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A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model

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ABSTRACT

In the study of pedestrian movements, a consideration of group behaviors is important because of their potential impacts on pedestrian flow dynamics. In this paper, we investigate the group behaviors during emergency evacuation, which is a critical case for emergency crowd management but has not been fully explored and understood. It has been well recognized that in evacuation situations, some people within a crowd, especially those who are with families and friends, often move in small groups and act in particular patterns distinct from individuals. As a result, the crowd is a mixture of individuals and groups rather than a pure collection of individuals. To capture and evaluate the influence of group behaviors on crowd evacuation, we propose an extended floor field cellular automaton (CA) model that takes into account such phenomena. Our model is formulated by leveraging the leader-follower behavior rule that is evident in pedestrian group behaviors. To calibrate and validate the proposed model, a few field experiments of crowd evacuation were conducted in a university building. Through a representative case study, it is demonstrated that the proposed extended floor field CA model can replicate the well-known phenomena in crowd evacuation such as collective arch-like clogging at the exit as well as other commonly observed group behaviors in evacuation. Moreover, it is found that the total crowd evacuation time significantly increases with the presence of pedestrian groups in the crowd. The results also show that such negative effects of group behaviors in crowd evacuation intensify when the density of the crowd is higher. Subsequently, sensitivity analyses are performed to further explore how pedestrian group behaviors are influenced by model parameters that reflect the pedestrian flow dynamics in evacuation scenarios. With its capability of realistically replicating the field pedestrian evacuation, the proposed model can serve as a valuable tool for predicting crowd evacuation time and designing guidelines for pedestrian evacuation in emergency situations, in particular when group behaviors are salient.

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1. Introduction

Recently, the simulation models of pedestrian dynamics have been widely utilized by researchers in certain research fields including evacuation planning (Helbing et al., 2001, 2007; Richter et al., 2013; Schadschneider et al., 2009), evacuation infrastructure deployment (Shiwakoti and Sarvi, 2013) and optimization of public transport operations (Abdelghany et al., 2014; Helbing et al., 2005; Shiwakoti et al., 2009). A prerequisite to realizing these applications is that the simulation models should be able to represent and replicate realistic pedestrian behaviors. Over the past few decades, various approaches have been proposed to simulate crowd evacuation including fluid dynamics models (Henderson, 1971, 1974), gas-kinetic models (Agnelli et al., 2015; Degond et al., 2013; Hoogendoorn and Bovy, 2000), social force model (Anvari et al., 2015; Helbing and Molnar, 1995; Henderson, 1971), cellular automaton model (Jian et al., 2014; Xiao et al., 2016; Yu and Song, 2007), agent-based model (Farhan, 2015; Wang et al., 2014, 2016; Yin et al., 2014), network-based model (Kunwar et al., 2016; Løvås, 1994). In general, these models can be classified into continuous and discrete models. Compared with the discrete models, the continuous models are more sophisticated in terms of representing pedestrian behaviors, whereas they are more computationally intensive to simulate complicated geometries and large-scale scenarios (Guo and Huang, 2012).

The demand of high computational efficiency can be well alleviated by using the classical cellular automation (CA) model, which allows for large-scale computer simulations due to its discrete property (Abdelghany et al., 2016). The CA model creates an approximation of actual individual behavior with simple local rules. It has been proven that the CA model is capable of replicating sophisticated pedestrian motions and reproducing a variety of pedestrian dynamics phenomena such as lane formations in bi-direction pedestrian flow and jamming and clogging in dense crowds (Kuang et al., 2008; Ma et al., 2010; Xiao et al., 2016; Zhang, 2015). However, although the CA model has many merits, it cannot well represent pedestrian's walking behavior since it is formulated on the basis of discrete space and time. Specifically, in the CA model, a pedestrian looks like a hopper that jumps from one lattice to another. Consequently, the more complex collective phenomena of pedestrian flows such as oscillation patterns at intersections or freezing-by-heating cannot be replicated with the CA model.

As the extensions of the classical CA model, a variety of CA-based models for pedestrian flow simulations have been proposed over the last decade such as the Blue and Alder CA model (Blue and Adler, 2000, 2001), the floor filed CA model (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Kirchner et al., 2003). Most of these CA models treat pedestrians in a crowd as homogeneous individuals. However, it is well known and generally recognized that pedestrian crowds are often a mix of individuals and groups. The existing empirical and observational studies have shown that pedestrian groups account for a large proportion of crowds in walking areas and the group behaviors significantly affect crowd dynamics (Moussaïd et al., 2010). After recognizing this phenomenon, some researchers have tried to incorporate the group behaviors when developing a reliable pedestrian simulation model. Moussaïd et al. (2010) extended a general social force model by introducing an interaction force within group members and successfully simulated group spatial patterns at different pedestrian density levels. Other existing models for pedestrian group behavior were mainly based on the behavior rule that group members were likely to stay close to each other and keep a certain spatial structure (Bandini et al., 2011; Köster et al., 2011; Qiu and Hu, 2010; Reynolds, 1987; Vizzari et al., 2013). These studies have demonstrated that pedestrian groups act in a way distinct from isolated individuals and have a meaningful impact on crowd dynamics. However, few studies have addressed the modeling of pedestrian group behaviors in emergency evacuation, a most critical scenario among all use cases.

Evacuation often occurs at places where people gather to live, work, study or entertain. As pointed out in an early literature that crowds were often dominated by small groups at large events (James, 1953), it is reasonable to deduce that a significant portion of a crowd is likely to act in groups during evacuation, in particular when they evacuate with families and friends. In addition, according to some empirical investigations, the pedestrian group behaviors in evacuation are quite different from those in normal situations. Specifically, pedestrians in groups tend to stay close to each other and choose the same egress to exit during evacuation. The behavior of backtracking often occurs when a pedestrian realizes that his or her partners are lost. However, a majority of existing models for group movements in evacuation did not fully account for these group behavioral characteristics. For example, while Xu and Duh (2010) modeled the pedestrian group behavior in evacuation by introducing the bond force to reflect the fact that groups are tend to walk abreast in evacuation, their study didn't cover the aforementioned characteristics of pedestrian group behaviors, such as staying together or backtracking. Yang et al. (2005) studied the psychological effect of being with a crowd and the kin behavior inside the crowd by simulating a two-dimensional CA model. However, their study mainly focused on the descriptive analysis of the psychology and lacked a detailed description of lacked a detailed specific description on its simulation model approach.

To address the deficiency in the previous studies and to enhance the understanding of crowd dynamics in evacuation, the primary objective of our work is to develop a reliable simulation model that takes into consideration all these important characteristics of group behaviors. In this paper, an extended floor filed CA model is proposed to model the group behaviors in pedestrian evacuation. The main idea of the typical floor filed CA model is based on bionics that aims to capture pedestrians' herding behaviors, as well as the behaviors of seeking the shortest path in the evacuation process (Kirchner and Schadschneider, 2002). The model has been successfully used in previous studies to investigate pedestrian evacuation dynamics (Hsu and Chu, 2014; Jian et al., 2014). The formulation of such a model is flexible and extensible to incorporate additional social and psychological factors for crowd evacuation simulation (Bandini et al., 2014; Duives et al., 2013). However, the general floor field CA model hasn't been extended to incorporate the pedestrian group behavior in crowd evacuation, which is the main contribution of our work reported here.