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Simulation of bi-direction pedestrian movement using a cellular automata model

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Abstract

A cellular automata model is presented to simulate the bi-direction pedestrian movement. The pedestrian movement is more complex than vehicular flow for the reason that people are more flexible than cars. Some special technique is introduced considering simple human judgment to make the rules more reasonable. Also the custom in the countries where the pedestrian prefer to walk on the right-hand side of the road are highlighted. By using the model to simulate the bi-direction pedestrian movement, the phase transition phenomena in pedestrian counter flow is presented. Furthermore, the introduction of back stepping breaks the deadlock at the relatively low pedestrian density. By studying the critical density of changing from freely moving state to jammed state with different system sizes and different probabilities of back stepping, we find the critical density increases as the probability of back stepping increases at the same system size. And with the increasing system size, the critical density decreases at the same probability of back stepping according to the scope of system size studied in this paper.

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Keywords: Pedestrian movement; Bi-direction; Cellular automata; Phase transition

1. Introduction

In recent years, considerable research has been done on the study of traffic flow [1–10]. Cellular automata (CA) models are widely used on this topic and have attracted a lot of attention. After its success in traffic flow, it has also been introduced to model

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the pedestrian movement. The simple CA local rules describing the behaviour of each automaton can create an approximation of actual vehicle or human behaviour and the emergent group behaviour is an outgrowth of interaction of the microsimulation rule set.

In simulating traffic flow, some one-dimensional [11–14] and two-dimensional models [15–18] have been proposed to study various traffic flow problems such as the jamming transitions from the freely moving traffic to the jammed traffic, which has been observed in the actual highway traffic [8–10] and the self-organization phenomena [15]. Pedestrian movement is also an important component in the analysis and design of transportation facilities, pedestrian walkways, traffic intersections, markets, and other public buildings. It seems the pedestrian movement is similar to the traffic flow dynamics. However, up to now studies on this topic are very scarce [19–26]. The reason may be that the pedestrian movement is more complex than vehicular flow. First, pedestrians are more intelligent than vehicles and they can choose an optimum route according to the environment around. Secondly, pedestrians are more flexible in changing directions and not limited to the "lanes" as in vehicular flow. Thirdly, the slight bumping is acceptable and need not be absolutely avoided as in traffic flow models. So the model developed for pedestrian movement should fully consider these differences in order to study the special phenomena in pedestrian movement. It is pity that till now, most pedestrian movement models are established based on the rules used for traffic flow and consider little of the special characteristics of pedestrian movement itself.

In this paper, a bi-direction pedestrian movement model considering the human behaviour which can make judgment in some complex situations is proposed. And then some simulations are proposed to test the feasibility of the model and study the phase transition of the bi-direction pedestrian movement also the effect of back stepping on the forming of the jam.

2. Model description

The model is described in the two-dimensional system. The underlying structure is a $W \times W$ cell grid, where W is the system size. Each cell can either be empty or occupied by exactly one pedestrian. The size of a cell corresponds to approximately $0.4 \times 0.4\ \mathrm{m}^2$. This is the typical space occupied by a pedestrian in a dense crowd [19]. The update is synchronous for all pedestrians. Each pedestrian can move only one cell per time-step. Empirically, the average velocity of a pedestrian is about $1.00\ \mathrm{ms}^{-1}$ under normal [20]. So one time-step in our model is approximately 0.4 s, it is of the order of the reaction time, and thus is consistent with our microscopic rules.

In CA, a rule defines the state of a cell in dependence of the neighbourhood of the cell. In this model, the Von Neumann neighbourhood shown in Fig. 1 is used. Thus, the state of the core cell at the next time-step is dependent on the states of the cells in the neighbourhood including the cell above and below, right and left, also the core cell itself, of this time-step.

In the model, there are two components of walkers including the up walkers moving from the bottom to the upper boundary and the down walkers moving from the upper

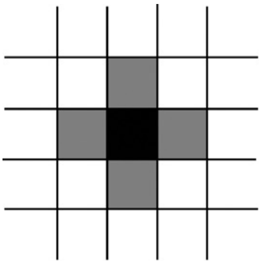

Fig. 1. Von Neumann neighbourhood.

