J. Marine Sci. Appl. (2011) 10: 340-346
DOI: 10.1007/s11804-011-1078-x

Research on a Multi-grid Model for Passenger Evacuation in Ships

Miao Chen*, **Duanfeng Han and Haipeng Zhang**

College of shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

Abstract: In order to enhance the authenticity and accuracy of passenger evacuation simulation in ships, a new multi-grid model was proposed on the basis of a traditional cellular automata model. In the new model finer lattices were used, interaction of force among pedestrians or between pedestrians and constructions was considered, and static floor fields in a multi-level exit environment were simplified into cabin and exit static floor fields. Compared with the traditional cellular automata model, the multi-grid model enhanced the continuity of the passengers' track and the precision of the boundary qualifications. The functions of the dislocation distribution of passengers as well as partial overlap of tracks due to congestion were realized. Furthermore, taking the typical cabin environment as an example, the two models were used to analyze passenger evacuation under the same conditions. It was found that the laws of passenger evacuation simulated by the two models are similar, while the simulation's authenticity and accuracy are enhanced by the multi-grid model.

Keywords: passengers' evacuation in ships; multi-grid model; simulation evacuation; floor field; interaction of force

Article ID: 1671-9433(2011)03-0340-07

1 Introduction

Recently, well-published ship disasters together with trends of largely increased passenger carrying capacity in ships have brought more and more attention to the issue of passenger evacuation. Being the last line of defense in ship safety, it has become a hot topic of investigation all over the world.

The methods of simulating passenger evacuation are usually separated into two categories: the macroscopic method (Bradley, 1993) and the microcosmic method. Comparatively, the dynamical process of passenger evacuation is simulated more exactly by microcosmic method. The models set up by the microcosmic method can also be separated into two approaches: the continuity model and discrete model. The social force model (Helbing and Molnar, 1995; Helbing *et al*., 1997; Helbing *et al*., 2000) is the most widely researched continuity model. As the self-driven force, repulsion, and friction brought during the process of pedestrian movement are solved by the classical Newton's mechanics equation and the position and velocity of the pedestrians changes continuously in the social force model, the calculated result is quite accurate. However, it isn't suited for large-scale computer simulations due to its lower operation speed. At present, discrete models are widely used not only in theoretical research, but also in engineering application because of their higher operation speed; some examples are the cellular automata model (Burstedde *et al*., 2001; Yue *et al*., 2010) and lattice gas model (Guo and Huang, 2008). The accuracy of their calculated results is lower as a result of their lack of expression of the interaction force between pedestrians.

For the sake of combining the advantages of the social force and discrete models, some scholars have developed new models. The so-called bionics-inspired floor field model and friction model can behave the self-driven force of pedestrians (Kirchner and Schachneider, 2002) and repulsion among pedestrians (Kirchner *et al*., 2003) preferably. On that basis, the cellular automata with force essentials (CAFE) model (Song *et al*., 2006a) got similar results as the social force model by quantitative analysis of repulsion and friction between pedestrians and by simulating some basic pedestrian dynamics phenomena. Those models could neither realize the dislocation distribution of pedestrians practically nor consider the impact of boundary qualifications and exit conditions sufficiently because the size of the smallest cell is the same as that of one person. In order to research the characteristics of passenger evacuation more carefully, some scholars have made the lattice finer, which allows one person to take up multiple cells. Kirchner *et al*. simulated the passenger evacuation process in a corridor and single-exit room by the method of one person occupying 2×2 cell (Kirchner *et al*., 2004). Weng *et al*. (2007) analyzed the relationship between the evacuation time and the number of cells moved at one time step by setting up a small grid model (Weng *et al*., 2007). Song *et al*. (2006b) proposed a multi-grid model which imports the interaction force among pedestrians and

Received date: 2010-11-24.
Foundation item: Supported by the Ph.D Programs Foundation of Ministry of Education of China under Grant No.201023041108 and the Fundamental Research Funds for the Central Universities under Grant No.61004008.
***Corresponding author Email:** chenmiao_1102@163.com

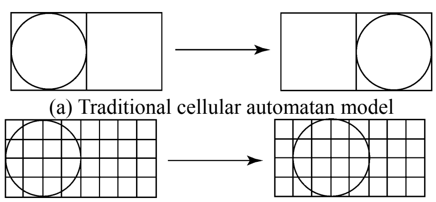
interaction force between pedestrians and constructions in a social force model (Song *et al*., 2006b), and the result of the model was close to that of the social force model.

