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Agent-Based Evacuation Model Incorporating Fire Scene and Building Geometry*

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Abstract: A comprehensive description of the key factors affecting evacuations at fire scenes is necessary for accurate simulations. An agent-based simulation model which incorporates the fire scene and the building geometry is developed using a fire dynamics simulator (FDS) based on the computational fluid dynamics and geographic information system (GIS) data to model the occupant response. The building entities are generated for FDS simulation while the spatial analysis on GIS data represents the occupant's knowledge of the building. The influence of the fire is based on a hazard assessment of the combustion products. The agent behavior and decisions are affected by environmental features and the fire field. A case study demonstrates that the evacuation model effectively simulates the coexistence and interactions of the major factors including occupants, building geometry, and fire disaster during the evacuation. The results can be used for the assessments of building designs regarding fire safety.

Key words: evacuation; fire safety; multi-agent; fire dynamics simulator (FDS); geographic information system (GIS)

Introduction

The rapid development of computer hardware has led to larger memories and faster computing speed so that more complex practical problems can be analyzed. Several occupant evacuation computer models, such as EGRESS[1], EXODUS[2], and SIMULEX[3], have been developed based on various principles to predict the effectiveness of evacuations. Multi-agent systems designed for many-body systems have been widely applied in evacuation models[4-7]. These models use the agent-based technology to specify the attributes and behavioral features of a variety of agents incorporated into virtual scenarios. The performance of each agent contributes to the movement of the crowd so that the whole evacuation process can be simulated in detail.

Applications of agent-based models have shown that the actual evacuation environment, e.g., a fire, may involve complex conditions and the agent-based technology cannot simultaneously model all these factors and their interactions. Thus, for better accuracy, other technologies and computational models need to be integrated into the original model. Various simulation frameworks have been developed[8-11] with various algorithms used to model the sophisticated phenomena to achieve more comprehensive representations.

This paper primarily focuses on an agent-based evacuation simulation model which incorporates the fire effects and the building geometry. Unlike existing pure agent-based models, this model emphasizes a comprehensive description of the actual evacuation scenario. The key factors are identified and then described in detail in the model. The simulations use a fire dynamics simulator (FDS)[12], which is a computational fluid dynamics (CFD) model, and use a

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geographic information system (GIS) model with the multi-agent technology to model the occupant behavior. The real time interactions among these elements are also taken into account. The integrated model traces the occupant movement to predict the clearing time for enclosures, floors, and stairs. The model is used for a case study of an office building evacuation. The model can be extended to large public buildings such as sports arenas, hotels, and even transport hubs. The objective is to provide the ability to assess building designs with respect to fire safety.

1 Overview

Realistic simulations of evacuations during fires require an understanding of the occupant response during the event. The movements of individuals are impacted by the distribution of combustion products and the enclosure layout. The propagation of the combustion products, such as the fire growth and smoke spread, is also affected by the building geometry. This model includes the three key elements in the evacuation environment, the fire, the geometry, and occupants in three separate sub-models as shown in Fig. 1. Communications between the sub-models influence the fire spread and the occupant evacuation.

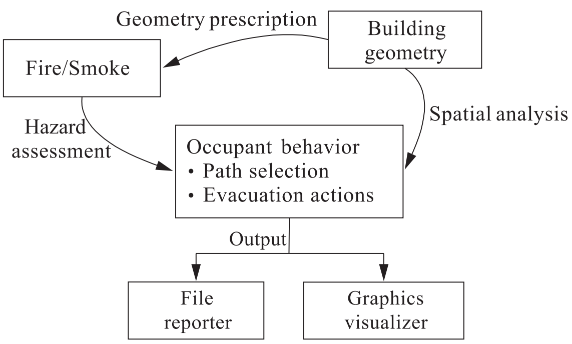

Fig. 1 Model flowchart

The building geometry module supplies the geometric information for the geometry in the fire sub-model and the environmental knowledge of the occupants in the occupant sub-model. The fire sub-model then organizes the fire simulation data which indicates the distribution of the combustion products over space and time. The toxic and physical hazards are then assessed as the input into the occupant sub-model. The behavior and decisions of the agents are influenced by the distributions of both the enclosures and the combustion products. Finally, the movement data is output for 2D and 3D visual representations.

