Chapter 5

Human Evacuation Modeling

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1. Introduction

The modeling of movement patterns of human crowds at the exit point of an enclosed space is a complex and challenging problem. In a densely populated space, if all the occupants are simultaneously rushing for the exits, shuffling, pushing, crushing and trampling of people in the crowd may cause serious injuries and even loss of lives. An analytical study of crowd dynamics through exits may provide useful information for crowd control purposes. Proper understanding of the evacuation dynamics will allow, for example, improvements of designs of pedestrian facilities. In particular, the dynamics of evacuation through a narrow door during an emergency is a complex problem that is not yet well understood. The possible causes for evacuation may include building fires, military or terrorist attacks, natural disasters such as earthquakes, etc. In the light of tightened homeland security, research on evacuation modeling has been gaining impetus and attracting the attention of researchers from various fields.

In the published literature, one of the first computational studies of human evacuation was reported by Helbing *et al*. [1]. They applied a model of pedestrian behavior to investigate the mechanisms of panic and jamming by uncoordinated motion in crowds and suggested an optimal strategy for escape from a smoke-filled room involving a mixture of individualistic behavior and collective herding instinct. Subsequently, two main approaches, referred to as cellular automata or the lattice gas model and the continuum modeling framework, have been pursued by researchers in this field for modeling studies of human evacuation over the last decade. In the cellular automata approach, the computational domain is discretised into cells which can either be empty or occupied by one human subject exactly. Each human subject is then simulated to either remain stationary or move into an empty neighboring cell according to certain transition probability rules. Kirchner and Schadschneider [2] applied such an approach to model evacuation from a large room with one or two doors and observed that a proper combination of herding behavior and use of knowledge about the surrounding was

necessary for achieving optimal evacuation times. Perez *et al.* [3] used the same modeling approach and found that in situations where exit door widths could accommodate the simultaneous exit of more than one human subject at any given time, subjects left the room in bursts of different sizes. Takimoto and Nagatani [4] applied the lattice gas model to simulate the evacuation process from a hall and observed that the average escape time was dependent on the average initial distance from the exit. The same conclusion was reached by Helbing *et al.* [5] who applied the same modeling approach and compared escape times with experimental results. Subsequently, the authors extended their lattice gas model to simulate evacuation of subjects in the absence of visibility and found that addition of more exits did not improve escape time due to a kind of herding effect based on acoustic interactions in such situations [6]. Nagatani and Nagai [7] then derived the probability density distributions of the number of steps of a biased random walk to a wall during an evacuation process from a dark room, first contact point on the wall and the number of steps of a second walk along the wall. In a following study, the probability density distributions of escape times were also derived and shown to be dependent on exit configurations [8]. Qiu *et al.* [9] simulated escaping pedestrian flow along a corridor under open boundary condition using the cellular automata approach. It was found that transition times were closely dependent on the width of the corridor and maximum speed of people but only weakly dependent on the width of doors. More recently, a contrasting mathematical approach for modeling crowd dynamics that is based on the framework of continuum mechanics has also been introduced by some research workers [10]. Such an approach uses the mass conservation equations closed by phenomenological models linking mass velocity to density and density gradients. These closures can take into account movement in more than one space dimension, presence of obstacles, pedestrian strategies and panic conditions. However, it is also recognized that human evacuation systems do not strictly satisfy the classical continuum assumption [11] and so macroscopic models have to be considered as approximations of physical reality which in some cases, such as low density regimes, may not be satisfactory. Furthermore, such macroscopic models are derived based on the assumption that all individuals behave in the same way, or namely, that the system is homogeneous.

In the present study, a particle-based simulation approach known as the Discrete Element Method (DEM) was applied for modeling of human evacuation from a room with a single exit. The governing equations used in this method will be presented in the following section.

2. Mathematical model

2.1. Discrete Element Method

The molecular dynamics approach to modeling of granular systems, otherwise known as the Discrete Element Method (DEM), has been applied extensively for studies of various aspects of granular behavior. The method of implementation in this proposed study followed that used by the author in previous studies of various types of granular systems [12–20]. The

translational and rotational motions of individual solid particles are governed by Newton's laws of motion:

$$m_i \frac{dv_i}{dt} = \sum_{j=1}^{N} \left(f_{c,ij} + f_{d,ij} \right) \tag{1}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{N} T_{ij} \tag{2}$$

where m_i and v_i are the mass and velocity of i^{th} particle respectively, N is the number of particles in contact with i^{th} particle, $f_{c,ij}$ and $f_{d,ij}$ are the contact and viscous contact damping forces respectively, I_i is the moment of inertia of i^{th} particle, ω_i is its angular velocity and T_{ij} is the torque arising from contact forces which causes the particle to rotate.