On the basis of the research content mentioned above, a new multi-grid model is introduced in this paper. In the new model the number of cells that one person occupies is added to 4×4 cells, and the effects of extrusion, repulsion, and friction in the social force model are also imported. The flexibility and practicability of the new multi-grid model are analyzed compared with the traditional model.

2 The multi-grid model

2.1 Mathematicization of the multi-grid model

As Fig.1(a) shows, in the single-grid model the size of a single cell is 0.4 m×0.4 m, the same as the typical space occupied by a person in a dense crowd. At any moment, the state of each cell is empty or occupied by one person at most. As long as the state of adjacent cells is empty, the central pedestrian can move up and down, left and right. But as Fig.1(b) shows, the space is significantly finer in the multi-grid model and the size of each cell is 0.4 m/n×0.4 m/n. That is to say, each person occupies $n \times n$ cells. According to (Fang *et al*., 2008) research on the multi-grid model, the evacuation efficiency is the highest under the same velocity when the distance moved in one time step is as long as the size of one person under the same velocity (Fang *et al*., 2008). In a common situation the velocity of an individual is 1 m/s. So, it can be seen that n=4. Furthermore, in order to make the simulation result closer to a practical situation, the directions of a pedestrian's movement are extended from 4 to 8 adjacent cells as shown in Fig.2.



(a) Traditional cellular automatan model

(b) Multi-grid model

Fig.1 Movement of pedestrian

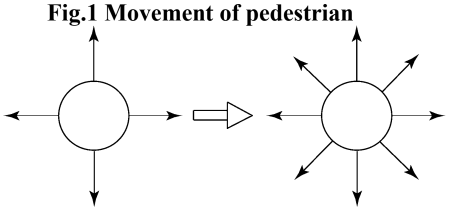


Fig.2 Direction of pedestrian's movement

2.1.1 Advantages of finer lattice

Compared with the single-grid model, the multi-grid model is improved in several aspects.

1) The continuity of a pedestrian's movement

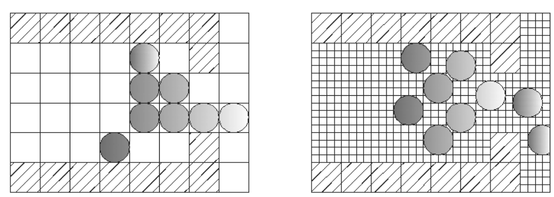
In the single-grid model each pedestrian stops or moves with the length equal to that of a person in each time step. That coincides with a practical situation when the density of passengers is low. But the distance that a pedestrian moves could be less when the density of passengers is high. In this case the single-grid model can't show the fine movement of pedestrians. However, the multi-grid model can express fine movement better and allow the position of pedestrians to vary more continuously.

2) Passenger distribution character

For the single-grid model the space between pedestrians is multiple times of the length of a cell. But for the multi-grid model the space between pedestrians can be less than the length of a person. Therefore the multi-grid model can realize the dislocation distribution of pedestrians.

3) Effect of conclusions concerning the exit

For the multi-grid model the dislocation distribution of pedestrians has intensified the repulsive effect between pedestrians greatly, especially at the exit. As Fig.3 (a) shows it is easy for two pedestrians to pass through the exit at the same time in the single-grid model. On the contrary, the probability is much lower for two pedestrians to pass through the exit at the same time in multi-grid model due to the effect of the dislocation distribution of pedestrians. As Fig.3(b) shows, if one pedestrian occupies the middle position of the exit, others can't pass through in the multi-grid model. In a practical situation, the phenomenon described in Fig.3(b) always happens. But for the single-grid model as the length of the exit is multiple times the size of one person, the effect of exit's exclusion can not happen.



