



A Relationship-Based Pedestrian Social Groups Model

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Abstract. In the crowd evacuation process, pedestrians will produce self-organization phenomenon. Family members, friends and other closely related people will be formed group according to the degree of intimacy. The closer the relationship between people, the higher their aggregation in the group. Although the original social force model can simulate arching in the portals, “faster-is slower” and other phenomena. But in the process of movement, pedestrians are an isolated individuals, who have no association with the rest of surrounding people. This cannot truly reflect the group characteristics during crowd movement process. To simulate this pedestrian behavior in the process of movement, a social groups force model is proposed. However, the social groups model does not take the influence of strength of group membership on the group behavior into account. In view of the above shortcomings, this paper proposes a pedestrian social groups force model based on relationship strength. To consider the influence of the relationship strength on the group attribution force in the model, the model can reflect the features of pedestrian behaviors in the process of movement, and achieve a more efficient and more realistic crowd movement.

Keywords: Social groups · Pedestrian simulation · Social force model
Relationship

1 Introduction

During the development of urban areas, the personnel security issue in crowd intensive public places becomes increasingly serious. Studying the characteristics of crowd evacuation behavior and movement law, then assessing the ability of evacuation in public places is a suitable approach to solve the public security problem. There is been more or less contact between the people of the crowd. People’s sociality makes independent people unable to exist independently from the society. Human behavior is governed by their internal psychological activity. Psychologically, most of the individuals in the crowd possess the so-called “herd mentality” features, which makes pedestrian usually spontaneously form a group during the process of movement. Therefore, setting appropriate inducing factors, according to this behavior, can effectively improve the evacuation speed of the crowd.

In the process of crowd evacuation, pedestrians will have the self-organizing phenomenon [1, 2]. Pedestrian movement will be affected by the surrounding pedestrian, which can produce phenomenon like bottleneck swing, zipper effect, pedestrian stratification, Mexican wave and group movement [3] etc. At present, we mainly refer to the social psychology model [4]. In the group composed of several people, there is a certain inherent connection among the members. The connection can be divided into family relationships, friend relationships and colleague relationships. Individuals with different types of relationships compose families, friends and colleagues respectively. The intensity of the relationship gradually weakens. The movement of the members in the same group is similar. They will take the approach of mutual assistance, choosing similar walking routes as well as the same export targets. Also, they are able to maintain a certain aggregation in this process. In this way, loose individuals in a group become several small groups that are closely connected.

In order to make evacuation simulation results more realistic, in this paper, we considered the relationship between groups of pedestrian. Groups with large-scale crowd were used as the research object. We used a relationship coefficient to reflect the interaction strength between family members or friends in the process of evacuation. Based on the original pedestrian social groups force model, we proposed a modified pedestrian social groups force model based on relationship strength. It reflects the impact of relationship strength on the social groups attractive force in the model. The results show that the model has great potential to simulate the group behaviors of evacuation pedestrians, and achieve a more efficient and more realistic crowd movement.

The rest of this paper is structured as follows. Section 2 introduces some related works on simulation application of SFM and grouping behavior. Section 3 introduces the SFM and the modified pedestrian social groups model. Section 4 shows and analyzes the simulation results. Conclusion and future works are presented in Sect. 5.

2 Related Work

The security problem of carry out crowd evacuation research under the real scene is difficult to solve. Researchers started to use computer technology and virtual reality technology to simulate crowd movement to research the movement law and characteristics of crowd evacuation model. Researchers have come up with a series of crowd simulation system, such as EXODUS, Myriad, Pathfinder, Guarder [5–9], and etc.

There are two problems needed to be solved in studying the crowd evacuation model, which are path planning and collision avoidance. At present, there are two main types of evacuation models and the first one is macroscopic model. Henderson analogized pedestrian behavior into a gas or liquid molecules motion and proposed pedestrian traffic fluid mechanics model [10, 11]. Another is microscopic model. Helbing analyzed crowd panic then proposed social force model [12, 13]. He thought pedestrian behavior is the result of nonlinear interaction with the surrounding environment. Neuman proposed a cellular automaton model based on discrete model [14, 15]. This model is a dynamical system that divides time and space into discrete states.

2.1 Simulation Application of SFM

SFM has been adjusted to solve many evacuation problems [16–18]. In the crowd movement driven by social force model, Hou [19] introduced trained leaders which the number of leaders was equal to exits. Then analyze the effect of the number of the leaders and leaders' position settings on the crowd evacuation. Wang [20] introduced the exit attraction and the friends attraction while taking the impact of relative velocity on psychological forces into consideration. Shang [21] used self-adaptive ant colony optimization algorithm to choose the best route for movement.

