A HYBRID MODEL FOR COLLECTIVE MOTION OF PEDESTRIANS

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ABSTRACT

Pedestrian crowds display elements of collective behaviour during emergency situations. Collective patterns are not restricted to humans, but have been observed in other biological systems that display herding, flocking, schooling and swarm intelligence. Previous research into animal dynamics has explored collective behaviour in various biological systems. Even in molecular/granular systems, pattern formation has been reported through extensive molecular dynamics research. This paper present a hybrid microscopic model of the collective motion of pedestrians based on animal dynamics and molecular dynamics. It is observed that even with a relatively simple mathematical formulation, the model is able to produce the collective motion of pedestrians. The model's performance is assessed by comparing its predictions with observed pedestrian traffic from experimental data. The capability of the model for addressing extreme case as in panic is also discussed.

1 INTRODUCTION

The collective movement of large numbers of people is important in many situations, such as the evacuation of buildings, stadiums, theatres, ships, aircraft or outdoor events like public assemblies, open concerts, religious gatherings and community evacuation. As such planning and designing for safe pedestrian movements is a challenging task for managers of emergency response. Although initial scientific studies on pedestrian evacuation were carried out as long ago as the 1930's (Kholshevnikov & Samoshin 2008), the problem of enhancing pedestrian safety under emergency conditions still exists. This difficulty may be due to the complex behaviour of humans under those conditions and their continuous mental, social and physical interactions with the surrounding environments. Shiwakoti et al. (2008a) provide a review of state-of–the-art modelling of pedestrian behaviour under emergency conditions. The nature of collective behaviours as outlined in various socio-psychological literatures (Quarantelli 1957, Sime 1995) has an important role in determining the safety of pedestrian crowds. The collective patterns are not restricted to humans, but have been observed in other biological systems that display herding, flocking, schooling and swarm intelligence (Okubo 1986, Charlotte 2005). Mathematical simulation models of animal dynamics have been used since the 1970's to study the collective movements of animal (Okubo 1986). However limited attention has been directed at translating the findings observed from collective animal dynamics to the study of the collective dynamics of humans. Shiwakoti et al. (2009) discusses the potential contribution of various biological entities in understanding the collective pedestrian dynamics under emergency conditions. Extensive research in molecular dynamics has examined collective pattern formation where the nature of the collective motion of the constituents of matter is observed through the interactions of many molecules (Rapaport 1995, Bell 2005). Examples of collective dynamical properties of granular materials as studied from a molecular dynamics perspective include heap formation, force chains and particle size segregation. (Bell 2005).

This paper present a hybrid microscopic model of the collective motion of pedestrians based on animal dynamics and molecular dynamics. The next section outlines the proposed model and that is followed by an assessment of the model's performance based on experimental data. That is followed by a discussion of how the model could find application in the study of an extreme case, specifically panic under emergency conditions. The conclusions are presented in the final section of the paper.

2 SIMULATION MODEL

2.1 Background

Previous studies of animal dynamics have been based on Newton's second law of motion and consider the dispersive, attractive and repulsive forces along with population pressure due to interference between individual animals (Okubo 1986). In collective animal motion, it is important to consider whether individuals are "close to" or "far from" from their surrounding neighbours since those distances ultimately dictate the patterns of the collective motion. For example, observations of fish schools reveal that the critical distance that fish maintain varies within 16 to 25 % of their mean body length while attraction forces start at distance beyond body length (Okubo 1986). There is a zone of attraction and a zone of repulsion that maintain the collective patterns. Kholshevnikov & Samoshin (2008) based on several studies on pedestrian evacuation carried out by researchers in Russia and around the world in the past summarizes that all the studies gives the identical structure of collective pedestrian flow. They mention that the distance between people constantly changes and causes local squeezing which later on disappear and appear again. It can be therefore assumed that like in animal dynamics, it is the zone of attraction and zone of repulsion that maintains the collective movements of pedestrian crowds. The "tendency to follow others" and "strong local interactions" as observed in the collective motion of both animals and pedestrians provides the foundation for modelling the collective motion of pedestrians based on an interactive range of interpersonal distance (Shiwakoti et al. 2008b, 2009). While the concept of repulsive forces based, on interpersonal distance, has been addressed in models of pedestrian dynamics (Helbing et al. 2000) the importance of attractive forces has received limited attention in the study of the collective motion of pedestrians. To develop a realistic simulation model, it is important to consider the attractive and repulsive forces to capture the "pulsating" (expanding and contracting in a spatial sense) nature of the collective movements of pedestrians.