2 Fire Simulation

A variety of models have been used for fire simulations. This study selects the CFD-based FDS, which has been successfully applied in practical fire protection engineering projects. The FDS simulation can predict the variations of various quantities, such as the soot density and heat release rate, at any point in the fire field.

The computational domain for the FDS calculation is meshed using axis-aligned rectangular grids. The elements are each 0.4 m×0.4 m, which is also the space occupied by each individual. The time step is set to 0.5 s, a reasonable time step for each movement.

The hazard assessment quantifies the relationship between the volume of toxic substances (including low O_2 concentration) and the injury to the occupants. The analysis assesses the effect of toxic gases and burn severity from the fire's heat release based on experimental data[13-16].

3 Geometry

The geometric representation includes both a spatial analysis and the environmental visualization. The geometric information which represents the enclosure layout at the scene is captured and shared with other sub-models. The visualization requires a common display of the building geometry and other factors, which means that other elements such as the occupants can be freely added into the scene. The geometric representation is depicted in Fig. 2.

GIS technology is used for the geometry representation (Fig. 2). The GIS model is an information system which organizes geometric data in an extensible structure and supplies data operations including the spatial analysis. The extensibility of the GIS database allows convenient addition of custom properties to the geometric elements. The ability to process massive amount of spatial data over a large environment enables further development of the model to simulate evacuation scenarios in large public buildings or even outdoor areas.

The building enclosures are classified into nine categories in a set Ψ defined as {ROOM, CORRIDOR, LOBBY, STAIRCASE, STEP, LANDING, DOOR,

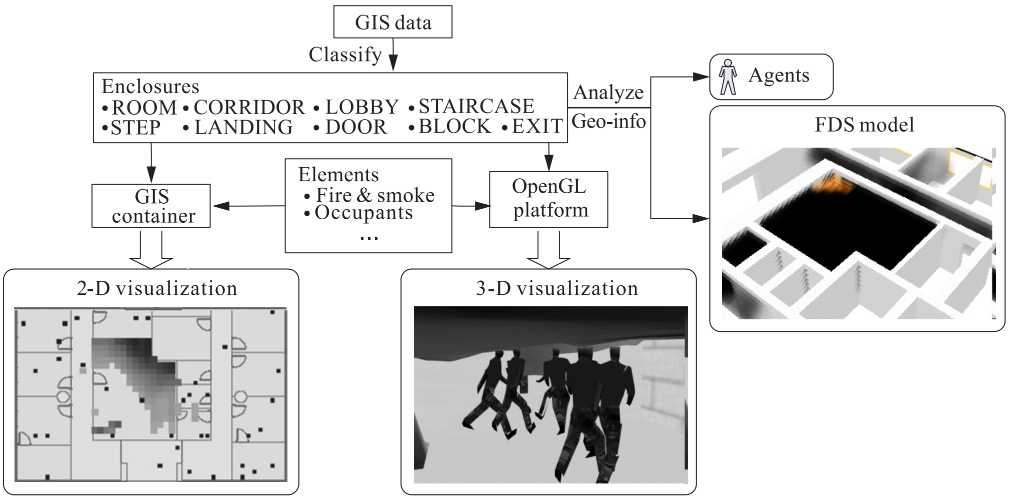

Fig. 2 Geometric representation

BLOCK, EXIT}. In the simulations, the information about the enclosure positions is first used for the entity generation in the FDS. Then the spatial analysis module provides the geographic information among the geometrical elements, such as topological, distance, and direction relations, used for strategy judgments and selections in the occupant sub-model. Thus, the spatial analysis results form the environmental knowledge of the occupants, which constitutes their decision-making basis before each movement.

The GIS controls are also capable of displaying the building conditions; thus, the 2-D visualizations use the GIS controls instead of writing routines on other platforms. The building plan is loaded and displayed as a feature layer with the enclosures and other graphic elements representing other entities in the scene, which can be easily appended to the GIS graphic container as different symbols. The 3-D visualizations use the open graphics library (OpenGL) in a visualization program in which the scene can be observed from different angles of view.

4 Occupant Modeling

The multi-agent occupant sub-model uses an agent, who behaves autonomously, to represent each individual in the scene. The agents judge the current situation and analyze the factors including the fire conditions, geometry, and other individuals to select their own egress paths and evacuation strategies. The behavioral autonomy of each agent is based on the agent's attributes and behavior rules.

