Fast Marching Method Applied For Emergency Evacuation in High-rise Building Fire

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ABSTRACT

In this paper, we use the fast marching method to solve the emergency evacuation in high-rise building fire. This method is a numerical method which is used to solve the Eikonal equation in rectangular grids. As we know, building fires are very common in the world. They have caused a great deal of personnel casualty and property losses. How to reduce the casualty and ensure the life safety of trapped persons and rescuers have become the most important problem of the fire department. We carry out fire experiment and FDS simulation to research the structure fire firstly. Second, we divide the construction into 0.4m*0.4m grid. This size is a person who occupied when he is standing. After that, we use interpolation method to analyze the experiment and FDS simulation data so that we can get the risk value of each grid. At last, we calculate the global potential energy field of the scene based on the fast marching method and obtain a safest path for the trapped persons. The safest path represents the fastest-risk-decline path. In the cause of fire rescue we can provide the safest path to the trapped persons through evacuation signals of the building in order to guide them to evacuate and self-rescue.

Keywords

Evacuation path, Fast marching method, Global potential energy field, Risk distribution.

INTRODUCTION

Emergency evacuation can be mandatory, recommended, or voluntary, besides it may differ by scale, objects of relocation and by level of control by authorities. In this short paper, we only consider the fire evacuation which is mandatory. In recent years, the high-rise building fire disaster has happened frequently around the world. It calls attention to the impact on evacuation movement of the presence and location of exit signs, position of exits, width and other conditions of stairs. Increasingly, people recognize the importance of emergency training and exercises, constant environment monitoring in high-rise buildings. A key part of the emergency management measures is evacuation simulation model. There have been a lot of widely known simulation methods, including flow based, cellular automata and agent-based models. There were also some business softwares such as the FIRESCAP, EXODUS, and Multi-Agent Simulation for Crisis Management [1-4].

This short paper uses the fast marching method which is very new in the evacuation area, according to the distribution of risk in the building, works out the potential energy field of risk quickly, and plans the least risk distribution route which is the safest evacuation route. Then provides the route to the commander to guide firemen to rescue and people evacuation. The most obvious feature of this model is strong timeliness. It can almost calculate the escape path in real-time which other models don't have this characteristic. This short paper is one of the most important part of paper "Investigation on an Integrated Evacuation Route Planning Method Based on Real-Time Data Acquisition for High-Rise Building Fire", IEEE transactions. This short paper focus on discussing the fast marching method using in fire evacuation in high-rise building from the aspect of algorithm. And the biggest difference is using CAD design drawings to make the building grid-enabled and digitalization quickly. Besides that, we consider more evacuation parameters during the computation such as crowd density and the risk of high crowd density.

FAST MARCHING METHOD

Fast marching method was first put forward independently by J.A. Sethian and J.N. Tsitsiklis. It is a numerical method which is used to solve the Eikonal equation in the rectangular grid. Because of the fast computation speed, lots of researchers use this method to refactor their algorithm. The time complexity of this method is $O(M \log M)$, M is the number of the rectangular grid [5].

Eikonal equation is a kind of special first order partial differential equation, the aim of the fast marching method is to solve this kind of equation and the form of the equation is shown as formula (1):

$$\left|\nabla T\right| F = 1 \qquad (1)$$

The ∇T is the gradient of T, T is global potential energy field. F is reciprocal of risk value of each grid point in this paper.

We only consider 2-D situation in this short paper. We use an approximation to the gradient to simplify the Eikonal equation. The result may be discretized as formula (2). x_i and y_i are the coordinates of the grid i.

$$\frac{1}{F^2} = \max(D_{ij}^{-x}T, 0)^2 + \min(D_{ij}^{+x}T, 0)^2 + \max(D_{ij}^{-y}T, 0)^2 + \min(D_{ij}^{+y}T, 0)^2$$

$$D_{ij}^{-x}T = \frac{T_{ij} - T_{i-1,j}}{x_i - x_{i-1}},\ D_{ij}^{+x}T = \frac{T_{i+1,j} - T_{ij}}{x_{i+1} - x_i},\ D_{ij}^{-y}T = \frac{T_{ij} - T_{i,j-1}}{y_j - y_{j-1}},\ D_{ij}^{+y}T = \frac{T_{i,j+1} - T_{ij}}{y_{j+1} - y_j}$$

$$T(x, y, 0) = 0$$

(2)

With regard to the solution of this kind of question, we may image starting from an initial point and solving upper formula for adjacent point constantly, and select the minimum T value of point as well, then compute repeatedly, at last compute all the grid region to finish the numeration of T value of all grid points [5].

