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Analysis of the pedestrian arching at bottleneck based on a bypassing behavior model

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HIGHLIGHTS

- Velocity–time domain was constructed for modeling behavior decision.
- Bypassing strategy of pedestrian behavior was modeled in the velocity–time domain.
- The expectation time of the pedestrian arching at the bottleneck is depending on the width of the exit exponentially.

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ABSTRACT

A bypassing behavior model was proposed, in which the local optimal decision behavior in the strategy level was modeled in velocity–time domain, to describe how pedestrians bypass the local obstacles considering the relative speed.

The model contains (1) pedestrian visual and contact information acquisition; (2) motion state prediction of the local obstacles based on the visual and contact information; (3) pedestrian bypass strategy modeling in the velocity–time domain; (4) moving and overlapping solution. In the numerical solution, velocity domain was divided into n equal angle, the value of n ranges from 2 to infinity, the Manhattan space was refined gradually to Euclid Space accordingly, in which the movement of pedestrians was described.

The model was applied to the analysis of pedestrian arching at the bottleneck in the emergent evacuation situation. (1) The results showed that the formation of the pedestrian arching at the bottleneck was deformation pressure, because many pedestrians try to pass through the bottleneck simultaneously, even in the absence of friction, the pedestrian arching still occurs; (2) In the emergent situation, we are more concerned about the bottleneck attribution of resistance to form the arching, the calculation and simulation results showed that the probability of an arching and the bottleneck width is an exponential function relationship, so when the stampede occurs in the middle of the bottleneck, the probability of arching will increase exponentially.

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1. Introduction

Pedestrian behavior model has been an important topic for decades due to its ability to give insight into the crowd dynamics, which is helpful to optimize the design of facility and improve the safety management of mass events. The pedestrian individual behavior model can be grossly divided into two categories, cellular automata & lattice gas model (CA & LG) in discrete space and social force (SF) model in continue space [1–3].

The CA model can reproduce the collective phenomena grossly with little cost of calculation time than the continuum models. In the field of finer CA, on the one hand, researchers proposed more and more field variables and parameters based on the pedestrian behaviors, such as friction, repulsion, contain and press effects, and the finer CA can reproduce more complex self-organization phenomenon such as pedestrian arching [4–6]; on the other hand, researchers intend to describe the complex pattern by using simple rules, so the finer CA only depending on the smaller grid, without adding more field variable and parameters, and the pedestrian arching pattern also occurred based on the model [7–10]. The smaller grid CA gains the abilities to describe the complex phenomenon by improving the details of the movement and increasing calculation amount, which let us observing the pedestrian movement in smaller scale and slow motion. However, in the smaller grid CA model, pedestrians can move multi grids in one step, this cause a new problem of the local route accuracy, the research [10] has noticed this and given a static solution briefly. Another two studies [11,12] about moving CA were valuable and interesting, pedestrians can move continually in Euclid space, and their surroundings were discrete fan-shaped grids.

The continuum space SF model has been derived from Boltzmann-like equation, which was successfully describe the collective phenomenon such as clog, arching and faster-is-slower effect, the research [2] became a milestone and a standard for pedestrian modeling. However, there are two problems in the SF model, (1) the model trajectory is still not fully consistent with empirical observations [13,14], the obstacle avoidance behavior is based on the repulsion which is a function of the distance between target pedestrian and the obstacles, this convenient method made the model face the difficulty to adjust its repulsion to different direction of obstacles movement, Ref. [13] proposed a heuristic behavior model to find the tradeoff that an unobstructed direction which were not deviating too much from the direct line to the object, Refs. [15,16] solve this problem by considering the relative velocity or classification of obstacles. (2) Even in the absence of friction, the self-driven force will decrease when pedestrians bypass an obstacle (see Fig. 1), Refs. [4,15] constructed direction field to solve this problem, this problem also was solved simply by increasing navigation points around the static obstacles in the engineering application software. Ref. [17] defined the concept of velocity obstacle and the set of reachable avoidance velocities for motion planning in dynamic environments, Ref. [18] proposed the method of reciprocal *n*-body robots collision avoidance based on velocity obstacle. Most of the model fulfilled the pedestrian self-driven movement based on the attractive force of a **long-range destination** (LRD), this mechanism could not describe the dynamic decision making process of pedestrians about the **temporal local destinations** (TLD). The essence of pedestrian movement is that, consciously or subconsciously, pedestrian moves to the LRD safely and effectively according to the sequence of TLD.

In this study, the velocity–time domain was proposed for describing pedestrians temporal local decision, and the active bypassing behavior was modeled in the velocity–time domain, which was optimized by a max–min distance function. The model was applied to the bottleneck analysis in the emergent evacuation situations. The simulation results showed that, (1) the complex phenomenon such as clogging, arching pattern and faster-is-slower effects can be reproduced in the model; (2) the formation probabilities of pedestrian arching at the bottleneck depend on the crowd density, width of the bottleneck and pedestrian radius.

2. The model

2.1. Vision and contact information

The information collected by pedestrian from the environment was classified as vision and contact, and was updated by scanning the vision area and contact area (see Fig. 2) at each time step. Each of pedestrian *i* faces direction $Df_{(i)}$ at position $x_i(t)$ with radius r_i, and a certain desired direction $Dg_{(i)}$ points to the LRD (in Fig. 2 means the Exit location). The vision and contact information can be formulated as the follows.

$$\begin{aligned}&Vision(i,t)=\left\{x_j(t),v_j(t),\ldots\right\}_{j=1,2,\ldots,m}\cup\{w_k\}_{k=1,2,\ldots m'}\\&x_j(t)\ subject\ to\begin{cases}(1)\ \left\|x_i(t)-x_j(t)\right\|\le R_{scan},\\(2)\ \angle\left(\overrightarrow{x_jx_i},Dir(i)\right)\le\Phi/2\end{cases}\end{aligned}\tag{1}$$

$$\begin{aligned}&Contact(i,t)=\left\{x_j(t),v_j(t),\ldots\right\}_{j=1,2,\ldots,m}\cup\{w_k\}_{k=1,2,\ldots m'}\\&x_j(t),w_k\ subject\ to\ \left\{\left\|x_i(t)-x_j(t)\right\|\le r_i\right\},\{\|x_i(t)-w_k\|\le r_i\}.\end{aligned}\tag{2}$$

Here, $\left\{x_j(t),v_j(t),\ldots\right\}$ is the position and velocity information of the pedestrian *j*, who was defined as the neighbor of the target pedestrian *i*, the item $\{w_k\}$ is the location of the wall *k* or other static obstacles.

Fig. 3(a) shows a static pedestrian *j* blocks the route of pedestrian *i* in the direction $Df_{(i)}$ as the blue arrow shows, if pedestrian *i* keep his/her direction, there will be a collision at the red arrow point. Pedestrian *i* need turn the left θ angle