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Driving-forces model on individual behavior in scenarios considering moving threat agents

Shuying Li [a,b], Jun Zhuang [b,*], Shifei Shen [a], Jia Wang [a]

[a] Department of Engineering Physics, Institute of Public Safety Research, Tsinghua University, China

[b] Department of Industrial and Systems Engineering, University at Buffalo, SUNY, United States

HIGHLIGHTS

- Driving-forces model is built considering scenarios including threat agents.
- An experiment is conducted to validate the key components of the model.
- The advanced Elliptical Specification II model is used for comparison.
- The fitting errors show the accuracy and stability of the Driving-forces model.
- The simulation results show the practicality of the Driving-forces model.

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ABSTRACT

The individual behavior model is a contributory factor to improve the accuracy of agent-based simulation in different scenarios. However, few studies have considered moving threat agents, which often occur in terrorist attacks caused by attackers with close-range weapons (e.g., sword, stick). At the same time, many existing behavior models lack validation from cases or experiments. This paper builds a new individual behavior model based on seven behavioral hypotheses. The driving-forces model is an extension of the classical social force model considering scenarios including moving threat agents. An experiment was conducted to validate the key components of the model. Then the model is compared with an advanced Elliptical Specification II social force model, by calculating the fitting errors between the simulated and experimental trajectories, and being applied to simulate a specific circumstance. Our results show that the driving-forces model reduced the fitting error by an average of 33.9% and the standard deviation by an average of 44.5%, which indicates the accuracy and stability of the model in the studied situation. The new driving-forces model could be used to simulate individual behavior when analyzing the risk of specific scenarios using agent-based simulation methods, such as risk analysis of close-range terrorist attacks in public places.

1. Introduction

Recently, terrorists have created tension around the world. For example, the terrorist group Islamic State of Iraq and al-Sham (ISIS) and its followers carried out a series of attacks against France, England, and America in 2015. Governments across the world are facing great difficulty in allocating defensive resources to reduce the risk of terrorist attacks. Public

* Corresponding author.
E-mail address: jzhuang@buffalo.edu (J. Zhuang).

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places, especially those gathering large crowds of people, such as airports, train stations and theatres, have always been at a high risk of attack. For example, in the case of the November 2015 ISIS attack in Paris, 89 of the 130 victims were killed in the Bataclan theatre [1]. When an attack happens in a public place, it is difficult for individuals to get out of danger in time due to secondary effects, such as panic and overcrowding [2]. Thus, effective precautionary measures, such as evacuation signs and guides based on risk assessment of specific attack scenarios, become important in such situations.

The agent-based simulation (ABS) method is often used to simulate crowd behavior in different scenarios when conducting risk analysis. Some researches focused on crowd behavior in different layouts of circumstances under normal situations. Dai [3] simulated the pedestrian counter flow through bottlenecks. Johansson [4] simulated pedestrian behavior in waiting areas. More studies have focused on emergency situations, especially evacuation situations in different architecture layouts and scenarios, for example, the T-shaped intersection [5], the multi-room multi-floor building [6] and the escalator transfer area [7]. Some studies have also talked about key factors in emergency evacuation, such as the leadership effect [8] and the guidance effect [9]. Such studies even extended to terrorist attack scenarios. Wan [10] conducted a crowd evacuation simulation for bioterrorism in subway station environments.

In order to improve the accuracy of simulation results, building more suitable models and identifying the parameters for different types of agents in different scenarios becomes a critical point [11]. There are two categories of behavior models in general, macroscopic and microscopic models. Macroscopic models often treat crowd flow as a flowing continuum using the physical features of the gas flow or liquid flow [12]. Microscopic models, such as cellular automaton (CA) model [13] and social force (SF) model [14], consider an individual as a self driving particle. Among these models, the SF model is often used to set rules in ABS because of its good performance in describing individual behavior, especially the influences coming from other pedestrians, in continuous space [15].

The SF model was put forward by Helbing in 1995 [14]. The classical model considered other pedestrians and walls as influential factors to individual behavior. Then Helbing et al. [16] extended the model to escape panic situations, which considered the influence of a sliding friction force caused by body compression. Since then, many researchers have modified the details of the SF model, which made the model more suitable for different scenarios. For example, Kretz [17] modified the SF model accounting for oscillation situations. However, studies considering scenarios including threat agents, especially moving threat agents, such as an attacker in a terrorist attack scenario, are still inadequate. One reason may be that individual behavior in emergency situations is much more complex than normal situations. More factors need to be considered in such situations.

There still remain some aspects to be improved when looking at these related studies. Risk studies of crowds in different scenarios based on ABS methods often used the classical SF model as individuals' behavior rules without validating the accuracy of the model and the parameters in the specific scenario considered [18,7]. Some studies did not even list the values of the parameters in the social force model while doing simulations [5,10,19]. Studies focused on modifying the SF model under different conditions, especially under emergency situations, always lack validation from cases or experiments with real human subjects [20,4,9,19,8,17].

Due to these challenges, this study moves forward by building a driving-forces individual behavior model in scenarios including moving threat agents, and validating the key components of the model with experimental data. This could contribute to later ABS risk studies of emergency response. The remainder of this paper is structured as follows: Section 2 formulates the seven individual hypotheses and builds the driving-forces model; Section 3 introduces the experiment conducted to do the model calibration; Section 4 calibrates and validates the model; Section 5 presents the model fitting and simulation results, as well as the sensitivity analysis results; and Section 6 concludes and provides future research directions. Appendix A shows the flowchart of the data process programming; and Appendix B shows the probability density curves of the offset angle.

2. The model

In the basic SF model [16], the change of an individual's velocity $\boldsymbol{v}_i$ is influenced by the individual i's desired speed v_i^0 and its direction $\boldsymbol{e}_i^0$, as well as the interaction forces generated by other pedestrians $\boldsymbol{f}_{ij}$ and walls $\boldsymbol{f}_{iW}$. The individual adapts his current speed to the desired speed in the period of characteristic time τ_i. The velocity change of individual i with weight m_i can be presented as Eq. (1).

$$m_i \frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = m_i \frac{v_i^0 \boldsymbol{e}_i^0 - \boldsymbol{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \boldsymbol{f}_{ij} + \sum_{W} \boldsymbol{f}_{iW}. \tag{1}$$

Individual behavior during an emergency differs a lot from normal conditions. Firstly, most individuals in emergency situations do not think as rationally as they do in normal situations. So they behave more instinctively when they panic, and need more time to form a behavioral strategy. Secondly, the most important factor that influences individual behavior is the threat agent rather than other pedestrian or obstacle under emergency. Thirdly, most individuals run faster in emergency situations than usual. The running speed may not always remain constant. So there hardly exists a certain desired speed. Individuals keep adjusting their speed to fit the situation they face and to avoid becoming utterly exhausted. Finally, the existence of uncertainty and randomness makes an individual's behavior more difficult to predict when facing an emergency.