Simulation of evacuation behaviors in fire using spacial grid*

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Abstract A two-dimensional Cellular Automata (CA) model to demonstrate the special phenomena of occupants evacuating from fire room is presented. A set of simple but effective models is proposed to investigate the effect of fire smoke on route choice. The concept of danger grade is introduced, and occupants select the target cell according to the value of danger grade at each time step. Some technique is introduced to substitute the human intelligence, such as premeditation. The simulation results show that human evacuation is influenced greatly by both human visual field and building exit.

Keywords: cellular automata, fire, evacuation, danger grade, performance-based design.

Research on quantifying and modeling of the human movement and behavior in fire has been carried out for many years. The simulation models for evacuation can be essentially classified into two types: those that only consider the human movement and those that attempt to consider individual behavior. Apparently, models induding many behavior details have become a trend[1—3]. It is the underlying principles of these approaches that influence the model capabilities.

1 Description of cellular automata

CA is a discrete, decentralized, and spatially extended system consisting of large numbers of simple identical components with local connectivity. CA is an alternative to differential equations to model the physical systems. Because CA models can exhibit the artificial intelligence, they are usually called the artificial life models.

After CA was successfully used to model traffic flow, some researchers began to introduce it into modeling pedestrian flows. The models in Refs. [4~6] are based on collective behaviors of people but not on rules of individual behaviors. Some continuum models such as the social force model have also simulated the pedestrian dynamics successfully[7, 8]. However, up to now, there has been little research on occupant evacuation.

This paper presents CA models for simulating the four-directional occupant evacuation in fire, including a basic model and some extended models based on it. By defining the problem of occupant evacuation in fire, a rule set that is different from the pedestrian-flowing behavior in some important respects is presented.

2 Model descriptions

2.1 Basic model

Basically, our model is developed to study the crowded, large, and open spaces. In such situations the evacuation time depends mainly upon the response time of the first occupant and the movement time of the whole occupant population[9]. Our model is focused on study of the phenomena after all the people start evacuating but not during the whole evacuation process. The pre-movement time will studied elsewhere. Thus, we assume that all the people begin to evacuate at the same time and the evacuation time presented in this paper excludes the pre-movement time.

Considering a large room with one or two exits, the basic structure of the model is a two-dimensional grid. Each cell is either empty or occupied by one occupant. In our basic 2D model, each cell has two states: 0 for no occupant, 1 for occupants with the maximum velocity of 1. The size of a cell is $0.4\,m \times 0.4\,m$[10], which is the typical space occupied by an occupant in a dense crowd. The synchronous update is performed for all occupants. Empirically the aver-

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age velocity of an occupant in nervous can reach 1.50 $m \cdot s^{-1}$[8], so the time step in our model is 0.4/1.5≈0.27 s, which is in the order of the reaction time and consistent with our microscopic rules.

In order to determine each occupant's moving direction, danger grade (TD) is introduced to describe the occupant's knowledge of danger in the fire room, including the position danger grade (PD) and the fire danger grade (FD). PD is determined by the distance from the safety exit, i.e. the nearer the distance to the exit is, the less the PD of the cell is. FD is determined by the distance from the fire source, i.e. the longer the distance from the fire source is, the less the FD of the cell is. An optional stage can be used to describe the more realistic evacuation, and we call it the familiar stage. During this stage, occupants are introduced into the room to get familiar with the structure and the TDs are determined. When one walks into a cell, he compares the cell's TD with those of the four adjacent cells. If the TD of the cell he occupied now is not the minimum, TD will be changed to the sum of 1 and the minimum value of the four adjacent TDs. For example, if TD of the cell he occupied is 5 and the minimum TD of the four adjacent cells is 3, then TD of the cell he occupied will be changed to 4. Different occupants may have different views on the cells' TDs which depends on the exit selected, the walking route and the total time steps of the familiar stage. In the evacuation stage, the route choice of each occupant is dependent on his view on the cells' TDs.

