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Evacuation dynamics with fire spreading based on cellular automaton

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ABSTRACT

This paper investigates the dynamics of pedestrian evacuation with the influence of the fire spreading. An extended floor field model is proposed. In the new model, the effect of fire on the evacuation is considered by introducing the fire floor field. Thus, the floor field intensity is weighted by static, dynamic and fire floor fields. Numerical simulations are carried out to study the dynamics in the process of the evacuation. The influence of the parameters – weight of fire floor field, fire spread rate – on the evacuation efficiency is analyzed in detail. The simulation results show that the number of pedestrians evacuated out of the room is highly related to both the original location of the fire and the configuration of the room. Those results can bring some guidance to design the evacuation strategy in panic situation.

1. Introduction

If fire occurs in a large gathering place, inefficient evacuation will result in a large number of casualties and losses of property. According to statistics, in 2009, there were 127,000 fires in China, 1076 people were died and 580 people were injured. Those disasters resulted in direct property loss of 1.32 billion Yuan. In 2010, a total number of 131,705 fires occurred in China, 1108 people were killed and 513 people were injured. Those disasters resulted in the direct economic losses of 1.77 billion Yuan. This paper applies the extended model in a typical scenario that the pedestrian escape from the room under fire. The numerical simulation provides us both the personnel movement rules with fire and the reasonable assessment of evacuation safety of the building construction. Recent progress in modeling pedestrian dynamics [1–5] is remarkable and many valuable results are obtained by using different models. Currently, the pedestrian evacuation models can be classified into two types: the macromodel and the micromodel. As to the macromodel, it usually takes nodes and connections as space structure unit. This model is fast calculating, but it cannot describe the details of human behavior, so the results usually deviate from the reality. In the micromodel, the personnel individual characteristic in a crowd is described, pedestrians move to the exit according to certain algorithms. In this method, pedestrians' behavior is affected by all kinds of interaction factors such as surrounding environment, building structure, etc., so the micromodel is more realistic. The micromodel can be further divided into continuous model and discrete model. Social force model [6,7], proposed by Helbing, is the most famous continuous model. As to the discrete model, the cellular automaton model [8–20] and the lattice gas model [21–26] are used most. Zhang et al. and Zhao et al. used cellular automaton model to study the evacuation in emergency [27,28]. Zhou et al. investigated the evacuation from large building under fire, considering the influence of smoke on pedestrians' movement [29].

As to the cellular automaton model for the evacuation, the Floor Field (FF) model is widely used. It has been investigated in a great deal of literature [30–37]. In the FF model, the direction of pedestrians' movement is determined by the exits' position and the interaction between the pedestrians, namely, the static floor field and the dynamic floor field. In recent

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years, a lot of extended FF models were proposed. For example, in Ref. [38], the number of exits and the effect of obstacles in the room were studied. In Ref. [39] two important factors – conflict and cost of turning – which affect the pedestrian outflow at a bottleneck significantly were studied to analyze the effect of an obstacle setup in front of an exit. Nishinari et al. considered how to calculate the static field intensity in the room with complex geometry and the effect of width of the exit on the pedestrians' evacuation [33]. In Ref. [40], pedestrians were divided into different types with different panic level, the pedestrian of each type had his own behavior in evacuation. In Refs. [41,42] discretization of the cell was studied and one pedestrian took more than one cell, so the results were more precise. Zheng et al. proposed an evacuation model considering the effects of selection of an exit and social forces on the movement of pedestrians [43]. Peng et al. reported the study of the conformation of congestion in a "T" intersection by using a cellular automaton procedure with multi-floor fields [44]. Tanimoto et al. established an improved cellular automaton model for pedestrian dynamics, where both static floor field and collision effect were derived from game theory [45].

Many scholars have studied the evacuation from the public area with fire, but they mainly assumed that the fire is static and ignored the fire's feature of spreading. This paper introduces the effect of the fire spreading during the evacuation process and proposes an extended FF model. For the calculation of the floor field density, the distance to the exit, the virtual trace left by pedestrians, the effect of the fire to pedestrians are considered. Then the influence of the fire spreading on the dynamics of evacuation process is investigated. The details of the new model are introduced in Section 2. The scenarios for simulation are given in Section 3. The simulation results are analyzed in Section 4. At last the conclusion is given.

2. Evacuation model under the fire

Without considering the influence of the fire, the traditional FF model usually uses position attraction and personnel appeal to calculate the selection probability of target cells. In the case of the evacuation process with fire, we have to consider the influence of fire on personnel movement. So, on calculation of the target cells' selection probability, the fire repelling force is taken into consideration.

2.1. Introduction of the FF model

The competition between collective and individual behavior is essential for modeling evacuation phenomena. It is included in the static and dynamic floor field model [34]. They are introduced to translate a long-ranged spatial interaction into an attractive local interaction, but with memory, similar to the phenomenon of chemotaxis in biology. For the evacuation process, the static floor field S_{ij} describes the shortest distance to the exit. The field intensity is set inversely proportional to the distance from cell (i, j) to the exit. The dynamic floor field D_{ij} is the virtual trace left by the pedestrian. It has its own dynamics, namely diffusion and decay, which leads to broadening, dilution and finally vanishing of the trace. The Von Neumann neighborhood (Fig. 1) is used, and the four neighbor cells of each cell locate in its top, bottom, left and right direction, respectively. Each pedestrian can move to one unoccupied neighbor cell (i, j) (or stay at the present cell) at each discrete time step $t \to t + 1$ according to certain transition probability P_{ij} (Fig. 1) which is decided by static and dynamic floor fields as explained below:

$$P_{ij} = N \exp(k_D D_{ij}) \exp(k_S S_{ij})(1 - \eta_{ij})\varepsilon_{ij}. \tag{1}$$

Here, N is a normalization factor for ensuring $\sum_{i,j} P_{ij} = 1$. The static floor field S_{ij}, which is initialized at the beginning of the simulation and kept unchanged during the simulation, is gradient with high values nearby desirable areas (i.e., the exits of the evacuation space) and low values far from those areas. The dynamic floor field D_{ij} is the number of bosons, dropped by moving pedestrians on the cell (i, j). k_S and k_D are two positive parameters for scaling S_{ij} and D_{ij} respectively. $k_S \in [0, \infty]$ is the coupling to the static floor field characterizes the knowledge of the shortest path to the exits, or the tendency to minimize the costs due to deviation from a planned route. This considerably controls one's velocity and evacuation times. $k_D \in [0, \infty]$ is the coupling to the dynamic floor field characterizes the tendency to follow other pedestrians (herding behavior). The parameters

$$\eta_{ij} = \begin{cases} 1, & \text{cell } (i, j) \text{ is occupied by obstacle or fire;} \\ 0, & \text{cell } (i, j) \text{ is empty.} \end{cases} \tag{2}$$

$$\varepsilon_{ij} = \begin{cases} 1, & \text{cell } (i, j) \text{ is empty;} \\ 0, & \text{cell } (i, j) \text{ is occupied by a pedestrian.} \end{cases} \tag{3}$$

2.2. An extended floor field model

When the fire occurs in a room, pedestrians tend to avoid walking close to the fire, so pedestrians' transition probability should be different from that in the FF model, especially around the fire. In Ref. [46], it is assumed that one takes the route whose distance from the fire is a constant in order to keep away from the burning area. In this paper, we take the effect of the fire as one kind of the floor field which we call fire floor field. The fire floor field is inversely proportional to the distance