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Evacuation dynamics considering pedestrians' movement behavior change with fire and smoke spreading

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ABSTRACT

This paper proposes an extended Floor-Field (FF) model to study the pedestrian evacuation dynamics with the influence of the fire and the smoke spreading. The spreading of smoke is from top to bottom, which leaves less and less room for the movement of pedestrians. And thus, the movement behavior of pedestrians is divided into three stages: normal walk, bent-over walk, and crawl. In the new model, the influence of the fire and the smoke on the movement of pedestrians is modeled by the fire floor field and the smoke floor field respectively. Numerical simulations are carried out to study the evacuation dynamics under fire and smoke. The influences of personnel density, fire location, exit width, fire spreading rate, and smoke spreading rate, on the evacuation efficiency are analyzed in detail. The simulation results show that the pedestrian evacuation dynamics is highly related to fire location in the room and the spreading rates of the fire and the smoke. Those results can bring some guidance to design the building structure and make the evacuation strategy in emergency situation.

1. Introduction

Fire is a kind of frequent disasters. When a fire occurs in the building, the rapid spread of the fire and smoke can cause a lot of property damages and casualties. According to statistics, in 2015, there were 338,000 fires in China, 1742 people were died and 1112 people were injured. Those disasters resulted in direct property loss of 3.95 billion RMB. How to reduce the casualties in large-scale activity places and public gathering places with the fire emergency is remarkable. It is also the important content of public security research.

In recent years, a large number of works have been done to investigate the pedestrian dynamics by using different models and many significant and valuable results are obtained. These models can be divided into two categories: the macroscopic model and the microscopic model. The macroscopic model mainly contains fluid dynamic model and queuing-theoretical model. The microscopic model could precisely describe individual behavior and thus is more realistic. It mainly contains social force model, lattice gas model and cellular automata model. Helbing and Molnàr (1995) and Helbing et al. (2000) studied the pedestrian evacuation using social force model, analyzed the phenomenon of "fast is slow", "arching before the exit". Li et al. (2015) used social force model studying the real-life 2013 Ya'an earthquake evacuation in China. Cellular automata model (Yamamoto et al., 2007; Fukui and Ishibashi, 1999; Alizadeh, 2011; Li and Han, 2015; Liao et al., 2014) and lattice gas model (Guo et al., 2013; Li et al., 2008) are also widely used in modeling evacuation dynamics, especially in emergency situations (Zhao et al., 2006; Zhou et al., 2009; Zheng et al., 2011; Tanimoto et al., 2010; Nguyen et al., 2013; Cirillo and Muntean, 2013; Cao et al., 2014), since they have the advantages of simple rules and fast computing. FF model (Kirchner and Schadschneider, 2002; Huang and Guo, 2008; Nishinari et al., 2004) is a typical evacuation model based on cellular automaton. In this 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.

Zhao et al. (2006) studied the evacuation in emergency by using cellular automata. Zhou et al. (2009) studied the personnel movement in large building with fire, considering the effect of smoke. Tanimoto et al. (2010) established an improved cellular automata model to simulate the bottleneck evacuation under emergency situation. Isobe et al. (2004) tested and simulated the evacuation process in smoke-filled room. Nguyen et al. (2013) integrated the smoke effect and blind evacuation strategy within fire evacuation, the simulation results were confirmed by empirical data from the metro supermarket. Cirillo and Muntean (2013) studied the dynamics of pedestrians in regions with no visibility by using the

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lattice model. Cao et al. (2014) studied the effect of fire and smoke on evacuation, and simulated the pedestrian evacuation under fire emergency by using cellular automata model.

At present, most of the research on evacuation under fire ignored the dynamic spreading process of fire and smoke. Pedestrians' moving behavior is very different with and without fire and smoke spreading. If there is no fire and smoke, or the fire and smoke are assumed static, pedestrians will walk upright during the whole evacuation process. When the fire and smoke spread dynamically, pedestrians' movement behavior changes from walk to bent-over walk, crawl according to the surrounding environment. Nagai et al. (2006) studied the evacuation of crawlers and walkers from corridor through an exit. Yang et al. (2012) carried out experimental studyies on bent-over walking behavior of occupants in corridors, and obtained the evacuation characteristics of bent-over walkers. The pedestrians' movement behavior change—normal walk, bent-over walk, and crawl—is rarely mentioned in the previous articles. Our previous work (Zheng et al., 2011) introduced the fire spreading dynamics into the traditional FF model. This paper introduces the effect of both the fire and the smoke spreading during the evacuation process and proposes an extended FF model. The influence of the fire and smoke spreading on the evacuation dynamics is investigated.

The details of the extended 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. Model

2.1. FF model

In the FF model, pedestrians move to their target cells according to the selected probability, which is decided by static floor field and dynamic floor field.

