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A social force evacuation model with the leadership effect

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HIGHLIGHTS

- The effect of the number and positions of evacuation leaders on the evacuation dynamics with limited visibility range is investigated.
- Only one or two leaders could get remarkable effect for a single-exit configuration.
- For configurations with multi-exits, evacuation leaders would make the dynamic slower unless the guidance sufficiently utilizes every exit.

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ABSTRACT

When planning for the evacuation guidance, how to efficiently set the trained evacuation leaders is an important problem which has great impact on the evacuation process. This paper investigates the effect of the number and positions of evacuation leaders on the evacuation dynamics in rooms with limited visibility range. In the improved social force model, only the trained leaders exactly know the exit positions, and the others could only follow the guidance according to the positions and directions of evacuation leaders. According to the simulation results, only one or two leaders could get remarkable effect for a single-exit configuration. But for configurations with multi-exits, evacuation leaders would make the dynamic slower unless the guidance sufficiently utilizes every exit. The results indicate that, we should set as many leaders as the number of exits in the center of the multi-exits regular squared room, and when emergencies occur, each leader heads to a different exit. Moreover, if we do like this, the evacuation would be even faster than that with 20 random-position-leaders. This work may shed some light on the drawing up of emergency scheme for large public-gathering places like stadiums and shopping malls.

1. Introduction

Despite that fire is the beginning of human civilization, it is still one of the biggest enemies which human beings have fought against since it was made. According to the statistics of U.S. Fire Administration,[1] in 2007, 1557.5 thousands fires occurred in America where 3430 people lost their lives and 17,675 people were injured. So far, understanding the evacuation mechanism has been an important subject [1–5]. To describe and investigate the evacuation dynamics, scientists have proposed quite a few markable models [6–14]. The cellular automaton model [6–8] and the lattice gas model [9–11] are quite famous discrete models, and as to the continuous model, the social force model (SF model) [12–14] proposed by Helbing is extensively investigated. Considering both of the psychological and physical forces, the SF model calculates the movement of pedestrians through the acceleration equation. Compared with the other models, the SF model can better describe

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[1] Fire in the United States fifteenth edition (2003–2007). (http://www.usfa.fema.gov/statistics/.)

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the interactions between individuals and simulate the congestion phenomenon. Therefore, the SF model is introduced to investigate the effects of the leadership on the evacuation dynamics.

It is widely accepted that a proper evacuation could save many lives in emergencies. Therefore, better preparations of evacuation guidance are significant [15–22]. If the fire occurred in a large public gathering place under the circumstances of some of the known paths being blocked and vision being blurred by the smoke, the problem might be fatally aggravated [15]. Pelechano et al. [16] investigated the way-finding process out from a maze-like building with limited visibility where normal pedestrians could communicate with some trained leaders who definitely knew where the exits were. Vihas et al. [17] simulated the crowd behavior with movement leaders using a Follow-the-Leader Cellular Automata Based Model. Besides the trained leader, some scholars discussed the guidance systems consisting of evacuation signs [18] and digital images [19] as well. Yuan et al. [20] investigated the effects of the visibility range and the guiders in the panic evacuation process, and they found that, the smaller the visibility range was, the more difficult the evacuation would be. Furthermore, evacuation leaders can efficiently accelerate the dynamic. However, they only simulated single-exit cases and we argue that, for multi-exits rooms, the dynamics may be completely different. In addition, there was a large increase of the number of guiders in their study, neglecting one problem that we could not set too many guiders.

In this paper, we investigated the effects of the number and positions of the trained evacuation leaders in single-exit, double-exits and four-exits room structures with limited visibility. For single-exit configurations, one or two trained leaders are enough to accelerate the evacuation efficiently. But for multi-exits configurations, when setting a few leaders in the room with random positions, the evacuation may be slower because of the insufficient utilization of each exit. We argue that, in multi-exits rooms, we should focus on the initial positions and responsible areas of evacuation leaders.