Classifications of Grid Points

Fast marching method is applied on grid points, so grids are classified in three different types: alive points, trial points, far away points. Alive points are points where values of T are known and won't change at all. Trial points are points around the alive points, where the T value must be computed. The set of trial points is called narrow band. To compute propagation, points in the narrow band are updated to alive points, while the narrow band advances. The T value of trial points is calculated by formula (2). Far away points are points where the T value wasn't computed yet. During the propagation far away points are converted to trial points [6] [7]. The algorithm will finish when the T values of all points are calculated.

Basic Framework

Initialize Step:

1. Alive Points: Let A be the set of all grid points $\{i_A, j_A\}$ the represents the

initial curve;

2. Narrow Band: Let NarrowBand be the set of all grid points neighbors of A;
3. Far Away Points: Let FarAway be the set of all others grid points {i, j}. Set $T_{i,j} = \infty$ for all points in FarAway;

Fast Marching Process:

4. Begin Loop: Let (i_{min}, j_{min}) be the point in NarrowBand with the smallest value for T;
5. Add the point (i_{min}, j_{min}) to A. Remove it from NarrowBand;
6. Tag as neighbors any points (i_{min-1}, j_{min}), (i_{min+1}, j_{min}), (i_{min}, j_{min-1}), (i_{min}, j_{min+1}) that are either in NarrowBand or FarAway. If the neighbor is in FarAway, remove it from that list and add it to the set NarrowBand;
7. Recompute the values of T at all neighbors according to discrete Eikonal equation, selecting the largest possible solution to the quadratic equation;

Return to top of Loop.

Computational Process

The basic framework above describes the overall computational process of fast marching method, some of the details are as follows.

Calculation of initial T value of alive points and narrowband points: mark a curve as $C = \{ f(x,y)=0 \}$, $\Delta x, \Delta y$ as the size of the grid. If $f(i\Delta x, j\Delta y) \le 0$ and $f > 0$ for any neighbor point (i_{min-1}, j_{min}), (i_{min+1}, j_{min}), (i_{min}, j_{min-1}), (i_{min}, j_{min+1}), then point (i, j) is classified as alive and its neighbors where $f > 0$ are classified as trial.

Suppose point $(i+1, j)$ is a narrowband point, the T value of this point meets the formula (3).

$$T_{rig} = \frac{\Delta x \cdot f(i\Delta x, j\Delta y)}{f(i\Delta x, j\Delta y) - f((i+1)\Delta x, j\Delta y)} \quad (3)$$

The other three neighbor points can be done in the same manner. The T value of point (i, j) can be computed as formula (4).

$$T_{i,j} = \max(T_{rig}, T_{lef}, T_{top}, T_{bot}) \quad (4)$$

As $T_{rig}, T_{lef}, T_{top}, T_{bot}$ have negative values, $T_{i,j}$ is the smaller absolute value among them. The values of the trial points are computed in the same way [6] [7].

DIGITIZATION OF CONSTRUCTION DRAWING

The establishment of construction model includes the simplification of architectural drawing, mesh generation and evacuation exit. The basic parameters for people safely evacuate are composed of crowd density, body external dimensions and people evacuation movement [8]. The body external dimensions are the grid size when people are walking. Some experiments had determined the size is 0.4m*0.4m. In the preliminary study stage, in order to plan the evacuation route for different buildings in fire disaster, we encountered a difficult problem which was the expression of building structure. How to conduct mesh generation for different architectural layout and substitute different number for architectural element of each grid (including wall, barrier, evacuation exit and empty space in rooms) become the focus of the preliminary study.

