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Discussion

A fuzzy-theory-based behavioral model for studying pedestrian evacuation from a single-exit room

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ABSTRACT

Many mass events in recent years have highlighted the importance of research on pedestrian evacuation dynamics. A number of models have been developed to analyze crowd behavior under evacuation situations. However, few focus on pedestrians' decision-making with respect to uncertainty, vagueness and imprecision. In this paper, a discrete evacuation model defined on the cellular space is proposed according to the fuzzy theory which is able to describe imprecise and subjective information. Pedestrians' percept information and various characteristics are regarded as fuzzy input. Then fuzzy inference systems with rule bases, which resemble human reasoning, are established to obtain fuzzy output that decides pedestrians' movement direction. This model is tested in two scenarios, namely in a single-exit room with and without obstacles. Simulation results reproduce some classic dynamics phenomena discovered in real building evacuation situations, and are consistent with those in other models and experiments. It is hoped that this study will enrich movement rules and approaches in traditional cellular automaton models for evacuation dynamics.

1. Introduction

Pedestrian evacuation is an important branch of safety research. It is also one of the most useful ways to ensure human safety under emergency situations. With the increasing number of unexpected events in recent years, pedestrian evacuation has drawn significant interest and attention. Research on evacuation dynamics is helpful in the design of walking facilities and crowd management.

It is easy to observe evacuees' behavior through evacuation experiments [1–3]. Nevertheless, conducting experiments is sometimes expensive, dangerous and time consuming [4]. Hence, evacuation modeling is widely employed. To date, many evacuation models have been proposed [5–8]. In a broad categorization, they can be classified into three types, i.e., macroscopic, mesoscopic and microscopic models [9–11].

Macroscopic models regard pedestrians as a fluid, and focus on pedestrian movement in a crowd through flow, density and speed relationships. These fluid-dynamic models depend on the behavior of the fluid in a large scale interactive system, and are more suitable for an aggregate representation of pedestrian movement over a large population. Hughes [12] was the first to employ a continuous potential field approach to depict crowd movement. Then hydrodynamic principles have been adopted to develop simulation models by some researchers [13–17]. However, macroscopic approaches are difficult to generate fine-grain simulation results to discover individual diversities, since individual characteristics are not involved. In contrast, mesoscopic and microscopic models are available to reflect individual issues.

Mesoscopic approaches do not focus on a single pedestrian, but emphasize groups of pedestrians in an identical environment [11]. Every group has its own rules of behavior [18]. According to kinetic theory methods, the microscopic state of persons is described by the individual position and velocity, while their representation is given by an appropriate probability distribution over the microscopic state [19,20]. Hanisch et al. [18] transformed the idea of grouping individuals in the area of traffic simulation to mesoscopic pedestrian flow models, which was used for online simulation of pedestrian flow in public buildings. Tolujew and Alcalá [21] also developed models for pedestrian traffic flows at a mesoscopic level.

Microscopic models describe pedestrian flow at the level of individuals, in order to present individual behavior and interactions. Such models deliver a more realistic representation of pedestrian movement in a crowd, and are usually classified into four groups, namely multi-agent models, queuing network models, physical based models and cellular based models [11].

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Multi-agent models assume that pedestrians have different characteristics, and personal desires have an effect on their decision making. They have been employed to investigate crowd evacuation under various conditions [5,22–25]. Nevertheless, multi-agent models are generally more computationally expensive than three other types of microscopic models.

Queuing network models [26–28] treat each pedestrian as a separate flow object. Priority rules are given to govern interactions between pedestrians, moving toward a destination. Pedestrian facilities can be modeled as a network of walkway sections. This is convenient to identify pedestrian flow pattern, especially in complex scenarios [29].

Physical based models simulate pedestrian movement according to optimal acceleration which depends on physical forces. Okazaki and Matsushita [30] introduced a magnetic model to simulate evacuation from an office building and pedestrian movement in queue spaces. A magnetic field, where the positive pole represented each pedestrian and obstacles, and the negative pole was located at the goal of pedestrians, was given. Thus pedestrians could move to their goals by attractive forces resulting from the negative poles, and avoid collisions with others or obstacles by repulsion forces due to the positive poles. Helbing et al. [31] developed a social force model to investigate the mechanisms of panic and jamming in uncoordinated crowd motion. This model was according to Newton's second law of motion. Interaction forces comprising socio-psychological and physical forces were involved. Simulation results reproduced some classic phenomena in real evacuation, such as clogging and "faster is slower effect". Yu et al. [32] presented a centrifugal model to study pedestrian dynamics, and reproduced the self-organization phenomenon of lane formation in pedestrian flows. In general, these models are always defined on simple spaces, and are difficult to simulate complex or large-scale scenarios. In contrast, cellular based models can solve this problem.

