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Simulation of Emergency Evacuation in Virtual Reality*

REN Aizhu (任爱珠)**, CHEN Chi (陈 驰), LUO Yuan (罗 元)

Department of Civil Engineering, Tsinghua University, Beijing 100084, China

Abstract: A virtual reality system was developed to simulate emergency evacuations during fires. The spreading of the flame and smoke in the virtual fire was modeled based on numerical fire simulations, so that the conditions are similar to real life. A multi-grid, multi-base-state database model was used to overcome the disadvantages of traditional smoke spreading simulations. Textured images and particle systems provide visualization of the flame and smoke. The system immerses the user in a virtual environment with detailed interactions between the users and the virtual environment. The system can show which evacuation methods are effective for building safety evaluations.

Key words: virtual reality; emergency evacuation; fire simulation; visualization

Introduction

Emergency evacuations are very important in fire safety studies. Surveys of building fire injuries indicate that if occupants are successfully evacuated right after the fire begins, casualties can be greatly reduced even though the fire is not rapidly suppressed. Two reasons for the failure of timely evacuations of occupants from burning buildings are that the evacuation is delayed due to an improper layout of the building structure and that the occupants make unreasonable choices due to panic or unfamiliarity with the building.

For the first issue, the solution is to simulate emergency evacuations during fires when a building is being designed. Therefore there have been many evacuation simulations and many computer based evacuation models developed to address the needs[1-3]. In current evacuation models, the building space is normally represented by a collection of tiles or nodes (a fine network) or by arcs and nodes (a coarse network), while the evacuees' behavior is predicted mathematically[4-7]. However, human psychological responses and physical behavior are usually quite complex during fires and very difficult to correctly predict. For example, the spreading of flame and smoke may create panic and lead to unusual behavior, while the decorations and lighting of the building may sometimes mislead evacuees into choosing the wrong evacuation route. Thus, mathematical models can not easily provide accurate predictions of human behavior during fires.

For more accurate predictions of human behaviors, emergency evacuation training and drills are conducted in real buildings. However, drills have some disadvantages such as high cost, limited repetitiveness, and inherent danger.

The rapid development of virtual reality (VR) technology has made it possible to overcome these disadvantages using VR methods[8-11]. With VR, the safety professionals and the occupants immerse themselves in the virtual building environment with virtual fire scenes. They can interact with the virtual environment, simulate emergency evacuation processes, judge whether the building design is reasonable, and conduct evacuation training and drills. Also, the VR overcomes the disadvantages of high cost, poor repetitiveness, and danger.

This paper introduces a VR system for simulations,

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** To whom correspondence should be addressed.
E-mail: raz-dci@tsinghua.edu.cn; Tel: 86-10-62782706

drills, and training during fire emergency evacuations. The system provides users with a virtual building environment similar to the real world. The users are able to navigate in the virtual building environment with "real" flame and to obtain an insight into fire spread. The spreading of the flame and smoke in this system is based on numerical fire simulations, so the fire evolution in the virtual environment is similar to that in the real world.

1 System Architecture

The system architecture is shown in Fig. 1. The system consists of the graphical user interface (GUI), information management module, fire simulation module, emergency evacuation module, fire fighting simulation module, and databases. The fire simulation module provides a vivid virtual building with "real" fire scenes for the users. The emergency evacuation simulation module enables users to perform emergency evacuation drills and training and to evaluate emergency evacuations of buildings. The fire fighting simulation module allows the users to perform some simple fire fighting tasks in the virtual environment such as using a virtual foam extinguisher to suppress a fire. The user is fully immersed through a head mounted display to view the GUI when the user is performing emergency evacuation drills and training.

The system was developed using Vega, Multigen Creator, fire dynamics simulator (FDS), and Visual C++ .Net. Vega is a real-time scene simulation platform for visual reality applications. Multigen Creator is used to generate the 3-dimensional (3-D) building model. Both Vega and Multigen Creator are produced by MultiGen-Paradigm Company, so they provide adequate support to each other. The fire numerical simulation model FDS is used to predict the fire development, especially the spreading of the flame and smoke. The visualization of the flame and smoke and the interaction between the user and the virtual environment use Vega APIs with the C++ programs developed using Visual C++ .Net.