For most of the constructions, there are CAD design drawings. So we decide to process these drawings to make them grid-enabled and digitalization so that the algorithm can work under different constructions. Considering the area occupied when people are walking, we decide the grid size as 0.4m*0.4m. This size can ensure that every person occupy a separate grid and bring convenience to the computation. After meshing we start to digitalize it with different numbers instead of different elements in the CAD drawing. For example, use 4 to take place of wall grid, use 3 to take place of barrier grid, use 2 to take place of evacuation exit grid, use 1 to take place of empty space in rooms. After doing this, the CAD drawing of the construction will be changed into a matrix with number 1, 2, 3 and 4. Taking a building for example, shown in Fig. 1. There are three floors in the building. (a), (b) and (c) are the CAD drawings of each floor. In the preliminary study stage, we can only plan one layer's evacuation path independently and link the three paths together as the complete evacuation path of the building. But now, through the CAD software we can join the three floors together as shown in figure 1-(f).

Import the CAD drawing into the drawing digital program. Specify the size of the grid in configuration file, then the program will automatically generate the grid

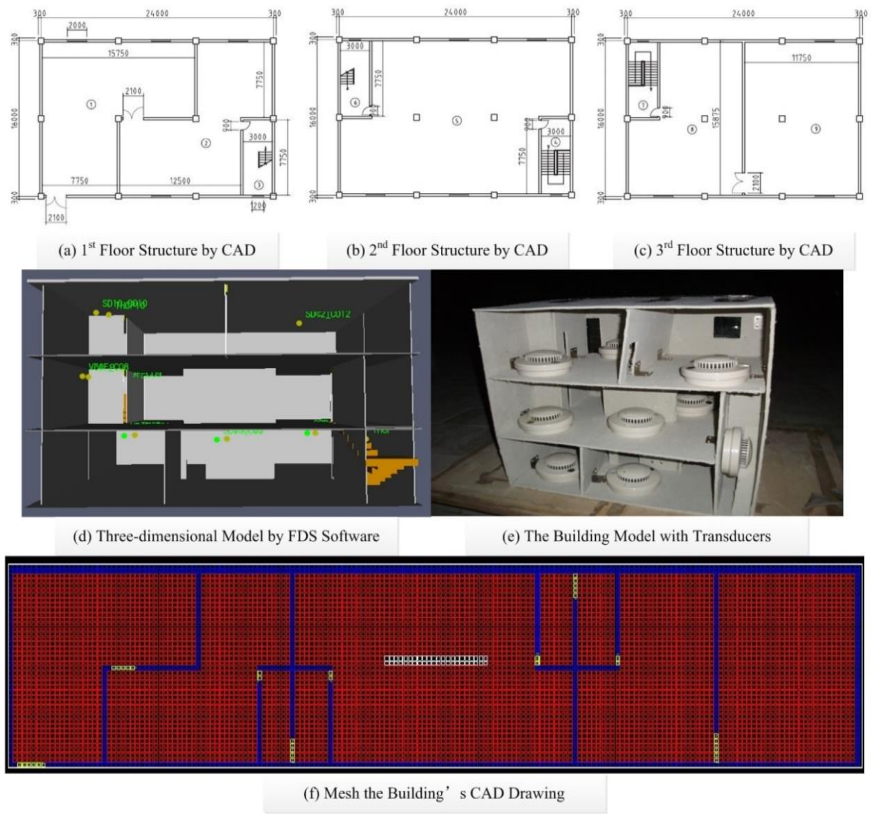


Figure 1. The Structure of The Building and Its Grids

according to the size of the CAD drawing. The grid number of the figure below is 183*42 (length*width). After that, we need to configure the attribute of each grid. The blue part of figure 1-(f) is wall, the red part means the empty space, the white part is barrier and the green part is door and evacuation exit. The evacuation exit is at the bottom. After configuring the attribute of every grid, we can export a digitized matrix. This matrix is the initial matrix used in the fast marching method.

CALCULATION OF RISK DISTRIBUTION

In order to obtain the risk value of each grid, we make a real building model for fire experiment. The real building model used here has three floors, five rooms and two stairwells. The length of this model is 48cm, the width is 32cm and the height is 45cm. The height of each floor is 15cm. Every room connects with at least one room or stairwell nearby. Fig. 1 shows the structure of this building.

