Establishment of Simulation Model of Indoor Pedestrian Evacuation

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Abstract: Pedestrian simulation is an important approach for engineers to evaluate the safety issues of metro buildings. Although there exist many works of pedestrian evacuation, it is still lacking of specific classic simulation models fitting the reality well. To overcome this problem, we tried to conduct a typical model. Within this essay, we will use the modified Social Force model and A*algorithm to simulate the practical condition of the pedestrian evacuation with python code, so that we could directly observe the phenomenon emerging during the pedestrian evacuation. What's more, we can even quantitatively analyze the problems during the evacuation and find out the solutions by our simulation model in further research. Besides, fundamental speed-density diagram will be drawn to show its feasibility, which would help us draw the conclusions.

Keywords: Social Force model**,** A*algorithm, Speed-density diagram pedestrian-door distribution

Contents

1 Introduction

1.1 Problem background

In recent years and decades, the development of ever more powerful computer hardware has been accompanied by the evolution of simulation or computer physics as a third element of physics next to theory and experiment. Pedestrian model has long been a problem faced by many government officers, physicists, and computer scientists. From the perspective of pedestrian model granularity, current works can be divided into two classes: macroscopic models and microscopic models based on a simple or complex topology. This thesis deals with the simulation of pedestrian with a focus on evacuation processes.

1.2 Our work

We tried using the classic models to simulate the pedestrian evacuation. Based on that, we analyzed the flaws of the classic models and put forward some modification to make it more practical. Finally, we successfully observed some phenomenon in real life by our simulation model.

(a) We carried out the Social Force model and the A* algorithm basic models to simulate the pedestrian evacuation.
(b) We used the python code to practically construct the system in two different scenes.
(c) We analyzed the phenomenon out of reality, such as the obstacles crashing problem and pedestrians' stagnation. Then we thought about several adjustments according to the actual situation, and basically solved the problems finally.
(d) We used two different ways to judge which door to go through. One is the nearest door in distance and the other is chose thinking about the influence of crowd and the width of doors in addition. Then we compared the evacuation time.

2 Preparation of the models

2.1 Assumptions

To construct the model, we need several important assumptions.

(a) Each pedestrian can be regarded as a circle whose radius is 0.2 meters.

(b) The mass and initial position of each pedestrian are randomly generated. According to the real mass of adults, the mass of the pedestrian ranges from 45 kilograms to 80 kilograms.

(c) The room is a rectangular wireframe and there is one or several doors at the edge of the room. The thickness of the walls is 0.4m.

(d) According to the practical condition, the constants in the Social Force formula are plugged as the following. Take Ai as 2000N. Take Bi as 0.08m. Take k as 120000kg/s^2 . Take K as 240000kg/(m·s).

These are the reasonable assumptions we could carry out to simplify the problem and the calculation.

2.2 Notations

To make the essay clearer, here we will elaborate on the symbols and physical meanings to be used.

m_i: the mass of the pedestrian i.
$\boldsymbol{v}_i$: the speed of the pedestrian i.
$\boldsymbol{a}_i$: the acceleration of the pedestrian i.
d_{ij}: the distance between pedestrian i and pedestrian j.
d_{iw}: the distance between pedestrian i and obstacle w.
r_i: The radius of the pedestrian i.
r_{ij}: the sum of ri and rj.
$\boldsymbol{f}_{self}$: the force of pedestrian to go out.
$\boldsymbol{f}_{ij}$: the force of pedestrian to avoid bumping into others.
$\boldsymbol{f}_{iw}$: the force of pedestrians to avoid bumping into obstacles, including $\boldsymbol{f}_p$ and $\boldsymbol{f}_e$.
$\boldsymbol{f}_e$: the force of pedestrians to avoid bumping into the corner of obstacles.
$\boldsymbol{f}_p$: the force of pedestrians to avoid bumping into the plane of obstacles.
τ: characteristic time, generally regarded as 0.5 second.
$\boldsymbol{v}_i^0(t)$: desired velocity of the pedestrian i.
$\boldsymbol{v}_i(t)$: current velocity of the pedestrian i.
$\boldsymbol{e}_i^0(t)$: unit direction vector of the pedestrian i.
A_i, B_i, k, K: constants in the equations of Social Force model.
g(x): a function. g(x) is zero if x>0, and is otherwise equal to the argument x.
$\boldsymbol{t}_{ij}$: the tangential direction
l_v: a constant to adjust the $\boldsymbol{f}_{ij}$ at certain desired velocity.

w: the half of the width of the door.
T_i: the estimation of the evacuation time of pedestrian i.
d_{id}: the distance between pedestrian i and door d.
n_{id}: the number of the pedestrians in front of pedestrian i going to door d.
n: the total number of the pedestrians to evacuate.

3 The Models

3.1 Social Force Model

In 2000, Dirk Helbing published a paper titled "Simulating dynamical features of escape panic" [1], in which Social Force was proposed. It is a psychological force among individuals to avoid collisions.

