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A fine discrete field cellular automaton for pedestrian dynamics integrating pedestrian heterogeneity, anisotropy, and time-dependent characteristics

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ABSTRACT

This paper proposes a discrete field *cellular automaton* (CA) model that integrates pedestrian heterogeneity, anisotropy, and time-dependent characteristics. The pedestrian movement direction, moving/staying, and steering are governed by the *transfer equations*. Compared with existing studies on fine-discretized CA models, the proposed model is advantageous in terms of flexibility, higher spatial accuracy, wider speed range, relatively low computational cost, and elaborated conflict resolution with synchronous update scheme. Three different application scenarios are created by adjusting the definite conditions of the model: (1) The first one is a unidirectional pedestrian movement in a channel, where a complete jam in the high-density region is observed from the proposed model, which is missing from existing floor field CA models. (2) The second one is evacuation from a room, where the evacuation time is independent of the discretization factor, which is different from previous work. (3) The third one is an ascending evacuation through a 21-storey stair system, where pedestrians move with constant speed or with fatigue. The evacuation time in the latter case is nearly twice of that in the former.

1. Introduction

The accurate and realistic modeling of pedestrian movement is essential for the efficient and safe flow of pedestrians. Application scenarios include, but are not limited to, planning of pedestrian facilities, prevention of crowd disaster, and optimization of evacuation routes. Pedestrian heterogeneity, anisotropy and time-dependent characteristics may play dominant roles on the modeling of pedestrian dynamics. Some well-known examples are as follows.

(1) Pedestrian traffic is physiologically heterogeneous in terms of age, gender, incapacitation, and psychological characteristics (e.g. perception and reflection of the surrounding environment) (Fu et al., 2015a; Fu et al., 2015b).
(2) The physical size and behavior of a pedestrian in different directions are varied, i.e., anisotropy. For example, pedestrians react mainly to stimuli in front of them (Kirchner et al., 2004). Additionally, the free speeds of walking forward, laterally, and backward are different, which is modeled as a specific kind of behavior termed *sidestepping* in this paper.
(3) Parameters of pedestrian movement may change with time. Examples include fatigue (Luo et al., 2016), falling and injury.

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Usually, a pedestrian adjusts continuously his/her velocity to the surrounding pedestrian density, a phenomenon quantified by the fundamental diagram (Seyfried et al., 2009; Bandini et al., 2014).

Numerous models for pedestrian dynamics have been proposed so far, and can be categorized as macroscopic/microscopic or discrete/continuous (Schadschneider et al., 2011). The three key theoretical and practical criteria against which a pedestrian model is evaluated are:

(1) How to realistically model pedestrian movement using some relatively simple rules or equations (Moussaïd et al., 2011);
(2) How to easily extend the general model to simulate specific pedestrian movement (such as evacuation from a complex structure building) by adding/removing or modifying definite conditions; and
(3) How to efficiently conduct large-scale crowd simulation with acceptable errors.

As one type of microscopic discrete model, traditional *floor field cellular automaton* (FFCA) model enjoys flexibility, extendibility and computational efficiency (Burstedde et al., 2001). It has successfully reproduced many self-organization collective phenomena (Alizadeh, 2011), such as jamming and clogging, lane formation, and oscillation at bottlenecks. However, like many other grid-based models, *cellular automaton* (CA) models are often criticized for the over-discretization of space and time (Dietrich et al., 2014, Liu et al., 2014a), resulting in unrealistic pedestrian movement such as diagonal movement trajectories and limited speed range.

In most CA models, each pedestrian occupies exactly one cell and moves through one grid per time step. It is a finite approximation of the reality. According to Kirchner et al. (2004) and Guo (2014), a fine (spatial) discretization can enable: (1) an easy implementation of realistic velocity distribution; (2) accurate geometric structure of pedestrian facilities; (3) analysis in relation to continuous models; (4) characterization of specific phenomena such as dead-lock and misalignment; (5) quantitative analysis and calibration of pedestrian dynamic models; and (6) modeling of pedestrian anisotropy.

