Stair Evacuation Simulation Based on Cellular Automata Model Considering Social Forces

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Abstract Building evacuation in case of emergencies has long been recognized as a crucial issue, especially for the stair evacuation because evacuees may spend most of the evacuation time in stairs. To predict the evacuation time in stairs, simulations are commonly used, but known simulations ignore the stair structure and the fact that people may change their speeds during evacuation. As a result, how to introduce a reasonable mechanism on how evacuees change their speeds and improve the stair evacuation simulation are important. In this paper, a new Cellular Automata (CA) model where a new grid map is introduced based on the stair structure, and then the interaction among evacuees can be simulated better than the existing CA simulations. To make a reasonable mechanism of changing speed, the social forces will be introduced to the new CA model based on the advantages of social force models. However, social force model is a continuous model and CA model is a discrete model, and there is a gap to use social forces directly into a discrete model. To bridge the gap, the system time interval is shortened, and then evacuees have variable speeds by updating their positions during several intervals. To validate this simulation, an experiment was held in a high-rise building. In the fire drill, harmless smoke was released to make the drill similar to real events. The simulation results are similar to the fire drill data by comparing evacuation time.

1 Introduction

Building evacuation in case of emergencies has long been recognized as an important issue, especially for the evacuation in stairs because the stair is the only way to evacuate. For building safety, simulations are commonly used, but most

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of the existing simulations ignore the stair structure and the fact that people may change their speeds during evacuation. As a result, how to introduce a reasonable mechanism on how evacuees change their speeds and improve the stair evacuation simulation are important.

Among the simulation models, the social force model and CA models are the most popular. Social force model [1, 2] is a continuous model, which is good at simulating the evacuation process in a room or a corridor. Several virtual forces called "social forces", which make the model reasonable to simulate human behaviors, are introduced in the model. But social force model is computational complex, and it is not appropriate for simulating stair evacuation because such kind of evacuation is always large-scale. On the contrary, CA model [3–7] is a discrete model, which is fit for both small-scale and large-scale evacuation [1, 8–12]. But the transition rule, which decides how evacuees move, is defined based on experience [2, 13, 14]. Furthermore, the existing CA simulation cannot reflect the human behaviors well in stairs based on traditional grid and cell size [7, 15, 16].

To improve stair evacuation simulation, a new CA model is established in Sect. 2. According to our previous work [17], a new simulation map is drawn according to both human body size and stair structure. To make a mechanism to change evacuees' speeds reasonably, the concept of social force will be introduced to the new CA model based on the advantages of social force models. However, as mentioned above, social force model is a continuous model and CA model is a discrete model. There is a gap to use social forces directly into a discrete model, and the system time interval is shortened to bridge the gap. Evacuees have variable speeds by updating their positions during several intervals, and social forces, such as self-driven force and push force, are used to change evacuees' speeds.

To validate this simulation in Sect. 3, an experiment held in a high-rise building was video recorded. In the experiment, 33 people evacuate from the 10th floor to the lobby. A simulation is carried out based on the experiment. The simulation results are similar to the fire drill data by comparing evacuation time.

2 Problem Formulation

A new CA model for stair egress simulation is established in this section. In Sect. 2.1, to improve the basic structure of CA model, a size of the cell and a new grid map are drawn based on the structure of stairs (tread and landing). Then the neighborhood and transition rule are introduced in Sect. 2.2. As the grid map is divided into six areas [17], the transition rule is defined separately on each area. In Sect. 2.3, several social forces are introduced in the simulation model. There are two kinds of social forces: self-driven force and push force.