According to the size of different rooms, we arrange 2-3 temperature and carbon monoxide sensors in each room. With the fire stimulation progresses, these sensors will get the value of temperature and carbon monoxide in the rooms. Since the real-time data acquired is the temperature and carbon monoxide concentration at the position of the transducers, it is very important to calculate the temperature field and carbon monoxide concentration field in the building by interpolating method. For the convenience of calculation, the least square method is chosen for the interpolation calculation in this work. For the small rooms that have just one transducer inside, the data acquired by the transducer can be used as the value for the whole room. In addition, we gain relevant information of human tolerant limitation in the case of different temperature and carbon monoxide concentration by consulting literature [9][10], shown as Tab. 1 and Tab. 2. The reason for choosing the two parameters is because the main cause of deaths for fire victims are smoke inhalation and high temperature. Through these tables, we can translate temperature and carbon monoxide concentration value of each point into risk value, the range of the risk value is from 0 to 1.

Temperature (℃)	time of tolerant limitation (min)
120	15
140	5
170	1
300-400	Can't stop for a minute

Table 1. Temperature and Time of Tolerant Limitation

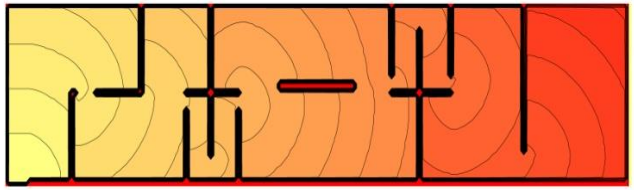
CO concentration（ppm）	Approximate respiratory time	Arisen symptom
50	Within 8 h	Healthy young can endure maximal concentration
200	2-3 h	Headache, feeble slightly
400	1-2 h	Forehead pains
	3 h	Threatening life
800	45 min	Dim eyesight, nausea, spasm
	2 h	Anesthesia
	2-3 h	Death
1600	20 min	Headache, dim eyesight, nausea

Table 2. CO Concentration and Time of Tolerant Limitation

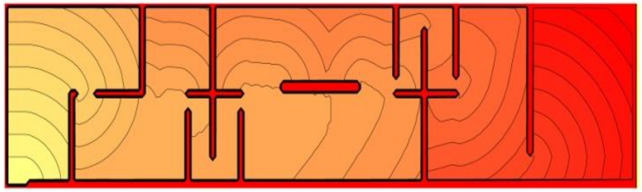
Considering the risk of carbon monoxide concentration is higher than the risk of temperature. We give higher weights to carbon monoxide concentration. The weighted stacking of the carbon monoxide risk and the temperature risk is the total risk of the point. If the risk value is greater than 1 (fatality rate of this point is greater than 100%), the risk value of this point is equal to 1. If the risk value is less than 1, this value is equal to the sum of the two kind of risk. After computing the risk value of every point, we will use the fast marching method to calculate global risk potential energy field. Of course, the risk value of the wall and barrier is out of calculation, the initial value is infinite.

CALCULATIONS OF RISK POTENTIAL ENERGY FIELD AND PLANNING OF EVACUATION ROUTE

After obtaining risk value of each grid point in the building, we use fast marching method to plan evacuation route. In the process of calculation, wall, barrier and building edge are eliminated from evacuation route plan. In addition, risk value of evacuation exit should be special considered, because evacuation exit is the only way which people must go through during the evacuation. So the risk value of the evacuation exit (left bottom corner) is 0 and these grid points are alive points for the fast marching method. The results are shown below. It shows the global potential energy field of 300s and 600s after fire disaster. We can conclude that the safest path is vertical to isopotential line. This path is also the direction which the risk falls fastest.



(a) **300 Seconds after Fire Disaster**



(b) **600 Seconds after Fire Disaster**

Figure 2: Global Risk Potential Energy Field Calculated by Fast Marching Method

CONCLUSION

In this short paper, a new evacuation method is put forward. We hope it will be an useful method for fire rescue and people evacuation in the future. But we must recognize that there are still many problems before practical application of this method such as information transmission and people location at fire scene. In order to solve this two problems. Wireless module is integrated into temperature and carbon monoxide sensors and ZigBee protocol is used for information transmission and people location. At last the evacuation route and other relevant information can be displayed in the on-site command terminal [11] [12]. At present, this method and relevant equipment are making a test run in the World Trade Center Phase 3 in Beijing.

13.

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