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Experiment of bi-direction pedestrian flow with three-dimensional cellular automata

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ABSTRACT

In order to effectively depict bi-directional pedestrian flow characteristic in the three-dimensional space, a novel pedestrian model is proposed based on cellular automata. In the model, at first, the calculation formula of target position in the next time step is given according to direction gain and collision gain, and the system evolution rules are defined. Second, the experiment is conducted with the simulation platform to study the relationships of average system velocity, flow, system scale, pedestrian density and stair series for obtaining the bi-directional pedestrian flow characteristic. The results of numerical analysis had shown that when the pedestrian density reached the critical value, the pedestrian flow was changed from free flow status to blocking flow status, and the distribution ratio of bi-directional pedestrians and channel width had great effect on the average system velocity and the flow. Moreover, the more the stair series was, the more obvious the "faster-is-slower" effect was.

1. Introduction

As urban population density increases rapidly, it is very important to ensure the security of pedestrians in public space. It has become the main method to explore macro pedestrian flow and reasonable design of building architecture by studying microscopic behavior to discover formation mechanism of macro phenomenon.

Currently, the typical pedestrian flow characterization methods are social force, lattice gas and cellular automata, etc. [1–8]. Helbing et al. [9,10] used social force to study pedestrian evacuation process, discovering and analyzing formation mechanizm of phenomenon such as "faster-is-slower" effect and "arching" effect. The results had shown that macro cluster effect was caused by non-liner effect between pedestrians. Burstedde et al. [11] established pedestrian flow model of two-dimensional cellular automata by means of field concept, studying typical phenomenon such as "lining" effect, etc. Tajima and Nagatani et al. [12–14] studied the change of pedestrian evacuation efficiency in bottleneck channel, T-type channel and hall by combining lattice gas model, analyzing the critical value of phase change under the different condition. Yue et al. [15] used four dynamic parameters to depict the actual situation in the movement area of pedestrians, which defined the behaviors of pedestrians choosing to move forward, backward, left and right, wait and exchange position, and studied the change of pedestrian flow status based on cellular automata. Based on the lattice gas, Nagai et al. [16] investigated the counter flow of students going on all fours, and the result had shown that the jamming transition does not occur in the experiment because of the finite size effect, but the velocity decreases abruptly with increasing density. Nagatani et al. [17] proposed a bi-directional cellular automaton model for the facing pedestrian traffic on a passage with a partition line at rush hour, and had found that the complex jamming and freezing transitions occur with variations in the threshold. Guo et al. [18] proposed a microscopic pedestrian model with discrete space representation, and the route choice of pedestrians during evacuation under the conditions of both good and zero visibility was investigated. Yang et al. [19] proposed a counter-flow model of the channel by considering right-moving preference. Meanwhile, the collision probability in moving process might influence the choice of pedestrians over position. Kirchner [20,21] made a good depiction of the mutual avoidance when many pedestrians were competing for the same position by considering the repulsive force between pedestrians in cellular automata. Song et al. [22] introduced friction force and repulsive force into classic cellular automata model by considering the interaction between pedestrian and pedestrian, pedestrian and environment, which effectively combines advantages of continuous model and discrete model, enabling the calculation speed and accuracy to be improved. Fukamachi et al. [23] proposed a channel bi-directional pedestrian flow model based on sideways effect to

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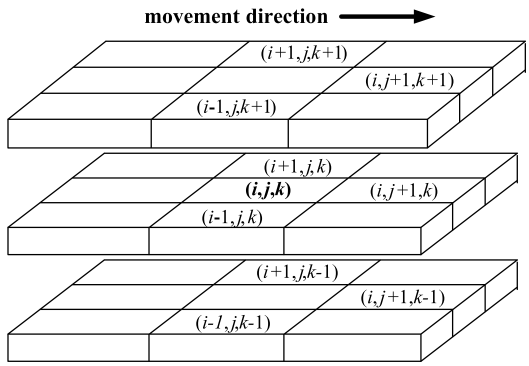

Fig. 1. Movement status of pedestrians in the three-dimensional space.

avoid collision of surrounding pedestrian. Moreover, factors such as pedestrian vision [24], panic [25], game behavior [26] and kinship [27] are introduced into cellular automata to study pedestrian flow characteristics.

Currently, the characterization of method concerning bi-directional pedestrian flow is mainly based on the two-dimensional space. But in actual situation, there exist a large number of three-dimensional spaces containing stairs. Stair factor has large effect on the average system velocity and the flow, resulting in big difference between the simulation results and the actual situation. Therefore, this paper proposes a novel bi-directional pedestrian flow model by combining the three-dimensional space. The model stipulates that pedestrians can choose to move forward, left and right, stay still and exchange position according to the surrounding conditions, and studies the change of pedestrian flow status by defining direction gain and collision gain.