2.2 Model

The optimal instantaneous acceleration $\vec{a}$ of each pedestrian is determined from forces acting on the pedestrian from other surrounding pedestrians and obstacles as given below:

$$\vec{a} = \frac{1}{m_i}(\vec{F}_d + \sum_{j=1(i\neq j)}^{N}(\vec{F}_{ij} + \vec{F}_{ijp}) + \sum_{1}^{N_w}\vec{F}_{wi}) \tag{1}$$

Where, N =number of pedestrians, N_w = number of walls/obstacles, $\vec{F}_d$ =desired force based on Helbing et al. 2000, $\vec{F}_{ij}$ = local interactive forces (attraction and repulsion) acting on pedestrian (i) from nearby pedestrian (j), $\vec{F}_{ijp}$ = pushing forces in the high density case where pedestrians are touching each other, $\vec{F}_{wi}$ = repulsive forces from walls/obstacles and

m_i = mass of each pedestrian (i). With the optimal acceleration, the position and velocity of each pedestrian is updated in each small discrete time step (Δt) based on the integration of equations of motion. The flow chart of the simulation program is shown in Figure 1.

INPUT

At time step t =0 (Initialization)

Geometrical Layout	Population distribution (1, 2, 3,……..N) • Position(random) • Initial velocity =0 • Desired Velocity • Parameters

MODEL PROCESSING

At time step t = t + Δ t

For all the population (1, 2, ..N),
Calculate optimal instantaneous acceleration $\vec{a}$ for pedestrian i based on the local interactive forces acting on pedestrian i from pedestrian j and from walls / obstacles.

$$\vec{a} = \frac{1}{m_i}\left(\vec{F}_d + \sum_{j=1(i\neq j)}^{N}(\vec{F}_{ij} + \vec{F}_{ijp}) + \sum_{1}^{N_w}\vec{F}_{wi}\right)$$

Update the position p and velocity v of each individual i based on integration of Newton's equations of motion.

$$p(t+\Delta t) = p(t) + v(t)\,\Delta t + \frac{1}{2}a(t)\,\Delta t^2$$

$$v(t+\Delta t) = v(t) + \frac{1}{2}\left[a(t) + a(t+\Delta t)\right]\Delta t$$

Simulation Time (T)

OUTPUT

- Visual graphics for qualitative validation
- Data file (speed, position etc.) for quantitative validation

Figure 1: Flow chart of simulation program

The interactive forces $\vec{F}_{ij}$ consist of repulsive and attractive forces at a certain range of interpersonal distances and their formulation is based on the approach used to describe the schooling motion of fish (Matuda & Sannomiya 1985, Okubo 1986). It is assumed that the forces are inversely proportional to the square of the distance between the individuals:

$$\vec{F}_{ij} = \sum_{j=1, i \neq j}^{N} \lambda \frac{[(d_{ij} - r_{ij}) - r]}{[(d_{ij} - r_{ij}) - r]^2 + a^2} \cdot \vec{n}_{ij} \tag{2}$$

Where, $\vec{n}_{ij}$ = normal unit vector, λ = constant for attractive and repulsive forces, d_{ij} = interpersonal distance between pedestrians (centre to centre), $r_{ij} = r_1 + r_2$ = sum of radii of the circular representation of pedestrians, r = repulsion distance, a = attraction distance. Figure 2 shows the components of the interactive forces based on Equation 2. A weighting factor can be added to represent the influence of the pedestrian in front and back.