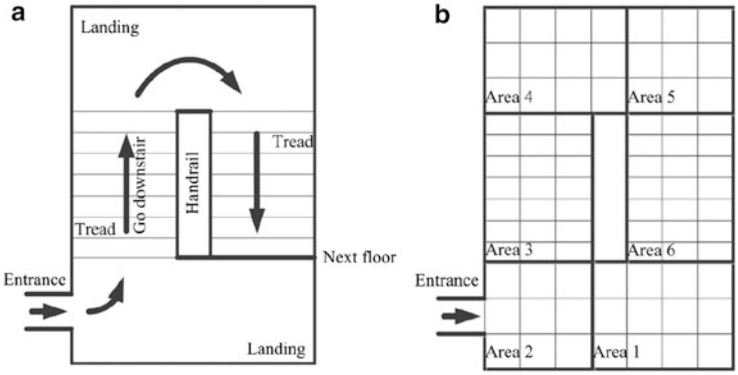

Fig. 1 The stair structure and the six areas of stair

2.1 *Cell Size and Grid Map*

CA model is a kind of discrete model where both the space and the time are discrete. In the existing studies, the cell size is 0.4 [4] or 0.5 m [18] which is similar to the cell size used in the corridor simulation. In our new model, the cell size is drawn based on the stair structure and human body size. Given this, the cell size of the tread area is the width of the shoulder the depth of the tread since one pedestrian can only occupy a space on one tread. Landings (as is shown in Fig. 1) are connected with treads, and the cell size of the landings is the width of the shoulder the width of the shoulder. This cell size is larger than that on the tread because it is used to simulate turning behaviors on landings. To connect the landings and the treads, the joint cell size of the landing and tread is the width of the shoulder. Stair structure is shown in Fig. 1a, and the corresponding cell space is shown in Fig. 1b. To distinguish pedestrians of different directions, the stair on between two floors is divided into six areas: Areas 1–6. The moving directions on these areas are also different, and the directions are the same as it is shown in Fig. 1a.

2.2 *Neighborhood and Transition Rules*

Neighborhood cells are the environment around an evacuee, and the neighborhoods on treads and landings are not the same in the model. When evacuees are going downstairs, they will move forward, left ahead or right ahead (shown in Fig. 2a) because evacuees can hardly move back, move to the left, or move to the right in stairs. As a result, the neighborhood on the treads areas is the three cells in the front of an evacuee which is shown in Fig. 2b. For landings, the neighborhood is the eight cells around a pedestrian because he/she can move to any direction on a horizontal

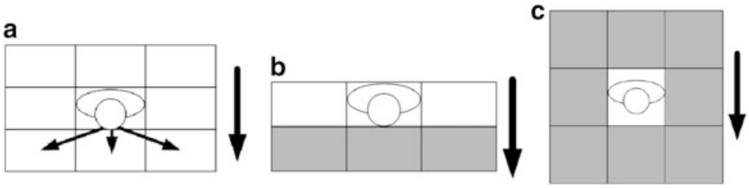

Fig. 2 Neighborhoods on treads and landings

place. This neighborhood is a typical Moore [12] neighborhood which is shown in Fig. 2c.

The rule of pedestrian's movement in the simulation is defined as transition rule, and the transition rule determines the pedestrian's moving directions and positions in the next system time interval. As the stair on each floor is divided into six areas, the transition rule of each area is defined separately to measure the probabilities of the moving directions of pedestrians in the next time interval. Take Area 3 for example, the destination of pedestrians in Area 3 is Area 4, and one pedestrian has three directions to move: straight forward, left ahead and right ahead. If one of pedestrian's moving direction is blocked, the probability of which direction he/she moves to will change. In the transition rule in Area 3, P_F, P_L, P_R, and P_S represents the probability of chosen the direction forward, left ahead,right ahead and stop, respectively. As they are probabilities of one event, we have $P_F+P_L+P_R+P_S = 1$. The transition probabilities of pedestrian movement are as follows:

$$P_F = \frac{1}{3}, p_L = \frac{1}{3} - w, P_R = \frac{1}{3} + w, P_S = 0; \tag{1}$$

$$P_F = 0, P_L = 0, P_R = 0, P_S = 1; \tag{2}$$

$$P_F = \frac{1}{2} - \frac{3w}{2}, P_L = 0, P_R = \frac{1}{2} + \frac{3w}{2}, P_S = 0; \tag{3}$$

$$P_F = 0, P_L = \frac{1}{4} - \frac{3w}{4}, P_R = \frac{3}{4} + \frac{3w}{4}, P_S = 0; \tag{4}$$

$$P_F = \frac{1}{2} + \frac{3w}{2}, P_L = \frac{1}{2} - \frac{3w}{2}, P_R = 0, P_S = 0; \tag{5}$$