Pedestrians in cellular based models move in discrete space and time, and their movement direction is decided by a calculation of transition probabilities in neighboring cells. The cellular automaton (CA) model is the most widely employed to simulate discrete pedestrian movement guided by a set of simple rules [33,34]. Accordingly, many types of CA models have been proposed. Muramatsu et al. [35] introduced a lattice gas model to study pedestrian counter flow in a two-dimensional system. They revealed the critical density corresponding to a dynamical jamming transition. Kirchner and Schadschneider [36] were inspired by chemotaxis, and proposed a floor field model which consisted of the static floor field and dynamic floor field. This model could describe different types of behavior in evacuation processes. Song et al. [37] associated the force concept in the social force model with the CA model, and well obtained some evacuation phenomena. They also developed a multi-grid model [38], which discretized a cellular space into a finer lattice, i.e. pedestrians occupied multiple cells rather than a cell. This method enabled pedestrians to move with various speeds. According to these models depicted above, some researchers extended them through involving more factors [39–43].

From the broad categorization described above, larger scale models usually neglect heterogeneous behaviors at low scales. Macroscopic models are difficult to simulate all relevant behavioral processes and characteristics shown in crowds, such as self-organization and phase transitions for pedestrian dynamics. Nevertheless, microscopic approaches are able to reproduce heterogeneous crowds and more accurate pedestrian movement by involving interactions between individuals. Therefore, we focus on microscopic approaches (cellular based) for crowd modeling.

In general, modeling and simulation are required to be able to reflect decision processes in real evacuation. The review of cellular based models demonstrates that more challenging work is needed to satisfy this. Pedestrians' decision processes, particularly under evacuation situations, are related to various factors, such as stimuli, perception, interactions and psychological characteristics. The way that a pedestrian perceives the situation or environment has an influence on his/her behavior. Different perceptions, which may be inaccurate or misguided, towards an emergency lead to various emotions and mental stress levels [44], evoking different decision results. In this light, prior work on cellular based models was conducted according to the assumption that precise values of complex interactions between pedestrians or surroundings, e.g., distance and force, could be achieved in real time. In fact, it is difficult to quantify perception-based information in real-life scenarios. There is a compelling need to propose an approach that is able to describe perception-based information integrated with cellular based models.

Previous CA models highly depended on the transition probabilities. The state value of each cell was 0 or 1, which correspondingly represented an unoccupied cell or occupied cell. In this light, these CA models are according to probability theory which is related to classic set theory and two-valued logic, e.g., yes-or-no and happen-or-not-happen statements [45]. This theory is used to handle random phenomena which are not predicable, but exhibit certain statistical regularities. Hence, probabilistic uncertainty correlates with well-defined and unambiguous events. Nevertheless, decision-making statements for heterogeneous individuals are usually difficulty to be well defined. Individuals receive perception-based information from environments under most situations, such as "near", "fast" and "approximately 1 m/s" [46]. This is not measurement-based information. In this regard, probability theory is not suitable, while fuzzy set theory [47] is available. Cellular automata in fuzzy backgrounds (FCA) have been deeply investigated by Cattaneo et al. [48] and Betel et al. [49]. The relationships between FCA and CA were also systematically studied.

The classic characteristic mapping (or "crisp set") involves only two values, namely 0 if an element belongs to a set and 1 if not [45]. However, the fuzzy set theory defines membership through a grade or degree, i.e. a fuzzy set (A) has a membership function valued between $[0, 1]$ rather than only two values $\{0, 1\}$. For example, if $x \in X$, then $A(x)$ denotes x's membership degree in fuzzy set A. Here, values 1 and 0 respectively represent complete membership and complete lack of membership, while intermediate values denote intervening degrees of membership. According to this definition of the fuzzy set, it has been extended to handling ambiguous events through linguistic rules [50–52]. Dell'Orco et al. [53] proposed a microscopic model of crowd evacuation defined on a continuous space, and used fuzzy logic technique to reproduce human reasoning. Chen et al. [54] developed a fuzzy cellular automaton model to simulate pedestrian movement at crowded signalized pedestrian crossings. Zhu et al. [55] integrated fuzzy logic with the social force model, and reproduced dynamical features of pedestrian evacuation. Nevertheless, in prior work, it is observed that the fuzzy logic approach was rarely combined with cellular based models for investigating crowd dynamics, especially under evacuation situations. Moreover, original cellular based models focused little attention on pedestrians' perception-based uncertain information resulting in different types of behavior during pedestrians' movement processes. This deserves deeper study.

Combined with information fusion techniques, the fuzzy-theory-based approach is adequate to describe imprecision, vagueness or uncertainty, such as pedestrians' perception-based information, in cellular based models. Motivated by this, in this paper, a fuzzy-theory-based behavioral model is proposed to investigate the real evacuation process rather than pre-evacuation process in a cellular space. The state value of each cell in the cellular space is extended to belong to $[0, 1]$ instead of the traditional crisp set