of the building (e.g., the situation where the building collapsed due to prolonged fire) were not considered. Furthermore, for the parameter setting of the agent, the physical and mental factors associated with dangerous situations (e.g., panic and coma) were not considered. Future studies should include the two aforementioned factors or other factors to enhance our proposed fire management model.

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