Yang [22] put forward a crowd mechanical model for joining the leader in basic social forces. Individuals were attracted by the leader and move toward the leader's position. As a result, it realized the small-scale aggregation behavior of individuals and accelerated the crowd evacuation process.

The SFM can simulate arching in the portals, “faster-is-slower” and some other phenomena. But in the movement process, pedestrian in the model is an isolated individual that has not associated with the surrounding neighbors. Therefore, it can't truly reflect the group characteristics in the crowd movement.

2.2 Grouping Behavior

In the movement model, the introduction of the group concept can simulate the pedestrian behaviors more realistic. A pedestrian grouping behavior model was proposed based on the combination of microscopic model and some algorithm [23–25]. Through experiment [26, 27] extracted different characteristics to analyses behavior and define its communities.

Kang [28] extracted pedestrian group characteristics from the captured videos and concluded a data-driven pedestrian group behavior model by using machine learning algorithm. Musse [29] considered the influence of both group relationships and originated emergent behaviors on group behaviors. The combination of the group inter-relationship and the collision detection algorithm was used to simulate the behavior of the crowd.

Vizzari [30] established agent groups model by synthetically considering the individual's motive movement and the impact of the groups on individual. Qiu [31] modeled group structures by multi agent method and the simulation was carried out in a hallway. The experimental result showed that, with the intensity of action among the intra-group members and the inter-group members increasing, the movement efficiency of the population decreased.

Grouping behavior has been introduced in above method, but less considered the influence of strength of relationship between groups. Generally, closely related individuals converge more closely to smaller groups resulting in a group phenomenon. Thus, to reflect this influence in Sect. 3 we present a modified pedestrian social groups force model to simulate the group behavior in video surveillance.

3 Modified Pedestrian Social Groups Model

3.1 Original Social Force Model

The social force model was proposed by Helbing [12, 13]. Individual movement is driven by the resultant force includes: its own driving force, the force with other individual, the force with environment, etc. Social force model is based on Newtonian mechanics, and is a continuous micro-simulation model. According to Newton’s second law, the mathematical expression of the force for individual can be described as follow:

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_w \vec{f}_{iw} \tag{1}$$

Where:

$$\vec{f}_i^0 = m_i \frac{v_i^0(t) \vec{e}_i^0(t) - \vec{v}_i(t)}{\tau_i} \tag{2}$$

$$\vec{f}_{ij} = \vec{f}_{ij}^s + \vec{f}_{ij}^p = A_i \exp\left[\frac{r_{ij} - d_{ij}}{B_i}\right] \vec{n}_{ij} + kg(r_{ij} - d_{ij}) \vec{n}_{ij} + \kappa g(r_{ij} - d_{ij}) \Delta v_{ji}^t \vec{t}_{ij} \tag{3}$$

$$\vec{f}_{iw} = A_i \exp\left[\frac{r_i - d_{iw}}{B_i}\right] \vec{n}_{iw} + kg(r_i - d_{iw}) \vec{n}_{iw} + \kappa g(r_i - d_{iw}) (\vec{v}_i \cdot \vec{t}_{iw}) \vec{t}_{iw} \tag{4}$$

For an individual i , m_i is the quality, $\vec{v}_i(t)$ is the current movement speed, \vec{f}_i^0 is the target driving force, v_i^0 indicates the desired speed of the individual moving towards to the desired direction \vec{e}_i^0 , to adapt to the actual walking speed individual i need “relaxation time” τ_i , $\vec{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\vec{r}_i - \vec{r}_j) / d_{ij}$ indicates the unit vector point from the individual j to the individual i , where \vec{r}_i indicates the location of individual i , $\vec{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$ indicates the tangential direction, $d_{ij} = r_i - r_j$, $\Delta v_{ji}^t = (\vec{v}_j - \vec{v}_i) \cdot \vec{t}_{ij}$ indicates the speed difference between two individual in tangential direction. A_i, B_i, k, κ , are constant.

3.2 Modified Social Groups Force Model

Human’s social attribute determines there are social groups in the pedestrian flow. Between the social group members will produce some certain movement structure and movement relationship. If we do not consider the influence of group behavior to pedestrian speed, we may underestimate the evacuation time.

Analysis of relevant data found that in pedestrian flow the proportion of two to five walk together in groups is much higher than the proportion of independent walk. By analyzing the trajectory of the pedestrian activity, Moussaid [32] introduced the

interaction force between the group members into the social model then generated the social groups force model. In the social groups model, the influence from three factors was considered: pedestrian’s visual field, group center and repulsion among the group members. The force among the members of a social groups can be described by three forces: the visual force, the attractive force and the repulsive force among group members (Fig. 1).

