International Journal of Automation and Computing 6(4), November 2009, 351-355
DOI: 10.1007/s11633-009-0351-9

Technology for Simulating Crowd Evacuation Behaviors

Wen-Hu Qin* Guo-Hui Su Xiao-Na Li
School of Instrument Science and Engineering, Southeast University, Nanjing 210096, PRC

Abstract: This paper presents a model for simulating crowd evacuation and investigates three widely recognized problems. For the space continuity problem, this paper presents two computation algorithms: one uses grid space to evaluate the coordinates of the obstacle′s bounding box and the other employs the geometry rule to establish individual evacuation routes. For the problem of collision, avoidance, and excess among the individuals, this paper computes the generalized force and friction force and then modifies the direction of march to obtain a speed model based on the crowd density and real time speed. For the exit selection problem, this paper establishes a method of selecting the exits by combining the exit′s crowd state with the individuals. Finally, a particle system is used to simulate the behavior of crowd evacuation and produces useful test results.

Keywords: Crowd evacuation, behavior simulation, particle system, social force model.

1 Introduction

With the rapid development of city construction, research on city public security becomes especially important. The main emphasis is placed on the problem of quick and safe evacuation in public buildings when there occur such urgent events as fire, explosion, traffic accidents, and so on. The research on crowd evacuation started several decades ago, and has already found more and more uses in many areas. For example, how can people escape from a building which is on fire? How can people evacuate from public places such as the subway station, gym, museum, and so on, when emergency situations happen? How will people act when public health events and natural disasters break out? Research on this field is helpful in making decisions for public security management and emergency management.

Social force models on panic have been researched by Helbing et al.[1] They reached the conclusion that congestion is the reason for a crowd′s weird behavior. Besides, individual emotional fluctuations may result in bad influence on crowd behavior during evacuation. Still[2] studied the control of crowd behavior from the view of particles and applied it to crowd evacuation in gyms and stations. It was proved that this is significant to egress the design of those places. Reynolds[3] made a simulation on crowd behavior of human beings, birds, and fish, using three rules with different priorities (avoidance, velocity matching, gathering zone) to control crowd behavior. Mataric[4] adopted natural crowd behavior to define four basic behaviors — escaping, following, assembling, and dispersing. In China, Fang and Lu′s mesh model[5], Xu′s agent-based model[6], and Pan′s geometry model[7] have achieved the simulation of crowd evacuation and achieved good results.

The crowd evacuation models and simulation methods referred to above mostly use the mesh model. That is to say, the plane space is divided into equal-size square or rectangular cells. The cell size is related to the pace and the space the individual holds, and each cell can only be occupied by one individual or one obstacle at a time. Each individual location is decided by the cell it belongs to, and an individual′s following motion is decided by the cell he/she occupies and the adjacent 8 cells. In Mesh simulation, because all agents have the same pace and an individual can only move in cells with the same velocity and distance, the differences between individuals and continuity of space are missing and the simulation looks unreal. To solve this problem, Fang and Lu[5] adopted geometry to simulate crowds. Space is continuous with this method; however, this method calls for a large consumption in simulation calculation, because path searching is required per step for every individual. Hence, if there are many individuals in the environment, the simulation is very slow, and the effect is not good.

With the development of computer technology, crowd evacuation simulation demands more in terms of reality and speed. In order to make it realistic, not only should individuals′ state, the interaction between individuals and the influence of the environment should be taken into consideration, but virtual reality technology should also be used to realize the 2-D and 3-D crowd evacuation simulation. In some sense, realistic simulation is a challenge in the field.

In safe egress design of pubic buildings (stations, museums, gyms), the location of the exit and obstacle should be taken into consideration to ensure that the space layout meets the safe design requirements. In this paper, computer simulation technology is used to imitate the evacuation process in public areas. The coordinates of obstacle′s bounding box is obtained by mesh method. On the basis of these coordinates, geometry is applied to decide the starting path for every individual. The social force model and exit choosing model are used to simulate dynamic avoidance, circumambulation, exceeding, and congestion of the exit. Finally, we use the particle system to realize crowd evacuation simulation.