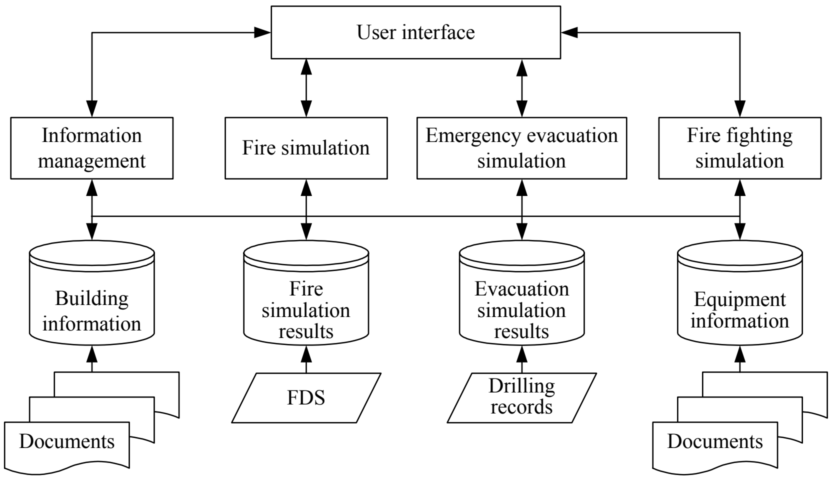


Fig. 1 The system architecture

2 Fire Scene Simulations

2.1 Integration of numerical fire simulations and the virtual reality

The development of a fire in a building is very hard to predict accurately. Therefore, most previous emergency response simulations modeled the spreading of the flame and smoke with simplified simulation approaches such as cellular automata or random variables[11]. The emergency response for such simplified fire conditions may then not be reliable.

In this system the fire evolution in the virtual environment is predicted using FDS, the computational fluid dynamics (CFD) fire model developed by the National Institute of Standards and Technology (NIST), USA, to predict the potential fire evolution scenarios. FDS predicts smoke and/or hot air flow movement caused by the fire, wind, ventilation systems, and other factors by numerically solving the fundamental equations governing the fluid flow, commonly known as the Navier-Stokes equations. FDS's predictions of velocities and temperatures are accurate within 20% of experimental measurements[12].

The integration of the numerical fire simulations and the virtual reality can immerse the users in a computer-generated fire scenario which is too dangerous, difficult, or expensive to play out in real life[13]. However, real-time numerical simulations of the fire as the users navigate in the virtual environment are not possible since the numerical simulations usually need large amount of memory and CPU time. Therefore, in this system FDS is used to calculate the fire development for a variety of scenarios in advance. The fire simulation results are then put into a database including temperatures, soot densities, smoke layer heights, and the heat release rates. The system retrieves the needed data from the fire simulation results database as it runs to achieve real-time visualization of the flame and smoke spreading. The numerical fire simulation results for the temperature, soot density, etc. are processed to form time-dependent data. This time-dependent data can be used to model the dynamic spreading of the flame and smoke for various properties (e.g. position, number of particles, velocity, and life cycle, etc.) of the particle systems. Therefore, the numerical fire simulation is integrated into the virtual reality simulations.

2.2 Multi-grid, multi-base-state model for the smoke spread process

The smoke spreading is a very dynamic process that is a function of time and location. Thus the fire simulations need to have discrete time and space coordinates arranged in order to follow the variable changes. A grid effectively divides the space into discrete volumes with specified thermophysical properties. This method has at least three advantages.

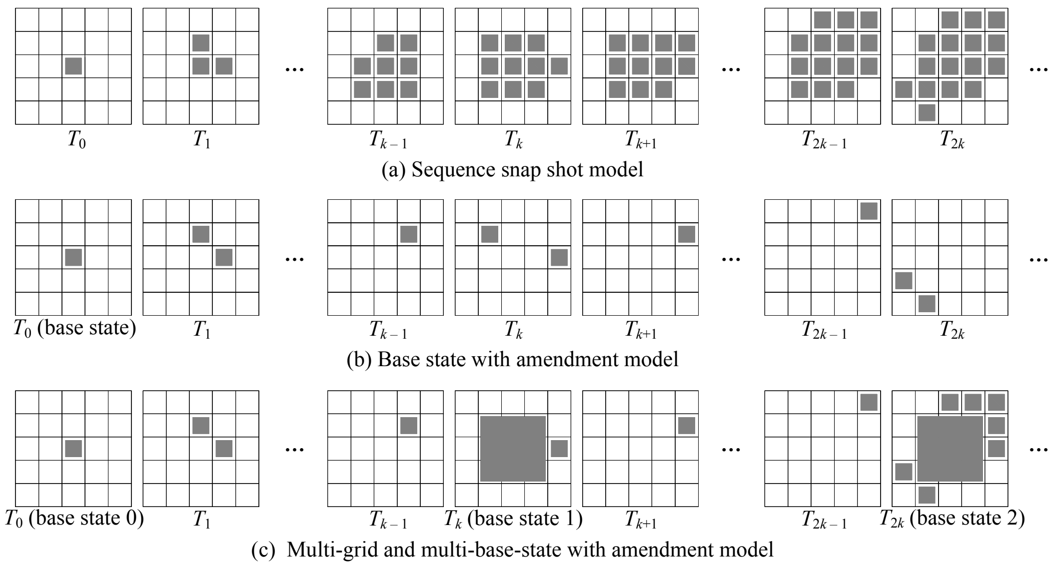
(1) Vectors can not be easily defined to describe the continuous spreading and distribution of smoke, especially with moving objects.