4.1 Agent attributes

The following attributes are specified for the agents:

State The state of each agent includes its current position, health, and mobility. Since the spacial locations are discrete, the position should be evaluated as a point in the world lattice. The following equations are used to establish the position at time t:

$$\text{position}(t) = \text{Lattice}[i(t), j(t)] \quad (1)$$

$$i(t+\Delta t) = i(t) + \text{int}\left(\frac{V_x(t)\bullet\Delta t}{X}\right) \quad (2)$$

$$j(t+\Delta t) = j(t) + \text{int}\left(\frac{V_y(t)\bullet\Delta t}{Y}\right) \quad (3)$$

where X and Y are the width and height of mesh grids and Δt is the time interval between steps. Here, X and Y are set to 0.4 m and Δt is 0.5 s. The value intervals for health and mobility are both [0, 100] with both decreasing as the agent is influenced by hazards. When health falls to zero, the agent is erased.

Speed Speed is defined as running speed and walking speed. The running speed ranges from 3-7 m/s while the walking speed is 1.2-1.8 m/s.

Vision Vision is the visible range from the current spatial location. This attribute is calculated at any given point in time and space as

$$\text{Vision}(\text{position}, t) = \text{Intersection}(V_{\text{obs}}(\text{position}, t), V_{\text{haz}}(\text{position}, t)) \quad (4)$$

The GIS functionality determines the view field V_{obs}, which reflects the influences of obstacles. V_{haz} is a function of the smoke, which is more complex to calculate. This model uses some equations in the literature[17,18].

Reaction time Reaction time (RT) is the time that an occupant spends before his evacuation behavior starts. Within this period, the occupant needs to confirm the alarm and perform some necessary measures. The existence of RT imparts phase deviations to the evacuation and may mitigate congestion. The distribution of RT is related to the building plan. Normally, agents within the same enclosure can be regarded to have similar RT.

Collaboration Experimental studies have shown that occupants collaborate with others during an evacuation[19]. The collaboration factor is designed to quantify the possibility of collaboration among agents. Collaboration has a range of [0, 1], with agents connecting and acting together when

$$\begin{cases} \min(C_1, C_2) \geqslant C_0, \\ \text{Distance}(\text{position}_1, \text{position}_2) \leqslant R_0 \end{cases} \tag{5}$$

where C_1 and C_2 are the collaboration factors for the two agents. The critical values C_0 and R_0 in this study are set as

$$C_0 = 0.7 \tag{6}$$

$$R_0 = 1.2\ \text{m} \tag{7}$$

Insistence The occupants may need to change their strategy at any time during an evacuation as a result of environmental factors. In many experiments, for example, researchers have noticed that occupants make different decisions when confronted with smoke[20,21]. The insistence factor defined on the interval [0, 1] indicates the probability of maintaining the current evacuation strategy. When an agent is experiencing low evacuation efficiency, the attribute decreases and leads to strategy adjustments.

Knowledge Knowledge represents the agent's familiarity with the surrounding environment which comes from a spatial analysis of the agent's awareness range, varying from the individual's vision to the entire scene. The agent makes his strategy, e.g., path selections, according to his knowledge.

4.2 Agent behavior rules

The main content of the behavior rules is the egress path selection. The geographic information captured from the spatial analysis includes features of the enclosure layout with the evacuation strategy established as shown in Fig. 3. As the simulation continues, the agents flow directionally from one type of enclosure into another through the element DOOR. Each agent within an enclosure has an optimal target exit and for each movement, each agent moves in the optimal direction. These targets and directions form the evacuation trajectory. This layout-based evacuation strategy utilizes the agent knowledge during the simulation.

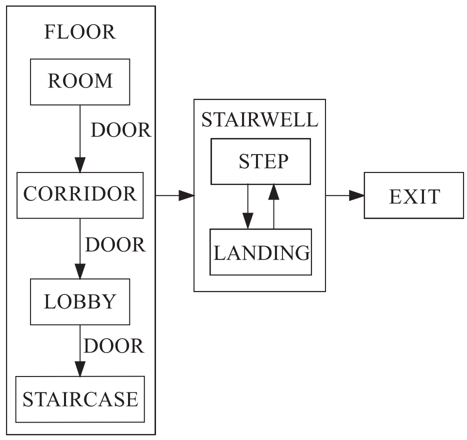

Fig. 3 Layout-based evacuation strategy

These rules may not be applicable in some circumstances, e.g., when congestion occurs or smoke spreads within the target enclosure. Then adjustments must be made to the strategy. Thus, the agents may change their current target for a secondary target or select a subordinate direction for the next movement to balance safety and efficiency.