2. Model

The Von Neumann structure of two-dimensional cellular automata is extended in this paper, and the three-dimensional space is divided into uniform grids. Each grid (cell) is 0.4 m × 0.4 m × 0.4 m, as shown in Fig. 1. It has shown the movement of pedestrians moving from left to right in position (i, j, k), while the movement from right to left is similar. There only exist three statuses in any grid: occupied by pedestrians, occupied by obstacles, or vacant. In every time step, pedestrian calculates the moving gain of the neighboring nine grids and his own position q_{ijk} according Eq. (1), and choose the maximum value as the target position in the next time step.

$$q_{ijk} = \left(S_{ijk} + \frac{1}{D_{ijk}} + U_{ijk}\right)(1 - n_{ijk})\xi_{ijk}\varphi_{ijk} \tag{1}$$

In the formula, i, j and k are position coordinates of cell; n_{ijk} is the spare coefficient of cell, if cell (i, j, k) has been occupied by other pedestrians, then $n_{ijk} = 1$, otherwise $n_{ijk} = 0$; ξ_{ijk} is obstacle coefficient, if cell (i, j, k) is the obstacle, then $\xi_{ijk} = 0$, otherwise $\xi_{ijk} = 1$; S_{ijk} indicates the direction gain of cell (i, j, k), D_{ijk} indicates the collision gain of cell (i, j, k), and U_{ijk} indicates the vacancy gain of cell (i, j, k). Meanwhile, in order to differentiate the two-dimensional cellular automata, here the parameter ε_{ijk} is used to indicate whether the cell (i, j, k) exists or not, if the cell (i, j, k) does not exist, then $\varepsilon_{ijk} = 0$, otherwise $\varepsilon_{ijk} = 1$.

The model regulates that pedestrians can only move forward or side (as shown in Fig. 2), and the gain of moving forward is the biggest, the gain of moving right side is the second biggest. Here we set the direction gain S_{ijk} is:

$$S_{ijk} = \begin{cases} 2, & \text{moving forward} \\ 1, & \text{moving right side} \\ 0.5 & \text{moving left side} \end{cases} \tag{2}$$

Meanwhile, in the three-dimensional space, the moving velocity of walking upward and downward is different from his moving velocity on the same platform. Therefore, it is necessary to consider the change of velocity. The time step is set as 0.3 s, in every time step, pedestrians move to the neighboring position by one cell. But in the three-dimensional Von Neumann structure defined above, the distance between the neighboring cells is different (as shown in Fig. 3), thus the moving velocity of pedestrians is different. If pedestrians' moving target and his current position is on the same platform, when moving forward, backward, left and right, the moving distance is 0.4 m, the moving velocity $v = 1.33$ m/s; If pedestrians walk upward or downward the stair, the forward distance is 0.4 m, the velocity $v = 1.33$ m/s.

2.1. Collision gain

As influenced by the surrounding conditions, pedestrians may change their moving direction in moving process. When the distance between two pedestrians is smaller than the threshold value, the psychological force and physical force between pedestrians can make them decelerate, stop or turn around to avoid collision. Therefore, on the basis of the cellular automata, the collision probability in the moving process is introduced to perfect the bi-directional pedestrian flow model.

Supposed pedestrian A is located in cell (i, j, k), the collision probability comes from the cubic area with cell (i, j, k) as the center and spacing distance of two. When other pedestrian B bursts into the cubic area, it is regarded there exists the collision probability between pedestrian A and pedestrian B. Different from the two-dimensional space, the collision probability in the three-dimensional space may come from vertical direction, side direction and perpendicular direction. We set the overlapping probability of pedestrian A and pedestrian B in vertical direction (x), side direction (y) and perpendicular direction (z) as p_x, p_y and p_z. Here the calculation method of the overlapping probability is given.

In every time step, pedestrian A calculates the movement gain $q_{ijk}(A)$ of moving towards the neighboring grid and keeping still according to Eq. (1), here the movement probability $p_{ijk}(A)$ of pedestrian A is defined as:

$$p_{ijk}(A) = N_{ijk} q_{ijk}(A) \tag{3}$$

$$N_{ijk} = \frac{1}{\sum_{i,j,k} q_{ijk}(A)} \tag{4}$$

N_{ijk} is normalized parameter, which makes the sum of probability equal 1. In the same way, the movement probability $p_{ijk}(B)$ of pedestrian B can be calculated. When a direction is overlapping, that is pedestrian A and pedestrian B choose the same direction, the overlapping probability can be defined as the product of movement probability of pedestrian A and pedestrian B in this direction.

$$\begin{cases} p_x = p_{ijk}(A, x) p_{ijk}(B, x) \\ p_y = p_{ijk}(A, y) p_{ijk}(B, y) \\ p_z = p_{ijk}(A, z) p_{ijk}(B, z) \end{cases} \tag{5}$$

In this formula, $p_{ijk}(A, x)$, $p_{ijk}(B, x)$, $p_{ijk}(A, y)$, $p_{ijk}(B, y)$, $p_{ijk}(A, z)$ and $p_{ijk}(B, z)$ are the movement probability component of pedestrian A and pedestrian B in vertical direction, side direction and perpendicular direction. If pedestrians move in some platform, the movement probability will not produce component in the perpendicular direction (that is $p_{ijk}(A, z) = 0$, $p_{ijk}(B, z) = 0$), and p_{ijk} is the movement probability of the direction. When pedestrians walk upward or downward the stair, the component is produced in the perpendicular direction.

Here, the Fermi rule in game theory is introduced to depict the competitive behavior. If two pedestrians compete to the same position with different strategies, the loser will likely mimic the victor