Automation in Construction 17 (2008) 377–385
AUTOMATION IN CONSTRUCTION
www.elsevier.com/locate/autcon

Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches

Nuria Pelechano *, Ali Malkawi

T.C. Chan Center for Building Simulation and Energy Studies, School of Design, University of Pennsylvania, Philadelphia, PA 19104-6311, USA

Accepted 27 June 2007

Abstract

Building evacuation simulation provides designers with an efficient way of testing the safety of a building before construction. A significant number of models have been developed in a variety of disciplines (computer graphics, robotics, evacuation dynamics, etc.). This paper presents a review of crowd simulation models and selected commercial software tools for high rise building evacuation simulation. The commercial tools selected (STEPS and EXODUS) are grid-based simulations, which allow for efficient implementation but introduce artifacts in the final results. This paper focuses on describing the main challenges and limitation of these tools, in addition to explaining the importance of incorporating human psychological and physiological factors into the models. The paper concludes with an overview of fundamentals that should be applied to simulate human movement closer to real movements of people, where interaction between bodies emerges and flow rates, densities, and speeds become the result of those interactions instead of some predefined value.

Keywords: Evacuation simulation tools; Crowd simulation; High rise building design

1. Previous work

There have been many models developed in order to provide designers with ways of forecasting evacuation times for buildings. A large number of models for pedestrian simulation have been developed over the years in a variety of disciplines (computer graphics, robotics, evacuation dynamics, etc.). These models can be classified into two subsets: macroscopic and microscopic models. Macroscopic models focus on the systems as a whole while microscopic models study the behavior and decisions of individual pedestrians and their interaction with other pedestrians in the crowds. Macroscopic models include regression models, route choice model, queuing models, and gas-kinetics models.

Regression models use statistically established relations between flow variables to predict pedestrian flow operations under specific circumstances. The characteristics of this flow depend on the infrastructure (stairs, corridors, etc.) [15].

Route choice models describe pedestrian wayfinding based on the concept of utility. Pedestrians choose their destinations in order to maximize the utility of their trip (in terms of comfort, travel time, etc.) [11].

Queuing models use Markov-chain models to describe how pedestrians move from one node of the network to another. Nodes are usually rooms, and therefore links are usually portals or doors. Markov-chain models are defined by a set of states together with transition probabilities. At each extrapolation step, a successor state is selected by either sampling from the transition distribution, or identifying the most probable successor [12].

Gas-kinetics models use the analogy with fluid or gas dynamics to describe, using partial differential equations, how density and velocity change over time [10].

Microscopic models include social forces (particle systems) [9], rule based, [24] and cellular automata models [22]. Research models in computer graphics, also considered microscopic models to explore ways of creating virtual humans or animals that behave in an autonomous way. They address realistic body and leg movements with graphical display realism.

The most commonly used techniques to simulate crowd evacuation using microscopic models are social forces and

* Corresponding author. Tel.: +1 215 573 8718; fax: +1 215 573 2192.
E-mail addresses: npelecha@seas.upenn.edu (N. Pelechano), malkawi@design.upenn.edu (A. Malkawi).

0926-5805/$ - see front matter
doi:10.1016/j.autcon.2007.06.005

Table 1
Microscopic models features

Behavior method	Communication or signals	Individualities or roles	Spatial structure for motion
Social forces	No	Some	Continuous
Rule based	No	No	Continuous
CA	No	No	Regular grid

cellular automata (CA) models. The main difference between them is whether they treat the space as continuous (social forces) or discrete (CA), as can be observed in Table 1.