Manuscript received October 17, 2008; revised April 28, 2009
This work was supported by Shanghai Science and Technology Committee (No. 08515810200) and Jiangsu Province Development Foundation (No. BS2007048).
*Corresponding author. E-mail address: qinwenhu@seu.edu.cn

2 Crowd evacuation model

The crowd behavior obeys the so-called "psychology-behavior" rule. In normal conditions, the crowd behavior is decided by group. Each member′s behavior corresponds with the group leader, and there is at least one member in the group. The character of the crowd can be described as follows: each group has the same action and target as its all members, but it is not necessary to adopt the same action among groups. When the environment of the crowd falls into dangerous environments such as fire or explosion, the members, due to their fear and instinct for survival, will enter into an emergent state and will not follow the group. The characteristics of this situation[8, 9] can be described as follows: 1) each member wishes he/she could escape as soon as possible; 2) everyone hopes to find the shortest way; 3) the more the member knows about the environment, the more easily he/she can escape; 4) the fear and chaos of the individuals make the exits crowded and "arch phenomenon" emerges, thus slowing down the speed of the flow and the phenomenon "more haste, less speed"; 5) some members may fall down to the ground, thus making the escaping speed even slower; 6) the scared crowd usually congregate at one exit and ignore the others; 7) with the excessive crowding, the wall nearby may collapse and bring about extra injuries.

Research on the individual behavior in emergent states shows that the individual can hardly escape at a fixed speed along a previously selected path. The individual is affected by the circumstance, the crowd density, and the mental state, so his/her escape speed and route are variable. Thus, the evacuation path, velocity, and exit choosing are topics of crowd simulation research.

2.1 Evacuation route

When escaping, an individual will usually take the "perceive-decision-making-act" strategy. In the real case, the escaping route is mostly selected by vision. If there is no obstacle between the individual and the exit, he/she will go straightforward. Otherwise, he/she has to move to the edge of the obstacle in the nearest direction. As the individual vision is difficult to simulate with a computer, we use a grid to get the coordinates of the bounding box of the obstacle, as shown in Fig. 1.

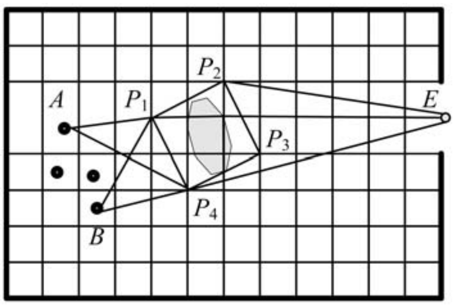


Fig. 1 Obstacle estimation and route selection based on grid method

In Fig. 1, the unit size of the grid is associated with the space occupied by an individual. The coordinates of P_1, P_2, P_3, and P_4 can be obtained by calculating the outermost bounding points. As there is an obstacle between A and E, A will select the closest points P_1 or P_4 to escape. The crowd will move from A to P_1 to P_2 to E or from A to P_4 to E. Which path to choose is decided by the acquaintance degree of the environment. When the crowd is moving to E from point A, both existences are coincident with the facts.

2.2 Evacuation speed

The evacuation speed of an individual is concerned with his/her strength, mentality, the crowd density nearby and location. According to experimental statistics, a human being walks with a speed of 1.2 m/s in the normal cases while in emergent case, the speed can reach up to 1.5 m/s. The crowd speed decreases as density increases. This relationship is given by

$$v = v_0 \cdot \rho^{-0.8} \quad (1)$$

where v_0 is a constant set at 1.34 m/s; ρ is the crowd density, standing for the human number in a square meter.

Lu et al.[10] drew the conclusion that the push from the people ahead and behind impacts mostly on evacuation speed. The crowd speed is expressed as

$$v(\rho) = v(\alpha A + \beta B + \gamma) \quad (2)$$

where $A = 1.32-0.82\ln(\rho)$, $B = 3.0-0.76\rho$, $\alpha \in [0.25, 0.44]$, $\beta \in [0.014, 0.088]$, $\gamma \in [0.15, 0.26]$, and ρ presents the crowd density.

By experiments and comparison, we select (2) as the model of the individual movement. The human density is defined as the number of persons in a circle with a 5 meters long radius centered with individuals.

