Simulation of Fire Evacuation by Real-Coded Cellular Automata (RCA)

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Abstract. We present simulation of fire evacuation by real-coded Cellular Automata (RCA), which is a new approach for pedestrian dynamics. Here, we consider the evacuation from a relatively large room with one or two exits. To describe the flame spread in fire, a percolation model is applied, where the flame position is determined stochastically. In the simulation, we focus on several parameters including the number of people in room, the distance from the flame, and the location and size of the exit.

1 Introduction

Fire is one of the most serious disasters. The damage in fires is mainly caused by high heat fluxes from the flame, accidental explosions, and toxic species in smoke generated by combustion reaction, which causes fatalities, destruction of houses and buildings, and air pollution [1]. In order to mitigate these losses, it is important to design the room size and exit location in the building for the fire evacuation so as to set the evacuation route and provide effective instruments including fire extinguishers and alarms. Additionally, an appropriate management for safety such as dairy training for fire evacuation is needed. In planning individual actions for safety and in evaluating the effectiveness of facilities and instruments, it is plausible to understand the phenomena in fires and validate the fire evacuation plan in advance. However, it is difficult to conduct experiments inside room or building in fire, because the costs are expectedly huge, and the evacuating people are exposed to danger. Therefore, the simulation of fire evacuation is needed.

For this purpose, we need to describe the pedestrian flow in fire evacuation. Since its dynamics is caused by collective crowd behavior, we have difficulties to handle directly each pedestrian by solving coupled differential equations, although the social force model has been proposed [2]. As one of the key approaches, the model of Cellular Automata (CA) has been developed to describe pedestrian dynamics, where a physical system of time and space are all discrete. So far, CA have been applied in a variety of scientific researches including traffic models and biological fields. In the original CA model for pedestrian dynamics

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[3-5], the von Neumann neighborhood is adopted. In this case, the pedestrian is moved to the nearest cells at next time step, but his movement is limited only in four directions: forward, backward, left, and right. Even if Moore neighborhood cells are used, the pedestrian is forced to move much faster in oblique directions. This might be a problem if we discuss the evacuation time.

Then, we have proposed a new model, which is called the real coded-Cellular Automata (RCA) [6,7]. In this model, it is possible to consider any direction and any velocity of pedestrian movement. Some examples have been already presented, including the lane formation in the street and the bottleneck in the room evacuation. It is confirmed that RCA can be a good tool for simulating the pedestrian dynamics.

In this study, we attempt to simulate fire evacuation by RCA. To describe the flame spread in fire, a percolation model is applied, where the flame position is determined stochastically. Here, we consider the evacuation from a relatively large room with one or two exits. In the simulation, we consider several parameters including the number of people in room, the moving velocity of the evacuee, and the location and size of the exit. The distance from the flame is also changed to evaluate the safety route, which is the unique parameter in fire evacuation. The evacuation route and number of fatalities involved in fire are discussed.

2 Numerical Method

2.1 RCA Model for Pedestrian Dynamics

Here, we explain our approach for arbitrary velocity and directions for pedestrian dynamics. The update rule of RCA consists of 4 steps to determine the position of the evacuee. These rules are applied to each pedestrian randomly. The velocity of all evacuees is the constant of v_i, which is changed in simulation. The update rules are almost the same as the original RCA rule [6,7], except that the evacuee is moved based on the floor field. Examples of the floor field are shown in Fig. 1, where there is one exit in the room. It is the static floor field describing the shortest distance to the exit. In fire evacuation, it could be possible that, along the path of the shortest distance to the exit, the evacuee may cross the burning area or encounter the flame. Then, we assume that he takes the route whose distance from the flame is L in order to keep away from the burning area, which is shown in Fig. 2. The rule for the flame spread is explained in the next section.