(a) Single-grid model (b) Multi-grid model

Fig.3 Effect of exit's exclusion

4) Accuracy of boundary qualifications

In both of the models the size of the cabin's boundary is multiple times of the size of one cell. The size of one cell in the single-grid model is 0.4 m×0.4 m but 0.1 m×0.1 m in multi-grid model. So the accuracy of boundary qualification can reach 0.1 m.

2.1.2 Floor field of multi-grid model

$P_{-x,y}$	$P_{0,y}$	$P_{x,y}$
$P_{-x,0}$	$P_{0,0}$	$P_{x,0}$
$P_{-x,-y}$	$P_{0,-y}$	$P_{x,-y}$

Fig.4 Matrix *P*

In the model each pedestrian could be in one of the eight possible directions with different transition probabilities and move to one of the neighboring grids. As Fig.4 shows, a preferential matrix ***P*** is adopted to describe the probability value of the directions one pedestrian could move to. The value of the probability is determined by four interactive elements: trace of pedestrians, self-driven force of pedestrian movement, interaction force among pedestrians, and interaction force between pedestrians and constructions. The probability of a pedestrian's center moving to cell (i, j) can be calculated as below.

$$p_{ij} = N \cdot \exp(k_D D_{ij} + k_S S_{ij} + k_r r_{ij} + k_f f_{ij}) \cdot (1 - n_{ij}) \qquad (1)$$

$$N = \sum p_{ij}^{-1} \qquad (2)$$

$$n_{ij} = \begin{cases} 1 & \text{occupied} \\ 0 & \text{not occupied} \end{cases} \qquad (3)$$

where N represents the standardization coefficient and n_{ij} the state of cell (i, j) at time t.

D_{ij} is the dynamic floor field value at the present position. D is a virtual trace left by the pedestrians along with its own dynamics, diffusion, and decay. It is used to model different forms of interactions between the pedestrians. At $t = 0$ the dynamic field is set to zero for all sites (i, j) of the lattice ($D_{ij} = 0$). Whenever a particle jumps from site (i, j) to one of the 8 adjacent cells, D_{ij} at the origin cell is increased by one: $D_{ij} \to D_{ij} + 1$. Furthermore the dynamic floor field is time dependent; it has diffusion and decay controlled by two parameters, δ and α .

S_{ij} is the static floor field value at the present position. S represents the self-driven force of pedestrians. S is used to specify regions of space which are attractive. In case of an evacuation simulation the static field S describes the shortest distance to the closest exit. As Eqs.4 and 5 show, S_{ij} represents the character of the floor and its largest value is at center of the exit. All the other values of S_{ij} are the difference with S_{ij} at center of the exit. k_D and k_S are coupling constants of the dynamic floor field and static floor field separately.

$$S_{ij}^0 = |x_i - x_{\text{exit}}| + |y_i - y_{\text{exit}}| \qquad (4)$$

$$S_{ij} = \max(S_{ij}^0) - S_{ij}^0 \qquad (5)$$

The interaction forces among pedestrians or interaction forces between constructions are made up of extrusion, repulsion, and friction. r_{ij} represents the repulsion and f_{ij} the extrusion and friction between pedestrians. k_r represents the coupling constant of r_{ij} and k_f represents the coupling constant of f_{ij} .

If one of the cells that a pedestrian occupies is overlapped, he/she will suffer from the force from the direction of overlapped cell. According to the positions of overlapped cells different effects will be generated in the eight directions that one pedestrian could move to. If more than one cell is overlapped, the interactive effect will be stacked. As the Eq.6 shows, F is the average interaction force, μ is the friction coefficient, and f_{ij} is the force applied in the 8 directions. As Fig.5 shows, F is decomposed into the force in the direction of f_{ij} and the force vertical to the direction of f_{ij} . The value of f_{ij} is the sum of the component forces of F in the direction of f_{ij} and the component forces' friction vertical to the direction of f_{ij} .

$$f_{ij} = \sum_{k=1}^{n} (F \cdot \cos\theta + \mu \cdot F \cdot \sin\theta) \qquad (6)$$