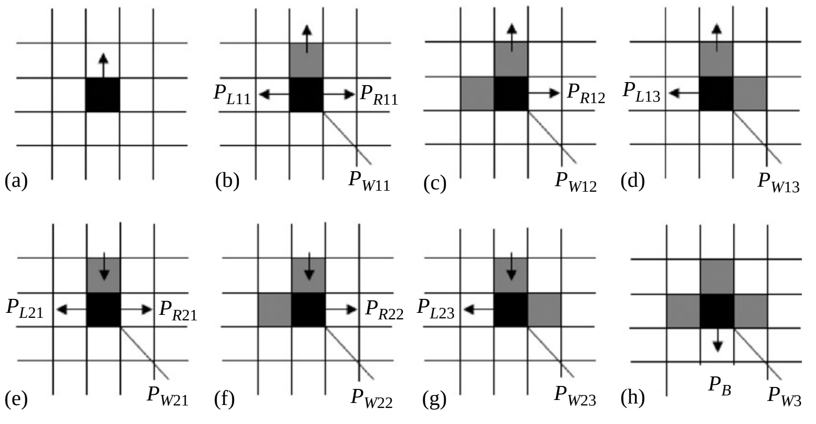

Fig. 2. (a–h) All the possible configurations that the up walker in the core cell may encounter. The arrow in the upper adjacent cell indicates the moving direction of the walker in that cell. The arrow from the core cell indicates the possible direction of the up walker in the core cell may select.

to the bottom boundary. The periodic boundary conditions are adopted, that is, if the up walker arrives on the upper boundary, he moves to the bottom boundary, if the down walker arrives on the bottom boundary, he moves to the upper boundary. And the left and right boundaries are close. Thus the total number of walkers of each type is conserved.

The update is synchronous for all pedestrians at every time-step and at every time-step two problems i.e., the route choice and the confliction occurring when more than one pedestrian vying for a cell, will be resolved. Fig. 2 shows all the possible configurations that the up walker may encounter. In Fig. 2(a), the upper adjacent cell is unoccupied, the up walker will select it to move into whether his left and/or right adjacent cells are occupied or not. But if the upper adjacent cell is occupied at this time-step, his route choice is dependent on the type of the walker in the upper adjacent cell. In Fig. 2(b–d), the upper adjacent cell is occupied by another up walker; in Fig. 2(e–g), the upper adjacent cell is occupied by a down walker. For configuration (b), the up walker in the core cell will select to move to the left unoccupied adjacent cell, the right unoccupied adjacent cell or wait in the core cell with the probability of p_{L11}, p_{R11} and p_{W11}, respectively. For configuration (c), the probability of selecting the right unoccupied adjacent cell or waiting is p_{R12} and p_{W12}, respectively. For configuration (d), the probability of selecting the left unoccupied adjacent cell or waiting is p_{L13} and p_{W13}, respectively. For configuration (e), the probability of selecting the left unoccupied adjacent cell, the right unoccupied adjacent cell or waiting is p_{L21}, p_{R21} and p_{W21}, respectively. For configuration (f), the probability of selecting the right unoccupied adjacent cell or waiting is p_{R22} and p_{W22}, respectively. For configuration (g), the probability of selecting the left unoccupied adjacent cell or waiting is p_{L23} and p_{W23}, respectively. For configuration (h), the probability of selecting the back unoccupied adjacent cell or waiting is p_B and p_{W3}, respectively and in order to strengthen the effect of back stepping, the walker back stepping at a time-step will wait for one time-step before he can move again. If all the adjacent cells are occupied, he has to wait at this time-step.

In the same way, we can define the similar treatment for the possible configurations that the down walkers may encounter. Because in this model one cell can only be occupied by one pedestrian at a time-step, the confliction occurs when more than one pedestrian vying for a cell. In this situation, only one of them will be chosen randomly, with equal probability. The others have to wait at this time-step. Till now the whole performance procedure is presented. Of these rules two characteristics are very important as we can see in the following parts, that is, first, the walker can distinguish the type of walker in the adjacent cell ahead and make optimum decisions correspondingly; secondly, the walker can move backward if necessary.