5 Case Study

The evacuation from a sample building was chosen for a case study of the simulation model. The building is a standard frame structure with stairwells located at each end of the wing. The building has seven floors with lecture halls and offices with similar layouts on each floor.

5.1 Fire simulation

The fire source was assumed to be located in one room on the fifth floor. The fire load was 300 kW with a surface temperature of the fire source of 500℃. The ventilation devices were taken into account, but the outside weather was not considered.

The geometry for the FDS analysis was generated from the building geometry with each enclosure discretized with hexahedrons. The FDS then simulated the fire growth and smoke spread within the computational domain. The simulation gave the peak total heat release rate as 902 kW at 107 s. The total mass of the various gas species at the scene at different times are shown in Fig. 4. Oxygen was consumed while CO, CO_2, and soot were produced during the combustion. These conditions are unfavorable for occupant evacuation.

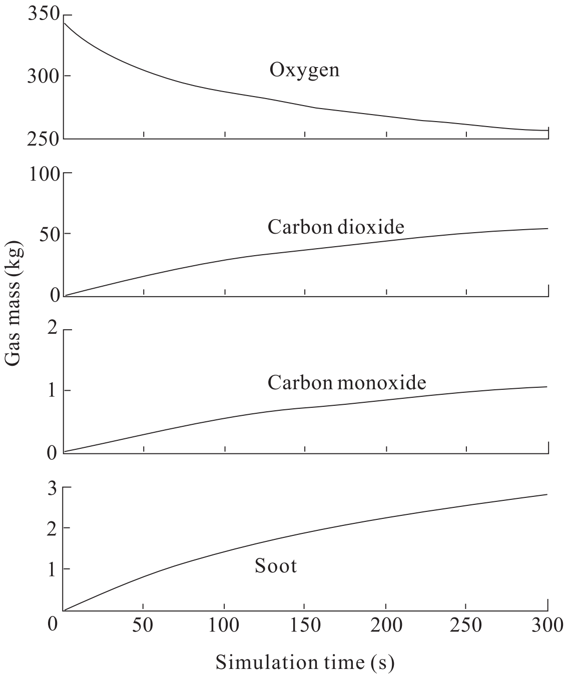

Fig. 4 Total gas levels during the simulation

5.2 Occupant evacuation

The occupants were initially positioned in the scene according to selected densities with their positions initialized randomly. Health and mobility were initialized as 100. Speed, collaboration, and insistence factors were randomly selected over their intervals. RT was assumed to be 10 s for the occupants in the room where the fire originates, 20 s for those in other rooms on the fifth floor and 30 s for rooms on the other floors. Each agent was assumed to be quite familiar with the entire building, i.e., the agent knowledge was based on his spatial analysis of the whole scene.

The numerical results are difficult to validate especially for fire evacuation scenarios, but still the model can be verified qualitatively by analyzing the simulation performance. During the simulation, the agents acted individually within the rooms so the evacuation routes differed. After entering the corridors, the agents began to converge and formed flows. Congestion occurred at bottlenecks such as stairwells when the flow density exceeded the threshold.

The hazards were quantified from the FDS results with the hazard assessments then used to reduce the health and mobility of the affected agents. As the mobility declined, the agents became handicapped, which posed further physical hazards. The soot density influenced the agent's vision so that their movements in the smoke became inefficient. They may detour in the scene and their paths deviated from optimal evacuation routes.

In view of the random nature of the simulation, the simulations were repeated 30 times with the average values used for the analysis. The simulation results (initialization density: 0.3 agent / m^2, altogether 870 agents) are shown in Fig. 5.