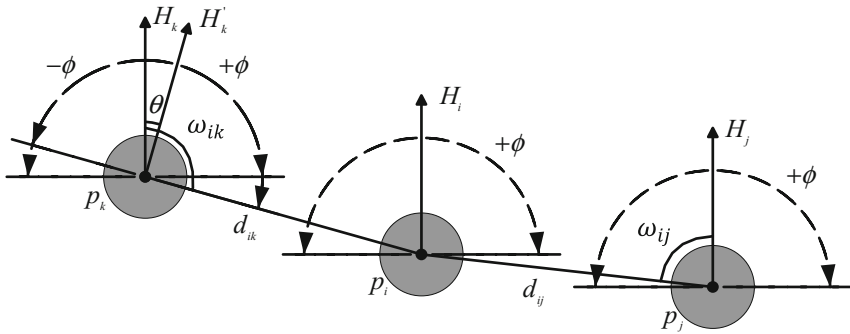


Fig. 1. Rotation angle of social group members.

Social Groups Visual Force. The gazing direction vector of pedestrian i, j, k are respectively H_i, H_j, H_k . The vision angle of pedestrian i is ϕ . It indicates the maximum range of gazing direction that pedestrian can observe to the left and right. Visual force shows the motivation to communicate with other members in the group. To realize the internal communication of the group members, the group members’ head need to rotate the corresponding angle θ . Then the center member of social groups can be included in the vision field of group members. However, the greater the angle of head rotation θ is, the less comfort the member feels. In order to increase the comfort of members, members need to constantly adjust their position to enhance the ability of members of the group using visual language to communicate. In the movement process, the greater the angle of head rotation of pedestrian i is, the less comfort he feels when walking. Therefore, the pedestrian i constantly adjust his position through visual force to reduce the rotation angle of the head. And increase the comfort level.

Social Groups Attractive Force. In the initial social force model, the forces between pedestrians are exactly the same, which does not match with the real situation. The social groups attractive force reflects the aspiration of the members in social groups not to deviate from the social groups center. It can be able to distinguish between friends and strangers. The social groups attractive force direction points to the center of the social groups. The magnitude of the force increases with the distance between the social groups’ center and the individual.

Social groups force model that proposed by Moussaïd makes a distinction between different types of pedestrian movement and reflects the behavior of the group. The model didn’t base on the strength of relationship between the members of the group to consider the interaction between the individual. In the pedestrian flow, the aggregation

degree for close relationship pedestrian is always higher than estranged relationship pedestrian. Reflecting into the model can be expressed as the greater the relationship value the greater the attractive force of the individual is. Moreover, it has added the contact force in the initial social force model, there is no need to repeatedly add. Integrated above deficiencies, a modified social groups model is proposed. Social groups member i are subjected to group forces which mathematical expression as shown in (5), (6), and (8).

$$\vec{f}_i^{group} = \vec{f}_i^{vis} + \vec{f}_i^{att} \tag{5}$$

In a social groups with N members, social groups visual force of individual i can be expressed as:

$$\vec{f}_i^{vis} = -m_i \varphi(\vec{V}_i, \vec{V}_h) \beta_1 \theta_i \vec{V}_i \tag{6}$$

$$\varphi(\vec{V}_i, \vec{V}_h) = \begin{cases} 0, & \omega < 90^\circ \\ 1, & \omega > 90^\circ \end{cases} \tag{7}$$

Where β_1 is a parameter that indicating the social interaction strength between group members. \vec{V}_i is the current velocity vector of pedestrian i . θ_i is head rotation angle of pedestrian i that is after gazing direction of pedestrian i rotate θ_i the center member can be included in the vision field. Select an individual who has the nearest distance with $C'_i = \frac{1}{n} \sum_{j=1}^n P_j$ as a group center C_i . ω is the angle between gazing direction of pedestrian i and line connecting from i to group center C_i . If $\omega > \frac{\pi}{2}$ indicates that C_i is not in the visual field of pedestrian i . Pedestrian i is subjected to social groups visual force. Otherwise if $\omega \leq \frac{\pi}{2}$ indicates that C_i is in the visual field of pedestrian i . Pedestrian i is not affected by the social groups visual force.

In reality, there are some relationships between the people of the crowd such as families, friends, colleagues or strangers. These relationships divide people into small groups and different groups have different relationships. In order to quantify the relationship in the pedestrian flow, we define a hyperparameter λ ($[0, 1]$) [25, 35] to represent the degree of relationship. The value of the relationship between pedestrian i and j is defined as follows:

$$\lambda_{ij} = \begin{cases} 0.7 \sim 0.999, & i \text{ and } j \text{ are relatives} \\ 0.4 \sim 0.699, & i \text{ and } j \text{ are friends} \\ 0.001 \sim 0.399, & i \text{ and } j \text{ are colleagues} \\ 0, & i \text{ irrelevant with } j \end{cases} \tag{8}$$