3. Simulation and result

Initially, the up and down walkers are distributed randomly on the square lattice of $W \times W$ with probability p, where the density of each type of walkers is $p/2$. The total density is defined to be the value of N, the number of total walkers, divided by the total number of cells, $W \times W$. The mean velocity $\langle v \rangle$ of pedestrians moving in one time-step is defined as the value of the number of walkers moving forward, not including those moving to the left, right and back adjacent cell, divided by the total number of walkers existing on the lattice, N. The mean flow $\langle f \rangle$ of pedestrians is defined as the number of up walkers moving through the upper boundary and the down walkers moving through the bottom boundary at one time-step. Following the rules mentioned above, all the cells' states are parallel updated. For each simulation, total 15,000 time-steps are carried out, the value of $\langle v \rangle$ and $\langle f \rangle$ are computed according to the last 5000 time-steps, although in all of our simulations it takes no more than 5000 time-steps to reach the steady states.

In the simulations, the custom in the countries where the pedestrian prefer to walk on the right-hand side of the road is highlighted, that is, if the adjacent cell ahead is occupied by the other type of walker, for example, an up walker encounters a down walker, he will prefer to move to the right adjacent cell if possible, so in the model

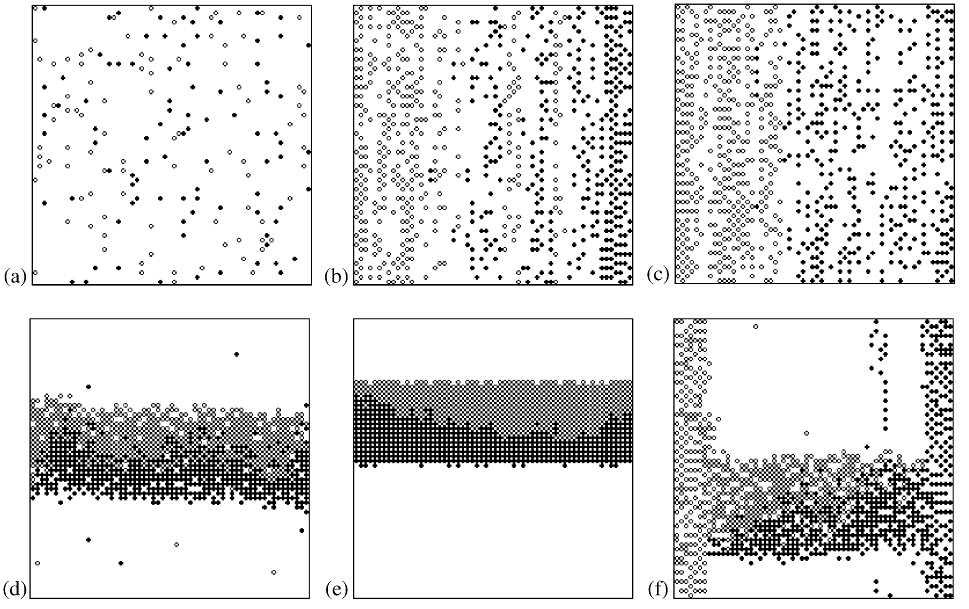

Fig. 3. The configurations of the bi-direction pedestrian movement obtained at $t = 15,000$ time-step where $W = 60$. The freely moving phase when (a) $p = 0.05$, $p_B = 0.5$, (b) $p = 0.20$, $p_B = 0.5$, (c) $p = 0.22$, $p_B = 0.5$. The jammed phase at (d) $p = 0.30$, $p_B = 0.5$, (e) $p = 0.30$, $p_B = 0$, i.e., no back stepping, (f) $p = 0.33$, $p_B = 0.8$. The full circles represent the up walkers moving to upper boundary; the open circles represent the down walkers moving to bottom boundary.

$p_{R21} > p_{L21}$ and $p_{R22} > p_{L23}$ are adopted. In the other countries where the pedestrian prefer to walk on the left-hand side of the road, the contrary rules can be adopted accordingly.

