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An optimization-based overtaking model for unidirectional pedestrian flow

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A B S T R A C T

We propose an optimization-based model for simulating the overtaking behaviour in the unidirectional pedestrian flow. A 'visual area' is introduced so that agents could receive the information regarding their surroundings and react by choosing one of three options: to move straight on, to dodge to the left, or to dodge to the right. And a side preference of each pedestrian for evading and overtaking is implemented based on traffic 'social norms'. The model was validated by reproducing the experimentally obtained pedestrian flow patterns. The effects of the initial pedestrian formation on overtaking behaviour and the evacuation time have been analysed in different geometries. The results show that pedestrian flow patterns after overtaking are obviously influenced by both the initial positions and density of the slow pedestrians in the front. Phase changes of pedestrian formation are observed in both experiment and simulations. On the other hand, for sparse pedestrian crowds, the egress time of the fast individuals is mainly impacted by the horizontal distance between the initial positions of the slow pedestrians in the front, especially in the geometry with a bottleneck.

1. Introduction

Human dynamics have attracted much attention over recent decades not only in the fields of granular flows [1] and transportation [2] but also in physics [3]. One topic that has been intensely studied is the relevance of the collision avoidance mechanisms such as the self-stopping mechanism [4], overtaking behaviour [5], and counter-flow-based active decision [6]. Numerous efforts and studies can be classified into two main streams of discrete and continuum models, among which the cellular automata (CA) model and the social force model are the most popular approaches [7]. The discrete CA model was originally employed in traffic models [8], and then its extensions have been widely used to capture various characteristics of crowd movement [9–11] where pedestrian dynamics are defined by the interactions between a cell of interest and the neighbourhood cells. For real-world applications, pedestrian eyesight and game theory are implemented [12] to study the negotiation process of collision avoidance. Additionally, the effect of different walking speeds of pedestrians on the collision has been considered [13] by applying different update intervals. The variation in walking speed was extended further by introducing transition probabilities [14] to take into account the overtaking behaviour in the pedestrian crowds. However, since all cells are identical, there is no variation in size and shape among different individuals, and the stepwise movement from cell to cell does not allow for movement in arbitrary directions [10].

The social force model [15,16] is based on analogies to Newtonian mechanics and has the advantage of operating in continuous space and time. In this model, the motion of a pedestrian is described by using acceleration that depends on the motive, normal contact and repulsive forces. The function describing the interactions among the individuals plays a significant role in the resulting collective patterns [17] such as lane formation [18], stop-and-go waves [19], and crowd turbulence [20]. Another famous self-organization phenomenon the 'faster-is-slower effect' [16] shows that panicking evacuees tend to become more motivated (e.g., continuously push each other), which will reduce their chances of survival. However, for decades, there has been a consensus that actual panics occur rarely in real crowds [21,22], and the evacuating people tend to behave rationally in a normal walking situation. Thus, the initial social force model has been improved widely to adapt to different environments or to achieve more accurate results [7].

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Following the modifications of the social force model, researchers are currently working on the collision avoidance mechanism by predicting the positions and motion of pedestrians in the crowds. For instance, by calculating the closest collision point given the pedestrians' current velocities, a vector is added as an extra component to their desired velocity to ensure collision avoidance [23]. To specify the individual bias towards one evading side (i.e., left-side or right-side), a traffic 'social norm' is implemented by predicting the future motion of agent j and rotating its velocity vector counter-clockwise by angle θ_v [24]. However, this approach assumes that all pedestrians share the same 'social norms'. In addition to the modification of the pedestrians' velocities, the model is improved by adding some new force components. For example, based on the movement direction and the relative displacement between the pedestrians, new following and evasive force components are included to avoid collisions [25]. Generally, a personal area of the agent could be used for the detection of other pedestrians' positions and movement. A personal space [4] and a respect area [26] are used for modelling of the self-stopping phenomenon. The self-stopping behaviour will be triggered if other pedestrians invade the specific personal area. In a counter-flow-based active decision model [27,28], a short-range area is divided into three overlapping sectors, and a sector with the least counterflow is chosen. Additionally, a binary interaction model is specifically designed based on a decision zone to reproduce individual avoidance trajectories observed under experimental conditions [17]. Then, a cognitive heuristics method is proposed based on visual information [29]. The combination of heuristics with body collisions could reproduce the features of crowd disasters at extreme densities and the individual avoidance trajectories observed experimentally. However, owing to the heuristic of choosing most direct path to the destination point considering the obstacles, the cognitive model fails to correctly reproduce the situation where two pedestrians are facing each other at a narrow bottleneck [30]. A modified cognitive heuristics model introduces a discrete desired direction based on an optimization problem by adding personal territory to each agent. Pedestrians could choose the direct path or a path that has the least deviation from the direct path [31], which however may also cause the oscillation of slot selection during the simulation.