Similarly when there are other pedestrians or constructions within one sub-step distance of the central pedestrian's movement directions, repulsion will be generated because of psychological effect, as Fig.6 shows. The value of extrusion r_{ij} in different directions is the sum of component force of F in the directions of r_{ij} as Eq.(7) shows.

$$r_{ij} = \sum_{k=1}^{n} F \cdot \cos\gamma \qquad (7)$$

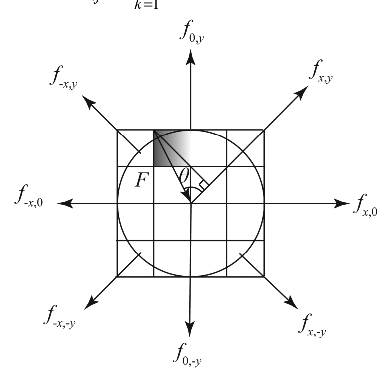


Fig.5 The force operates on pedestrian

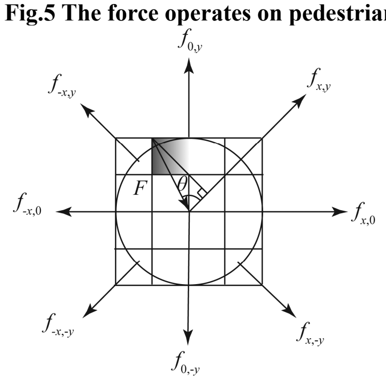


Fig.6 The repulsion operates on pedestrian

2.2 Static floor fields for an environment with multi-level exits

Network flow theory has been adopted for simulating typical scenarios in ships in traditional models. The cabins, corridors, rooms before the stairs, stairs, muster station, and other construction entities are simplified to network units. The network units are connected with doors and openings to compose a distributed connectionist network. In the traditional model, each network unit has an independent floor field from the center of its exit. However, when the lattice is finer and the number of cabin structures is large, the amount of storage data is great. It is too complex to simulate using the traditional method since too many circulation cycles have decreased the efficiency to the extreme. In order to solve the problem, the static floor fields are simplified into cabin static floor fields and exit static floor fields in order to create an environment with multi-level exits. Fig.7 shows the superposition cabin static floor field of an environment with multi-level exits. From Fig.7 it can be seen that a single static floor field suitable for an environment with multi-level exits can't be gotten by superposition of every cabin's static floor field because the value of the static floor field doesn't vary monotonously. Therefore, the exit static floor field is introduced to lead pedestrians going to the next level network unit. The value of the exit static floor field is the difference of two conjoint network unit exits. The cabin static floor field is made up of the superposition of all the cabins' static floor fields and the exit static floor field is made up of the superposition of all the exits' static floor fields. In the process of a pedestrian's movement he/she judges his/her location in the whole cabin structure first. If he/she is in a cabin, he/she will move to the exit of the cabin under the control of cabin static floor field. Moreover, if he/she is in an exit or opening he/she will move to the next level cabin under the control of the exit static floor field. At last the person will reach the final exit after such repetition.

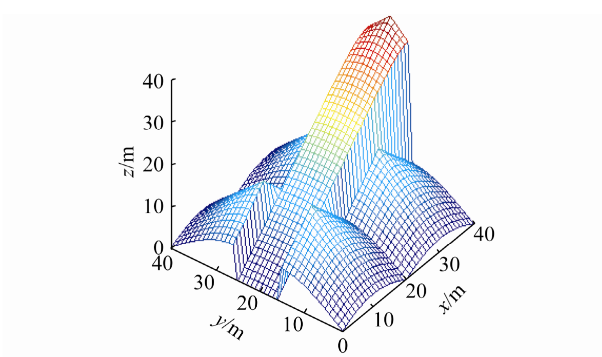


Fig.7 Superposition static floor field of multi-level exits environment

2.3 Circulation principles of the multi-grid model

According to the analysis mentioned above, particle movement will be updated in an orderly way in new principles through every time step, as Fig.8 shows.

1) Draw a multi-level exit environment arrangement chart.

2) Distribute the passengers randomly in the chart.

3) Set up cabin static floor field and exit static floor field.

