Safety Science 47 (2009) 395–404

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Modelling contra-flow in crowd dynamics DEM simulation

Alastair Smith [a], Christopher James [a], Richard Jones [a], Paul Langston [a,*], Edward Lester [a], John Drury [b]

[a] School of Chemical and Environmental Engineering, University of Nottingham, Nottingham, NG7 2RD, UK
[b] Department of Psychology, University of Sussex, Falmer, Brighton, BN1 9QH, UK

ARTICLE INFO

Article history:
Received 26 January 2007
Received in revised form 21 April 2008
Accepted 22 May 2008

Keywords:
Crowd dynamics
DEM
Safety
Mathematical modelling
Human behaviour

ABSTRACT

This paper highlights the growing need for a realistic crowd simulation in the design of large venues such as concert halls and stadia. A discrete element method (DEM) technique for modelling crowd dynamics has been developed that represents each person within the model as 3 overlapping circles, a position, orientation and velocity in 2D. Contact forces between elements are included in the model as well as psychological forces, motive forces and moments. The motion of each person is then modelled in a Newtonian manner with a numerical integration time-stepping scheme. The model has been shown previously to work well in predicting egress. In this paper the predicted model behaviour is compared to actual video footage shot at various locations around University Park Campus, Nottingham. It did not match well to the video footage when people are moving towards each other, as in cases of contra-flow on a walkway. In order to improve the model, a general algorithm for 'avoidance' was included which appeared to make the model significantly more realistic in these cases. The paper also shows areas for further potential development, such as incorporating people into associative groups such as family or friends.

1. Introduction

1.1. Requirements for crowd dynamic simulation

Crowd dynamics involves modelling the way crowds move and interact within their environment (Crowd Dynamics, 2006; Helbing et al., 2000; Langston et al., 2005; Fang et al., 2003). Understanding crowd dynamics is very important when designing any public venue likely to have a large number of people occupying its space at a given time, such as rock concerts and sporting events. Effective venue design can significantly reduce fatalities or eliminate them altogether, for example, through optimum positioning of emergency exits to ensure the design allows for safe crowd movement through the venue.

Generally the main aim of investigations in crowd dynamics is the reduction of risk to human life and of injury. There have been many instances of significant loss of life in this country and abroad due to poor venue design and crowd management in the recent past. On 15th April 1989 at the Hillsborough football stadium in Sheffield a crush against the metal railings designed to keep people off the pitch killed 86 people. One reason for the crush was a rapid influx of spectators through a gate with no turnstile onto an already overcrowded terrace. By the time the railings were breached there had already been significant loss of life, many of whom died standing up (Nicholson and Roebuck, 1993).

Due to the growing trend of litigation and the increased threat of terrorist attacks, the understanding and management of crowd dynamics is becoming more important and, for the vast majority of organisations, a dynamic simulation of crowd movement is a prerequisite for all new designs as well a being part of the mandatory safety reviews on existing venues. Moreover, theoretically there is also a growing recognition for a new type of crowd simulation. Those crowd modellers who have been employed in the planning and design of such projects as the Beijing and London Olympics stadia have each suggested that what is needed is far greater *granularity* (Galea, 2006; Gerodimos, 2006). In practice, this means enhancing existing mathematical models through a greater input from psychological theory and data (cf. Sime, 1995).

1.2. Simulation methods

Dynamic simulation models are used in many situations to analyse the space occupied by a crowd during both normal and emergency situations, such as in the event of a fire. The three main model types used are: optimisation, simulation, and risk assessment. No models have been found to be comprehensive with regard to the behavioural aspects of crowds (Gwynne et al., 1999; Santos and Aguirre, 2004).

Simulation can be considered in two different ways. Firstly the crowd can be modelled as a fluid as discussed by Helbing (1992).

* Corresponding author. Tel.: +44 115 951 4177; fax: +44 115 951 4115.
E-mail address: P.Langston@nottingham.ac.uk (P. Langston).

0925-7535/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ssci.2008.05.006

This means that the crowd is treated as a single entity for which a behavioural model is developed. The alternative is to model the crowd on a microscopic level, modelling each individual within the crowd separately. Examples of this include the cellula automata method (Hamagami and Hirata, 2003) and the discrete element method (Helbing et al., 2000; Langston et al., 2005). Discrete element models use a time-stepping sequence in order to track the trajectory and rotation etc of each "person" within the system in order to calculate their position and orientation and then to calculate the interactions between "people" as well as the interactions between "people" and the environment, such as walls, gates, platform edges, obstacles. The main advantage of DEM is that very complicated systems can be modelled with basic data without the need for oversimplified assumptions; however, valid data input is important. Another significant advantage is that it is capable of simulating complex boundaries including three dimensional objects such as buildings and staircases, such as the simulation of part of a station on the London Underground (Langston et al., 2005).