In CA a rule defining the state of a cell depends on the neighbourhood of the cell. In order to imitate human's intelligence, the term "premeditation" is introduced, which refers to time steps the occupant may consider in advance. In Fig. 1, the cells marked with digital are those that can be considered by the occupant in the central cell when he decides which adjacent cell to move into. If the neighbourhood defined in Fig. 1(a) is selected, the occupant can premeditate one time step and five cells can be considered including the cell occupied by himself. The radius of the neighbourhood defined in Fig. 1(a ~c) is 1, 2 and 3, respectively. Different route is selected according to different time steps of premeditation. In Fig. 1(a), the cell with the TD of 7 is selected to be moved into because this is the safest cell according to one's premeditation. In Fig. 1(b), the cell with the TD of 5 is the safest cell, so the adjacent cell with the TD of 8 is selected. In Fig. 1(c), the cell with the TD of 3 is the safest cell, so the adjacent cell with the TD of 9 is selected. The rule set proposed here is not always true for everyone. For example, some people would not like to consider further though he can see far enough. However, for most of us the rule is reasonable. Each cell's state in the next time step depends on the neighbourhood he selected and the TDs of the neighbouring cells, as well as other factors such as competitive selection and random stop.

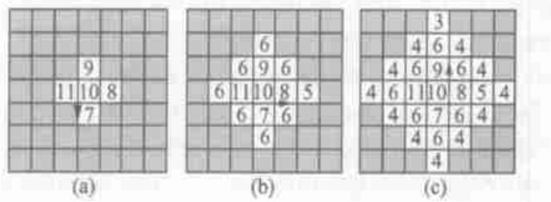

Fig. 1. The definition of neighbourhood.

There are four parallel updating stages of the set for occupants in the basic model: Stage 1: For each cell occupied, check the neighbouring cells according to the time steps he can premeditate, select a proper cell and assign the cell to be occupied. Stage 2: For each cell with more than one occupant vying, it is randomly assigned to be occupied by one of the viers with each one having the same chance, and the other occupants stay where they are. Stage 3: Give each person who has decided to move the probability p_{stay} to stay. The introduce of p_{stay} is to simulate the occupant's unexpected behaviors, such as the sudden stop for physical and other reasons. An experiential value, 5%, is selected here. Stage 4: Every occupant alters the dynamic danger grades of all the cells if necessary.

2.2 The extended model

The extended model considers more factors related to fires than the basic model. These factors can be introduced by many ways. One is the change of the route caused by the change of the view on cells' FDs. The other is the prevention of occupants from moving faster, or reducing their visibility due to the harm of fire to them.

The extended model can also be developed to simulate some interesting phenomena. For example, because real occupants are made up of all kinds of people, including the old and the handicapped, the occupants' maximum velocities can be assorted into several grades. In addition, some factors can also be considered, such as how one occupant will react when he knows of the fire, what one occupant will choose to do when he is not familiar with the situation, will he follow a group of more people or a group of fewer people, and so on. All these factors can be added into the basic model to make the extended simulations more practical.

3 Simulation results

Firstly, we describe the simulations of a typical scenario, i.e. the evacuation from a large room with one exit, using the basic model. For simplicity, all the occupants have the same view about the cells' PDs unchanged during the whole evacuation process. Typical results of different dynamic stages using the basic model are shown in Fig. 2. The occupants are randomly distributed at the time step of 0; all the occupants begin to move at the time step of 1. Fig. 2(a ~c) show the progress of the occupant distribution at the time steps of 5, 25 and 65, and the radius of neighbourhood is 2. It can be seen from Fig. 2 that the model is able to reasonably describe the typical phenomena in occupant evacuation from a large room.

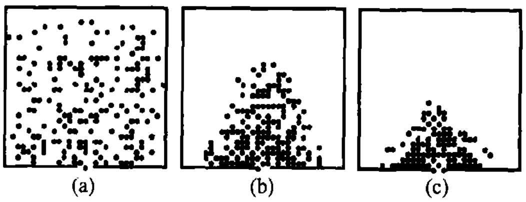

Fig. 2. Basic model's results of the occupant's distribution at the time steps of (a) 5, (b) 25 and (c) 65.

