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A three-stage evacuation decision-making and behavior model for the onset of an attack

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ABSTRACT

Pedestrian behavior models have successfully reproduced human movement in many situations. However, few studies focus on modeling human behavior in the context of terrorist attacks. Terrorist attacks commonly occur in crowded public areas and result in a large number of casualties. This paper proposes a three-stage model to reproduce a series of complex behaviors and decision-making processes at the onset of an attack, when pedestrians generally do not have clear targets and have to deal with fuzzy information from the attack. The first stage of the model builds a Bayesian belief network to represent the pedestrians' initial judgment of the threat and their evacuation decisions. The second stage focuses on pedestrians' global assessment of the situation through an analogy with diffusion processes. The third stage uses a cost function to reproduce the trade-offs of distance, safety, and emotional impact when considering a path to take. The model is validated using a video from the November 2015 Paris attack. The behavioral characteristics and trajectories of three pedestrians extracted from the video are reproduced by the simulation results based on the model. The research can be used to set rules when performing risk analysis and strategic defensive resource allocation of terrorist attacks using agent-based simulation methods.

1. Introduction

Many attacks were aimed at crowded public places, killing many people. Relatives, friends, and people across the world were left grieving. Some severe attacks since 2016 include the following: The July 2016, Nice (France) truck attack killed 86 people and injured 434 people (Nice Attack, 2016); The July 2016, Karrad (Iraq) bombing killed at least 323 people and injured 246 people (Karrada Bombing, 2016); The June 2016, Orlando (United States) nightclub shooting killed 50 people and injured 53 people (Orlando Nightclub Shooting, 2016). The unsafe feelings brought about by these severe attacks also had a large negative influence on public social stability.

Governments try to minimize the risk of being attacked by making decisions regarding defensive resource allocation, especially to critical yet vulnerable areas that have high probabilities of being attacked. It is generally believed that strategic defensive resource allocation considering specific risk characteristics of the target are more effective. For example, allocating more police boxes at high risk points (e.g., at the entrance) in the specific target area is better than random assignment in the full area.

Human factors (e.g., relationships, group behaviors) and environmental factors (e.g., the structural layout, locations of safety zones) are two main characteristics studied in risk assessment for emergency. These characteristics coupled with

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the interactions between them directly influence the consequence of an emergency. Examples include the information exchange and the spacing between pedestrians, and the shielding that obstacles provide to the pedestrians. The interactions between pedestrians and their surroundings during evacuation in general emergencies are well-studied by pedestrian behavior models (Helbing and Molnar, 1995; Burstedde et al., 2001; Hoogendoorn and Bovy, 2003), especially in different architectural layouts (e.g., exit (Helbing et al., 2000), bottle neck (Tanimoto et al., 2010), T-shaped intersection (Chen et al., 2012)). But the studied evacuation situations often happen near the end of emergency, sometimes even after interventions from authorities. Few studies shed light on the onset of an emergency, when pedestrians only get limited information and are not quite sure about where to go. Fewer studies focus on terrorist attacks, which are special types of emergencies with more interactions between pedestrians and the attacker (e.g., the interactions between the shooter and pedestrians in a shooting attack), and among the pedestrians themselves.

To fill the gap, this paper presents a new microscopic pedestrian evacuation decision-making and behavior model in the context of terrorist attacks, especially at the early stage. This is achieved by a three-stage model including the initial judgment stage, the global assessment stage, and the path choice stage. The model considers pedestrian decision-making process dealing with the fuzzy information received from signals at the onset of an attack. Decision-making processes include the evacuation decision, the global situation assessment, and evacuation path choice.

The remainder of the paper is organized as follows: After the literature review in Section 2, Section 3 introduces the model framework of the three stages. Section 4 introduces the case study used to validate the model. Section 5 concludes and provides some future research directions.

2. Literature review

Pedestrian movement behavior has been studied for decades, especially in general walking situations (e.g., uni-directional, bi-directional, uni-exit). In general, there are two categories of behavior models – macroscopic and microscopic. Macroscopic models often treat moving crowd as a flowing continuum using the physical features of a gas flow or liquid flow (Hughes, 2003; Hoogendoorn et al., 2015). Microscopic models, such as the cellular automaton model (Burstedde et al., 2001) and social force model (Helbing and Molnar, 1995), consider a pedestrian as a self-driving particle. For some special situations, the decision-making process is thought to be an important consideration in some advanced behavior models. For example, the Nomad model (Hoogendoorn and Bovy, 2003) focuses on solving daily activities by giving the pedestrian definitive tasks of movement. An integrated model of extended decision field theory and social force model (Xi et al., 2011) focuses on the pedestrian's strategic behavior in shopping scenario. This kind of model often uses the walking direction and velocity to decide the pedestrian movement, which can also be classified as the heuristics-based microscopic model (Moussaid and Nelson, 2014).

Pedestrian behavior modeling and agent-based simulation method are often used together. Good agent-based simulations, which perform well in reproducing observed phenomenon, can support the rules of pedestrian behavior models used in the simulations. Additionally, the agent-based simulations based on appropriate pedestrian behavior models are effective methods to conduct risk analysis in many situations, especially emergencies occurring in crowded public areas (Wang et al., 2016; Joo et al., 2013; Richter et al., 2013; Barrett et al., 2013; Pelechano and Malkawi, 2008). Compared to normal situations, pedestrian behavior becomes more complicated when the pedestrian is at risk or under evacuation condition. For example, some crowd self-organization phenomena (e.g., the herding effect (Helbing et al., 2005), the zipper effect (Hoogendoorn and Daamen, 2005), the Faster-is-Slower effect (Helbing and Johansson, 2011)) can be observed during stressful evacuation situations (Duives et al., 2013). At the same time, more behavioral strategies and tactics are used by the pedestrian before taking actions. For example, Asano (Asano et al., 2010) studied collision avoidance in the tactical level of pedestrian behavior during evacuation situations. Samuel (Rodriguez and Amato, 2010) studied the controlling behaviors showing the cooperations between directing pedestrians and the cooperating pedestrians. Hao et al. (2014) studied the exit selection strategy in pedestrian evacuation behavior.

Many aspects of crowd-based terrorist attacks have been studied using agent-based simulation methods. For example, Herbert (Tsang et al., 2010) developed a computational framework for simulating the crowd behavior in terrorist attacks, as well as the rescue missions of police or safety guards. Usmani (Imana and Kirk, 2009) studied the impact of a suicide bombing attack on humans in a crowd. Oğuz et al. (2010) used continuum dynamics-based crowd simulation to study the crowd behavior in emergency situations, such as fires, explosions, and terrorist attacks. He mainly considered the pedestrian emergency behavior of running away from the incidents under the propagation of panic. However, none of these studies focus on specific microscopic pedestrian behavior in attack situations, which contain more detailed decision-making processes for pedestrians to deal with uncertainties. The limitation of the parameter calibration and model validation due to a lack of data may be one reason there is a shortage of studies.

3. Model

3.1. Framework

This paper models the evacuation decision-making processes of a pedestrian at the onset of an attack, including the initial judgment, evacuation decision-making, the global situation assessment, and evacuation path selection. The model contains three stages, shown in the framework diagram in Fig. 1. (i) Initial judgment stage. When an attack happens, there is a series