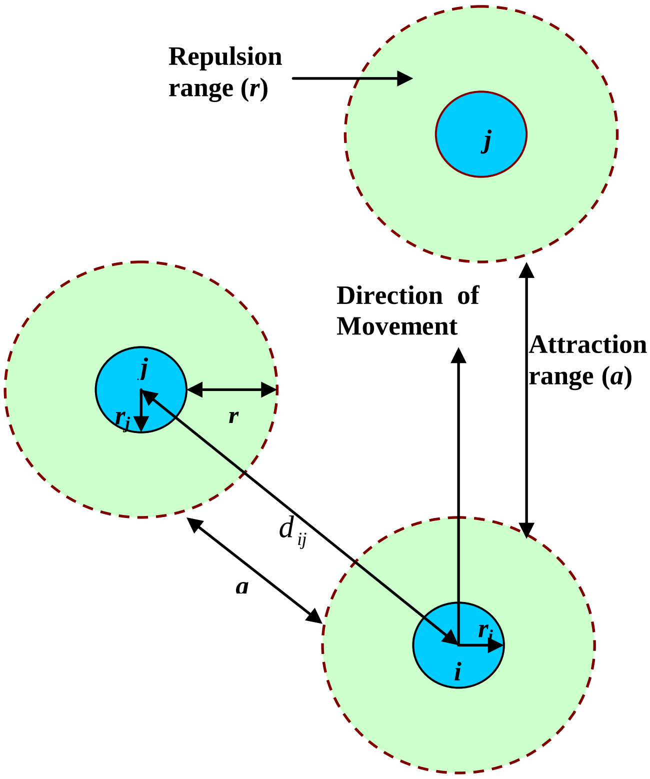


Figure 2: Components of the interactive forces

In the high density case or when people are moving at high speed, people tend to come very close and sometimes push each other. In such instances, there is the possibility of pedestrians colliding with each other or overlapping with each other in the simulation. In these cases, repulsive forces alone are not enough. These collision and overlapping phenomena have been also a notable problem in the study of rigid spherical body collisions in molecular dynamics. The problem is usually addressed by considering strong normal forces as well as frictional (shearing) forces between the colliding particles to avoid overlapping (Rapaport 1995, Bell 2005). Thus the pushing forces can be represented by two components; damped linear spring force (normal force $\vec{F}_n$) and shear frictional force (tangential force $\vec{F}_t$) as below.

$$\vec{F}_{ijp} = \vec{F}_n + \vec{F}_t \tag{3}$$

$$\vec{F}_n = k_n(\vec{v}_{rn}) + k_r\varepsilon.\vec{n} \tag{4}$$

$$\vec{F}_t = k_t\vec{v}_t + k_0\varepsilon.\vec{t} \tag{5}$$

Where k_n = constant (dampening coefficient), k_r = constant (elastic restoration coefficient), $\vec{v}_{rn}$ = relative velocity in normal direction, $\vec{n}$ = normal unit vector (radial), k_t = constant, k_0 = constant, $\vec{v}_t$ = tangential relative velocity, $\vec{t}$ = tangential unit vector, ε = overlap. While Helbing et al. 2000 proposed a similar approach for modelling pushing forces, Equation 4 and 5 are more flexible because they consider the case when the relative velocity is zero or near to zero. Expressions similar to those for $\vec{F}_{ij}$ and $\vec{F}_{ijp}$ hold true for repulsive forces from wall and obstacles ($\vec{F}_{wi}$).