2. The model

The SF model assumes a mixture of psychological and physical forces influencing the behaviors of pedestrians in a crowd. Each of N pedestrians i of mass M_i likes to move with a certain desired speed v_i^0 in a certain direction $\mathbf{e}_i^0$, and therefore tends to correspondingly adapt his or her actual velocity $\mathbf{v}_i$ within a certain characteristic time τ. Simultaneously, he or she tries to keep a velocity-dependent distance from other pedestrians j and walls W. This can be modeled by the 'interaction forces' $\mathbf{f}_{ij}$ and $\mathbf{f}_{iW}$, respectively. In mathematical terms, the change of velocity at time t is then given by the acceleration equation

$$M_i \frac{\mathrm{d}\mathbf{v}_i(t)}{\mathrm{d}t} = M_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t-\tau)}{\tau} + \sum_{j(\neq i)} \mathbf{f}_{ij}(t) + \sum_{W} \mathbf{f}_{iW}(t), \tag{1}$$

where the change of position $\mathbf{r}_i(t)$ is given by the velocity $\mathbf{v}_i(t) = \mathrm{d}\mathbf{r}_i(t)/\mathrm{d}t$. The SF model describe the psychological tendency of two pedestrians, say i and j, to stay away from each other by a repulsive interaction force $A_i \exp[(r_{ij} - d_{ij})/B_i]\mathbf{n}_{ij}$, where A_i and B_i are constants, $d_{ij} = \|\mathbf{r}_i - \mathbf{r}_j\|$ denotes the distance between the pedestrians' centers of mass, and $\mathbf{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\mathbf{r}_i - \mathbf{r}_j)/d_{ij}$ is a normalized vector pointing from pedestrian j to i. The pedestrians touch each other if their distance d_{ij} is smaller than the sum $r_{ij} = (r_i + r_j)$ of their radius r_i and r_j. In this case, we assume two additional forces inspired by granular interactions, which are essential for understanding the particular effects in panicking crowds: A 'body force' $k(r_{ij} - d_{ij})\mathbf{n}_{ij}$ counteracting the body compression and a 'sliding friction force' $\kappa(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij}$ impeding the relative tangential motion, if pedestrian i comes close to j. Here $\mathbf{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$ means the tangential direction and $\Delta v_{ji}^t = (\mathbf{v}_j - \mathbf{v}_i) \cdot \mathbf{t}_{ij}$ denotes the tangential velocity difference, while k and κ represent large constants. In summary, we have

$$\mathbf{f}_{ij} = A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij}, \tag{2}$$

where the function $g(x)$ equals to zero if the pedestrians do not touch each other ($d_{ij} > r_{ij}$), and otherwise equals to the argument x.

If d_{iW} means the distance from the pedestrian i to the wall W, $\mathbf{n}_{iw}$ denotes the perpendicular direction to the wall, and $\mathbf{t}_{iW}$ is the tangential direction, the corresponding interaction force with the wall could be given by:

$$\mathbf{f}_{iW} = A_i \exp[(r_i - d_{iW})/B_i] + kg(r_i - d_{iW})\mathbf{n}_{iW} + \kappa g(r_i - d_{iW})(\mathbf{v}_i \cdot \mathbf{t}_{iW})\mathbf{t}_{iW}. \tag{3}$$

The SF model was proposed to describe the pedestrian flow on the street at first [12], and when Helbing used the model simulating panic evacuation dynamics [13], pedestrians in the system had definite desired directions $\mathbf{e}_i^0$. However, this paper simulates the evacuation dynamics in a smoky room with limited visibility range δ, and pedestrians do not know where the exits are. Thus, we add some rules based on the basic model.

(1) The crowd of N pedestrians could be divided into two groups: n_L trained leaders and $N - n_L$ normal pedestrians. The desired direction of a trained leader $\mathbf{e}_j^0$ points to the nearest exit directly.

(2) When deciding the movement direction, a normal pedestrian tends to: (a) move toward the position of a trained leader; (b) keep the same movement direction with the trained leader. Thus, the desired direction of a normal pedestrian i is calculated as

$$\mathbf{e}_i^0 = \rho \mathbf{e}_j^0 + (1 - \rho)\mathbf{n}_{ij}, \tag{4}$$

where ρ is a distance dependent parameter, and $\rho = \exp(-d_{ij}/(2\delta))$. If there is no trained leader in the system ($n_L = 0$), normal pedestrians then choose a direction randomly and follow the direction until they meet a wall and turn to a random direction again. Furthermore, when the normal pedestrians see the exit, they would move to the exit directly.