The model is built by the three basic equations:

■Langevin equation

$$m_i \frac{d\boldsymbol{v}_i}{dt} = m_i \frac{\boldsymbol{v}_i^0(t)\boldsymbol{e}_i^0(t) - \boldsymbol{v}_i(t)}{\tau} + \sum_{j \neq i} \boldsymbol{f}_{ij} + \sum_{w} \boldsymbol{f}_{iw}$$

In the above equation, we can find that the social force consists of three parts: the force of pedestrians to go out ($\boldsymbol{f}_{self}$), the force of pedestrians to avoid bumping into others ($\boldsymbol{f}_{ij}$), and the force of pedestrians to avoid bumping into obstacles ($\boldsymbol{f}_{iw}$). Thus, we plug $m_i \frac{\boldsymbol{v}_i^0(t)\boldsymbol{e}_i^0(t) - \boldsymbol{v}_i(t)}{\tau}$ equals $\boldsymbol{f}_{self}$.

■Interaction force between pedestrians (repulsive force)

$$\boldsymbol{f}_{ij} = \left\{A_i \cdot e^{\frac{r_{ij}-d_{ij}}{B_i}} + kg\left(r_{ij} - d_{ij}\right)\right\} \cdot \boldsymbol{n}_{ij} + K \cdot g\left(r_{ij} - d_{ij}\right) \cdot \Delta v_{ji}^t \cdot \boldsymbol{t}_i$$

$$r_{ij} = (r_i + r_j)$$

$$d_{ij} = \left\|\boldsymbol{r}_i - \boldsymbol{r}_j\right\|$$

$$n_{ij} = \frac{\boldsymbol{r}_i - \boldsymbol{r}_j}{d_{ij}}$$

$$\Delta v_{ji}^t = \left(\boldsymbol{v}_j - \boldsymbol{v}_i\right) \cdot \boldsymbol{t}_{ij}$$

■ Interaction force between pedestrian and obstacles

$$\boldsymbol{f}_{iw} = \left\{A_i \cdot e^{\frac{r_i - d_{iw}}{B_i}} + kg(r_i - d_{iw})\right\} \cdot \boldsymbol{n}_{iw} - Kg(r_i - d_{iw})(\boldsymbol{v}_i \cdot \boldsymbol{t}_{iw}) \cdot \boldsymbol{t}_{iw}$$

According to the reality, we can consider that $\boldsymbol{f}_{iw}$ consists of the force of pedestrians to avoid bumping into the edge of obstacles ($\boldsymbol{f}_e$) and the force of pedestrians to avoid bumping into the plane of obstacles ($\boldsymbol{f}_p$).

3.2 A*algorithm

A* (A-Star) algorithm is the most effective way to solve the shortest path in a static road network.

The formula is expressed as: F(N) =G(N) + H(N), which:

F(N) is the evaluation function from the initial point through node n to the target point,

G(N) is the actual cost from the initial node to the N node in the state space,

H(N) is the estimation cost of the best path from N to target node.

To build up the model, we chose the Manhattan distance to evaluate the real distance, which is the sum of the distances generated by the line segments generated by two points in the fixed right angle coordinate system of Euclidean space. For example, in the plane, the distance between point P1 of coordinates (X1, Y1) and the point P2 of coordinates (X2, Y2) is: $|X1 - X2| + |Y1 - Y2|$. The Manhattan distance can avoid the influence of the obstacles while evaluating the real evacuation distance.

3.3 Model building

Firstly, according to the number of crowd and the desired velocity offered by users, the initial position and mass of pedestrians are randomly generated and the initial speed is recorded. Secondly, use A* algorithm to confirm the unit direction vector, and then use the three basic equations in the Social Force model to calculate the acceleration. During calculation, we only focus on the force generated by the obstacles and pedestrians within 1 meter. The speed and position coordinates of the next time are obtained according to the acceleration. Thus, the coordinates are updated successively until the person leaves the room.

4 Model modification

After we successfully built the classic model, we observed some phenomenon out of reality. Then, with our joint efforts, we offered some effective solutions to solve the problems.

4.1 Obstacles crashing

During previous tests, we found that the pedestrians were easy to crash on the obstacles, which was clearly out of reality, just like Fig.1.

We analyzed that there were basically two reasons for that. One of them is we ignored the force generated by the obstacles and other pedestrians away from the pedestrian more than 1 meter. The other is that the renewal time was too long.

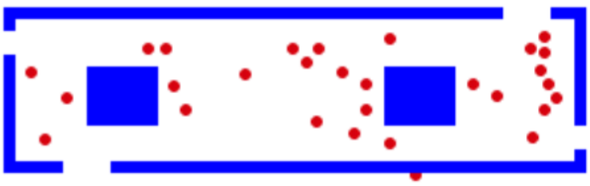


Fig.1. One of the pedestrians bumps into the wall.