The static floor field represents the attractiveness of the destination, which describes the shortest distance to the exits, it does not change with time and personnel movement during simulations. The dynamic floor field is the record of pedestrians' trails according to herding and panic behavior. Pedestrians are more likely to move to the cells which more pedestrians have passed. The dynamic floor field is similar to ants foraging. It is produced by the pedestrian movement and affects the movement of others in turn. When the pedestrian passes the cell, the value of dynamic floor field increases, but it diffuses and decays with time, and finally vanishes.

2.2. The extended FF model

When a fire occurs, pedestrians tend to move away from the fire and smoke. The transition probability is different from the traditional FF model, especially near the fire and smoke. In our previous work (Zheng et al., 2011), only the influence of fire spreading on the pedestrian evacuation is considered; this paper further introduces the influence of smoke spreading, and considers the change of pedestrians' movement behavior. The influence of the smoke is named as smoke floor field in this paper. We assume that all pedestrians are familiar with room structure and exit position, not considering the influence of vision scope caused by smoke. The transition probability of selecting the target cell (i, j) is calculated as follows,

$$P_{ij} = N(\exp(k_S S_{ij} + k_D D_{ij} - k_F F_{ij} - k_M M_{ij}))(1 - \eta_{ij})\varepsilon_{ij} \quad (1)$$

N is the normalization for ensuring that $\Sigma p_{ij} = 1$. S_{ij}, D_{ij}, F_{ij}, M_{ij} denotes static, dynamic, fire, and smoke floor field, respectively. k_S, k_D, k_F, k_M are scaling parameters. η_{ij} indicates whether the cell (i, j) is occupied by wall, obstacles, or fire, the value is 1 when the cell is occupied, and it is 0 when the cell is empty. ε_{ij} indicates whether the cell (i, j) is occupied by a pedestrian, the value is 0 when the cell is occupied, and it is 1 when the cell is empty.

S_{ij} describes the shortest distance to the exits. It is set inversely proportional to the distance from the cell (i, j) to the exits. And it is calculated as follows,

$$S_{ij} = \frac{1/d^*_{ij}}{\sum_i \sum_j 1/d^*_{ij}} \quad (2)$$

Here, d^*_{ij} represents the shortest distance from the cell (i, j) to all the exits of the room.

D_{ij} represents the attraction between pedestrians. There are three steps to calculate the dynamic floor field.

Step1, Whenever someone passes through the cell (i, j), $D_{ij} = D_{ij} + 1$.

Step2, Calculate the dynamic floor field according to decay and diffusion,

$$D_{ij} = (1 - \lambda) * (1 - \delta) * D_{ij} + \lambda * \frac{1 - \delta}{8} * \left(\sum_{i=i-1}^{i+1} \sum_{j=j-1}^{j+1} D_{ij} - D_{ij} \right) \quad (3)$$

λ is the diffusion probability; δ is the decay probability.

Step3, Normalize, $D_{ij} = D_{ij} / \sum_i \sum_j D_{ij}$.

F_{ij} reflects the fire avoidance behavior, it is inversely proportional to the distance from cell (i, j) to the fire. It is calculated as follows,

$$F_{ij} = \frac{1/d^{**}_{ij}}{\sum_i \sum_j 1/d^{**}_{ij}} \quad (4)$$

Here, d^{**}_{ij} represents the shortest distance from the cell (i, j) to the edge of fire within the influence scope of fire. In this paper the influence scope of fire is 8 cells' length around the fire.

M_{ij} reflects the smoke avoidance behavior, it only exists in the cells which the smoke spreads over. It is inversely proportional to the distance from cell (i, j) to the smoke source (the fire). It is calculated as follows,

$$M_{ij} = \frac{1/d^{***}_{ij}}{\sum_i \sum_j (1/d^{***}_{ij})} \quad (5)$$

Here, d^{***}_{ij} represents the shortest distance from the cell (i, j) to the smoke source (the fire).

2.3. Update rules

The update rules of the extended FF model have the following structure.

(1) The model is updated in parallel.
(2) In each time step, calculate the static floor field S_{ij}, the dynamic floor field D_{ij}, the fire floor field F_{ij}, and the smoke floor field M_{ij} according to Section 2.2, and then calculate the target cell selection probability P_{ij}. The Moor neighborhood is adopted, as shown in Figs. 1 and 2.
(3) Without considering any external factors, the fire spreads to the surrounding with certain rate V_f m/s.
(4) Without considering any outside influence, the smoke produced by fire spreads upward on the early stage with the rate V_{mu} m/s. When the smoke is up to the top of room, it diffuses around horizontally with the rate V_{mp} m/s. With the smoke produced continuously, it spreads downward with the rate V_{md} from the top of room and eventually fills the whole room. The smoke spreading process is shown in Fig. 3.