A step forward, fire is introduced into the room. The relations between TD, PD and FD are given by the following simple equation: $TD = PD + \alpha \cdot FD$. The coefficient α is determined by each occupant's knowledge of the danger degree of the fire, and larger α means greater danger. These data are basically obtained by questionnaire survey, and the value of FD usually varies with the spread and the decay of real fire. In the simulation, the value of α is selected to express the influence of fire on human and to ensure that every one will be able to evacuate finally.

Fig. 3(a ~ c) are the occupant distributions at the time steps of 0, 10 and 110, respectively. And the radius of neighbourhood is 2. The dark (shadow) zone represents the fire source, which does not change throughout the simulation. It can be seen that although "evacuating from the nearest exit" is applied, the existence of fire forces some occupants to move from left to right. Therefore, FD enables the model to deal with the fire scenario conveniently and reasonably.

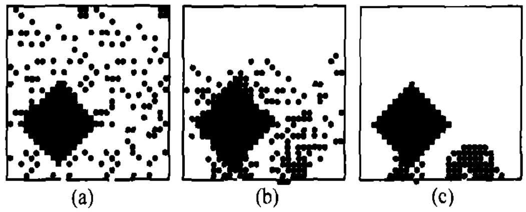

Fig. 3. The occupant distributions in a fire room at the time steps of (a) 0, (b) 10 and (c) 110.

3.1 Effect of human visual field on evacuation

Another scenario is considered to study the influence of neighbourhood radius. Premeditation may be affected by the smoke concentration or occupant's individual decision. Here, two exits are separated and the occupant density in the right half part is twice as that in the left. It can be seen from Fig. 4 that when the radius of neighbourhood is 1, the occupants in the right part do not realize the superiority of the left part. When the radius is larger than 1, the utilization of the two exits is more reasonable and fewer time steps are needed.

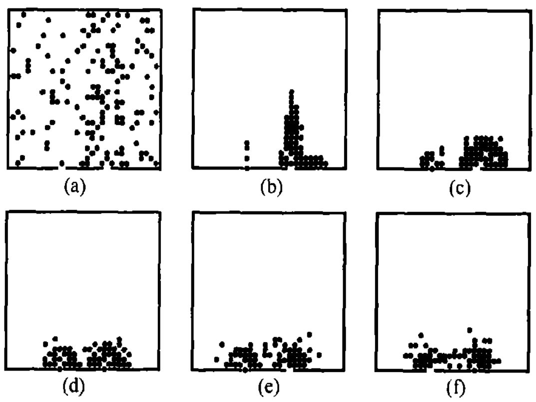

Fig. 4. The influence of premeditation (neighbourhood radius). (a) is the initial stage of the occupant distribution. (b ~ f) are the distributions at the same time step of 90 with different premeditation (radius) of (b) 1, (c) 2, (d) 3, (e) 4 and (f) 5, respectively.

Fig. 5 and Fig. 6 show that the number of total time steps needed mostly depends on the utilization of the two exits. When one can premeditate three time steps, the total time steps needed are the least. Usually, it is supposed to be more effective if one can select the route with further considerations, but it is not always the case. By watching the dynamic play of the model, we find that the occupants are more active when they can premeditate more than three time steps. Because when one can see farther, it is less possible for him to stay and wait when the safer adjacent cells are occupied. We all have such an experience that more time is needed if we frequently move from one exit to another when getting on a train. The optimal value of premeditation depends on the distance between exits and the occupant distribution, etc.

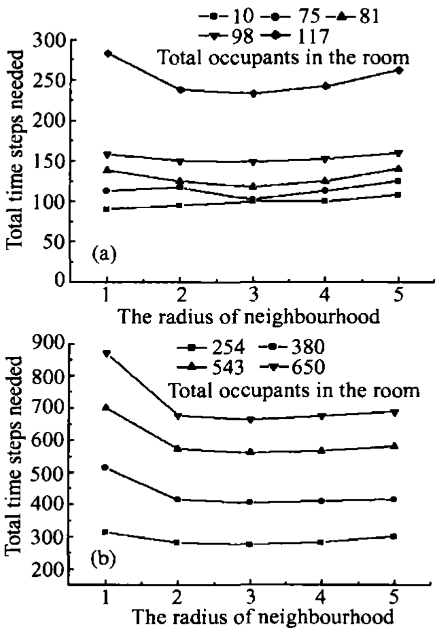

Fig. 5. Total time steps needed versus the radius of neighborhood.