Contact and damping forces have to be calculated using force-displacement models that relate such forces to the relative positions, velocities and angular velocities of the colliding particles. Following previous studies, a linear spring-and-dashpot model was implemented for the calculation of these collision forces. With such a closure, interparticle collisions are modeled as compressions of a perfectly elastic spring while the inelasticities associated with such collisions are modeled by the damping of energy in the dashpot component of the model. Collisions between particles and a wall may be handled in a similar manner but with the latter not incurring any change in its momentum. In other words, a wall at the point of contact with a particle may be treated as another particle but with an infinite amount of inertia. The normal ($f_{cn,ij}$, $f_{dn,ij}$) and tangential ($f_{ct,ij}$, $f_{dt,ij}$) components of the contact and damping forces are calculated according to the following equations:

$$f_{cn,ij} = -\left(\kappa_{n,i} \delta_{n,ij} \right) n_i \tag{3}$$

$$f_{ct,ij} = -\left(\kappa_{t,i} \delta_{t,ij} \right) t_i \tag{4}$$

$$f_{dn,ij} = -\eta_{n,i} \left(v_r \cdot n_i \right) n_i \tag{5}$$

$$f_{dt,ij} = -\eta_{t,i} \left\{ \left(v_r \cdot t_i \right) t_i + \left(\omega_i \times R_i - \omega_j \times R_j \right) \right\} \tag{6}$$

where $\kappa_{n,i}$, $\delta_{n,ij}$, n_i, $\eta_{n,i}$ and $\kappa_{t,i}$, $\delta_{t,ij}$, t_i, $\eta_{t,i}$ are the spring constants, displacements between particles, unit vectors and viscous contact damping coefficients in the normal and tangential directions respectively, v_r is the relative velocity between particles and R_i and R_j are the radii of particles i and j respectively. If $\left| f_{ct,ij} \right| > \left| f_{cn,ij} \right| \tan\phi$, then 'slippage' between two contacting surfaces is simulated based on Coulomb-type friction law, i.e. $\left| f_{ct,ij} \right| = \left| f_{cn,ij} \right| \tan\phi$, where tan ϕ is analogous to the coefficient of friction.

2.2. Simulation conditions

The geometry of the computational domain considered in this study was in the form of a room measuring 10 m × 10 m. A single exit located at the center of one of the walls of the room was simulated. The width of the exit was specified as 1 m. A total of 100 human subjects initially randomly distributed within the room were considered. During the evacuation process, each subject was simulated to move generally in the direction of the exit while interacting with other subjects through human-human collisions according to the governing equations of the model.

3. Results and discussions

Fig. 1 shows the top view of the evacuation process simulated. The exit of the room was simulated to be located at the centre of the bottom wall. The arrow symbols associated with each subject indicate the instantaneous direction of movement. The subjects were originally distributed randomly throughout the room and it was assumed that each subject sought to reach the exit in the most direct manner while obeying only basic laws of physics as defined by the governing equations of the DEM model. The typical phenomenon of jamming that is ubiquitous in various physical systems, such as the flows of granular materials for example, could be reproduced computationally with such an approach. It can be seen that there was a tendency for the subjects to first cluster round the exit of the room and then spread along the wall where the exit was situated. The limiting factor of the evacuation process in this case was the necessity for subjects to leave the room through the exit one at a time. The speed of movement during the initial stage of the evacuation process to form the human cluster around the exit did not play a significant role in determining the total amount of time required for the entire evacuation process to be completed. In other words, the limiting factor or bottleneck of the overall evacuation process in this case was movement of individual subjects through the exit. This is consistent with observations of other researchers utilizing other modeling approaches, such as cellular automata or the lattice gas model, for simulating such evacuation processes. This points towards the possibility of improving the evacuation time simply by increasing the width of the exit such that more than one subject can exit at any one time or by increasing the total number of exits of the room.

Fig. 2 shows the spatial distribution of collision forces that developed due to human-human collisions during the evacuation process. Here, the color contours indicate high (red) and low (blue) magnitudes of such collision forces. This ability to predict collision forces is a novel feature of the current approach for crowd dynamics modeling that is unavailable in all other approaches reported by other researchers in the literature to date. This will be important for subsequent estimations of the likelihood of the human subjects to sustain injuries as a result of the evacuation process and so will be crucial for casualty predictions. In terms of engineering designs of the interiors of buildings or any enclosed spaces, such predictions can also be applied in a reverse engineering sense with a view towards minimizing human casualties in such events of emergencies.

