Physica A 400 (2014) 1–11

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

New insights into discretization effects in cellular automata models for pedestrian evacuation

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HIGHLIGHTS

- Develop a cellular automata model with finer discretization of space.
- Simulate the evacuation process of pedestrians from a room with an exit.
- Find the effects of the discretization degree and walking velocities.
- Investigate the relations of the exit flow to the exit width.

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form 30 December 2013
Available online 10 January 2014

Keywords:
Cellular automata
Stochastic particle dynamics (theory)
Traffic and crowd dynamics
Traffic models

ABSTRACT

We develop a cellular automata model with finer discretization of space and higher walking velocities more than one cell. The model is used to simulate the evacuation process of pedestrians from a room with an exit. By simulation experiments, we find subtle effects of the discretization degree and walking velocities on the shape of the crowd near the exit, the evacuation time of each individual at different locations, and the evacuation efficiency of pedestrians formulated by two time indicators. We also investigate the relations between the exit flow and the exit width, formulated by the model, and compare the flow–width relations with those obtained by laboratory experiments in the existing literatures. This study is helpful for the validation and calibration of microscopic pedestrian models with discrete space representation and further narrowing the gap between these models' theory and their application to engineering.

1. Introduction

Increases in city and urban populations and mass events have raised interest among researchers and authorities on problems of pedestrians and crowd dynamics [1,2]. Pedestrians and crowd behavior in different scenarios have been researched using mathematical models and computer simulations [3–12]. These models and simulations help to shed light on pedestrian-dynamics problems and influence engineering decisions that maintain public facility service levels and ensure pedestrian safety. A class of typical models simulating pedestrians and crowd dynamics are the cellular automata (CA) models [5–7]. Generally, in the CA models, space is discretized into square or regular hexagon cells, each of which is either empty or occupied by exactly a pedestrian, and time is discretized into slices, in each of which each pedestrian moves a cell. We refer to the CA models as the traditional CA models. This makes the traditional CA models ideally suited for large-scale computer simulations. At the same time, the discretization has to be regarded as an approximation of reality.

In view of the above problem, some literatures, e.g., Refs. [13–21], introduced the idea of finer discretization of space and higher walking velocities more than one cell into the traditional CA models, in other words, the size of each cell is smaller

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http://dx.doi.org/10.1016/j.physa.2014.01.001

than that of a pedestrian, each pedestrian occupies more than one cell, and each pedestrian moves more than one cell in each time slice. These literatures have respective motivations for introducing the idea and these motivations can be summarized as follows:

(1) In a CA model with finer discretization of space and higher walking velocities, a realistic distribution of different walking velocities of pedestrians can be implemented easily [13,15,19,20];
(2) A CA model with finer discretization of space and higher walking velocities can reproduce some phenomena, which cannot be reproduced by the traditional CA models [16];
(3) A finer discretization of space corresponds to a more accurate representation of the geometrical structures of pedestrian facilities in a natural way, for example, the size of an exit, an obstacle, or a room, may not be an integral multiple of the size of a cell occupied by exactly an individual [13,17–21];
(4) It would be interesting to consider the case where the cell size approaches zero in order to make contact with the models with continuous space representation [13,19];
(5) In a CA model with finer discretization of space, pedestrians of different sizes can occupy different numbers of cells and pedestrians' locations can be out of alignment rather than in orderly rows or lines [17–20];
(6) The finer discretization of space makes the formulation of the interaction forces between pedestrians and between a pedestrian and an obstacle more convenient and accurate [14,19,20];
(7) In the traditional CA models, the timescale is too large to study pedestrian dynamics accurately in high density situations and some subtle effects are ignored as a result of the simplest update rule [17];
(8) The fundamental diagram of the flow along a corridor, formulated by the traditional CA models, is nearly symmetric with maximal flow at the critical density of approximately $1/2$; however, experimental data shows a non-symmetric fundamental diagram with maximal flow at the critical density not more than $1/2$ [13,15];
(9) The interaction horizon of pedestrians is not isotropic since pedestrians react mainly to stimuli in front of them, and this anisotropy can be better taken into account in a CA model with larger interaction range [13,15].

These literatures illustrated that the CA models with finer discretization of space and higher walking velocities are superior to the traditional CA models in these aspects: (1) formulating the flow-density relation [13,15]; (2) modeling interactions among pedestrians [14,19]; and (3) simulating the process of pedestrian evacuation in such areas as a classroom and a ship [18,20,21]. At the same time, finer discretization of space and higher walking velocities lead to some problems and the discretization degree and walking velocities have effects on pedestrian dynamics [13,16,17]. It needs to be noted that the walking velocities are measured in the number of cells, that is to say, its unit is cells per time slice. Studying these problems and effects are helpful for validating and calibrating the models and further narrowing the gap between the models' theory and their application to engineering.

In this paper, we focus on a CA model of simulating the evacuation of pedestrians from buildings and research the effects that the discretization degree and walking velocities have on the pattern and efficiency of pedestrian evacuation. In Section 2, a CA model with finer discretization of space and higher walking velocities more than one cell is developed. In Section 3, by simulation experiments, we illustrate the effects, which the discretization degree and walking velocities have on the shape of the crowd near the exit, the evacuation time of each individual at different locations, and the evacuation efficiency of pedestrians formulated by two time indicators. We also investigate the relations between the exit flow and the exit width, and compare the flow–width relations with some empirical data in the existing literatures. Section 4 concludes the paper.

2. Model description

For the sake of clarity, we present this model for a specific simulation scenario shown in Fig. 1. In this scenario, a number of pedestrians evacuate a room with the area of $L \times L$ m^2. There is an exit with the width of W m in the middle of the east wall. The space in the room is discretized into two-dimensional square cells. A pedestrian occupies $n \times n$ cells. The area occupied by a pedestrian is 0.4×0.4 m^2, corresponding to the typical space occupied by a pedestrian in a dense crowd. Thus, the area of a cell is $(0.4/n) \times (0.4/n)$ m^2. In each discrete time slice Δt, the positions of all pedestrians are updated in a random sequence (i.e., shuffled rule). That is to say, in each time slice, each of the pedestrians still in the room is given a sequence number at random and their positions are updated according to their sequence number. Each individual only moves into those cells, which are not occupied by others or obstacles (i.e., the excluded-volume effect is considered).

In each time slice Δt, each pedestrian moves not more than s cells in one of the horizontal and vertical directions (i.e. the Manhattan metric) or remains unmoving. Let directions 1, 2, 3, and 4 represent the east, south, west, and north directions respectively. s_{ij} denotes the feasible movement distance of pedestrian i in direction j, it is measured in the number of cells, and then the relation $0 \leq s_{ij} \leq s$ holds. This indicates that if pedestrian i moves $s_{ij} + 1$ cells in direction j, then either he (or she) will occupy those cells occupied by others (or obstacles) or he (or she) will move $s + 1$ cells. When $\bar{s}_i = \max\{s_{ik}, k = 1, 2, 3, 4\} > 0$ and $s_{ij} = \bar{s}_i$, we refer to the movement of pedestrian i in direction j as available. Fig. 2 gives two examples of illustrating how to compute the feasible movement distance and how to determine the available movement direction. In this figure, both pedestrians 1 and 2 move not more than 3 cells in each time slice. The feasible movement distances of pedestrian 1 in directions 1, 2, 3, and 4 are 2, 1, 2, and 1 cell respectively, and his (or her) movement in directions 1 and 3 is available; the feasible movement distances of pedestrian 2 in directions 1, 2, 3, and 4 are 2, 2, 3, and 0 cell respectively, and his (or her) movement in direction 3 is available.