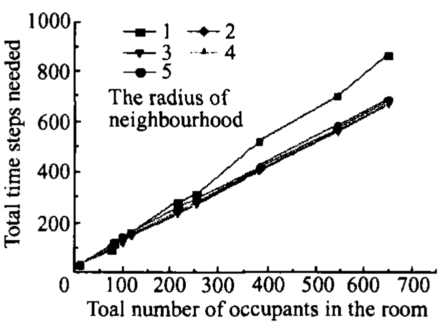

Fig. 6. Total time steps needed versus the number of the total occupants evacuated from the room.

3.2 Effect of building exit on evacuation

Considering a building as shown in Fig. 7, which is 22 m × 20 m, and the exit width of a, e, f and g (W_i, i = a, e, f, g) is 2.0 m, 1.34 m, 1.34 m and 0.67 m, respectively. We can obtain some interesting results. Table 1 gives some results for different width of the exits.

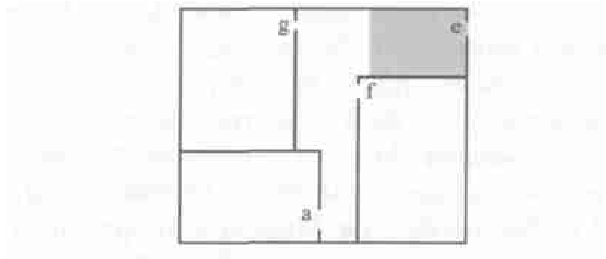

Fig. 7. The arrangement of the building.

Table 1. Evacuation under different exit width

Exit width of a, e, f, g	Total evacuation time (s)	Maximum number of people gathered at exit e
W_a, W_e, W_f, W_g	112	43
W_a, W_e, W_f, W_g+W_g	110	53
W_a, W_e, W_f+W_g, W_g	111	52
W_a, W_e, W_f+W_g, W_g+W_g	108	58
W_a, W_e+W_g, W_f+W_g, W_g+W_g	97	46
W_a, W_e+W_g, W_f, W_g	104	31
W_a, W_e+W_g, W_f, W_g+W_g	105	41
W_a, W_e+W_g, W_f+W_g, W_g	98	30

It can be seen from the simulation results that if only increasing the width of exit g or (and) f, the total evacuation time does not obviously decrease and the number of people gathered in exit e increases. If only increasing the width of exit e, the total evacuation time and the number of people gathered at exit e decreases obviously. The total evacuation time does not change but the number of people gathered at exit e increases if increasing the width of exit g again. However, if increasing the width of exit e and f simultaneously, fewer people will gather in exit e and the total evacuation time is about the same compared to the simultaneous increase of width of exit e, f, and g. These results have demonstrated that the best modification choice is to increase the width of exit e and f in order to optimize the evacuation measures. Using these simulations, more appropriate number and position of the exits can be designed.

4 Conclusions

The occupant's route choice in a fire room is often limited by the extent of his acquaintance with the room structure and of his information about the fire. In this paper, a stochastic cellular automaton model, which can consider more details of individual behaviors, is proposed to simulate the occupant behavior. The key in the model is the introduction of the danger grade and of an important term premeditation. The main work we have done is as follows: (1) CA model is successfully introduced to simulate human evacuation in fire. (2) The concept of danger grade is proposed to describe the occupant's knowledge of danger in the fire room. (3) By varying the time steps of premeditation, the model has expressed the interesting phenomenon in daily life, that is, more time is wasted if changing the aims too frequently under urgent conditions, such as in fire. (4) Visual field, affected by fire smoke, and building exit have great influence on human evacuation in fire. All the results have shown that the design for the building exit should pay much attention to how to evacuate from the building more effectively.

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