Fire Emergency Evacuation for Large-Scale Public Buildings In 3d Gis

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Abstract. High temperature and smoke poisoning during indoor fires can be fatal, yet traditional evacuation methods fail to account for the high temperature distribution and smoke flow. In this paper, we proposed a fire emergency crowd evacuation model for large-scale public building. Our model integrates fire numerical simulations, individual behavior, and a model to search for the shortest path. Navigation meshes for each floor are connected to form complex 3D multi-meshes for complex architectural interior spaces. The fire numerical simulation provides smoke diffusion flows and the temperature field distribution. The A* algorithm, with its heuristic social force model function for individual behavior, is applied to determine the safest and shortest evacuation route, avoiding risk hazard zones across different floors.

1. Introduction

The rapid urbanization and urban expansion occurring across the globe has placed many challenges for urban security. Fire is a major disaster, endangering public safety and threatening the survival of all living things \cite{1}. A total of 1,700 people have been reported to die from fires in China per year, with a further 1,500 people attaining injuries. The direct economic losses from fires in China amount to 1.6 billion yuan \cite{2}. The large number of accidents indicates the toxic fumes and the high temperature environments from the fires to be the principal factors harming human health, affecting the evacuation, reducing the walking speed, and causing casualties \cite{3}\cite{4}. Furthermore, the increasing amount of large-scale public buildings with complex architectural structures and excessive decorations of flammable materials increase the risk of evacuation.

It is generally considered more favorable to prevent fire accidents than to treat them \cite{5}, and numerous building evacuation models have been proposed. These models can be divided into network and grid models, depending on the type of spatial information implemented.

In the network model, the rooms, passages, stairs, and exits of the building are regarded as nodes, and the arcs connecting each node constitute the whole building space, with evacuation models (e.g., EVACNET+) considered as moving from one node to another via the arc segments \cite{6}. Grid models (e.g., SIMULEX) divide the whole building plane into various meshes and represent the geometry of the evacuation space and the obstacles of each floor using 2D grids in order to represent the exact location of the evacuees with time. This results in a heavy calculation burden for the grid model \cite{7}.

Without the support of smoke flow and temperature field distribution analysis, the majority of the aforementioned algorithms are not suitable for the determination of safe routes for fire emergency
evacuation. Therefore, in the current paper, we integrate fire numerical simulations \[8\] with a social force model to propose a fire emergency crowd evacuation framework for large-scale public buildings.

2. The Proposed Method

We can divide our proposed method into four components: navigation meshes for public buildings, the A* algorithm used to determine the shortest path across floors, the social force model for individual behavior, and fire numerical simulation analysis to obtain the impact of the smoke and heat distribution on the evacuation behavior.

![Figure 1. Technical flow chart.](image)

2.1. Navigation meshes for public building

The production steps of the proposed framework can be described as follows: (1) Obtain the indoor map data source (e.g., architectural blueprints). (2) Create the navigation mesh by gridding indoor maps for each floor. (3) Connect the navigation meshes with stairs in order to construct the 3D meshes for public buildings.

2.2. Indoor evacuation A* pathfinding algorithm

As an extension of Dijkstra's algorithm, the A* algorithm can perform breadth-first searches, with the advantages of not requiring heavy pre-computing and the implementation of a 3D mesh to represent complex building geometries. In addition, pedestrians act realistically when the fire scene changes, namely, fire or smoke blocks appear and disappear, and other pedestrians move on their way. Moreover, these changes do not affect the crowd pathfinding task.

The process required to design an A* path search algorithm for indoor evacuation meshes can be summarized in the following.

(1) The open and close lists are defined to store the cell, where the former stores the accessible cell and the latter stores the arrived cell.

(2) The first cell (x, y) is placed in the open and close lists, and the algorithm determines whether cell (x, y) is located at an evacuation exit: if so, the search is successful and subsequently ends here.

(3) If not, the algorithm searches for all adjacent cells of cell (x, y) and employs the heuristic function to calculate the value of F\[cell\] in order to determine whether it is in the open and close lists.

(4) The open list is sorted based on the heuristic value of F\[cell\], then repeat.

2.3. Heuristic function of social force model

The heuristic function F(n) of the A* algorithm is defined as:
\[
F(n) = G(n) + H(n)
\]

where \(G(n)\) is the cost of moving from the starting point to the current cell, and \(H(n)\) is the estimated cost of the current cell to the target cell. In addition to using distance as the weight, \(F(n)\) function adopted in this paper also introduces a social force model to characterize the law of human motion, employing several physical forces to analogize the interaction between individuals and the environment. \(H(n)\) function introduced into the social force model can be expressed as:

\[
H(n) = \sum_{ij} D(s,t)d(n_i, n_j)
\]

where cell \(n_i\) is the currently location of staff \(n\), cell \(n_j\) is adjacent to the current cell, \(D(s,t)\) represents the distance between \(n_i\) and \(n_j\), and \(d(n_i, n_j)\) is the weight determined by the social forces. The social force equations\(^{[9]}\) are defined as:

\[
M_p \frac{d\vec{v}_n}{dt} = F_s^n(t) + \xi
\]

where \(M_p\) is the mass of pedestrian \(n\), \(\vec{v}_n\) is the movement speed in the current environment, \(F_s^n(t)\) represents pedestrians via composition of social forces, and \(\xi\) is a small irregular force. Equation 3 and 4 describe how the social forces are calculated: the first and second terms on the right-hand side represent the driving force and resultant force of the interaction force between pedestrian \(n\) and pedestrian \(m\), while the third and fourth terms represent the resultant force of the interaction force between the pedestrian and environment and the resultant force of attraction, respectively.

