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The Trace Model: A model for simulation of the tracing process during evacuations in complex route environments

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ABSTRACT

In emergency evacuations, not all pedestrians know the destination or the routes to the destination, especially when the route is complex. Many pedestrians follow a leader or leaders during an evacuation. A Trace Model was proposed to simulate such tracing processes, including (1) a Dynamic Douglas–Peucker algorithm to extract *global key* nodes from *dynamically partial* routes, (2) a key node complementation rule to address the issue in which the Dynamic Douglas–Peucker algorithm does not work for an extended time when the route is straight and long, and (3) a modification to a follower's impatience factor, which is associated with the distance from the leader. The tracing process of pupils following their teachers in a primary school during an evacuation was simulated. The virtual process was shown to be reasonable both in the indoor classroom and on the outdoor campus along complex routes. The statistical data obtained in the simulation were also studied. The results show that the Trace Model can extract relatively *global key* nodes from *dynamically partial* routes that are very similar to the results obtained by the classical Douglas–Peucker algorithm based on whole routes, and the data redundancy is effectively reduced. The results also show that the Trace Model is *adaptive* to the motions between followers and leaders, which demonstrates that the Trace Model is applicable for the tracing process in complex routes and is an improvement on the classical Douglas–Peucker algorithm and the social force model.

1. Introduction

The simulation of emergency evacuations in public places is an important issue of security and is therefore the focus of dynamics models. Current typical dynamics models can be divided into 2 categories: discrete and continuous models. Cellular automata [1–3] and lattice gas models [4–6] are typical discrete models. Cellular automata models represent space with a uniform grid of cells with local states depending on a set of rules describing pedestrian behaviors, whereas lattice gas models use fluid or gas dynamics analogs to describe how density and velocity change over time. Zheng et al. [1] presented a cellular automaton model to simulate the evacuation process in a closed square with a partition wall. The effect of the length of the wall on the evacuation efficiency was analyzed. Li et al. [6] developed a modified lattice gas model by introducing a

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parameter called 'exit bias' to simulate evacuation dynamics in an office building. They found that the accuracy of the simulation heavily depends on the model's pedestrian speed. The social force model [7–10] is a typical continuous model. This model abstracts the pedestrians' behavior drivers into 3 types of forces: the attractive forces from the target, the repulsive forces from obstacles, and the repulsive forces from other pedestrians. A pedestrian's activities are controlled by these forces during an evacuation, and crowd behaviors are thus simulated when there are many pedestrians. Ha and Lykotrafitis [11] employed a social force model to investigate the effect of complex building architectures on uncoordinated crowd motions during urgent evacuations. Four scenarios with different room door sizes, main exit sizes, desired speeds and friction coefficients were simulated to determine how the various factors affected the evacuation time. Ma and Wang [12] modified the social force model by introducing a view radius to describe the range that can be observed by a pedestrian. The modified model was used to simulate pedestrians evacuating a hall full of smoke. The results showed that pedestrians require a longer time to evacuate for shorter view radii. Li et al. [13] proposed a five-stage model based on a modified social force model to describe the trampling process of an individual pedestrian caused by picking-up behaviors during escalator transfers, and based on this model, the individual trampling risks were studied.

In addition, many researchers have argued that in emergency evacuations, not all pedestrians know the destination or the routes to the destination, especially when the environment is complex or is unfamiliar to the pedestrians. In most cases, only a few pedestrians who are familiar with the environment can identify an appropriate path to the destination, and the others tend to follow these guides or leaders to the destination [14–16]. Researchers have attempted to modify the dynamics models to address such issues. Hou et al. [14] proposed a modified social force model considering the leadership effect. In their model, only the trained leaders know the exit positions, and the followers can only follow the guidance of the leaders. The effects of the number and positions of the trained evacuation leaders in single-exit, double-exit and four-exit room structures with limited visibility were studied. The authors found that the planning of leaders' positions was much more important than the number of leaders. Yang et al. [15] proposed a guided crowd model by modifying the social force model to simulate guided crowd dynamics in large-scale public places. The dynamics of the pedestrians and guides were mathematically modeled. Certain social phenomena, such as gathering, balance and conflicts were observed. Yuan et al. [16] modeled the crowd evacuation behavior of "flow with the stream" with guides using a CA model and found that a smaller visibility range makes the evacuation more difficult and that leaders can efficiently accelerate the evacuation.

However, there are still deficiencies in these modified models. In Hou's model, the authors assumed that the followers tend to (a) move toward the position of a trained leader and (b) maintain the same movement direction as the trained leader. In Yang's model, the authors also assumed that the direction of the followers pointed toward the guide. Such assumptions imply that the environment is simple, for example, a blank room, so that a follower can move toward a leader at any time. However, in reality, the evacuation routes are not always straight lines but rather are more complex, such as zigzag paths, and the route from a follower to a leader is also not always straight if there are obstacles on the routes. As a result, a follower cannot be assumed to move towards a leader all of the time. Therefore, the tracing process in complex route environments and in complex routes should be reconsidered, and new models should be proposed to address such issues.

Because the social force model can better describe the interactions between individuals [14] and can qualitatively reproduce certain self-organizing phenomena, such as lane formation and arching [15], the social force model was employed as the base model to help simulate such tracing processes. The classical social force model is given as Eqs. 1–3. In Eq. (1), the first element on the right side of the equation is the self-driving force from a target. The second element represents the social forces from other pedestrians or in other words, the pedestrian forces (given in Eq. (2)). The third element represents the repulsive forces from the obstacles (given in Eq. (3)). A, B, K, and κ are empirical parameters.

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_{w} f_{iw} \tag{1}$$

$$\mathbf{f}_{ij} = \{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\}\mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij} \tag{2}$$

$$\begin{aligned} \mathbf{f}_{iw} = &\{A_i \exp[(r_i - d_{iw})/B_i] + kg(r_i - d_{iw})\}\mathbf{n}_{iw} \\ &- \kappa g(r_i - d_{iw})(\mathbf{v}_i \cdot \mathbf{t}_{iw})\mathbf{t}_{iw} \end{aligned} \tag{3}$$

The structure of this paper is as follows. In Section 2, a "Trace Model" is proposed to model the tracing process in complex route environments, and the social force model is modified considering psychological factors in the tracing process. Based on the model, a virtual scenario of pupils tracing their teachers in a primary school is presented in Section 3; in Section 4, the results are evaluated to validate the Trace Model.

2. The Trace Model

2.1. Analysis of the issue

From the perspective of the social force model, a follower's tracing process in pursuit of a leader can be viewed as moving under the guidance of a series of targets. These targets are the leader's positions along the routes. When the follower has passed these targets one by one, the tracing process is achieved. One means of constructing such a series of targets is to