The expression of social groups attractive force:

$$\vec{f}_i^{att} = \lambda_{ic} f(d_{ic}, d_{th}) \beta_2 \vec{U}_{ic} \tag{9}$$

Where β_2 is a parameter indicating the strength of attraction force between members of social groups. \vec{U}_{ic} is the unit vector pointing from pedestrian i to the center of a social groups C_i : $f(d_{ic}, d_{th}) = \begin{cases} 0, & d_{ic} \leq d_{th} \\ 1, & d_{ic} > d_{th} \end{cases}$, d_{ic} is the distance between pedestrian i and C_i , threshold $d_{th} = \frac{N-1}{2}$. λ_{ic} is the relationship value between pedestrian i and C_i . The closer the relationship, the greater the value of the weight is. The value of the relationship is defined as follows:

After the modified of the model, individual is subjected to forces as shown in Eq. (10):

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_w \vec{f}_{iw} + \vec{f}_i^{group} \tag{10}$$

According to their own force situation, individual in a group use the Eq. (10) to calculate its acceleration. The displacement of each step of the individual is obtained after conversion to the speed. Then it realizes the movement of individuals in the scene. The same time as independent individuals not bound by other people’s social relations, it does not have a group behavior and movement only reflects the personal behavior.

4 Simulation Results

Through the analysis of surveillance video, we found the individual in the process of movement generated a phenomenon gathered into a group. In which closely related individuals converge more closely to smaller groups resulting in a group phenomenon. The surveillance video in Fig. 2 shows that the group phenomenon had always been existing in the whole movement process. In this paper, through the design of simulation experiments we illustrated the modified pedestrian social groups model can more realistic, more efficient simulated crowd movement.



Fig. 2. Surveillance video.

4.1 Initialization

As can be seen from the surveillance video, near the door can be divided into three regions: the center region of the door, left region of the door, right region of the door. Pedestrians near the exit would choose one of these regions to evacuate. Therefore, for simulating the crowd movement more realistic, the group number was defined as $Groupnum = Doornum * 3$. At the same time, it was stipulated that there need contain at least one family in a group. The number of family members was two, three, four and five. Different family members in the group were defined as friends. Different group members in the groups were defined as colleagues.

Individuals with kinship, friends, colleagues, and isolated individuals with no relationship to all individuals in a group were defined in a group in order to more realistically reflect social relationship characteristics of groups. Assumed that there are 20% of individuals did not contain social relations in a group. The relationship values between the individual were generated in accordance with the definition (9). Divided grid for the scene plane area and then the position of the individual was initialized in a grid. Meanwhile, in order to more real simulate the initial state of the group, a certain number of adjacent grids were merged into one region. The position of the same group was initialized in one region.

The relationships between individuals need to be stored in the corresponding data structure. Figure 3 defines the data structure for storing relational node. Figure 4 defines the data structure of the relational linked list node which is used to store the relationship values between individual and other individuals.

| | |
|----------------|--------------------|
| individual No. | Relationship Value |
|----------------|--------------------|

Fig. 3. Relational node.

| | |
|--------------------------|--------------------|
| Individual No. | Relationship Value |
| Pointer to the next node | |

Fig. 4. Linked list node.

In order to describe the process of grouping entire region more detailed, the individual data structures are defined. Individual data structure with the C ++-like language described as follows:

(1) Individual coordinates data structure

```
Struct
{
double dx;
double dy;
} d2dfiled;
```

(2) Individual data structure

```
Struct HMFV_Particle
{
    Ldbl *lv; // relationship value linked list
    d2dfiled d_pos;//x-axis and y-axis coordinates of the
individual
    double rav;// means of the relationship values
between individual and other individuals
    int ord; //individual order
    int group;//individual group number
} Particle;
```

4.2 Emulation Experiment

For verifying the effectiveness of the modified model in this paper and enhance the visualization effect of simulation experiment, and to reflect its practical application value, this paper designed multi groups simulation experiments. In the experiment, the individual information of the same coordinate was read every time. This ensured the consistency of the individual initialization position. The experiment was carried out in a crowd evacuation simulation system designed by ourselves. We used Visual Studio 2012+OSG as the development tool, in Windows7 environment development implementation [17]. The simulation experiment parameters were set as follows (Table 1):

Table 1. The pedestrian and model properties parameters.

| Parameters name | Parameter values or range |
|------------------------------|---|
| Pedestrian radius | $r = 0.25 \text{ m}$ |
| Pedestrian mass | $m = 80 \text{ kg}$ |
| Desired velocity | $v_i^0 = 0.8 \text{ m s}^{-1}$ |
| Social force model parameter | $k = 1.2 \times 10^5 \text{ kg s}^{-2}$ |
| | $\kappa = 2.4 \times 10^5 \text{ kg m}^{-1} \text{ s}^{-1}$ |
| | $A = 2000 \text{ N}$ |
| | $B = 0.08 \text{ m}$ |
| | $C = 2000 \text{ N}$ |
| | $D = 0.05 \text{ m}$ |

4.3 Simulation Results Analysis

In this paper, the crowd evacuation was simulated in a double-exit room scene. Figures 5 and 6 respectively show the simulation movement process of 200 individuals in the original model and the modified model. Different groups of individuals in the experiment used the color and the style of clothes worn by the individual to distinguish. The individual of the different families in the group used the color and style of the hat worn by the individual to distinguish.