2.3 Adjustment of individual behavior

The situation usually occurs where several individuals compete for the same place, or the fast persons exceed the slow ones in the movement. In the simulation, when the competition for one grid appears, only one person can move to that grid, while others should return back to their previous places. However, an active person is able to forecast the collision and detours or exceeds the obstacle as early as possible. In this paper, we use Helbing′s social force model[1] to determine the direction of the next step of the individual according to the value of the self-driven force and the repulsion force among the individuals. A pedestrian i with mass m_i, is expected to evacuate with a speed of v_i^0 and direction of e_i^0. During the moving process, there are repulsive forces and friction between individuals or between individuals and the wall. By f_{ij} and f_{iw}, we denote these two frictions, respectively. The smaller the distance between individuals or between a person and the wall, the larger the repulsion force; and the larger the speed in the tangent direction becomes, the larger the friction will be. Assume that a man′s real speed is v_i, when he speeds up to v_i^0 during the time of τ_i. Then, the speed variation equation with the parameter t can be written as

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = \frac{m_i[v_i^0(t)e_i^0 - v_i(t)]}{\tau} + \sum_{j=1}^{n} f_{ij} + \sum_{w=1}^{n} f_{iw}. \quad (3)$$

The effect individual j adds to individual i includes two parts: the repulsion force between individuals and the friction generated by the contact, expressed as

$$f_{ij} = \{A_i \exp\left(\frac{r_{ij} - d_{ij}}{B_i}\right) + kg(r_{ij} - d_{ij})\}n_{ij}v_{ji}^t t_{ij} + \lambda g(r_{ij} - d_{ij})\Delta \quad (4)$$

where $r_{ij} = r_i + r_j$ is the smallest distance between two individuals to keep from touching; $d_{ij} = \|r_i - r_j\|$ is the distance between the individual i and j; $n_{ij} = (r_i - r_j)/d_{ij}$ is the unit vector from j to i; A_i, B_i, k are constants; λ is the coefficient of friction; t_{ij} is a vector in tangent direction, $\Delta v_{ji}^t = (v_j - v_i)t_{ij}$ is the difference between the speeds in tangent direction. If $d_{ij} > r_{ij}$, function $g(x) = 0$, otherwise $g(x) = x$.

The force f_{iw} that an obstacle W acts on the individual is the summation of the force of each surface, given by

$$f_{iw} = \left\{A_i \exp\left(\frac{r_i - d_{iw}}{B_i}\right) + kg(r_i - d_{iw})\right\} n_{iw} + \lambda g(r_i - d_{iw})(v_i \cdot t_{iw})t_{iw} \quad (5)$$

where d_{iw} is the distance between an individual and the obstacle′s surface; n_{iw}, t_{iw} are the unit vector in normal and tangent direction of the surface of W, respectively. The former points to the movement space of an individual, while the latter points to the inverse direction of the movement.

2.4 Potential field model

Gloor et al.[11] proposed the potential field model for the adjustment of individual behavior during crowd evacuation. First, a potential field graph of the evacuation environment is generated, and the next step is selected according to the value of potential energy in every single step. The key point is the generation of a potential field distribution graph.

Firstly, the environment is dispersed into grids with a size of 0.25–0.5 m. A 7 × 7 grid is given to demonstrate the generation of the potential field graph.

It is supposed that the potential energy of the exit is 0, and the potential energy of the adjacent grids is computed from exit. We add 1 to each horizontal or vertical grid, and add 1.414 to the diagonal move. Further, the effect of obstacle should be taken into consideration, so the potential energy of the grids adjacent to an obstacle is added by 2, while that of grids next to these grids is added by 1. There is an obstacle factor in the potential energy graph as shown in Fig. 2.

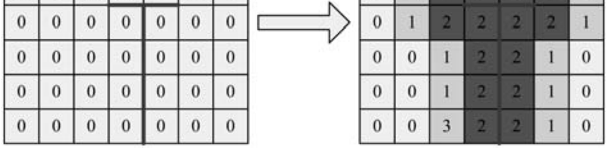


Fig. 2 Primitive incremental graph of potential energy with the consideration of obstacle

Take Fig. 2 as original potential energy graph. The lower left corner is the exit with a potential energy 0. The generation process is shown in Fig. 3. Fig. 3 (a) is the primitive one. Starting from the exit, the potential field of the three adjacent grids is generated as shown in Fig. 3 (b). Then, we search the smallest potential grid and take it as the starting point to get the potential energy of all the adjacent grids. Then, we find the next grid with minimum value, and get the potential fields of all grids in the environment using the same method. Finally, a potential field distribution model is generated as shown in Fig. 3.