3 PRELIMINARY VERIFICATION AND VALIDATION WITH EXPERIMENTAL DATA

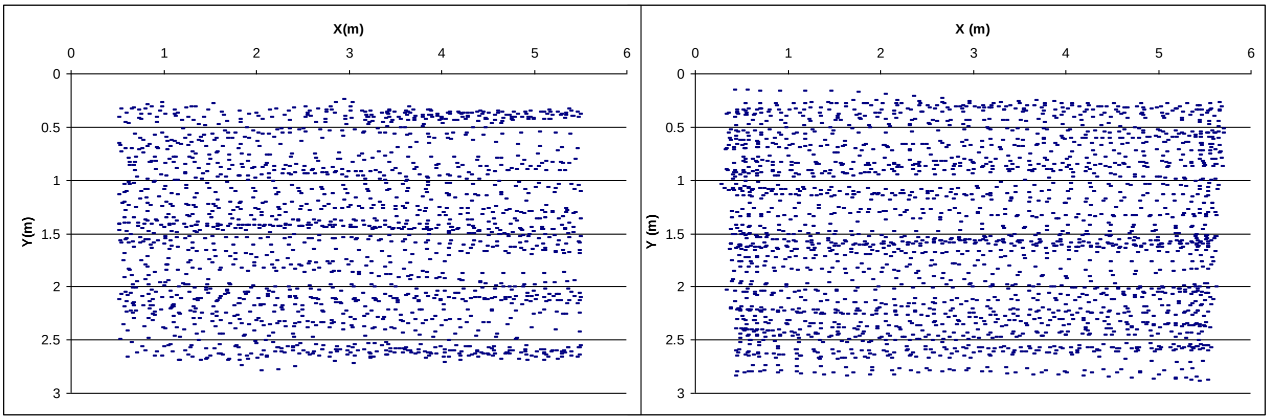
Preliminary verification and validation of the simulation model was conducted by comparing the trajectories and speeds of pedestrians measured in an experimental setting. The experimental consisted of uni-directional pedestrian movements through a 3 m wide corridor. The pedestrian movement through the test corridor 5m long and by 3m wide was recorded by a video camera mounted above the test area. The number of participants in the experiment was 92.The simulation model was verified qualitatively, with trajectory data, and validated quantitatively, with speed distribution data (minimizing the difference between the speed distributions), obtained from the experiment. The parameter value used in the simulation are summarised in Table 1.

Table 1: Typical values of the parameters for the simulation

Parameters	Value
v_d	1.3 m/s
m_i	50 kg to 80 kg
r_1 , r_2	0.2 m to 0.25 m
λ	19.5 kg m^2 / s^2 (Repulsion), 1.95 kg m^2 / s^2 (Attraction)
r	1.0 m
a	2.0 m
k_n	100 kg/s
k_r	800 kg/ s^2
k_t	5 kg/s
k_0	5 kg/ s^2
Δt	0.05 s

Uni-directional flow is the simplest and most common characteristic of pedestrian flow in an evacuation when pedestrians herd towards an exit through a corridor. The width of the corridor and the number of pedestrians determines the evacuation rate of the people. With an increase in the number of pedestrians and /or a decrease in the width of the corridor, the collective motion of pedestrians is constrained resulting in a decrease in their average speed. At low density, people tend to walk in the middle of the corridor while at higher density people use all of the available space (Daamen & Hoogendoorn 2003). In the experiment, pedestrians were observed to be distributed uniformly on the 3 m width corridor suggesting the effect of higher number of pedestrians on a relatively narrow corridor as shown in Figure 3(a). Figure 3 (b) and (c) shows the trajectory data from the simulation and experiment respectively. It can be observed that the trajectories are uniformly spread over the corridor width in both the experiment and simulation suggesting the effect of the density that force the people to use the available space uniformly for compensating delays. Also the tendency of pedestrians to maintain a certain gap from the boundary line is also revealed from the trajectories data obtained from both simulation and experiment.

(a)



(b) (c)

Figure 3: Uni-directional experiment (a), comparison of trajectories data from simulation (b) with experiment (c)

Figure 4 shows the speed distribution from the experiment and simulation along with average speed and standard deviation. The distribution of speed measured in the experiment is represented well in the simulation. It is to be noted here that although the desired speed was assigned to be 1.3 m/s in the simulation, the average speed was observed to be 1 m/s which reflects the effect of density on average speed. The standard deviation in simulation $\sigma_s = 0.16$ m/s is less than that of experiment $\sigma_E = 0.26$ m/s due to the assumption of constant desired speed of all pedestrians.