(2) The numerical fire simulation results are usually recorded using a grid. So the data does not need to be manipulated if the source grid is used in the virtual reality simulation.

(3) The visualization of the smoke by particle movements is easier on a grid which relates the discrete smoke particles to specific spatial grids.

The database for the smoke spreading stores the smoke distribution based on a grid structure with the distribution changing with time. However, as the number of elements and time steps increase, the size of the database increases sharply. Thus, the spatio-temporal data storage must be carefully designed to reduce the data storage and enhance the efficiency of the data query and analysis.

Several spatio-temporal data models have been designed to efficiently store data, such as the sequence snap shot model, base state with amendment model, space-time composite model, and space-time cube model. The sequence snap shot model and the base state with amendment model are both appropriate for grid data. The sequence snap shot model discretizes continuous time data into a series of time spots, with all element properties recorded at each time spot, as shown in Fig. 2a. This model has the advantage of



(a) Sequence snap shot model

(b) Base state with amendment model

(c) Multi-grid and multi-base-state with amendment model

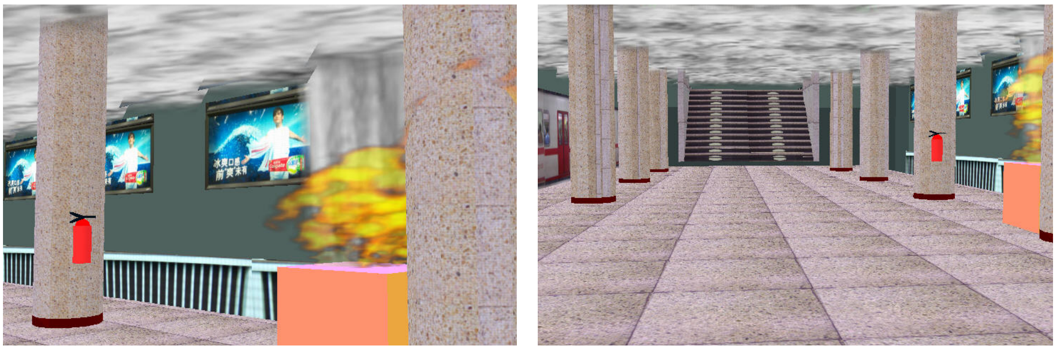
Fig. 2 Spatio-temporal data models for smoke spread

quickly providing the gird property data, but requires a huge amount of data. In addition, since it does not distinguish between variable grids and fixed grids at each time spot, spatial variations are difficult to analyze. Unlike the sequence snap shot model, the base state with amendment model only records the element properties at the starting time. Then, the model only records the changes in element properties at other time spots, as shown in Fig. 2b. Therefore, the base state with amendment model greatly reduces the storage space and is convenient for analysis of spatial variations. The disadvantage of this model is the difficulty in obtaining the spatial properties since the computer has to superimpose all the data before the required time spot to calculate the properties at that point. This operation increases the calculations and reduces the query efficiency.

The number of elements whose properties change for each time spot is often much less than the total number of elements, so the base state with the amendment model provides a much more efficient description of the smoke spread than the sequence snap shot model. The model used here was based on a multi-grid, multi-base-state model which improves the query efficiency of the base state with the amendment model. As shown in Fig. 2c, this model adds a series of base states in addition to the starting base state during the smoke spread. Between base states the system only records the element data for elements whose properties change, with all the element data recorded at each base-state spot. The time between two base-state spots is decided by the number of elements and the properties change rates. Thus, queries of the space state at some spot only require data from the nearest base-state and subsequent times. In addition, the properties of elements that are very similar are combined into one large element to reduce storage and significantly enhance the query efficiency.

2.3 Virtual reality visualization of the flame and smoke

The virtual environment uses textured images and particle systems to implement flame and smoke visualization. Vega provides the special effect module that sets the texture and particle properties. The flame and smoke images were snapped from selected frames from a fire video with image processing tools used to edit the static frames to make the part without fire and smoke transparent. Then, a sequence of such fire textured images are mapped to the particle systems. In this way, the system provides very fast and accurate flame and smoke animations. Different types of flame and smoke can be simulated by using different particle systems properties. Figure 3 demonstrates a visualization of the flame, vertical plume, and spreading smoke in the system.