2.4. Fire numerical simulation analysis

FDS (fire dynamic simulation) is a fire field simulation software developed by NIST\(^{[10]}\) to calculate the smoke and heat transfer process. Due to the complex architectural structure of large-scale public building, we adopt the sub-regional variable-scale meshing method for fire scene simulation model to improve computational efficiency.

The main equation for fire numerical simulation is as follows:

(1) Fire combustion chemical model

\[
\sum_v v_1 (\nu_{v,0} \nu_{v,0} \nu_{v,0} + \nu_{v,0} \nu_{v,0} \nu_{v,0} + \nu_{v,0} \nu_{v,0} \nu_{v,0} + \nu_{v,0} \nu_{v,0} \nu_{v,0} + \nu_{v,0} \nu_{v,0} \nu_{v,0} + \nu_{v,0} \nu_{v,0} \nu_{v,0})
\]

(2) Smoke fluid dynamics model

\[
\frac{\partial}{\partial t} \left( \rho h_s \right) + \nabla \cdot \left( \rho \nu h_s \right) = \frac{D_p}{\tau} + \mu \cdot \nabla p - \nabla \cdot q + \nabla \cdot \lambda \nabla T + \sum_i \nabla \cdot h_i \cdot pD_i \nabla Y_i
\]

where \(v_1\), \(v_2\), and \(v_3\) are the fractions of the air, fuel, and product components. Fire is a relatively inefficient combustion reaction of a hydrocarbon fuel with air oxygen, producing carbon dioxide, water vapor, and soot particles.

(2) Smoke fluid dynamics model

where \(h_s\) is sensible enthalpy (unit J/kg), \(q\) is the thermal radiation flux (unit W/m\(^2\)), \(D_i\) is the diffusion coefficient of component \(i\) (unit m\(^2\)/s), and \(Y_i\) is the mass fraction of component \(i\), \(T\) is the temperature (K), and \(\lambda\) is the thermal conductivity.

3. Experimental Data and Result Analysis

3.1. Study area introduction

The public building of China-Singapore Tianjin Eco-city was selected as the research area. The structural and interior designs of the building were obtained through cooperation with the China-Singapore Tianjin Eco-City Administrative Committee. The building consists of three blocks; the middle block contains an 8-floor arc-shaped building, while the floors on either side are square with
four floors. Furthermore, seven exits are spread around the building, and a courtyard is located in the middle block.

Figure 2. 3D model of public building and plan map of left block.

3.2. Fire numerical simulation

We consider the most conservative and unfavorable fire scene design principle and assume that a household on the first floor caused a fire in the restaurant. Figure 2 presents the fire scene simulation for the public building based on the proposed fire scene and sub-regional variable-scale meshing method.

The ignition of the fire lasted 2.9 s and resulted in the spreading of smoke from the 2nd-floor window. Following 4.7 s, the smoke spread to the fourth floor and patio, while after 72 s, the room on the west side of the A-seat patio was filled with smoke, and the smoke spread to the east side of the patio.

Figure 3. Numerical simulation model of the fire scene (72 seconds after fire ignition).

3.3. Crowd emergency evacuation analysis

The high temperature environment and smoke visibility in the fire scene are considered to strongly affect the evacuation route selection in the proposed evacuation model. For example, the human skin gets burnt at temperatures exceeding 45 °C.

Therefore, for a given cell, if the temperature exceeds 45°C or the smoke visibility is less than 10 m, we dynamically update the evacuation cell attribute according to the fire risk zones of the simulation timeline. In particular, the A* path search algorithm described in Section 2.2 searches for the path and judges whether this cell attribute is an obstacle.

Figure 4 compares the indoor evacuation routes with or without fire based on the proposed method. Due to the rapid spreading of the smoke, the soot visibility affects the cognitive ability of most individuals, which consequently prolongs the escape time (Figure 5). Despite the increase in evacuation time, individuals will avoid fire and smoke in dangerous zones and choose the safest
evacuation routes via the stairs and exits. For example, the 6th-floor person is initially located on the 2nd floor and would normally select the shortest path from this position: 3rd-floor stairs to 5th-floor exit on the first floor. However, in this fire simulation, the 6th-floor person selects an alternative route from the initial position, namely 5th-floor stairs to 1st-floor exit in order to avoid the fire and smoke near the 3rd-floor stairs.

(a) Fire risk zones on the 2nd floor
(b) Comparison of indoor evacuation routes with or without fire

Figure 4. Fire risk zones and indoor evacuation routes.

Figure 5. Comparison of indoor evacuation time with or without fire.

4. Conclusion

Due to the influence of fire and smoke, individuals not only base their evacuation route on distance but also attempt to avoid fire danger zones. In this paper, based on the smoke flow and temperature field distribution, we propose a fire emergency evacuation solution for large-scale public buildings. Multi-layer meshes are composed in order to represent the complex architectural structure by gridding indoor maps for each floor. Moreover, the fire numerical simulation equation is introduced to calculate the spread of fire and smoke throughout the building as a function of time. Finally, the A* pathfinding algorithm, which is based on the heuristic function improved by the social force model, is applied to search for the shortest and safest route for indoor evacuation. The proposed method has been adopted by the fire department of Tianjin Eco-City to formulate an urban emergency plan.
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