$$P_F = 0, P_L = 1, P_R = 0, P_S = 0; \tag{6}$$

$$P_F = 1, P_L = 0, P_R = 0, P_S = 0; \tag{7}$$

$$P_F = 0, P_L = 0, P_R = 1, P_S = 0. \tag{8}$$

In the new model, the tendency of walking along the inner of a stair is considered in the transition rules. To simulate the tendency of walking, a parameter w is introduced with $0 \leq w \leq 1/3$. The transition rule on the landings is similar to the rule (Eqs. (1)–(8)) on the tread.

2.3 *Social Forces*

The basic assumption of the social force model is that the interactions among evacuees are determined by "social forces" which are not real forces, but such forces will influence people's movement. The social forces in the social force model [14] are as follows:

$$m_i \frac{d\vec{v}_i}{dt} = m_i \frac{v_i^0 \vec{e}_i^{\,0}(t) - \vec{v}_i(t)}{\tau_i} + \sum_{j \neq i} f_{ij} + \sum_{w} f_{iw}, \tag{9}$$

where m_i and $\vec{v}_i$ is the mass and velocity of pedestrian i,respectively. The desired velocity value of pedestrian i is v_i^0, and the direction of this velocity at time t is $\vec{e}_i^{\,0}(t)$. The τ_i is a relaxation time of a pedestrian to achieve the desired velocity, and it equals 0.5 s in the social force model. Social force $\vec{f}_{ij}$ reflects the forces by other pedestrians, and $\vec{f}_{iw}$ represents the force by the wall. To introduce social forces to change the speeds, variable speed is required in the new simulation model. The simulation time interval is shortened, and the pedestrians can update their positions (no more one cell) in several time intervals.

Two kinds of social forces, self-driven force and push force, will be introduced to change the pedestrians' speeds in the new simulation. Self-driven force $\vec{f}_S$ is a force driven by the inner desire, which is reflected by the concept "desired velocity" or desired speed in the paper, to move to the exits as fast as possible. The force is similar to the desired velocity mentioned in the original social force model:

$$\vec{f}_S = m_i \frac{\vec{v}_d(t) - \vec{v}_i(t)}{\tau_i}, \tag{10}$$

where $\vec{v}_d(t)$ and $\vec{v}_i(t)$ is the desired speed and current speed of pedestrian i at time t. Push forces are used to demonstrate the forces among evacuees, and such forces including two kinds: forward push force $\vec{f}_{FP}$ and backward push force $\vec{f}_{FP}$. Forward push force is the force from the people in the back, and this force is related to the speeds of a pedestrian i and a pedestrian j who is in the back of pedestrian i. If $|\vec{v}_i(t)| > |\vec{v}_j(t)|$, $\vec{f}_{FP} = 0$; otherwise, $\vec{f}_{FP}$ is as follows:

$$\vec{f}_{FP} = m_i \frac{\vec{v}_j(t) - \vec{v}_i(t)}{\tau_i}, |\vec{v}_j(t)| \leq |\vec{v}_j(t)|, \tag{11}$$

where $\overrightarrow{\nu}_i(t)$ and $\overrightarrow{\nu}_j(t)$ is the speed of pedestrian i and pedestrian j, respectively. On the contrary, the backward push force $\overrightarrow{f}_{BP}$ is the force from the people in the front, and this force is related to the speeds of a pedestrian i and a pedestrian j who is in the front of pedestrian i. If $|\nu_j(t)| > |\overrightarrow{\nu}_i(t)|$, $\overrightarrow{f}_{BP} = 0$; otherwise, $\overrightarrow{f}_{BP}$ is as follows:

$$\overrightarrow{f}_{BP} = m_i \frac{\overrightarrow{\nu}_j(t) - \overrightarrow{\nu}_i(t)}{\tau_i}, |\nu_j(t)| \leq |\overrightarrow{\nu}_i(t)|. \tag{12}$$

Above all, the final social force equation is as follow:

$$13\, m_i \overrightarrow{a}_i(t) = \overrightarrow{f}_S + \overrightarrow{f}_{FP} + \overrightarrow{f}_{BP} \tag{13}$$

where $a_i(t)$ is the acceleration of pedestrian i at time t, and the change of the speed is $\Delta\nu_i = a_i t$.