A number of fine discrete models have been proposed in the literature. Kirchner et al. (2004) first investigated the discretization effect, and found that the fundamental diagram with pedestrians velocity $v_{\max} > 1$ (grid/time step) fits better with empirical results than $v_{\max} = 1$ (grid/time step). In Kirchner's model, a $0.4\,\text{m} \times 0.4\,\text{m}$ square, which is the projection area of a pedestrian from empirical observation, is divided into 2×2 grids, and the pedestrian desired velocity is a multiple of 1.3 m/s. In many cases this coarse discretization does not yield accurate results, and finer grids combined with continuously varying velocity are needed. Song et al. (2006) introduced interaction forces, and allowed overlaps among pedestrians. In their 3×3 grid model, every pedestrian has the same desired velocity (1 m/s). However, this model lacks flexibility and computational efficiency when used in some complex pedestrian traffic scenarios. For example, in counter flow, the 'cores' of several pedestrians might collide with each other because of the forces. Weng et al. (2007) considered smaller spatial grids but again assuming that all the pedestrians have the same desired velocity, which is a multiple of 0.25 m/s. This results in unrealistic coarse trajectories. With finer spatial and temporal discretization, Xu et al. (2008) proposed a discrete model where the desired velocity is 1 m/s, and the distance traveled by a pedestrian is a multiple of the grid size (which is equal to the size of a pedestrian). As a consequence, in their model pedestrians always align with each other, leading to unrealistically high efficiency in evacuation scenarios. Zhang et al. (2008) stipulated that a pedestrian moves according to the free movement velocity and the unoccupied space in his/her moving direction; this yields the phenomena of monopolizing exit and dislocable queues. However, the velocity rule tends to generate coarse, unrealistic zig-zag trajectories of pedestrians. Considering contact forces among pedestrians, Guo and Huang (2008) modeled push and bump with a pedestrian occupying 3×3 grids by a modified floor field CA model. Later, under both good and zero visibility conditions, Guo et al. (2012) studied evacuation from a classroom with a pedestrian occupying 2×2 grids. In these two models, however, pedestrians have the same desired free velocity. Even though finer discretization was proposed in another work (Guo, 2014), pedestrians in the model still have the same desired free velocity of 1 m/s. The transfer probabilities of directions are calculable only for a specific structure (i.e. a square room), and cannot be applied to more complex building structures. Furthermore, pedestrians move in a single direction in one time step, resulting in unrealistic formation of crowds around the exit.

One should also note that for most of these aforementioned finer discrete models, shuffled or sequential update scheme is used. However, for sequential scheme, pedestrians are not equal-footing, and the results might be quite different depending on the sequences. Schadschneider and Seyfried (2009) believed that both shuffled and sequential schemes are difficult to calibrate (e.g. in reality, pedestrians always make decisions at the same time but not in any order), and appear to be rather unrealistic. Besides, Kirchner et al. (2003) argued that any other form of random or ordered sequential update schemes tends to disguise the real number of conflicts arising among pedestrians in the system. In reality, pedestrians in conflict situations slow down or hesitate for a short moment when trying to resolve the conflict. This reduces, on average, the velocity of all pedestrians involved. In some cases, for example evacuation of a room, the modifications of the update schemes make the models behave in different ways (Seitz and Köster, 2014). Xu et al. (2008) found that the update schemes have significant influence on the evacuation time when analyzing the discretization effect in FFCA model. Kirchner et al. (2004) pointed out that the evolution of flow rate changes with different update schemes. Most recently, Luo et al. (2018) investigated the influence of four different update schemes on pedestrian dynamics in a quantitative and systematic way. They found that for pedestrian evacuation, the evacuation time is enlarged, and the difference in pedestrians' walking abilities are better reflected, under parallel scheme. In face of a bottleneck, using a parallel scheme leads to a longer congestion period and a more dispersive density distribution. The exit flow and space-time distribution of density and velocity have significant discrepancies under different schemes when pedestrian flow with high desired velocity is simulated.

Thus, for the purpose of calibration and capturing conflicts, a synchronous/parallel update scheme is preferred. However, the complex conflict resolution due to fine discretization has to be taken into consideration as one employs a synchronous/parallel