Social forces models have been used to simulate panic situations. An agent's local motion within a room is based on Helbing's model [9] which describes human crowd behavior with a mixture of socio-psychological and physical forces. Pedestrians i, $(1 \le i \le N)$ of mass m_i like to move with a certain desired speed v_i^0 in a certain direction e_i^0 and they tend to adapt their instantaneous velocity v_i within a certain time interval τ_i. At the same time, the individuals try to keep a distance from other individuals j and from the walls w using interaction forces f_{ij} and f_{iw}. The change of velocity in time t is given by the acceleration equation (Helbing, 2000) [9]:

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_W f_{iW}.$$

This model generates realistic phenomena such as arching in the portals and the "faster is slower" effect, and mass queuing/herding behavior as individuals tend to follow what others do.

Rule based models [24,25] have been widely used among the computer graphics community to simulate flocks of animals, or virtual humans. The most well known model to simulate life-like complex behavior is Reynolds' local rules "boids" model [24]. This model is an elaboration of a particle system with the simulated entities (boids) being the particles. The aggregate motion of the simulated flock is created by a distributed behavioral model. Each simulated agent is implemented as an independent actor that navigates according to its local perception of the dynamic environment, the laws of simulated physics that rule its motion, and a set of behaviors programmed by the animator. The aggregate motion of the simulated flock is the result of the dense interaction of the relatively simple behaviors of the individual simulated boids.

The basic model to simulate generic flocking behavior consists of three simple rules which describe how an individual boid maneuvers based on the positions and velocities of its nearby flock mates (Fig. 1):

- separation: steer to avoid crowding local flock mates
- alignment: steer towards the average heading of local flock mates
- cohesion: steer towards the average position of local flock mates

Each boid has access to the whole environment description, but flocking only requires reaction within a specific neighborhood, which is given by a distance (from the center of each boid) and an angle (from each boid's direction of flight). This neighborhood can be considered as limited perception. Each boid will avoid not only collision against other boids but also with obstacles in the environment. In addition to the basic three rules used to simulate flocking, Reynolds [25] introduced the more general concept of steering behaviors and placed flocking within that context. Steering behavior enhances the behaviors already presented in the original boids model by building parts for complex autonomous systems. Each of these new rules defines only a specific reaction on the simulated environment of the autonomous system.

Cellular automata models divide the space in a uniform grid (Fig. 2). Each agent occupies a particular grid position (cell) and moves between these positions depending on the modeling system. Cellular automata evolve in discrete time steps, with the value of the variable at one cell being affected by the values of variables at the neighboring cells. The variables at each cell are updated simultaneously based on the values of the variables in their neighborhood at the previous time step and according to a set of local rules [22].

Research models in computer graphics have several cognitive agent architectures proposed to generate human-like behavior. They generally consist of knowledge representation, algorithms that learn, and modules that plan actions based on that knowledge [7,34]. Particle systems and dynamics for modeling the motion of groups with physics were also used [4,5]. In addition, multi-agent crowd systems were also utilized where the agents are autonomous, typically heterogeneous, and concerned with coordinating intelligent behaviors among themselves. Some of these applications include crowd behavioral models used in the training of military personnel [33] and crowd motion simulations to support architectural design for both everyday use [6] and emergency evacuation conditions [2,23].

2. Psychological and physiological factors that affect human behavior

It is necessary to study the psychology literature in order to understand the psychological factors that affect human behavior and movement. Crowd evacuation from large and complex public building spaces is usually slowed down by a lack of knowledge of the detailed internal connectivity of the building's rooms. In such circumstances, individuals may not be aware of some suitable paths for evacuation. Building occupants usually decide to make use of familiar exits, which are often the way in which they enter the building, and tend to ignore emergency exits or paths not normally used for circulation [28].

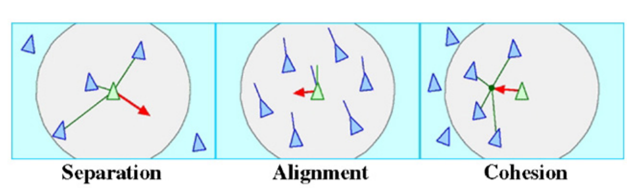

Fig. 1. Reynolds' boids.