4) All passengers choose the static floor field type according to their positions.

5) All passengers choose the movement directions according to the state of adjacent cells and the principles of the floor field.

6) According to the hard-core exclusion, one cell can only be occupied by one pedestrian in each time step. After four sub-steps moved by the first principle mentioned above, if more than one pedestrian competes for one target cell, only one of them can move to the cell and all the others have to go back to their original positions. In addition, the chance for moving to the target cell is fair for all the passengers.

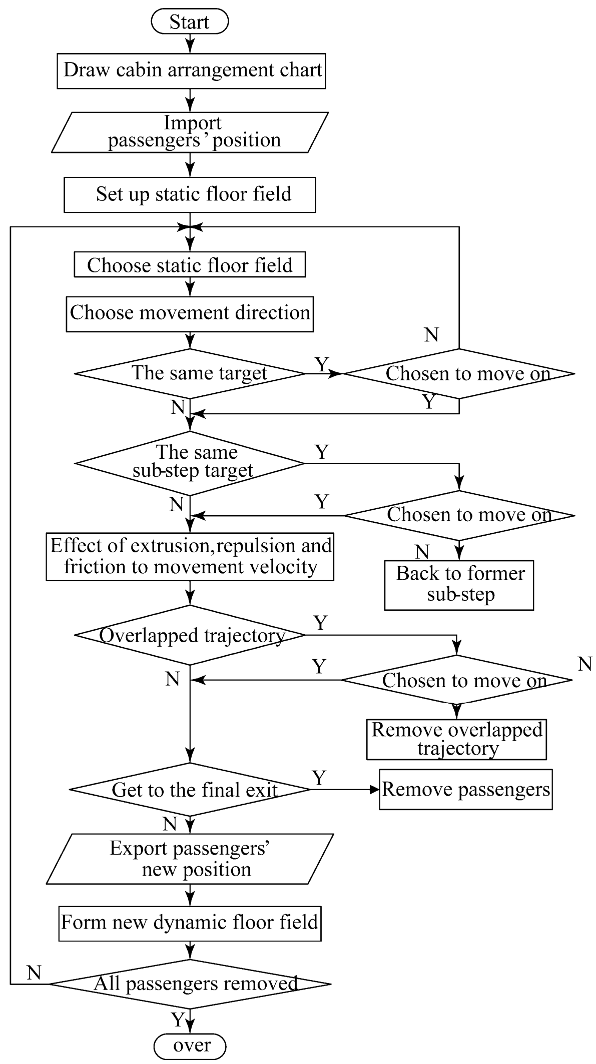


Fig.8 passengers' evacuation flow diagram

7) In order for the cell to be the target of more than one pedestrian in sub-step, it can only be occupied by one pedestrian with the same probability.

8) The velocity will be deceased for the effects of repulsion, extrusion, and friction during the process of evacuation in the sub-step (Song *et al.*, 2006a).

9) The trajectory cannot be overlapped in the sub-steps. If

the trajectory is overlapped, only one particle can take the path and all the others must change their way.
10) If somebody reaches the final exit, he/she will be removed from standing around for the purpose of getting away from the evacuation area.
11) Show the passengers' new position in the chart.
12) When passengers have moved to the new positions, new dynamic floor fields can be formed from the trajectory.
13) If there are passengers who have not reached the final exit, they have to move again according to principles (4)-(12) until they finish the task.

3 Simulation and analysis

3.1 Evacuation analysis for a single exit room

The size of the single exit room designed for the experiment is 12 m×12 m, and the width of the exit is 0.8 m. In the beginning 200 people are randomly distributed in the room. There is no overlapped grid if not pointed out. The value of coefficients is laid out below as Table 1 shows.

Table 1 Parameters in model

Explanation	Value
Coupling constant of dynamic floor field k_D	1
Coupling constant of static floor field k_S	0.125
Coupling constant of repulsion k_r	0.5
Coupling constant of extrusion and friction k_f	0.5
Friction coefficient μ	0.3
Average interaction force F	1.0
Trace broadening probability δ	0.3
Trace dilution probability α	0.3

3.1.1 Phenomenon of passengers' dislocation distribution

Compared with the traditional cellular automata model (Song *et al*., 2006a), the distance that a person moved in one time step in a multi-grid model doesn't match the size of a person. Therefore, dislocation distribution forms among pedestrians and the exit can't be efficiently used as seen in Fig.9. It is also found that the distribution of passengers in the multi-grid model matches with the practical situation better.