In the simulation, $p_{L11} = p_{R11} = 0.25$, $p_{W11} = 0.5$; $p_{R12} = p_{W12} = 0.5$; $p_{L13} = p_{W13} = 0.5$; $p_{L21} = 0.1$, $p_{R21} = 0.4$, $p_{W21} = 0.5$; $p_{R22} = p_{W22} = 0.5$; $p_{L23} = 0.1$, $p_{W23} = 0.9$ and $p_B = p_{W3} = 0.5$ are assigned. Fig. 3(a–c) shows the typical freely moving configurations obtained at $t = 15,000$, where $W = 60$ when total density p is 0.05, 0.20, 0.22, respectively. Fig. 3(d–e) is the jammed configurations obtained at $t = 15,000$, where $W = 60$ with different value of p_B.

The phase transition is shown in Fig. 3(a). When the total density p is low, the pedestrian can easily reach the freely moving state when each walker can move forward at every time-step, (b) as the total density increases, the system is self-organized into some lanes. In each lane the walkers are of the same type, (c) as the total density continues increasing, the small lanes merge into two large lanes with the left lane containing the down walkers only and the right lane containing the up walkers only, (d) when the total density p reaches the critical value the system transits into the jammed state when only some of the walker can go through the jam. For comparison we assign p_B to be 0 and 0.8 and obtain the jammed configuration in (e) and (f), respectively. In Fig. 3(e) none of the walkers can go through the jam. This is because

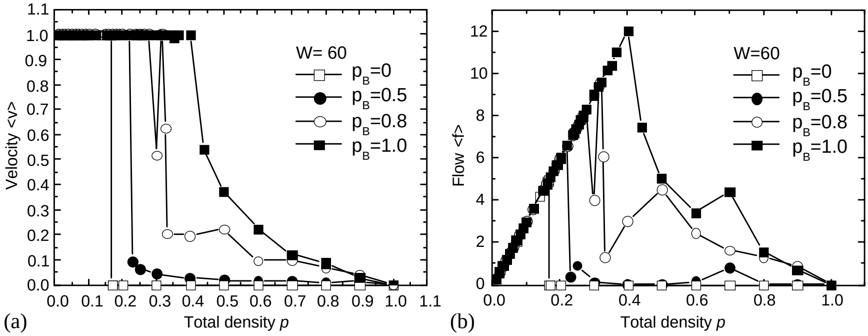

Fig. 4. The plot of (a) the mean velocity $\langle v\rangle$ and (b) the mean flow $\langle f\rangle$ against the total density p for system size $W=60$ in the bi-direction pedestrian movement.

without back stepping, the system will easily come to a deadlock at a relatively low density and the deadlock cannot be broken in this situation. In Fig. 3(f), the jam only exists in the middle area; the walkers can move freely along the left and right boundaries. This is because when p_B is high, the pedestrian will frequently adjust positions in the dense crowd; the deadlock will be broken in this situation. We also find, when p_B is high, the transition from freely moving state to jammed state is not so clear as p_B is low and the definition of critical density p_{cr} is difficult.

Fig. 4 shows the plot of (a) the mean velocity $\langle v\rangle$ and (b) the mean flow $\langle f\rangle$ against the density p when $p_B=0$, 0.5, 0.8 and 1.0, where $W=60$. When $p_B=0$, the system transits from freely moving state to jammed state at the critical density of $p_{cr}=0.167\pm0.005$. In the situation of $p<p_{cr}$, all the walkers can move freely i.e., $\langle v\rangle=1$, but when $p>p_{cr}$ none of the walkers can move forward i.e., $\langle v\rangle=0$ and $\langle f\rangle=0$. When $p_B=0.5$, the transition from freely moving state to jammed at a higher density of $p_{cr}=0.225\pm0.005$. Also, when $p>p_{cr}$, the mean velocity $\langle v\rangle$ and the mean flow $\langle f\rangle$ do not decrease to 0. As p_B increases to 0.8, the critical density increases to 0.325 ± 0.005. And when $p_B=1.0$, the critical density is 0.425 ± 0.005. From Fig. 3, we can find when p_B is high, the change of $\langle v\rangle$ and $\langle f\rangle$ from freely moving state to jammed state is not so drastic. Thus, by adopting the back stepping rule, the deadlock at the low density is broken and the model can simulate more realistic pedestrian movement.