The phenomenon of overtaking is widespread in reality because pedestrians commonly walk at different velocities. The examples of the overtaking behaviour could be found at railway stations, on campuses or pedestrian streets. Pedestrians with a higher walking velocity are accustomed to overtaking other pedestrians with a lower walking velocity to maintain their own desired walking velocity [32]. A side preference for avoiding the collision in the overtaking process has been commonly considered in the previous studies of overtaking. That is, pedestrians should decide whether to evade each other on the left-hand side or on the right-hand side [17]. For instance, in the overtaking model [24], the 'social norm' of avoiding on the left, and moving on the left when overtaken to give space to the overtaker (Japanese preference) is implemented by rotating the pedestrians' velocity vector counter-clockwise by angle θ_v. However, this fixed assumption could not account for the possibility of overtaking on the opposite direction which occurs in reality. Modelling of overtaking behaviour was divided into two parts in another study [32]. The degree of overtaking is determined by a two-dimensional Gaussian function. The direction of overtaking could be calculated according to the force from the surrounding pedestrians and boundaries. If the direction of the resultant force is upward, the pedestrian will walk upward, and vice versa. And if the downward resultant force is equal to the upward resultant force, the pedestrian will still walk downward. In a more general approach, i.e., the cognitive heuristics model [29,31], a pedestrian chooses the direction that allows for the most direct path to the target. However, this cognitive model exhibits technical limitations owing to the difficulty of its implementation and extension [30]. Thus, a side preference for avoiding the collision in the overtaking process could not be easily taken into account.

Based on the physics-based framework, we propose an optimization-based overtaking model for simulating unidirectional pedestrian flow, considering both the direct path to the target and a side preference of agents when evading and overtaking. The proposed overtaking model is a modification of the counterflow-based active decision model [27] that has been implemented in the FDS+Evac platform [28]. The extended social force model in Refs. [27,28] is used as the movement model of each agent in the proposed model. And the same short-range area is employed as 'visual area' for all pedestrians to receive the information regarding the environment and react by choosing one of three options: to move straight on, to dodge to the left, or to dodge to the right. However, the way of pedestrians' decision-making has been totally changed. Pedestrian agents in *FDS + Evac* model prefer following other agents in alternative uniform flow. While, in our overtaking model, pedestrian agents tend to evade and overtake other agents with same direction and to choose a walking direction with the least unidirectional flow. Furthermore, pedestrians' sensitivity to the space availability in the front 'visual area' is introduced so that only the pedestrians with high walking speed has the ability to overtake the obstructions in front of them. On the other hand, pedestrians with lower speed prefer the right-hand traffic and moving straight ahead without much detour. Additionally, the traffic 'social norms' of right-hand traffic and left-hand overtaking traffic are both considered. Pedestrians with high walking speed prefer the left-side direction to overtake slow individuals, and pedestrians with low speed prefer right-hand traffic and direct path to the target such as the exit. Consequently, the selection of a walking direction depends on the combination of the utility evaluated in the front area and a side preference based on the traffic 'social norms'. The effect of the initial pedestrian formation on overtaking behaviour and evacuation time has been explored in different geometries. The simulation results show that our model can reproduce the reasonable overtaking behaviour of individuals in pedestrian crowds.

The rest of the letter is organized as follows: in Section 2, the force-based movement model is briefly reviewed and then the optimization-based overtaking model is introduced in detail. Section 3 presents the model validation, simulation results and analysis. Conclusions are given in Section 4.

2. Model

2.1. Movement model

The extended version of the initial social force model [15,16] in FDS+Evac [27] is adopted to describe the movement of pedestrians. Each agent is represented by elliptical cross-sectional shape of a human body. Pedestrians experience normal contact, psychological and motive forces as well as the corresponding moments. In this letter, henceforth, the *MSF* model refers to this modified social force model. The movement of each agent evolves depending on the equation of motion:

$$m_i \frac{d^2\vec{x}_i(t)}{dt^2} = \frac{m_i}{\tau_i}(\vec{v}_i^0 - \vec{v}_i) + \sum_{j\neq i}(\vec{f}_{ij}^{soc} + \vec{f}_{ij}^{c}) + \sum_{w}(\vec{f}_{iw}^{soc} + \vec{f}_{iw}^{c}) + \vec{\xi}_i(t), \quad (1)$$

where $\vec{x}_i(t)$ is the position of pedestrian i. The velocity of pedestrian i at time t is given by $\vec{v}_i(t) = d\vec{x}_i(t)/dt$. The first term on the right-hand side describes the motive force on the pedestrian.

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