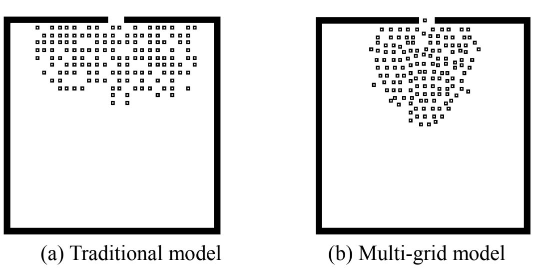


Fig.9 Comparison of two models' lane formation in the single exit room

Fig.10 shows the evacuation time of a traditional cellular model and multi-grid model when the pedestrian's velocity is 1 m/s. It is found that more time is needed to finish evacuation by the multi-grid model when the number of passengers is the same. But as the number of passengers increases, the increased evacuation time is longer and longer. That is to say, passenger dislocation distribution and the exit's exclusion have stronger impact on the evacuation time as the number of passengers increases.

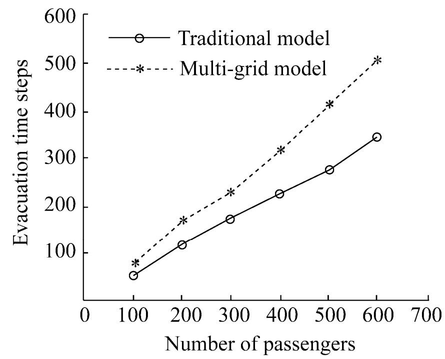


Fig.10 Comparison of evacuation time steps between the traditonal cellular automata model and the multi-grid model

3.1.2 Effect of interaction force among pedestrians

Compared with the traditional model the effects of extrusion, repulsion, and friction on the movement directions are increased in multi-grid model. As Fig.11 shows, the bigger the value of k_r and k_f, the longer the evacuation time. But the increasing velocity of evacuation is less and less until it is unchanging. It is known that k_r and k_f could potentially have an effect on the evacuation time to some degree when the average interaction force F and friction coefficient μ are stable.

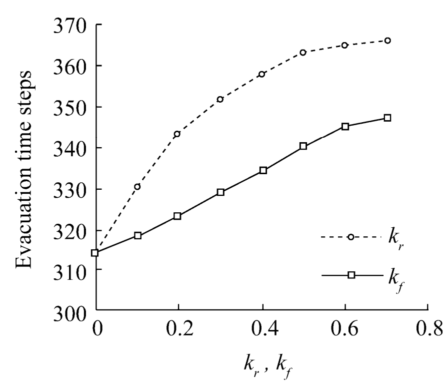


Fig.11 The impact on evacuation time steps of collision, repulsive, and friction force

3.1.3 Effect of the overlapped grids on evacuation

In the multi-grid model the overlap of grids occupied by different pedestrians is allowed to reflect the compression for panic and high passenger density. The reduction of distance between pedestrians has two effects on passengers.

On the one hand, the reduction of distance between pedestrians is good for the exit's utilization ratio when the width of the exit is limited. On the other hand, if the distance between pedestrians is too close, the evacuation ratio will be decreased for increased repulsion and friction. Fig.12 shows the variation of evacuation time with the increased number of overlapped grids and average interaction force F. It is found that the bigger the number of overlapped grids, the less evacuation time is needed when the value of F is zero. But the increased extrusion, repulsion, and friction make the needed evacuation time longer and longer with the increase of F. In conclusion, the increase of the number of overlapped grids is good for evacuation when the value of F is small. On the contrary, the increase in the number of overlapped grids reduces the evacuation ratio when the value of F is large.