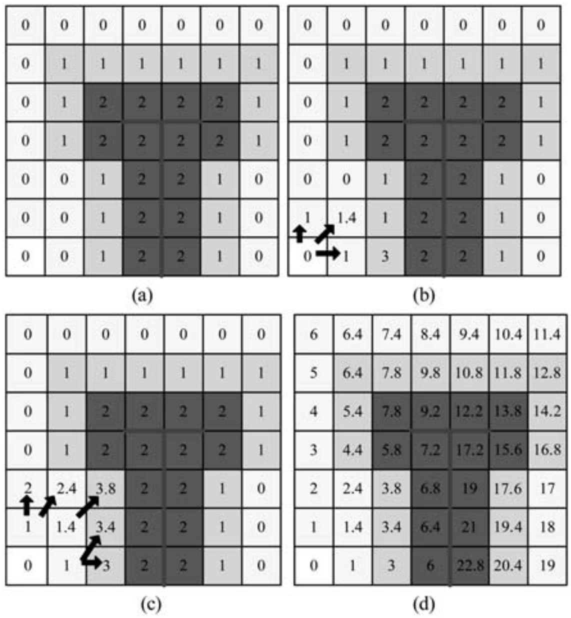


Fig. 3 The generation process of potential energy graph. (a) Primitive graph; (b) Graph after first step; (c) Graph after two steps; (d) Final graph

2.5 Exit selection

When there are several exits to be selected, in the simulation of the course of one′s decision, denote by J the crowd extent, by ω the individual nervous extent. Then, J is given by

$$J = \frac{2n}{\pi d^2} \quad (6)$$

where d is the width of the door, and n is the number of the individuals in the circle with radius d.

The nervous extent ω varies from 0 to 1, and a larger value means greater nervousness. The exit is chosen by the individual′s nervousness extent. That is to say, when the ω value is large, a nearer exit is chosen. Conversely, the exit with a small J is chosen.

2.6 Framework of program

Many factors are taken into consideration such as exit selection, path selection, speed adjustment, dynamic avoidance, moving around, and overtaking in simulating the evacuation. The software framework is shown in Fig. 4.

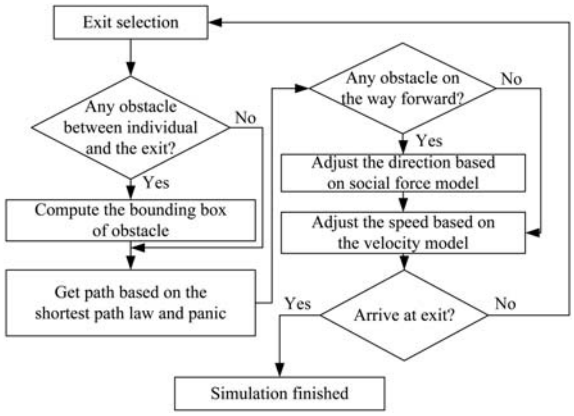


Fig. 4 The software framework of crowd evacuation simulation

3 Realization of visual simulation

The particle system proposed by Reeves in 1983 allows us to construct complicated objects with simple voxels. It further shows the dynamics and randomicity. Position, speed, color, and lifetime are the instinct properties of a particle, which combine the geometry and behavior together. The particle system undergoes a changing process, and 4 steps are to be finished during its lifetime: 1) produce a new particle from the source, 2) update the attribute of the particle, 3) delete particles whose lifetime is over, 4) render the particle. During the crowd simulation, every particle represents an individual. It is assumed that every particle has such properties as position, speed, direction, acceleration, range, radius, nervousness, size, color, brightness, shape, texture, life, and so on. In other words, the particle is an n-dimensional vector R_n ($n = 13$). $R_n = \{$Position, Speed, Direction, Acceleration, Range, Radius, Nervousness, Size, Color, Brightness, Shape, Texture, Life$\}$.

A crowd is the gathering of particles. The set of all particles states in each time is the track of movement. The update of particle attribute is used for the evacuation simulation. Visual C++ 6.0 and OpenGL are used to design the crowd evacuation simulation software. The algorithm of the software is realized in the following steps:

Step 1. Initialize the building environment and particle system.

Step 2. Choose exit according to the attraction force.

Step 3. Get the step to move for every single individual according to the shortest path graph.

Step 4. Change direction if there are obstacles in the way ahead.

Step 5. Update current individual′s speed based on speed evacuation model

Step 6. Judge the arrival of exit. If yes, delete the particle, or go back to Step 2.