(a) Flame and vertical plume (b) Spreading smoke

Fig. 3 Visualization of flame, vertical plume, and spreading smoke

2.4 Virtual reality immersion

Multigen Creator was used to construct the 3-D building models with spreading of the flame and smoke visualized as described in Section 2.3 to create a virtual world of fire. The users view the fire scene through a head-mounted display and navigate in the virtual environment using a mouse. Thus, the users are immersed in the burning building with no risk.

2.5 Interaction between the users and the virtual environment

The user can navigate freely in the virtual environment as if he were walking in the real building. Nine different motion model types are provided by the Vega platform, including fly, drive, walk, and spin. This system uses only the walk type for the emergency evacuation scenarios with the navigation controlled by the mouse. Moving the mouse left or right while holding down the left button causes the user to move in that direction. Moving the mouse up and down allows the user to look up and down. The height of the user's eye above the ground is changed by setting a parameter in the walk motion model. This is useful when the building has several floors.

In addition to the navigation function, other interactions between the users and the virtual environment are allowed in the system. The program used the vgPicker class API to implement the functionality of picking objects within the virtual environment in the system. This "pick" interaction allows the user who is navigating in the virtual fire scene to pick up fire fighting equipment (e.g. a foam extinguisher), carry it to the fire site, and suppress the fire. Thus, the users can perform fire fighting training in the virtual environment.

3 Application Instance

An underground subway station was simulated to test the practicality of the system. First, the Multigen Creator was used to create the 3-D model of the train station, the FDS was used to numerically simulate the possible fire scenarios and finally the simulation results were stored in the fire simulation results database using the multi-grid and multi-base-state model.

Figure 4 demonstrates an example of an emergency evacuation drill where Figs. 4a and 4b show the user walking through the virtual station when he notices that a box is burning. Figures 4c and 4d show the stairs up to the exit.

(a) A box burning in the station (b) The smoke spreading in the station

(c) The stairs up to the exit (d) The user running to the exit through the stairs

Fig. 4 Emergency evacuation to the upper floor exit

The architects and the fire fighting staff can then evaluate the emergency evacuation performance of a building by comparing emergency evacuation drills with numerical predictions of the evacuation process.

Emergency evacuation drills in real buildings are expensive, difficult, and dangerous. This system performs evacuation drills in a vivid virtual building environment which provides an excellent alternative. The emergency evacuation simulations in the virtual environment can be recorded for future analysis with the support of the vgVCR class provided by Vega.

This system provides an excellent method for evaluating emergency building evacuation. The evacuation routes and evacuation time of evacuees can be calculated and predicted by numerical simulation. Based on the numerical simulation result, this system can be used to demonstrate the evacuation processes of the evacuees in the virtual reality. Thus, architects can intuitively evaluate the emergency evacuation performance of a building. This method creates paths in the virtual environment based on the simulation results using the Vega Path Tool or the vgPath class API, creates virtual human models with the Multigen Creator or DI-Guy and then makes the human model travel along the designated path using the vgSplineNavigator class API. The predicted evacuation processes of virtual human models are shown in Fig. 5.

(a) Virtual human modes (b) The virtual humans travelling along the designated path

Fig. 5 Evacuation processes of virtual human models

4 Conclusions

A virtual reality system developed to evaluate emergency evacuation procedures was introduced. The system can be used to conduct inexpensive and safe emergency fire evacuation drills in a virtual environment.

The multi-grid and multi-base-state model overcomes the disadvantages of traditional models for smoke spread simulations. Texture mapping and particle systems are used to visualize the flame and smoke. The virtual building environment is created using Multigen Creator and Vega. Interactions between the users and the virtual environment are based on the Vega API and C++ programs. The system is powerful and easy to use. Future research will develop a distributed interactive simulation that will allow several users to simultaneously participate in an evacuation.

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Commencement for Graduate Students

A commencement ceremony to award graduate degrees was held in the Auditorium at Tsinghua University on July 5, 2008. There were 1022 doctorates and 3282 master's degrees awarded at the ceremony.

Tsinghua President and Chairman of the Degree Conferral Committee Gu Binglin and University Council Chairman Chen Xi, together with other university leaders, presented degrees and certificates to the new graduates.

In his commencement address, President Gu congratulated the graduates and commended them for their hard work and contribution to the development of Tsinghua. He encouraged the students to adopt a global vision, love the motherland and be brave to shoulder responsibilities to contribute to the development of the nation. He then urged them to study life long to make continuous progress. He finally told the students to be cooperative and be open-minded and learn from others.

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