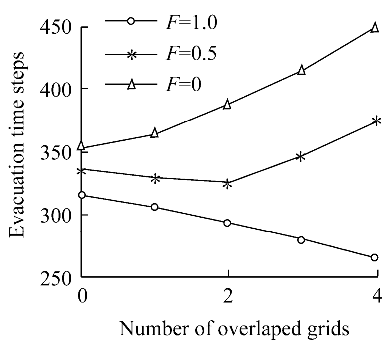
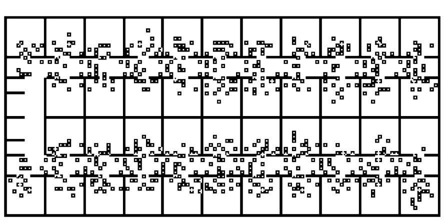


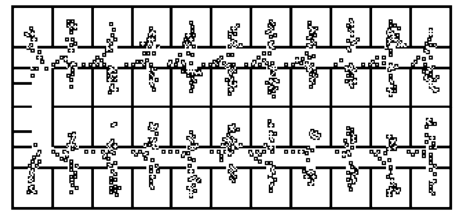
Fig.12 Evacuation time steps for most overlap grids

3.2 Evacuation analysis for a typical cabin arrangement environment

In considering fire prevention, the cabin environment of large vessels is usually separated into several main vertical zones. Each main vertical zone is closed to form independent aisles. Fig.13 shows a typical cabin arrangement environment on a deck with some vertical zones. It is made up of 42 cabins, 2 corridors, 1 room before the stairs, and 2 staircases. The total area is 44 m×20 m, the size of each cabin is 4 m×4 m, the width of the corridor is 1.6 m, the width of each cabin's door is 1.2 m, and the width of the stairs is 2 m. When the ship is in calm water, there is no emergency event and no other passenger impact on the passengers in the typical cabin environment after they have moved to the stairs.



(a) Traditional model



(b) Multi-grid model

Fig.13 Evacuation of passengers

All the passengers are distributed randomly in the 42 cabins before evacuation. They start to move to the stairs after receiving the evacuation information at the velocity of 1 m/s. Fig.13 shows the evacuation process of the traditional cellular automata model and multi-grid model when the density of pedestrians is 0.2 p/m^2. It is found that the arrangement of passengers in the multi-grid model is much tighter than in the traditional model. The phenomenon of the passenger arrangement in the multi-grid model agrees more closely with practical situations for shorter adjustable step length. Also, dislocation distribution of pedestrians and better continuity movement of pedestrians can be realized by a finer lattice.

Fig.14 shows the trend of the number of moving passengers varying with the evacuation time with various original densities of passengers. In the figure, the value of p represents the density of passengers. It is found that the number of moving pedestrians decreased with the increase of evacuation time. The trend that the number of moving passengers varies is similar for the two models. When most of the passengers move to the long and narrow corridors, the number of moving passenger decreases. The crowding situation is lightened when more and more passengers finish the evacuation task. For the traditional model the reduction of the number of moving pedestrians has a repeated process. But for the multi-grid model the speed of the reduction of the number of passengers is quicker, resulting in more optional movement directions for passengers and finer movement distance.

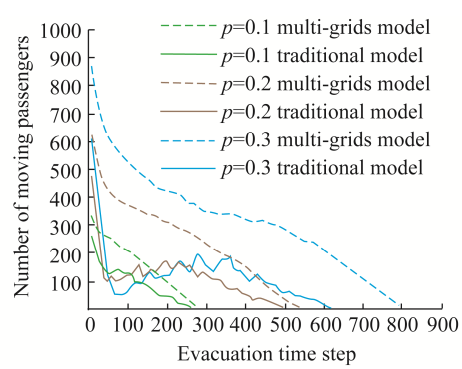


Fig.14 The number of moving passengers for different distributing amount of passengers

In conclusion, the trends of passenger evacuation are similar. But the evacuation time of the multi-grid model is longer than the traditional cellular automata model when the initial condition is the same. The new model provides a good simulation result to improve the traditional model's shorter simulation time and low accuracy. There are three reasons that make the evacuation time of multi-grid model longer. One is the interactive effect caused by the interaction force among pedestrians and interaction force between pedestrians and constructions. The second is the increased number of movement directions which can be chosen. The third is the finer movement distance.

