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Perceived cost potential field cellular automata model with an aggregated force field for pedestrian dynamics

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ABSTRACT

This paper proposes a perceived potential field and an aggregated force field for navigation of pedestrians in a walking domain with poor visibility or complex geometries. While the former field used in uncrowded cells simply reflects the pedestrians' desire to minimize their travel costs, the latter field used in crowded cells suggests much stronger interaction between pedestrians. Compared with a formulation that does not include the latter field, the proposed model displays an advantage in simulating over-crowded pedestrian flows, e.g., at the front of a bottleneck or at a left/right turn in a corridor; the simulated phenomena, including phase transitions and fundamental diagrams, agree well with the observation and studies in the literature.

1. Introduction

Pedestrian dynamics are important in the analysis and design of transportation facilities, walkways, and public buildings. Recently, various models have been developed to simulate walking behavior and investigate macroscopic and microscopic characteristics of pedestrian dynamics in complex scenarios; many of the typical collection effects (Burstedde et al., 2001; Kirchner and Schadschneider, 2002) and self-organized phenomena (Helbing et al., 2005) described have reflected the microscopic interactions of individuals and the effects of environmental information, which paves the way for further development of pedestrian dynamics.

Typical pedestrian flow models include the macroscopic continuum model (Hughes, 2002; Hoogendoorn and Bovy, 2004; Huang et al., 2009; Xia et al., 2009; Jiang et al., 2010; Xiong et al., 2011), the microscopic social force model (Helbing and Molnár, 1995; Moussaïd et al., 2011), and the cellular automata (CA) model (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Huang and Guo, 2008; Kuang et al., 2008; Kretz, 2010; Zhang et al., 2012). The continuum model describes pedestrian flow using partial differential equations, in which case the pressure inside a crowd reflects the compressibility of the crowd (Lee and Hughes, 2005) regardless of whether there is physical contact between the pedestrians. Physical contact can usually be avoided if the density is lower than 5.6 ped/m^2; however, contact becomes inevitable as the density

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increases and the accumulated pushing force takes effect. The social force model treats pedestrians as particles and establishes the acceleration of these particles using Newton's second law, the forces reflecting self-driven power toward destinations and interactions between pedestrians. The CA model divides the walking domain into cells, and each pedestrian remains in place or moves to an empty neighboring cell with a certain probability at each time step.

The CA model has attracted much attention in simulating complex pedestrian collection effects, due to its simple update rules. In particular, the floor field CA model (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Varas et al., 2007) introduces static and dynamic floor fields for navigating pedestrian motion. The value of the static floor field in a cell is measured by the distance between the cell and the destination, which is unchanging across the simulation. The value of the dynamic floor field in a cell is measured by a virtual trace left by pedestrians, which may decay and diffuse at each time step, and reflects the interactions between pedestrians. See also Huang and Guo (2008), Kretz et al. (2010) and Guo and Huang (2012). Another typical CA model (Zhang et al., 2012) incorporates the static and dynamic factors in a cost distribution, and the cost potential in all cells are derived by solving an Eikonal equation in each time step. Accordingly, a pedestrian remains in place or moves to an empty neighboring cell so that the reduction in potential is maximized. Such a path-choice strategy actually helps the pedestrian to minimize his/her cost to the destination, and thus the randomness in determining the probabilities for occupation is greatly reduced. This is reasonable under the assumption that all pedestrians are familiar with the surroundings.

To model a pedestrian crowd with a higher density or compressibility, the CA model is extended such that a cell is allowed to be occupied by, at most, two pedestrians (Xie et al., 2012). Moreover, a microscopic force field (Henein and White, 2007, 2010) is introduced to describe interpersonal contacts. To model pedestrian flow in a domain with complex geometries, the degree of visibility, which influences pedestrians' path-choice strategy, is considered (Moussaïd et al., 2011; Zeng et al., 2011; Guo et al., 2012; Xu and Huang, 2012). The floor field CA model is used to simulate pedestrian flow with multiple exits (Huang and Guo, 2008; Xu and Huang, 2012), through a corridor with bottlenecks (Kretz, 2010) or corners (Kretz, 2009; Bönisch and Kretz, 2009; Steffen and Seyfried, 2009; Zeng et al., 2011; Guo and Tang, 2012), in a T-junction walking domain (Peng and Chou, 2011), and in a room with obstacles (Alizadeh, 2011).

In this paper, the cost potential field (Zhang et al., 2012) is extended to simulate pedestrian flow in a walking facility with complex geometries, in which visibility is considered. For the extension, a perceived cost potential field is constructed by taking its value in a cell to be the weighted average between that of the cost potential in Zhang et al. (2012) and that of a memory potential. The memory potential is measured by the distance or displacement from the cell to the destination, which is actually a degenerated cost potential, such that the surroundings are completely invisible and pedestrians are only able to conceive of the path to their destination according to their experience. Thus, the weight on the cost potential is taken to be a measure of visibility.

We further introduce pushing forces for the simulation of crowded or over-crowded pedestrian flow, which is increasing of the density and decreasing of the visibility in the surroundings, pointing to the destination from referred cells. Moreover, we assume that these forces aggregate in a certain area behind a pedestrian with respect to that pedestrian, forming an aggregated force field that can take effect due to contact or phycological factors that push the pedestrian into a nonempty neighboring cell when a threshold value is exceeded. As a cell is allowed to be occupied by, at most, 2 pedestrians, the maximal density herein extends to 12.5 ped/m^2, which is twice that in most CA models (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Zhang et al., 2012).

The general path-choice strategy of the proposed model is as follows. For an occupied cell (one or two pedestrians) that is uncrowded, a pedestrian in the cell navigates using the perceived cost field; that is, he/she remains in place or moves to an empty neighboring cell, reducing the perceived cost potential to the fullest extent. This rule is the same as that in Zhang et al. (2012), except that the cost potential is replaced by the perceived cost potential and the cell might be occupied by two pedestrians. The formulation is reduced to that in Zhang et al. (2012) if the walking domain (including the destination) is completely visible and a cell can only be occupied by, at most, one pedestrian. For an occupied cell that is crowded, which means that all of its neighboring cells are also occupied and the local density is greater than 6.25 ped/m^2, the aggregated force field is used for navigation.

The remainder of this paper is organized as follows. In Section 2, we formulate the perceived cost potential field CA model and the aggregated force field. In Section 3, two scenarios are presented to show the robustness of the model in simulating crowded or even over-crowded pedestrian flow in a corridor, with a bottleneck, and with a 90° corner, respectively. The conclusions are presented in Section 4.

2. Model description

The walking domain is divided into cells of the size 0.4 m × 0.4 m. We assume that a cell can be occupied by, at most, two pedestrians, which suggests a maximal density of 12.5 ped/m^2. This is very close to the 11 ped/m^2 suggested by the field study (Helbing et al., 2007; Moussaïd et al., 2011), and twice the 6.25 ped/m^2 derived by assuming that a cell can be occupied by, at most, one pedestrian.

The dimensionless density is defined as $\rho(x,y,t)=\sum_{(x,y)\in D_{x,y}} n(x,y,t)/(2\mid D_{x,y}\mid)$, where $D_{x,y}$ represents the local domain around (x,y) including 25 cells, and $\mid D_{x,y}\mid$ denotes the number of cells in $D_{x,y}$. Considering that the mean velocity of a pedestrian is approximately 1 m/s, we choose the maximal velocity to be $v_{\max}=1$ m/s. This choice has the advantages of