3.1 Simulation of museum evacuation

Crowd evacuation software is used to imitate the evacuation process of 200 people in a museum of $20 \times 15\,\text{m}^2$ to test the security of design. Fig. 5 is the geometry graph of crowd evacuation with single and double exits. The outline of the obstacles and the shortest path which is the connected to the exit are shown in Fig. 5. The evacuation path is decided by the principle of shortest path according to the position the individual occupies. Fig. 6 is the result of using the above principle with different simulation time. Fig. 6 (a) is the result of a single exit. Fig. 6 (b) shows the decision-making among different exits. In other words, if the environment around an exit is crowded, many individuals may choose other exits.

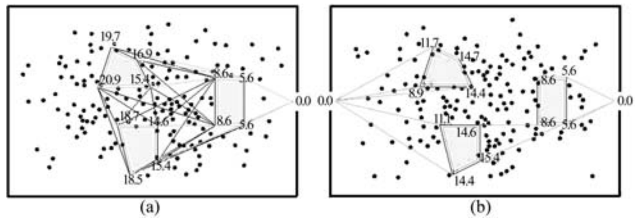


Fig. 5 The geometry graph of crowd evacuation. (a) Simulation with one exit; (b) Simulation with two exits

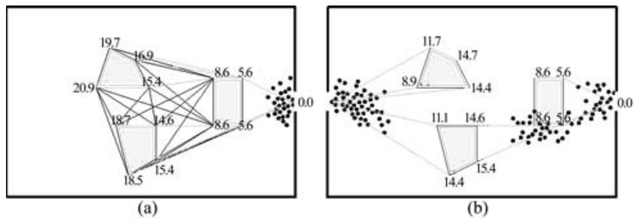


Fig. 6 The simulation of crowd simulation. (a) Simulation in 22 s of single exit; (b) Simulation in 15 s of double exits

In the simulation of Fig. 6, the total time used for a single exit is 97 s, and 61 s for double exits, implying that the exit design has met the security requirements. Crowd evacuation simulation software can be used for detailed quantification of evacuation time from different space layouts, so it is really useful for testing and guiding the security design.

3.2 Evacuation simulation in a vehicle

Taking Jinlong coach as an example, we simulate the process of evacuation by the method described above. The coach is $12000 \times 3800\,\text{mm}^2$ in size, with 41+1 seats in it. We imitate the evacuation when the coach is full. The results are shown in Figs. 7 and 8, and the time used is 38 s. In Fig. 7, the black points and gray points mean different panic levels.

4 Conclusions

Some conclusions are drawn as follows:

1) Using grids to recognize the outline of the obstacle and adopting geometry to get the evacuation path proves feasible because the problem of space continuity has been dealt with satisfactorily.

2) Social force is used to decide the direction, and the individual velocity is determined by a speed model. Using these methods, we can simulate the difference between agents, and make the results more realistic.

3) The combination of crowding extent and nervousness extent can be used to solve the problem of exit selection.

4) The particle system is a good means to realize the crowd evacuation simulation, because of visual representation of information as well as a good foundation for further 3-D simulation.

5) An empirical formula is employed during the process of simulation, so more comparisons with real situations should be made.

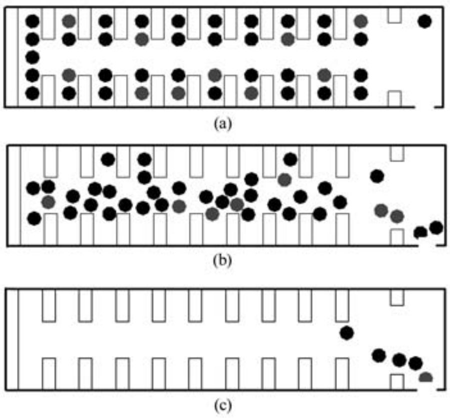


Fig. 7 2-D evacuation simulation in a vehicle. (a) The initial state; (b) Situation after 3 s; (c) Situation after 33.5 s