2.2 Percolation Model for Flame Spread in Fire

In general, a fire becomes more serious as the burning area increases by flame spread. The mechanism of flame spread is very complex. It is explained with heat transport from the flame, pyrolysis reaction of combustible material, and the mixing of gaseous fuel with ambient oxygen in the air [1,8,9]. In this study, we use simplified model of the flame spread. It is assumed that the combustion occurs under the homogeneous atmosphere. Here, the flame spread rate is the

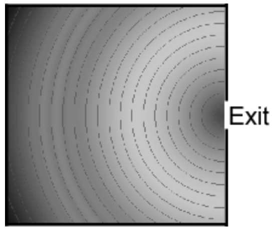

Fig. 1. Floor field in room with one exit

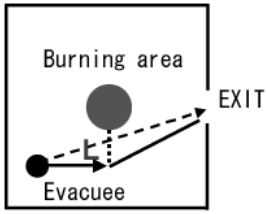

Fig. 2. Route of fire evacuation

only parameter to describe the degree of burning intensity. To consider the flame spread in CA code, the percolation model is used, which can be applied in the discrete time and space.

Figure 3 shows the percolation model for flame spread. The open circle is the combustible spot, which can be burned, and solid circle is the burning area. Fig. 3(a) is the example of an initial condition where the ignition point is shown at the center. Fig. 3(b) shows the burning area caused by the flame spread. In percolation model, the burning area is connected with each other. That is, the flame can not propagate if there are no combustible spots shown by open circles. As the time step goes, the burning area is developed in the neighborhood. At each time step, the flame spread occurs on the unburned combustible spots next to the burning area. There are 8 directions including forward, backward, left and right as well as four oblique directions. To control the flame spread rate, whether the flame can propagate or not is determined by the stochastic process. That is, the unburned region next to the burned region is ignited by some possibility. To consider the uniform flame spread, the probability in oblique direction is smaller than those in other four directions.

2.3 Calculation Domain

Figure 4 shows the calculation domain in the case of room fire. We consider three cases where only the number and location of the exit are different. There is one exit in case A. There are two exits in case B, which are located at both sides. In case C, there are two exits, but these are located at the same side. Each room size is 16m $\times$ 16m, and the exit width, W, is 1.2 or 2.4 m. The time step of Δ_t

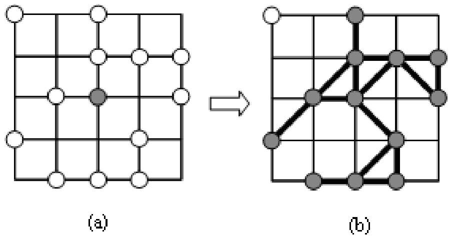

Fig. 3. Percolation model for flame spread

is 0.5 s, and the spatial grid of Δ is 0.4 m [7]. In this simulation, all grids are combustible spots.

As already explained in the previous section, the burning area is determined by the percolation model. For three cases, the initial ignition point is located at the center of the room. As the flame spread occurs, the burning area in the room increases. The possibility of forward, backward, left or right flame spread is set to be unity. In this case, the flame spread rate is 0.8 m/s ($= \Delta/\Delta_t = 0.4\text{m}/0.5\text{s}$). To consider the uniform flame spread, the possibility of flame spread in other four oblique directions is set to be 0.3.