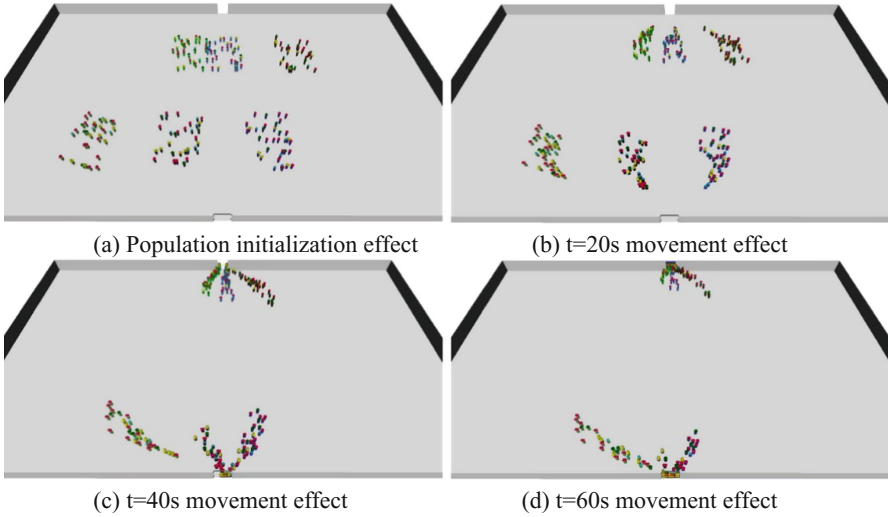


Fig. 5. The simulation movement process of original model.

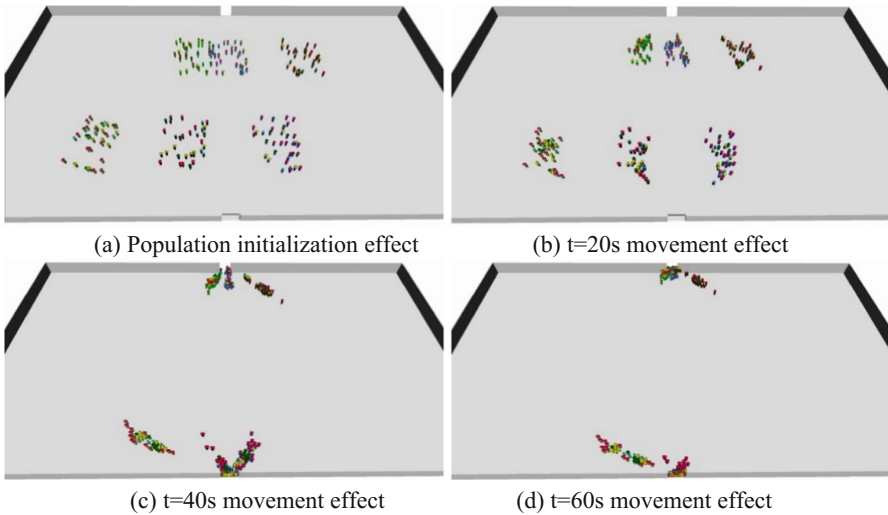


Fig. 6. The simulation movement process of modified model

Figure 6a is the initialization effect diagram. The same group of individuals are initialized in a certain range of regions. b, c and d are the effect diagram of group movement of 20 s, 40 s and 60 s respectively. Compared with the state at the same time in Fig. 5, in the process of the whole movement individuals with the same clothing color and style are gradually aggregating. While the individuals which have same color and style of clothes and hats also show aggregation tendency. As individuals with family relationships have larger relationship value than individuals with other types of relationships. The attractive force between family relationships is larger than between other types of relationships. Therefore the aggregating rate between family individuals is higher than between individuals with other types of relationships. The experimental effect well simulates the grouping phenomena appearing in the video. While it is found that the population forms an arch near the exit. Which reflecting the phenomenon in the crowd movement that faster is slower. As shown in the Fig. 7, the effect diagram for the movement of the 1000 individuals in the Matlab. Individuals forming an arch near the exit.