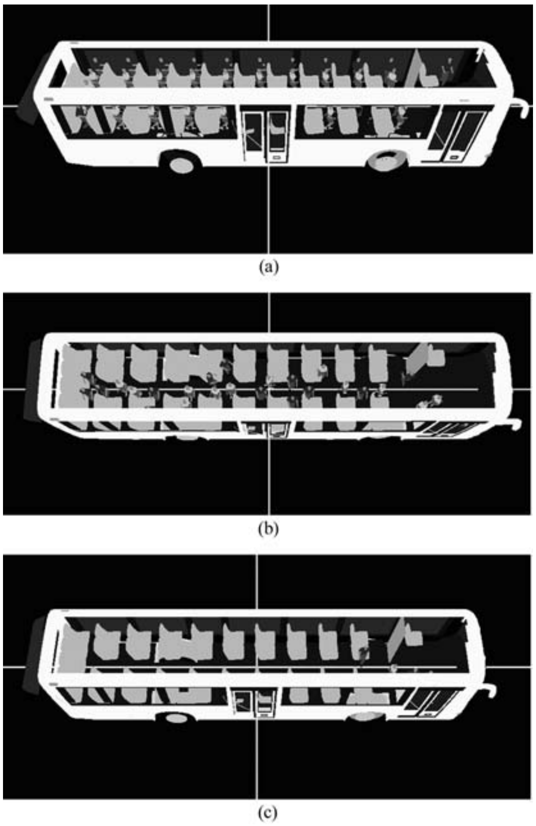


Fig. 8 3-D evacuation simulation in a vehicle. (a) The initial state; (b) The situation after 3 s; (c) The situation after 33.5 s

References

[1] D. Helbing, I. J. Farkas, T. Vicsek. Simulating Dynamical Features of Escape Panic. *Nature*, vol. 407, pp. 487–490, 2000.

[2] G. K. Still. Crowd Dynamics, Ph. D. dissertation, University of Warwick, UK, 2000.

[3] C. W. Reynolds. Flocks, Herds and Schools a Distributed Behavioral Model. *ACM SIGGRAPH Computer Graphics*, vol. 21, no. 4, pp. 25–34, 1987.

[4] M. J. Mataric. Learning to Behave Socially. In *Proceedings of the 3rd International Conference on Simulation of Adaptive Behavior – From Animals to Animals 3*, Brighton, UK, pp. 453–462, 1994.

[5] Z. Fang, S. M. Lu. A Spatial Grid Model for Emergency Evacuation from Building. *China Safety Science Journal*, vol. 11, no. 4, pp. 10–13, 2003. (in Chinese)

[6] G. Xu. Simulation Model for Crowd Evacuation Based on Agent Technology. *Journal of Southwest Jiaotong University*, vol. 38, no. 3, pp. 301–303, 2003. (in Chinese)

[7] Z. Pan, C. B. Wang, B. Y. Xie. Simulation of Evacuation Based on Continuous Geometry Model. *Journal of System Simulation*, vol. 18, suppl. 1, pp. 233–236, 2006.

[8] M. B. Villamil, S. R. Musse, L. P. L. De Oliveira. A Model for Generating and Animating Groups of Virtual Agents. In *Proceedings of the 4th International Workshop on Intelligent Virtual Agents*, Springer, Kloster Irsee, German, pp. 164–169, 2003.

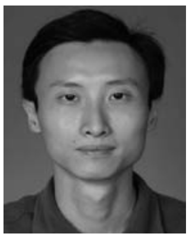
[9] L. Heïgeas, A. Luciani, J. Thollot, N. Castagné. A Physically-based Particle Model of Emergent Crowd Behaviors. In *Proceedings of International Conference on Computer Graphics and Vision*, Moscow, pp. 73–80, 2003.

[10] J. A. Lu, Z. Fang, Z. M. Lu, C. M. Zhao. Mathematical Model of Evacuation Speed for Personnel in Buildings. *Engineering Journal of Wuhan University*, vol. 35, no. 2, pp. 66–70, 2002. (in Chinese)

[11] C. Gloor, P. Stucki, K. Nagel. Hybrid Techniques for Pedestrian Simulations. In *Proceedings of the 4th Swiss Transport Research Conference, Lecture Notes in Computer Science*, Springer, vol. 3305, pp. 581–590, 2004.

Wen-Hu Qin received the B. Sc. degree in control science and engineering, the M. Sc. degree in measuring techniques and instruments from Southeast University, PRC in 1991 and 1997, respectively, and the Ph. D. degree in precision instrument and mechanism in Southeast University in 2005. He is currently an associate professor of School of Instrument Science and Engineering of Southeast University.

His research interests include measurement and control, computer simulation and virtual reality.



Guo-Hui Su received the B. Sc. and M. Sc. degrees in instrument science and engineering from Southeast University, PRC in 2004 and 2007, respectively. He is currently a soft engineer in Laboratory of Virtual Reality at Southeast University.

His research interests include computer simulation, virtual reality and digital image processing.

Xiao-Na Li received the B. Sc. degree in instrument science and engineering from Southeast University, PRC in 2005. She is currently a Ph. D. candidate at Southeast University.

Her research interests include virtual crowd modeling and computer simulation.