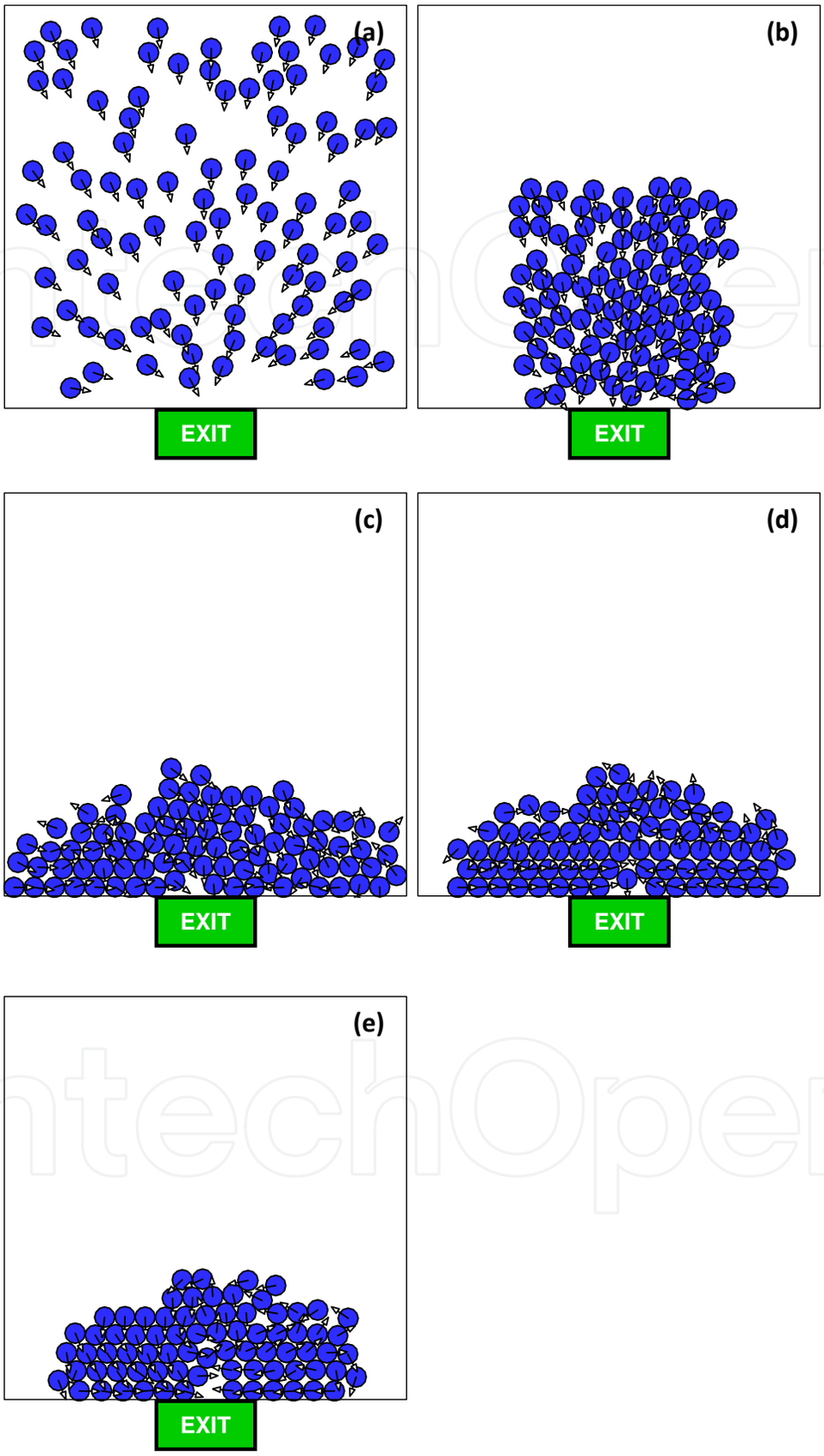

Figure 1. Top view of an evacuation process involving 100 human subjects from a room measuring 10 m × 10 m.