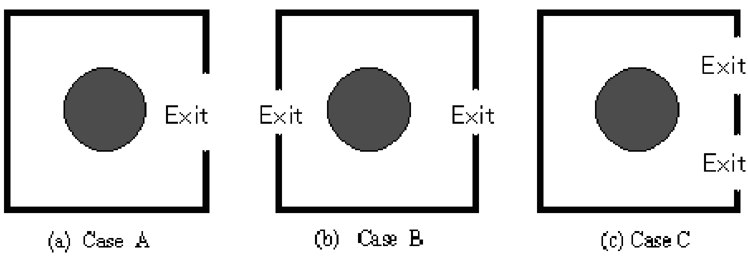

Fig. 4. Calculation domain for room fire; three cases are considered

3 Results and Discussion

3.1 Evacuee Velocity and Distance from Spreading Flame

Figure 5 shows the dynamics of fire evacuation. The calculation domain is case A, and the number of people in the room, N, is 100. The exit width is 1.2 m, and the evacuee velocity is 2.2 m/s. The distance between the evacuee and the flame is set to be 1.6 m. Three results at t = 0.5, 5.0, and 9.0 s are shown. The evacuees who can move directly toward the exit are not affected by the burning area. However, those passing near the burning area must keep away from the flame and take the longer route. It is found that more than 10 people are involved in fire and could not evacuate. It should be noted that, depending on the exit width, the bottleneck is observed at the exit [7]. Therefore, there are two circumstances the evacuee may be possibly involved in fire: one is the place where he passes close to the burning region, and the other is the exit of the room.

Next, we change the distance from the spreading flame, L. Figure 6 shows the examples of fire evacuation for $L = 0.4$ and 2.8 m, respectively. The calculation domain is also case A, and there are 50 people in the room with the exit width of 1.2 m. For each cases, the evacuee velocity is 3.0 m/s, and the time is at $t =$ 2.5 s. It is found that, as the distance from the spreading flame is shorter, the evacuee is forced to take the route close to the burning area. In this case, there are more possibilities to be involved in fire before the evacuee reaches the exit.

Needless to say, whether one can evacuate or not largely depends on his evacuee velocity, v_i. Therefore, we change the velocity of evacuees in the room. Three velocities of 2.2, 3.0, and 5.0 m/s are considered. We examine the number of fatalities involved in fire, N_D, by changing L and v_i. The results are shown in Fig. 7. It is found that more people can evacuate if they can move faster, resulting in the smaller N_D. Interestingly, as we increase the distance from the flame, N_D becomes smaller at the beginning, but N_D increases again. That is, the minimum N_D is observed around $L = 1.2$ to 1.6 m. Since the flame spread rate is 0.8 m/s, it is expected that the evacuee can easily keep away from the flame at higher v_i. Then, the number of fatalities becomes smaller as v_i is higher. However, it is not safe if he passes near the burning area, because the flame is coming toward the evacuee. When he must take more distance from the burning region, his evacuation route is longer. It takes more time to arrive at the exit, and there are more chances to be involved in fire. Hence, there is the minimum N_D in Fig. 7.

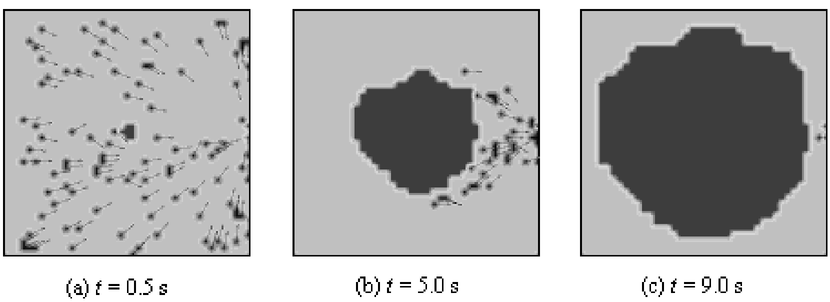

Fig. 5. The position of evacuee and burning area in the room in case A; $L = 1.6$ m, $N = 100$, $W = 1.2$ m, $v_i = 2.2$ m/s

3.2 Effect of Exit Location

Here, we change the number and location of the exit. In case A, the exit width is 2.4 m. On the other hand, we set $W = 1.2$ m in cases B and C, ensuring that the total exit width is 2.4 m. By changing number of people in room, we examine the number of fatalities involved in fire in three cases. Results are shown in Fig. 8. Expectedly, as more people in the room, the number of fatalities, N_D, increases.