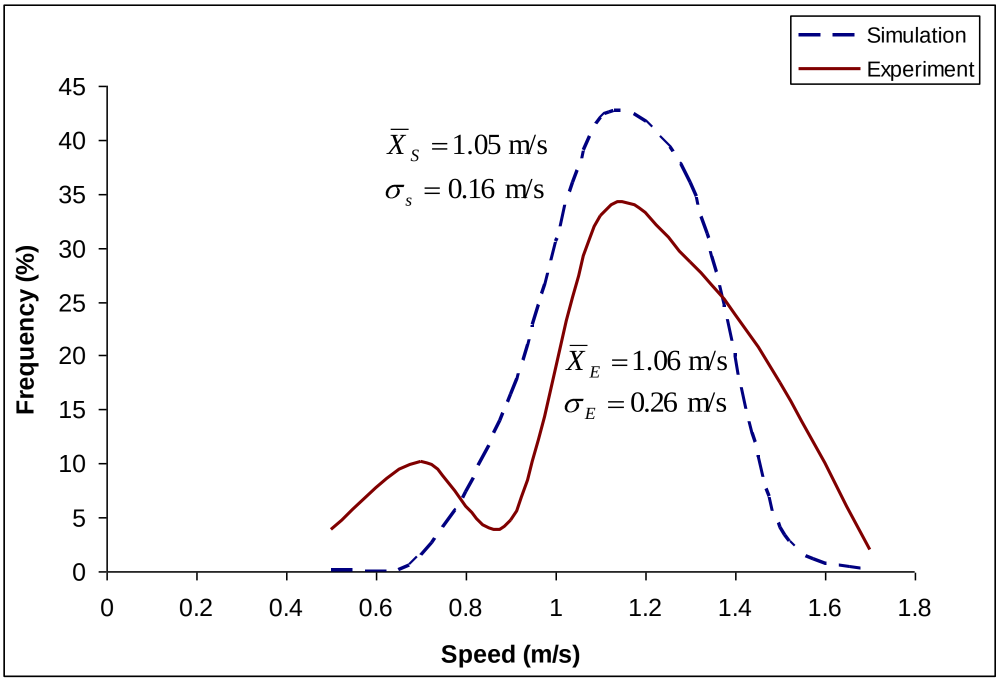


Figure 4: Comparison of speed data distribution from simulation with experiment for uni-directional traffic

4 FUTURE PROSPECTS

Future study could examine the impact of capacity constraints arising from bottlenecks and bi-directional movements. Also the model can be extended to study the extreme case such as panic under emergency conditions. Panic in pedestrian crowd has been associated with increase in desired speed (up to 5m/s) and frequent pushing behaviour (Helbing et al. 2000). In the model, this could lead to a change in the interaction range. In the case of panic, it is likely that there would be small interactions range for repulsive force with strong repulsive forces while large interactions range for attraction forces. This suggests it would be useful for future research to conduct sensitivity analysis of the impact of different parameter values under both normal evacuation and in the case of panic. Our preliminary empirical experiments using Argentine ants as a biological entity (Shiwakoti et al. 2008b, 2009) have demonstrated the potential for biological organisms to be used in the study of pedestrian traffic under emergency conditions. Such empirical data can be utilized to show that a developed model is robust to differences in the size, speed, and other biological details of the panicking individuals, and that by directly comparing the behaviour of biological entities and pedestrians, there is scope to identify improved strategies for evacuation. Also it is appropriate to note that although the model does not have any “intelligence” or “decision making” components, it was still able to produce the self-organised behaviour of pedestrian crowds. In the future, it would be possible to include some decision making rules into the model. However, there is a trade-off to be considered because of the added complexity of needing to then calibrate the parameters underlying the decision making rules.

5 CONCLUSIONS

Modelling and empirical study of pedestrian behaviour under emergency conditions can assist planners and managers of emergency response to analyse and assess safety precautions for those situations. In this paper, we presented a 2-dimensional discrete time step microsimulation model based on animal and molecular dynamics which has application in simulating the collective movement of pedestrians. The research brings together the insight from different multi-disciplinary fields such as biological science and molecular science to study pedestrian traffic. We highlighted how the consideration of both repulsive and attractive interaction range as observed in collective motion of several biological entities can represent the "pulsating" nature of the collective pedestrian movement. It was observed that even with the relatively simple mathematical formulation, it could reproduce the self-organised behaviour of pedestrians. This was preliminarily verified and validated with the comparison of trajectories and speed data from pedestrian traffic in an experimental setting for uni-directional flow. Extending model to simulate other self-organized behaviour (bottlenecks, bi-directional traffic) and the extreme case of panic was identified as a direction for future study. There is the potential for future research to continue to explore how the insight from other fields such as biological science can inform the development of capabilities to model the behaviour of pedestrian crowds under emergency conditions.

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