3 Validation and Simulation

To validate the simulation model, an experiment was held in a high-rise building, and there are 33 people took part in the experiment. The participants are all undergraduate students in Tsinghua University, and they all evacuated from the 10th floor of the building. When the alarm sounded, they start to evacuate from their rooms and all of them were told to use a specified stair in the building (a snapshot of the evacuation process is shown in Fig. 3).

The simulation is carried out according to the experiment data. The width of an evacuee's shoulder is 0.5 m and the length of the tread in the building is 0.3 m. So

Fig. 3 A snapshot of experiment process

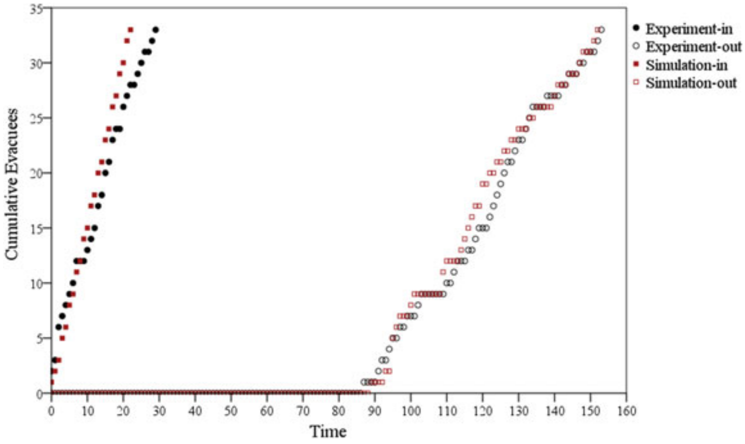

Fig. 4 Cumulative evacuees of experiment and simulation

the cell size on tread is $0.5 \times 0.3\,\text{m}^2$ and the cell size of the landing is $0.5 \times 0.5\,\text{m}^2$. Parameter w equals 0.2 to demonstrate that people incline to evacuate along the inner side of the stair. The desired speed (horizontal speed) of an evacuee is 0.85 m/s according to the free speed (tested in the building) of people in emergency conditions. The simulation is run in Matlab 7.8.0 and tested on an Intel Core i3 + 2.3 GHz Windows PC with 2 GB RAM. The simulation is run 20 times and the average CPU time is 8.32 s. Then we use IBM SPSS Statistics 19 to analyze the simulation data.

The evacuation times of the experiment data and the simulation results are shown in Fig. 4. The experiment-in and experiment-out data mean the times of evacuees entered in and exit out of the stair, so as to the simulation-in and simulation-out. The time of simulation-in is also shown in Fig. 4. The evacuation time of the experiment data is 153 s, and the result of simulation is 152 s, which is only 1 s smaller than the experiment data.

The data used for linear regression is from 87 to 153 s because the first pedestrian appears at 87 s and the last one evacuates out at 153 s. The linear regressions of the experiment-out data and the simulation-out result are as follows:

$$Experiment - out : y = 0.505x - 44.140, R^2 = 0.994, \tag{14}$$

$$Simulation - out : y = 0.511x - 44.054, R^2 = 0.993. \tag{15}$$

The slope and intercept of the experiment and simulation are similar to each other. Above all, the simulation results are similar to the experiment data according to the total evacuation times and the linear regressions.

Conclusion

This paper improves the stair evacuation simulation problem considering social forces. In the new simulation model, basic structure of the CA model is improved based on the structures of the stairs, and two kinds of social forces are introduced to change evacuees' speeds. The self-driven force is used to demonstrate the people's evacuation desire, and push forces are used to show the interactions among evacuees. To validate the new simulation, an experiment with 33 people is held in a high-rise building, and a simulation is carried out based on the experiment. Compared with the experiment data, the simulation results are accurate according to the evacuation time.

In the future, more experiments are required to validate the simulation from the micro level, and optimization guidance should be studied based on the new simulation.

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