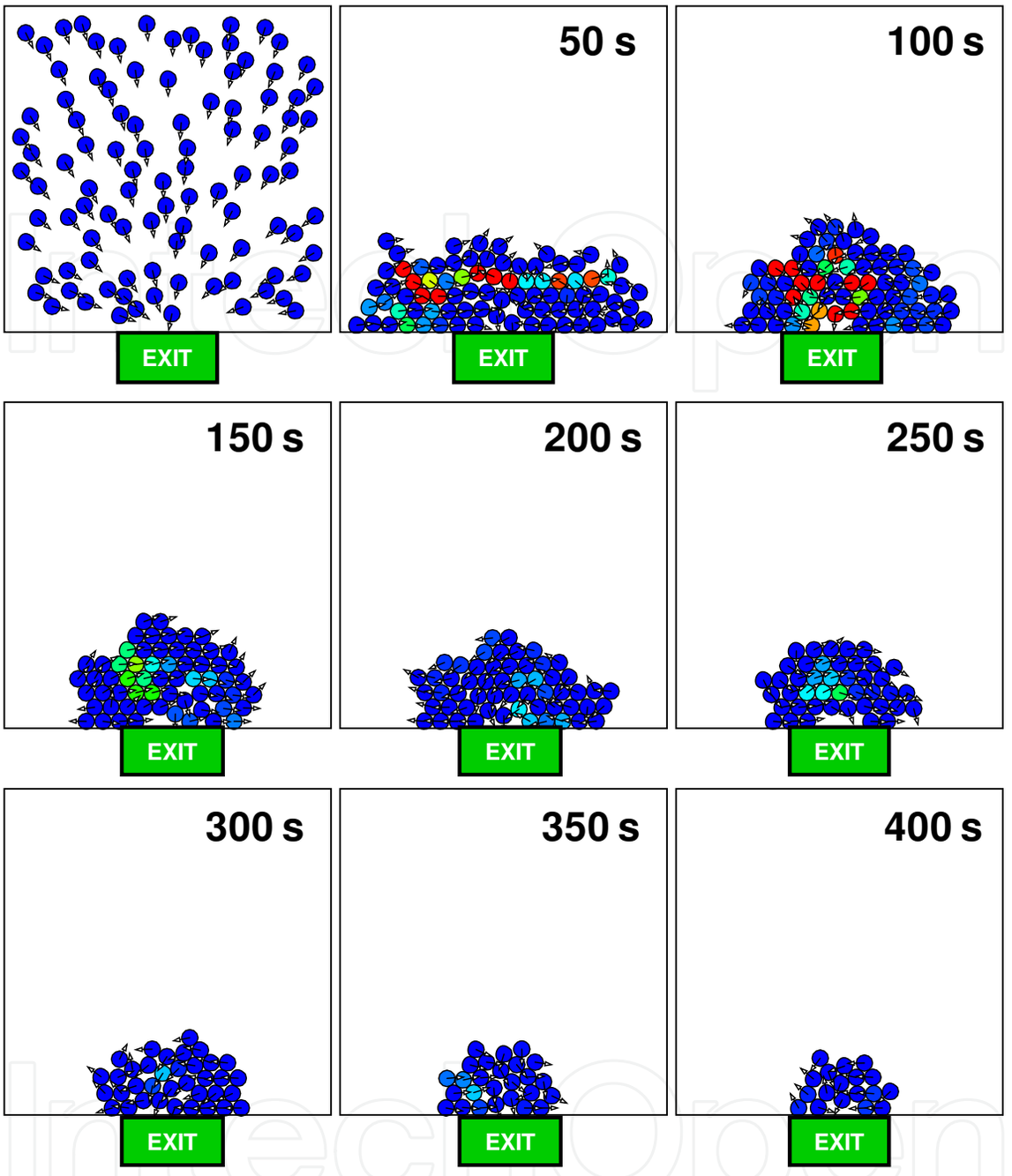

Figure 2. A novel feature of the current approach where collision forces developed due to human-human collisions during the evacuation process can be predicted by the algorithm.

4. Conclusions

An agent based model has been applied for modeling of the human evacuation process in this study. A relatively simple configuration consisting of a room without any obstacles and a single exit was considered and the evacuation of 100 subjects was simulated. The typical phenomenon of jamming that is ubiquitous in various physical systems, such as the flows of granular materials for example, could be reproduced computationally with such an approach. The evacuation process was observed to consist of the formation of a human

cluster around the exit of the room followed by departure of subjects one at a time that created a significant bottleneck for the entire process.

The application of the agent based approach for extensive parametric studies of effects of various engineering factors on the evacuation process such as number of human subjects present, initial configuration of the subjects, placement and number of exits, presence of unmovable obstacles, size and shape of the enclosed space will be the subject of a future study.

In particular, in order to study human decisions underlying an evacuation process more closely, a multi-objective evolutionary algorithm for emergency response optimization can be applied. These algorithms are stochastic optimization methods that simulate the process of natural evolution [21]. Such an evolutionary approach is expected to discover and develop human factors and useful psychological models that determine decision-making processes in an emergency context.

5. Summary

An agent based model was applied for crowd dynamics simulation in this study. The computational domain consisted of a room without any obstacles and a single exit and the evacuation of 100 subjects from the room was simulated. The typical phenomenon of jamming that is typical of such systems was reproduced computationally with such an approach. The evacuation process was observed to consist of the formation of a human cluster around the exit of the room followed by departure of subjects one at a time that created a significant bottleneck for the entire process. Future work can adopt an evolutionary algorithm to closely predict human decision processes in an emergency context.

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