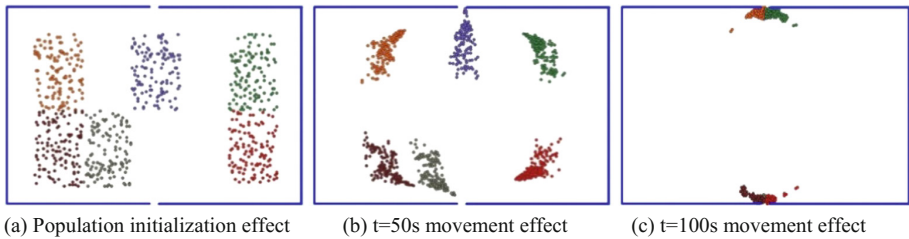


Fig. 7. Movement effect in matlab

To reflect the influence of this method on crowd motion, experiments were conducted on a population size from 100 to 1000 respectively. Each group carried out twenty groups of experiments. Then we obtained the average evacuation time of the crowd including different proportions of isolated individuals, see Fig. 8.

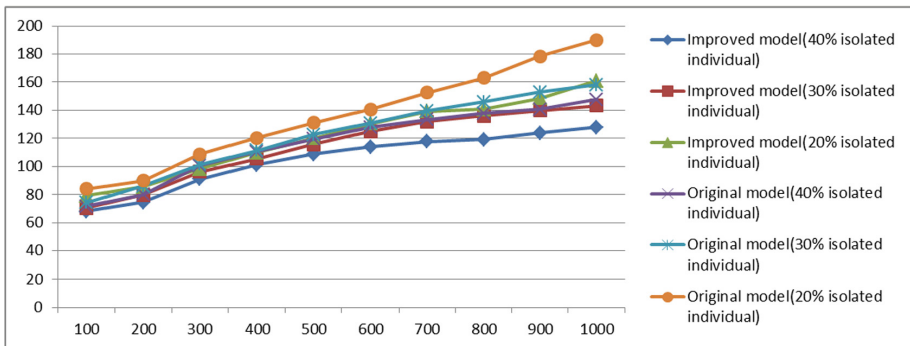


Fig. 8. Average evacuation time

Through the surveillance video, in the case of a certain number of exits with the increasing of individuals, they take more time to evacuate through those exits, in accordance with. From the data analysis in the Fig. 8, with the increasing in the number of individual, groups in both models need more time to complete the evacuation. In the groups with same scale, the evacuation time of our modified model is shorter than the original social force model, which indicates that the modified model can truly improve the evacuation efficiency of the population. While the larger the population size, the more obvious this model for the improvement of evacuation efficiency can be. With the total number of isolated individuals reduced, the evacuation time of groups increased accordingly. This is because the same group of individuals in the evacuation process will first mutual coordination before evacuation, resulting in evacuation efficiency of groups reduced. The result is consistent with the cognition pattern, and more accurately simulate the reality situation.

It is worth noting that the crowd evacuation efficiency increases nearly linearly with the increasing of the number of pedestrians. The reason for this phenomenon is that the evacuation efficiency mostly depends on the pedestrians number, and it is also discussed in literatures [25, 34].

In addition, the modified model algorithm is applied to the teaching building model. The scene and characters are rendered under the 3D simulation platform. Simulation results are shown in Fig. 9.

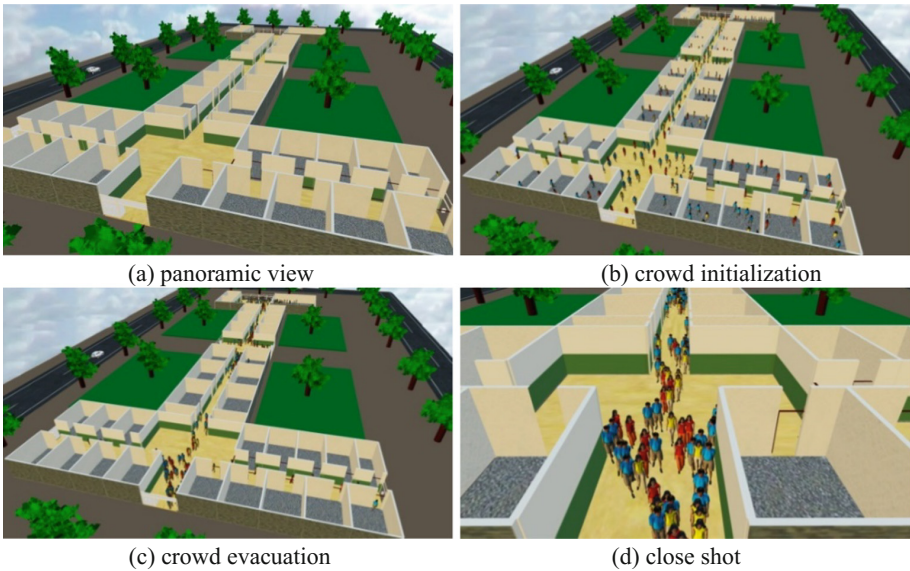


Fig. 9. Teaching building scenet

Figure 9a is the panoramic view of teaching building scene. Figure 9b is crowd initialization effect. Figure 9c is an effect diagram for evacuation to a certain moment.