Fig. 5 shows the jammed configurations obtained at $t=15,000$, where $W=60$ when $p_B=1.0$ at the total density of $p=0.44$, 0.60, 0.80. It presents the transition of the jammed configuration when $p_B=1.0$. At the initial stage, the jam forms in the middle of the area; along the left and right boundaries, most of the pedestrian can still move freely. As the density increases, the jam expands and more pedestrian are blocked, when the density near 1.0, most of the pedestrian cannot move because of too many people in the limited area.

Fig. 6 shows the plot of the critical density p_{cr} of different system sizes against the probability of back stepping p_B. Here, the critical density p_{cr} increases with the increasing of p_B. This means by frequently adjusting in the dense crowd, the system

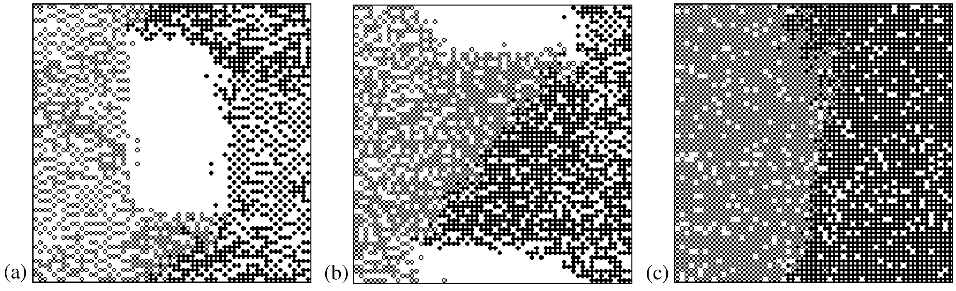

Fig. 5. The configurations of the bi-direction pedestrian movement obtained at $t = 15,000$ time-step where $W = 60$, $p_B = 1.0$. The jammed phase at (d) $p = 0.44$. (e) $p = 0.60$. (f) $p = 0.80$. The full circles represent the up walkers moving to upper boundary; the open circles represent the down walkers moving to bottom boundary.

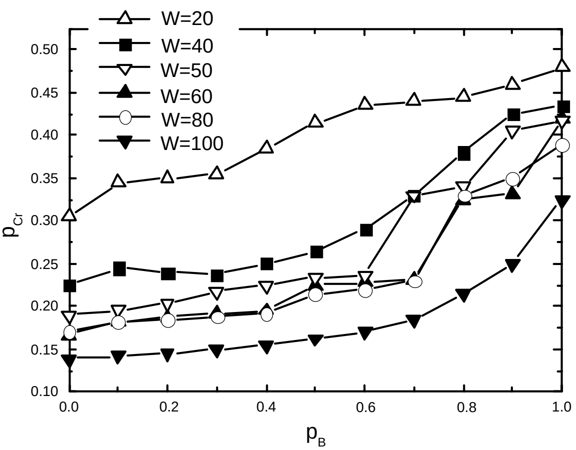

Fig. 6. The plot of the critical density p_{cr} of different system size against the probability of back stepping p_B.

can reach a more reasonable state. Also, the value of p_{cr} increases as the system size decreases at the same value of p_B. This means the value of p_{cr} is dependent of the system size according to the scope of system size studied in this paper.

4. Summary

In this paper, a CA model is presented to simulate the bi-direction pedestrian movement. Considering the simple human judgment, we have established a set of rules for bi-direction pedestrian movement models. Through some simulations, the phase transition of pedestrian counter flow is presented. And it is very useful for us to study the movement mechanism of pedestrian movement. Also the introduction of back stepping makes the model more reasonable. By comparing the value of critical density of different probabilities of back stepping at different system sizes, we find the critical density increases as the probability of back stepping increases at the same system size. And with the increasing system size, the critical density decreases at the same probability of back stepping according to the scope of system size studied in this paper.

To our knowledge, this paper is the first work establishing the CA pedestrian movement model based on the human judgment and studying the effect of back stepping on the critical density of phase transition. It can be safely predicted that the model will be useful in investigating the various pedestrian movement by doing some corresponding adjustment.

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