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Research paper

A fuzzy-theory-based method for studying the effect of information transmission on nonlinear crowd dispersion dynamics

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ABSTRACT

Emergencies involved in mass events are related to a variety of factors and processes. An important factor is the transmission of information on danger that has an influence on nonlinear crowd dynamics during the process of crowd dispersion. Due to much uncertainty in this process, there is an urgent need to propose a method to investigate the influence. In this paper, a novel fuzzy-theory-based method is presented to study crowd dynamics under the influence of information transmission. Fuzzy functions and rules are designed for the ambiguous description of human states. Reasonable inference is employed to decide the output values of decision making such as pedestrian movement speed and directions. Through simulation under four-way pedestrian situations, good crowd dispersion phenomena are achieved. Simulation results under different conditions demonstrate that information transmission cannot always induce successful crowd dispersion in all situations. This depends on whether decision strategies in response to information on danger are unified and effective, especially in dense crowds. Results also suggest that an increase in drift strength at low density and the percentage of pedestrians, who choose one of the furthest unoccupied Von Neumann neighbors from the dangerous source as the drift direction at high density, is helpful in crowd dispersion. Compared with previous work, our comprehensive study improves an in-depth understanding of nonlinear crowd dynamics under the effect of information on danger.

1. Introduction

Large scale public places are common in our daily life. Unexpected events such as fires, earthquakes and poison gas leakage may occur in these places. How to guarantee safety of crowd members has become an important issue. There is an urgent need to develop and evaluate emergency evacuation plans. However, this is difficult as crowd dynamics involves a nonlinear system with heterogeneous individuals, and crowd behavior under emergency situations may be affected by a number of factors, e.g., knowledge about the environment, response to environmental hazards and disasters, information processing and communication, social relationship, compliance with rules and tendency of herding [1]. Here, information of the dangerous source, which can spread rapidly among a crowd, plays an important role in pedestrians' decision-

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making process and collective behavior [2]. It is necessary to deeply discuss the effect of information transmission on crowd dispersion.

Crowd simulation has been proved to be an effective method to reproduce pedestrian behavior and assess evacuation plans [3,4]. In recent years, it has been a principal challenge to describe rules to faithfully demonstrate how pedestrians interact with each other in nonlinear pedestrian dynamics modeling. Many models have been proposed, such as social force models [5], cellular automaton models [6], agent-based models [7] and complex network models [8]. In the social force model introduced by Helbing et al. [5], socio-psychological and physical forces were employed to depict the interaction between pedestrians and crowd behavior under panic situations. The “faster-is-slower” effect and herding behavior were discovered in simulations. Then many researchers [9–12] modified the social model to investigate crowd evacuation or pedestrian flow. In cellular automaton models, both space and time were discretized. Pedestrian movement was updated according to probabilities where the interaction between each other was reflected. Due to simpler rules and higher calculation efficiency, the cellular automaton model has been widely used and developed to study pedestrian dynamics during evacuations or pedestrian flow, including the lattice gas model [13], floor field model [14] and multi-grid model [15]. Agent-based models described individuals as virtual agents which were defined by “bottom-up” social structures. They depended on some elementary forms of intelligence, and could obtain emergent phenomena [3]. However, modeling these agents is not a simple task because of multi-loop negative feedback systems. In complex network models, space was discretized into sub-regions which were connected to their neighbors [16]. Thus a large geometry may be composed of a number of nodes. Occupants may move from room to room rather than from one area inside a room to another, especially in coarse networks. This approach was difficulty to create pedestrian local movement and navigation, e.g., obstacle avoidance and overtaking. Some other mathematical models, such as fluid-dynamic models [17], magnetic force models [18] and centrifugal force models [19], have also been introduced to investigate pedestrian dynamics. However, important human factors in crowd dynamics such as information of the dangerous source and communication were rarely discussed in these original models.

Some researchers [20–24] began to consider more human factors in microscopic models under different situations. Qu and Dan [2] combined the spreading dynamics of dangerous source and risk coefficient with the social force model to investigate pedestrian movement characteristics of evacuation behavior. They proposed the concept of the most possible detouring directions and its corresponding calculation algorithm. The “Faster-is-slower” effect under dangerous situation was reproduced in simulation results. Henein and White [25] emphasized that human behavior of information processing and communication should be considered at the microscopic level. Therefore, they integrated these human factors with the floor field model, and claimed that communication with each other reduced barrier formation in a large room with ample exits, leading to increasing exit rates and crowd safety. Dong et al. [26] proposed a behavior model which combined information transmission processes with pedestrians' personalities when emergencies occurred. Good crowd evacuation simulation was obtained. Che et al. [1] presented a novel framework to simulate pedestrian exit selection behavior under emergency situations. The effect of information asymmetry such as crowd moving directions, exit signs and prior knowledge about exit locations on preferred velocity was investigated. Niu et al. [27] also studied pedestrians' decision-making behavior during an evacuation process, considering the effect of exit instructions and information sharing. Tian et al. [28] employed the lattice gas model to examine the influence of dangerous information on four-way pedestrian flow under an open boundary condition on a square grid. They confirmed that congested crowd disappeared under the action of dangerous information. Nevertheless, pedestrians' various personalities were not involved in this study, and thus decision strategies of heterogeneous pedestrians during crowd dispersion were not revealed.

Under emergency situations, information of the dangerous source may affect pedestrians' decision making and then behavior. It is believed that information exchange within a dynamic environment could be of crucial importance in human locomotion [29]. Due to personality differences, pedestrians may adopt various strategies when they receive this information. For example, when some pedestrians are informed of a fire, they may be nervous, and immediately accelerate their speed to leave. However, pedestrians who are far away from the fire may be curious about this event, and attempt to approach [2]. Furthermore, pedestrians' behavior will also be influenced by the amount of information and surrounding environment. These variables are difficult to be quantitatively measured, and render the prediction of pedestrians' decision making be an uncertainty and vague problem in pedestrian perception-action modeling. In order to solve this problem, in this paper, a fuzzy-theory-based method is proposed to discover the characteristics of crowd dispersion under the situation of four-way pedestrian flow on a square grid. Here the lattice gas model is employed, as it has been successful to discover four-way pedestrian flow characteristics with simple rules [30].

Fuzzy theory was introduced by Zadeh [31] in 1965. Because of well-developed mathematical properties, fuzzy logic and fuzzy sets are appropriate techniques for handling uncertainties through linguistic rules [32]. They have been successfully applied in the field of pedestrian traffic, such as pedestrian walking path planning [29,33,34], speed-updating analysis [35], collision avoidance [36,37] and traffic signal control [38]. As fuzzy logic has the capacity to imitate human thought processes, it serves as an appropriate framework to model imprecise and diverse nature of pedestrian perception and reaction towards environmental stimuli.

The novelty of this study is the establishment of a fuzzy-theory-based model which integrates fuzzy theory, pedestrians' attributes and information transmission into the lattice gas model in order to identify the effect of pedestrians' decision making on nonlinear evacuation dynamics. The primary contributions comprise the following perspectives: (i) a presentation of diverse characteristics of pedestrians' information processing and decision making through a fuzzy-theory-based method