Figure 9d is a close shot for evacuation to a certain moment. From Fig. 9c and d can be seen individuals with the same clothing color, that is friends show aggregation trend in the movement. The trend of relatives gathered more obvious and then take into account each other to evacuate jointly to a safe area. A more realistic simulation result has been realized.

It is necessary to notice that modifying the social force model by introducing new forces can simulate the evacuation crowd movement, and is validated in literatures [33–35]. For example, Liu et al. extracted motion data from video to establish a video data-driven social force model and simulated group movement. Therefore, it is feasible to use the group attribution force to modify the social force model for simulating the group movement, which is shown in the simulation results in this paper.

5 Conclusion

In this paper, a relationship-based pedestrian social groups model is proposed to simulate the group behavior in video surveillance, and the main contributions are summarized as follows:

1. A modified pedestrian social groups force model is proposed to simulate group movement. In the model, we used a relationship coefficient to reflect the relationship strength between individuals in group during the evacuation process and considered the influence of the relationship strength on the social groups attractive force.
2. The simulation experiment added the relationship-based pedestrian social groups model into the 3D simulation experimental platform. Through a high quality and visible way to show a real and vivid crowd evacuation simulation movement, the validity and feasibility of the model are verified, and a more realistic simulation result is achieved. In this manner, it provides a new approach to solve the group problem in emergency crowd evacuation.
3. Multi groups simulations were designed to verify the effectiveness of the proposed approach in this paper.
4. The experimental result show that this modified pedestrian social groups force model has realized the aggregation of individuals with close social relationships during the evacuation process and has modified the group evacuation efficiency. The next step is to extract the pedestrian's coordinates and motion trails from the video, to further improve the relationship-based model of pedestrian social groups and achieve a more realistic simulation result.

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References

1. Porzycki, J., Mycek, M., Lubaś, R., Waś, J.: Pedestrian spatial self-organization according to its nearest neighbor position. *Transp. Res. Procedia* **2**(2), 201–206 (2014)
2. Miguel, A.F.: The emergence of design in pedestrian dynamics: locomotion, self-organization, walking paths and constructal law. *Phys. Life Rev.* **10**(2), 168–190 (2013)
3. Deb, S., Strawderman, L., Dubien, J., Smith, B., Carruth, D.W., Garrison, T.M.: Evaluating pedestrian behavior at crosswalks: validation of a pedestrian behavior questionnaire for the U.S. population. *Accid. Anal. Prev.* **106**, 191–201 (2017)
4. Sakuma, T., Mukai, T., Kuriyama, S.: Psychological model for animating crowded pedestrians. *Comput. Animat. Virtual Worlds* **16**(3–4), 343–351 (2005)
5. EXODU. <http://fseg.gre.ac.uk>. Accessed 28 Dec 2016
6. Myriad. <http://www.crowddynamics.com>. Accessed 2 Mar 2017
7. Pathfinder. <http://www.thunderheadeng.com/pathfinder>. Accessed 10 May 2018
8. Wang, Z., Mao, T., Jiang, H., Xia, S.: Guarder: virtual drilling system for crowd evacuation under emergency scheme. *J. Comput. Res. Dev.* **47**(6), 969–978 (2010)
9. Gomez-Sanz, J., Pax, R., Arroyo, M., Cárdenas-Bonett, M.: Requirement engineering activities in smart environments for large facilities. *Comput. Sci. Inf. Syst.* **14**, 3 (2017)
10. Henderson, L.F.: On the fluid mechanics of human crowd motion. *Transp. Res.* **8**(6), 509–515 (1974)
11. Wen, J., Tian, H.H., Xue, Y.: Lattice hydrodynamic model for pedestrian traffic with the next-nearest-neighbor pedestrian. *Acta Phys. Sin.* **59**(6), 3817–3823 (2010)
12. Helbing, D., Johansson, A., Al-Abideen, H.Z.: Dynamics of crowd disasters: an empirical study. *Phys. Rev. E Stat. Nonlinear Soft Matter Phys.* **75**(2), 046109 (2007)
13. Helbing, D., Johansson, A.: Pedestrian, crowd, and evacuation dynamics. *Encycl. Complex. Syst. Sci.* **16**, 697–716 (2012)
14. Von Neumann, J.: The general and logical theory of automata. In: *Papers of John Von Neumann on Computing & Computer Theory*, vol. 1, no. 41, pp. 1–2 (1951)
15. Chen, C.K., Li, J., Zhang, D.: Study on evacuation behaviors at a t-shaped intersection by a force-driving cellular automata model. *Physica A* **391**(7), 2408–2420 (2012)
16. Johansson, A., Helbing, D., Shukla, P.K.: Specification of the social force pedestrian model by evolutionary adjustment to video tracking data. *Adv. Complex Syst.* **10**(Supp 02), 271–288 (2007)
17. Zeng, W., Nakamura, H., Chen, P.: A modified social force model for pedestrian behavior simulation at signalized crosswalks. *Procedia Soc. Behav. Sci.* **138**, 521–530 (2014)
18. Han, Y., Liu, H.: Modified social force model based on information transmission toward crowd evacuation simulation. *Physica A* **469**, 499–509 (2016)
19. Hou, L., Liu, J.G., Pan, X., Wang, B.H.: A social force evacuation model with the leadership effect. *Physica A* **400**(2), 93–99 (2014)
20. Wang, L., Cai, Y., Xu, Q.: Modifications to social force model. *J. Nanjing Univ. Sci. Technol.* **35**(1), 144–149 (2011)
21. Shang, R., Zhang, P., Zhong, M.: Investigation and analysis on evacuation behavior of large scale population in campus ☆. *Procedia Eng.* **52**(7), 302–308 (2013)
22. Yang, X., Dong, H., Wang, Q., Chen, Y., Hu, X.: Guided crowd dynamics via modified social force model. *Physica A* **411**(10), 63–73 (2014)
23. Xi, H., Son, Y.J., Lee, S.: An integrated pedestrian behavior model based on extended decision field theory and social force model. In: Rothrock, L., Narayanan, S. (eds.) *Human-in-the-Loop Simulation: Methods and Practice*, pp. 824–836. Springer, London (2010). https://doi.org/10.1007/978-0-85729-883-6_4