Discrete element methods have been extensively used for simulating a wide range of granular systems because they correspond to the discrete nature of the granulates. Granular ratcheting is one such application of this method (García-Rojo et al., 2004); the analogy between particle flow and people flow is obvious. It is assumed that there is no deformation when two particles collide. When the granulates come into contact they remain perfectly rigid only touching in one contact point (García-Rojo et al., 2004).

A second and key advantage of DEM, yet one which has not been fully applied, is that it has the potential to model (multi-) group features in a single physical crowd. As sophisticated as recent models have become mathematically (e.g. Helbing et al., 2000; Pan et al., 2005), they still lack a psychological model of spatial preferences (Still, 2000) – in particular they have tended to assume that all members of a physical crowd in a given space will behave in the same way – irrespective of whether they form a single group (say evangelists walking towards stadium rally), multiple groups (supporters of rival teams walking to a stadium) or no group at all (shoppers filling the selfsame streets) (Novelli et al., 2006).

This paper concerns the use of an existing DEM program and the development made in order for the model to accurately simulate two or more psychological groups or crowds seeking to move through one another. A study of some crowd video footage was then carried out and efforts were made to simulate the crowd accurately so that comparisons could be drawn and advantages and/or limitations of the new model could be discovered. Although it is primarily of interest to people involved in modelling work, it also has a wider applicability in that people who utilise crowd models may not be aware of all the features involved; how do the methods they are using account for collision avoidance?

1.3. The CrowdDMX model

The CrowdDMX model (Langston et al., 2005) concerns the application of the DEM technique to a 2D environment for the purposes of crowd simulation. It employs a multi-circular representation based on a method used by Thompson and Marchant (1995), using three intersecting circles to represent the body and arms of an individual as viewed from above as in Fig. 1. The simulation environment is defined by a number of wall elements as well as sequential aim points for the people to move towards. There are also a number of forces modelled in the simulation in order for movement to be as realistic as possible. The main forces are as follows:

- The psychological interaction taken from Helbing et al. (2000).
- A normal contact force modelled as a linear spring.

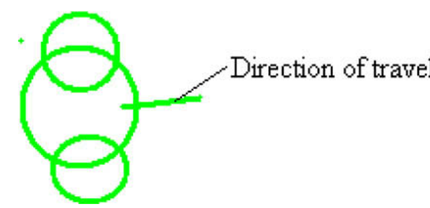

Fig. 1. Illustration of the multi-circle model used to represent one person.

- A sliding frictional force modelled as a function of the tangential velocity.
- A damping force which acts on contact and is proportional to the contact velocity.

A turning moment arising from each contact is also modelled resulting in angular acceleration as well as a motive moment to model how an individual will turn to face a desired direction. A motive force is calculated as function of the difference between the desired velocity and the actual velocity of the individual so that the aim point can be reached. After this the translational and angular acceleration are calculated at time "t", then again at "$t + \Delta t$" using a numerical integration sequence. Full details of the model are described in Langston et al. (2005) and a summary is provided in Appendix A. It is recognised that the model is a significant simplification of all the psychological and social factors involved in a real crowd. Individuals and groups can make decisions based on many criteria. However, it is also considered that such a simulation is a useful tool along with other methods, and such simulations will be improved by studies such as in this paper. This paper incorporates an avoidance algorithm in the multi-circle DEM model based on projected collisions from current relative velocities and positions in contra-flow situations. It uses a simple decision making process based on next likely collision or near miss.

2. Further development of the model

2.1. Contra-flow problems

The model described above works well for large crowds where people are generally travelling in the same direction and individual collisions are relatively few. Its main limitation, however, is that when people are travelling in different directions there is no algorithm in the program which enables them to avoid each other and as a result unrealistic "collisions" occur as shown in Fig. 2a. It can be seen that the two people "bounce off each other's psychological space" before continuing towards their aim points. In larger crowds this results in significant blockages to the point where not a single individual can get through as shown in Fig. 2b. Obviously this is not an accurate simulation of real life since normally people would change course to avoid a collision in the first place, usually by moving around each other. Clearly this needs to be included in the model in order to make the simulation more realistic.

Fig. 3 shows three potential ways in which avoidance action could be implemented (Goldenstein et al., 2001; Okazaki and Matsushita, 1993). It was decided to develop the idea adapted from Okazaki and Matsushita (1993), shown as idea (b), since it appears to be the closest model to human behaviour in a crowd situation. This meant that the people in the simulation had to be able to identify potential collisions and near misses and then take appropriate action in order to avoid them. In line with the requirement, described above, for the role and function of different psychological groups (with different aims and identities) in single physical crowds to be factored in, in the simulation here each individual is assigned to a group. Each group has its set of aim points which