4 Conclusions

Compared with the traditional cellular automata model, the multi-grid model can realize the dislocation distribution of passengers, enhance the accuracy of boundary qualifications, and improve the continuity of movement trajectory by a finer lattice. Furthermore, the multi-grid model considers the interaction force among pedestrians, interaction force between pedestrians and constructions, and more movement directions to make the passengers' movement more authentic. Finally it can simulate evacuation under different situations by changing the coefficients since the multi-grid model is a field model controlled by coefficients.

References

Bradley GE (1993). A proposed mathematical model for computer prediction of crowd movements and their associated risks. In: Smith RA, Dickie JF, editors. *Engineering for crowd safety*. Elsevier, Amsterdam, 303-311.

Burstedde C, Klauek K, Schadschneider A, Zittartz J (2001). Simulation of Pedestrian dynamics using a two-dimensional cellular automaton. *Physica A*, **295**(3-4), 507-525.

Fang Zhiming, Song Weiguo, Xu Xuan (2008). Analysis of single-room evacuation with multi-grid model. *Fire Safety Science*, **17**(3), 165-171.

Guo Renyong, Huang Haijiang (2008). A mobile lattice gas model for simulating pedestrian evacuation. *Physica A*, **387**(2-3), 580-586.

Helbing D, Molnar P (1995). Social force model for Pedestrian dynamics. *Physical Review E*, **51**(5), 4282-4286.

Helbing D, Farkas I, Vicsek T (2000). Simulating dynamical features of escape panic. *Nature*, **407**, 487-490.

Helbing D, Keltseh J, Molnar P (1997). Modelling the evolution of human trail systems. *Nature*, **388**, 47-50.

Kirchner A, Schadschneider A (2002). Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics. *Physica A*, **312**(1-2), 260-276.

Kirchner A, Nishinari K, Schadschneider A (2003). Friction effects and clogging in a cellular automaton model for pedestrian dynamics. *Physical Review E*, **67**, 056122.

Kirchner A, Klupfel H, Nishinari K, Andreas S, Michael S (2004). Discretization effects and the influence of walking speed in cellular automata models for pedestrian dynamics. *Journal of Statistical Mechanics: Theory and Experiment*, P10011.Masakuni Muramatsu, Takashi Nagatani (2000). Jamming transition of pedestrian traffic at a crossing with open boundaries. *Physica A*, **286**, 377-390.

Song WG, Yu YF, Wang BH, Fan WC (2006a). Evacuation behaviors at exit in CA model with force essentials: a comparison with social force model. *Physica A*, **371**(2), 658-666.

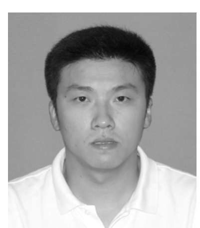
Song Weiguo, Xu Xuan, Wang Binghong, Shunjiang Ni (2006b). Simulation of evacuation processes using a multi-grid model for pedestrian dynamics. *Physica A*, **363**(2), 492-500.

Weng WG., Pan LL, Shen SF, Yuan HY (2007). Small-grid analysis of discrete model for evacuation from a hall. *Physica A*, **374**(2), 821-826.

Yue Hao, Guan Hongzhi, Zhang Juan, Shao Chunfu (2010). Study on bi-direction pedestrian flow using cellular automata simulation. *Physica A*, **389**(3), 527-539.

Miao Chen was born in 1983. She is a PhD candidate at Harbin Engineering University of China. Her current research interests include passenger evacuation simulation in ships and ship design.

Duanfeng Han was born in 1966. He is a professor at Harbin Engineering University of China. He is also a PhD advisor in the College of Shipbuilding Engineering. Currently, his main research interests include digital ship building, HOV design, virtual reality for ships, and many other research topics. Passenger evacuation in ships is a partial work of virtual reality for ships. In recent years, he has published more than 30 papers, two patents, and two books.



Haipeng Zhang was born in 1981. He is a PhD candidate at Harbin Engineering University of China. His current research interests include digital measurement for hull blocks and ship design.