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A novel grid-based mesoscopic model for evacuation dynamics

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HIGHLIGHTS

- A novel mesoscopic evacuation model with various grid size is proposed.
- The static floor field is extended in mesoscopic scale.
- Density map over time can intuitively reflect the evacuation process and the bottleneck area.
- A series of practical cases is executed to investigate the optimal time step.

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ABSTRACT

This study presents a novel grid-based mesoscopic model for evacuation dynamics. In this model, the evacuation space is discretised into larger cells than those used in microscopic models. This approach directly computes the dynamic changes crowd densities in cells over the course of an evacuation. The density flow is driven by the density–speed correlation. The computation is faster than in traditional cellular automata evacuation models which determine density by computing the movements of each pedestrian. To demonstrate the feasibility of this model, we apply it to a series of practical scenarios and conduct a parameter sensitivity study of the effect of changes in time step δ. The simulation results show that within the valid range of δ, changing δ has only a minor impact on the simulation. The model also makes it possible to directly acquire key information such as bottleneck areas from a time-varied dynamic density map, even when a relatively large time step is adopted. We use the commercial software AnyLogic to evaluate the model. The result shows that the mesoscopic model is more efficient than the microscopic model and provides more in-situ details (e.g., pedestrian movement pattern) than the macroscopic models.

1. Introduction

Efficient building evacuation saves lives in a fire. An inefficiently designed evacuation route may expose occupants to excessive levels of toxic gas, smoke or dangerously high temperatures before they can complete their evacuation. This danger is especially high in the mega-buildings of modern cities. Nowadays, a variety of approaches, both microscopic and macroscopic, have been widely adopted to manage pedestrian flows and optimise building layouts. The fluid-dynamic model, a typical macroscopic model, treats pedestrian flow as a fluid [1,2] and uses Navier–Stokes equations to model the motion in crowds [3]. Hughes [4–6] developed several time-dependent, nonlinear, simultaneous equation ns to represent crowds

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and to observe features of real pedestrian movement. Generally, microscopic models are divided into two types: continuous models, such as the social force model, and discrete models, such as the cellular automaton (CA) model [7]. The social force model proposed by Helbing et al. is a well-known continuous model that considers a mixture of socio-psychological and physical forces that influence the behaviour of a crowd and can reproduce several typical collective phenomena (e.g., clogging and the 'faster-is-slower effect') during evacuation [8–10].

Burstedde et al. [11] developed a floor field model inspired by the process of chemotaxis. As a representative CA model, the model offers a new concept – the floor field – that consists of a static floor field used to describe the distance from the evacuee to the nearest exit, and a dynamic floor field that reflects the dynamic attraction between evacuees [12]. Floor field models have been widely applied to investigate the influence of different room geometries, such as large exit scenarios [13], bottleneck areas [14], square rooms with a partition wall [15] and the influence of exits with different positions and widths [16]. Many factors, such as the inertia of pedestrians [17], a regular or panic situation [18], proxemic relationships [19], physical force [20] and fire spread [21] can be gradually added to the floor field model. All of these factors change the transition possibility and improve the floor field model. Another modification to the floor field model is to change the grid size or floor field assignment. Kirchner [22] systematically studied the discretisation effects by reducing the grid size in which each pedestrian was allowed to occupy multiple cells. Further investigation using finer cells has shown that when inertia and the forces received by or imposed on others are added to the model, they have an accumulative and asymmetric effect on pedestrians [23,24]. New static floor field methods, such as the most feasible distances method [25], the introduction of two additional cognitive coefficients (exit width and congestion near the exits) [26] and the use of 'virtual reference points' to redefine the static floor field [27] have proved to be feasible and to achieve high evacuation efficiency during simulation.

Although microscopic and macroscopic models are widely used to describe pedestrian flow in evacuation analyses, few studies have considered pedestrian models at the mesoscopic scale. Hanisch et al. [28] transferred the mesoscopic concept from traffic flow to pedestrian flow and proposed a mesoscopic evacuation model. Their model used nodes and links to present the macroscopic concept and focused on the movements of groups of people instead of individuals. A similar approach proposed by Di Gangi [29] used the density–speed function to control the movement of vehicles under emergency conditions. In 2008, Teknomo and Gerilla [30] developed a grid-based mesoscopic pedestrian movement model. A regular lattice was applied, with cells covering the floor layout. The size of the cells was larger than that of the cells in the CA model, but the movements of pedestrians were still individually tracked. Note that this model is an approximate CA model that reduces the requirement for the computation of individual movements inside the grid. However, a probabilistic approach was still used to determine the next moves of the pedestrians. Bellomo et al. [31] proposed a mathematical approach that combined mathematical measurements with generalised kinetic theory based on a complex system viewpoint. In the mesoscopic scale, an infinitesimal number of pedestrians forms the balance of pedestrians flowing in and out of a specific location. This formulation can be discretised into numerical models for application in a grid-based model.

In this study, we develop a novel grid-based mesoscopic model in which space and time are discretised. The grids have various sizes, and some of the grids are larger than in the CA model (i.e., 0.4×0.4 m). The traditional static floor field method is not appropriate for the larger cells. Therefore, we have developed a new static floor field algorithm for our mesoscopic scale modelling. In the mesoscopic scale, we consider the crowd evacuation as a continuum, which means that we compute movements in the density of pedestrian flows instead of tracking the movements of all of the individuals. Pedestrian density updates for each grid are processed according to the density–speed correlation. We apply this new model to five scenarios with different geometries. Parameter sensitivity studies are conducted to analyse the effect of time step on the simulation results. The performance of this novel mesoscopic model is compared with the results obtained by a commercial package.

2. Model development

To increase the calculation efficiency of the mesoscopic model, the room is divided into a squared mesh with cells that are larger than in the CA model. Instead of examining the movement of each pedestrian, our model examines the density flows between cells. The density flows move towards neighbouring cells that have lower floor fields, as measured by a particular density flow algorithm, and the density update is conducted in parallel for all of the cells. The floor field method is defined in the following subsections, which also summarise the model's density update rules.

2.1. Static floor field method

As shown in Fig. 1(a), in the traditional CA model, a room is divided into cells that have the same grid size (i.e., 0.4×0.4 m) [32]. In the mesoscopic model, the room is discretised into cells of different sizes. A discretisation example of our model is shown in Fig. 1(b). The size of the cells close to the exits is set as 0.4×0.4 m, which is the typical space occupied by a pedestrian; cells far away from the exit are larger, specifically, an integer multiple of 0.4×0.4 m. A cell that is 0.4×0.4 m is called a traditional cell (TC) and a larger cell is called a multiple cell (MC), such as MC1. This strategy of discretising a room into large cells greatly decreases the total number of cells and significantly reduces the overall calculation time. A new parameter, N_m, is introduced to represent the scaling factor for MC. N_m is calculated as MC/TC. Therefore, a cell can be empty or occupied by $1, 2, \ldots, N_m$ pedestrians.

In the mesoscopic model, each cell is labelled with a constant value called a static floor field (SFF), which reflects its distance from the exit. Lower SFF values correspond to cells nearer the exit. The assignment of SFF in the mesoscopic model is conducted as follows.