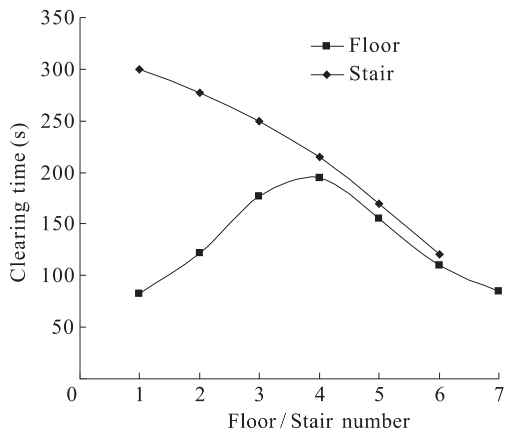

Fig. 5 Floor and stair clearing times

The evacuation of each floor was a parallel process while the evacuation within the stairwells was a serial process. The floor clearing time mainly depended on the floor layout and the population density within the stairwells. The stair clearing time, however, was totally different, since as a serial process, the stair clearing time increased from the top down and was equal to the total evacuation time at the bottom (Fig. 5). The evacuation paths as well as the final positions of people who died on the fifth floor are shown in Fig. 6. Note that Exit A was preferable to Exit B since the fire source had less influence on Exit A.

5.3 3-D visualization

The postprocessor built using the OpenGL provided 3-D animations. The 3-D visualizations were more revealing and provided a better understanding of the scenario. Figure 7 shows a snapshot of the simulation

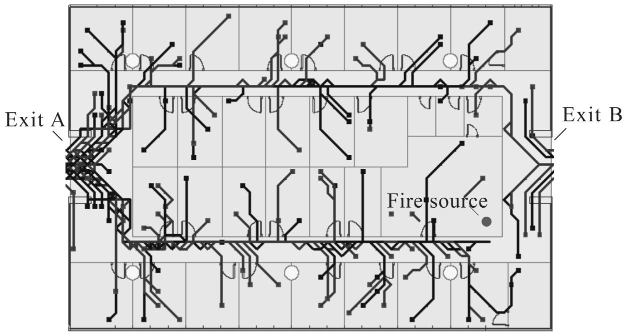

Fig. 6 Evacuation paths and final positions on the fifth floor

process on the fifth floor on the 3-D visualizer at $t = 35$ s.

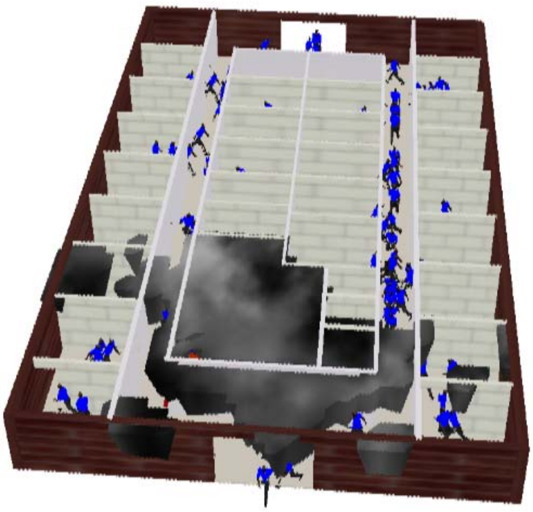

Fig. 7 3-D view of the fifth floor at 35 s after the fire began

6 Conclusions and Future Work

This paper presents an agent-based evacuation model which includes both the fire scene and the building geometry. A case study demonstrates how the model is able to simulate the coexistence and interaction of variables during the evacuation. The model can be easily used for other scenarios by modifying the geometry in the GIS files.

Future work will further validate the model by comparisons with experimental data and calculated results from other existing models, and develop the model into a simulation tool to evaluate fire evacuation efficiencies for buildings in the planning shape. The model will be extended to various types of buildings, including large public buildings. Additionally, component deformation or structural failure due to the fire will also be taken into account because these will have a tremendous impact on the evacuation process.

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US National Academy of Engineering President Visits Tsinghua

President Charles Vest of the National Academy of Engineering in the United States visited Tsinghua University on June 26，2008. Tsinghua Vice President Kang Kejun exchanged ideas with Dr. Vest on research, education, and future cooperation. During their discussion, VP Kang briefed Dr. Vest on Tsinghua's efforts in disciplines development, research, and international cooperation. Dr. Vest then visited the School of Information Science and Technology.

Before becoming President of the National Academy of Engineering in 2007, Dr. Vest served as President of the Massachusetts Institute of Technology from 1990 until 2004.

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