24. Lu, L., Chan, C.Y., Wang, J., Wang, W.: A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model. *Transp. Res. C Emerg. Technol.* **81**, 317–329 (2016)
25. Li, Y., Liu, H., Liu, G.P., Li, L., Moore, P., Hu, B.: A grouping method based on grid density and relationship for crowd evacuation simulation. *Physica A* **473**, 319–336 (2017)
26. Julien, P., Cretual, A.: Experiment-based modeling, simulation and validation of interactions between virtual walkers. In: *ACM Siggraph/Eurographics Symposium on Computer Animation*, pp. 189–198. ACM, New Orleans (2009)
27. Gonzalez-Pardo, A., Rosa, A., Camacho, D.: Behaviour-based identification of student communities in virtual worlds. *Comput. Sci. Inf. Syst.* **11**(1), 195–213 (2014)
28. Kang, H.L., Choi, M.G., Hong, Q., Lee, J.: Group behavior from video: a data-driven approach to crowd simulation. In: *ACM Siggraph/Eurographics Symposium on Computer Animation*, vol. 2007, pp. 109–118. ACM, San Diego (2007)
29. Musse, S.R., Thalmann, D.: A model of human crowd behavior: group inter-relationship and collision detection analysis. In: Thalmann, D. (ed.) *Computer Animation and Simulation 1997*. EUROGRAPH, pp. 39–51. Springer, Vienna (1997). https://doi.org/10.1007/978-3-7091-6874-5_3
30. Vizzari, G., Manenti, L., Crociani, L.: Adaptive pedestrian behaviour for the preservation of group cohesion. *Complex Adapt. Syst. Model.* **1**(7), 1–29 (2013)
31. Qiu, F., Hu, X.: Modeling group structures in pedestrian crowd simulation. *Simul. Model. Pract. Theory* **18**(2), 190–205 (2010)
32. Moussaïd, M., Perozo, N., Garnier, S., Helbing, D., Theraulaz, G.: The walking behaviour of pedestrian social groups and its impact on crowd dynamics. *PLoS ONE* **5**(4), e10047 (2010)
33. Liu, B., Liu, H., Zhang, H., Qin, X.: A social force evacuation model driven by video data. *Simul. Model. Pract. Theory* **84**, 190–203 (2018)
34. Liu, H., Liu, B., Zhang, H., Li, L., Qin, X., Zhang, G.: Crowd evacuation simulation approach based on navigation knowledge and two-layer control mechanism. *Inf. Sci.* **436–437**, 247–267 (2018)
35. Qin, X., Liu, H., Zhang, H., Liu, B.: A collective motion model based on two-layer relationship mechanism for bi-direction pedestrian flow simulation. *Simul. Model. Practice Theory* **84**, 268–285 (2018)