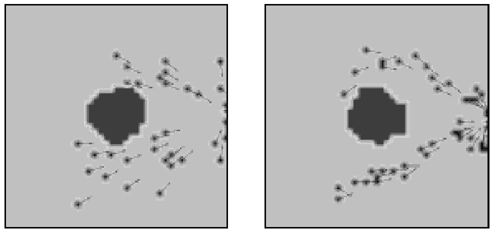

Fig. 6. The position of evacuee and burning area in the room in case A; t = 2.5 s, N = 50, W = 1.2 m, v_i = 3.0 m/s

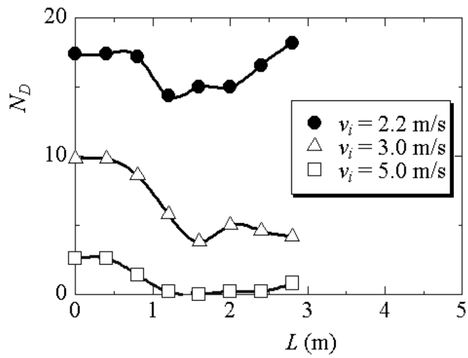

Fig. 7. Number of fatalities involved in fire by changing distance from spreading flame; three evacuee velocities of v_i = 2.2, 3.0, and 5.0 m/s are considered

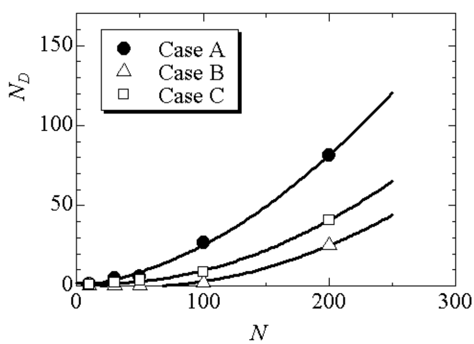

Fig. 8. Number of fatalities involved in fire by changing number of people in room; v_i = 2.2 m/s, and L = 1.6 m

In case A, even though the bottleneck is less observed at wider exit, the evacuee must take longer route. There are more chances to be involved in fire. In case C, although the situation is similar to case A, N_D is smaller. By comparing three cases, N_D in case B is the smallest. This is because the evacuee can move in the same direction of flame spread, and he has less chances to involved in fire. Moreover, the distance of the evacuation route is shortest, which is almost half of other two cases. Thus, as for the location of the exit, case B is the safest, where there are two exits at both sides.

4 Conclusions

We have simulated fire evacuation by real-coded Cellular Automata (RCA). To describe the flame spread in fire, a percolation model is applied. In the simulation, we have changed the number of people in the room (N), distance from the flame (L), the location and size of the exit, in order to discuss the evacuation route and number of fatalities involved in fire (N_D). The following results are obtained.

1. The evacuees who can move directly toward the exit are not affected by the burning area. However, those passing near the burning area must keep away from the flame and take the longer route.
2. Depending on the exit width, the bottleneck is observed at the exit. Therefore, there are two circumstances the evacuee may be possibly involved in fire: one is the place where he passes close to the burning region, and the other is the exit of the room.
3. Whether one can evacuate or not largely depends on his evacuee velocity. Three velocities of 2.2, 3.0, and 5.0 m/s are considered. It is found that more people can evacuate if they can move faster, resulting in the smaller N_D.
4. As the distance from the flame is increased, N_D becomes smaller at the beginning, but increases again. That is, the minimum N_D is observed around $L = 1.2$ to 1.6 m. This means that it may not be safe to keep away too much, because it takes more time to arrive at the exit due to longer evacuation route, resulting in more chances to be involved in fire.
5. To examine the effect of exit location, three cases are considered: one exit in case A, two half size exits at both side in case B, and two half size exits at one side in case C. It is found that N_D is the smallest in case B, which is explained by the fact that the evacuee moves in the same direction of flame spread, with the shorter evacuation route.

These are useful information for planning the safety guideline to mitigate the losses in fire.

Acknowledgement

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