So, to solve the problem we recalculated the force generated by the obstacles and other pedestrians which is within 3 meters from the pedestrians. In addition, we adjusted the renewal time to $\frac{0.008}{v_i^0(t)}$.

After the adjustment, the bump between pedestrians and pedestrians or between pedestrians and obstacles is reasonable. The problem was successfully solved.

4.2 Pedestrian stagnation (1)

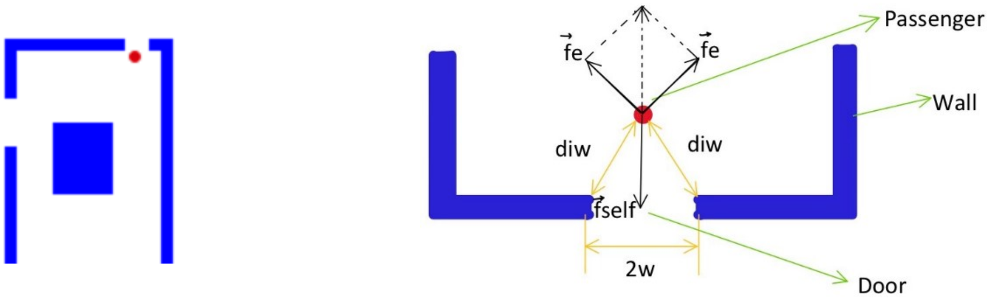
On the following several attempts, we met another problem. When the pedestrians move to the front of the doors, their final speed may be not fast enough to cross the narrow door and the acceleration of pedestrians is nearly zero. So instead of keeping moving out of the room, they would stay still right at the door like Fig.2(a). Similarly, when pedestrians would pass through the narrow door at a low speed such as 1m/s, they would also stop right at the door.

To analyze this phenomenon, we assumed that the acceleration and speed of pedestrians are zero. Then we could get the stagnation condition as following according to the force analysis like Fig.2(b).

$$\frac{\sqrt{\mathrm{d}_{\mathrm{iw}}^2 - \mathrm{w}^2}}{\mathrm{d}_{\mathrm{iw}}} = \frac{v_i^0(t) \cdot m_i}{2 \cdot \tau \cdot \mathrm{A_i} \cdot \mathrm{e}^{\frac{\mathrm{r_{iw}} - \mathrm{d_{iw}}}{B_i}}}$$

Plug the data into the above equation, we could get an important equation as following.

$$\frac{\sqrt{\mathrm{d}_{\mathrm{iw}}^2-\mathrm{w}^2}}{\mathrm{d}_{\mathrm{iw}}}=\frac{v_i^0(t)\cdot m_i}{2000\mathrm{e}^{\frac{5-25\mathrm{d}_{\mathrm{iw}}}{2}}} \tag{1}$$



(a) The pedestrians may stop at the front of the door. (b)the force analysis

Fig.2. The case that the pedestrian stays still at the door

Equation (1) exactly may be tenable. That's why the pedestrians can't go out. In addition, if pedestrian wants to go out of the door, the following inequation (2) should be tenable. And it is clear that the slower desired velocity of the pedestrian is, the harder inequation (2) is tenable.

$$\frac{\sqrt{\mathrm{d}_{\mathrm{iw}}^2-\mathrm{w}^2}}{\mathrm{d}_{\mathrm{iw}}}<\frac{v_i^0(t)\cdot m_i}{2000\mathrm{e}^{\frac{5-25\mathrm{d}_{\mathrm{iw}}}{2}}} \tag{2}$$

Considering pedestrians generally don't worry the oblique collision when they are stagnant, we tried a simple method to solve this problem. We only considered the force in the same direction as the $\boldsymbol{f}_{self}$ when acceleration and speed are zero. Then we recalculated the acceleration based on the new $\boldsymbol{f}_{self}$. Because the update time is very short, this disturbance will only make it move away from the equilibrium position but not hit near obstacles. As a result, this problem could be solved.

4.3 Pedestrian stagnation (2)

However, we found that in the most cases, pedestrians are hovering within a narrow range right at the doors rather than stop. In this condition, the acceleration of pedestrians is not equal to zero, so the above modification is useless. Besides, there are cases that several pedestrians block at the door at the same time so that they form a changing balance. That means everyone hovers within a narrow range or stop and nobody could evacuate from the room, such as the cases in Fig.3(a) and Fig.3(b).

(a)Two pedestrians at the door (b) Three pedestrians at the door

Fig.3. Pedestrians hover at the door

4.3.1 Attempt 1

In general, when congestion occurs, there will be some people conceding. Once the deadlock is broken, they may go out. Based on this reality, we put forward a model named comity model as following.

If the direction of certain pedestrian's speed turns more than 90 degrees, we regarded this situation as abnormal cases that pedestrian is being hit or avoiding bump. If he is avoiding bump, we assumed that he will take a bigger step back to avoid bump. The direction of the step is the same as original step. To make the step size in 1 second fit the reality, we calculated it as following conditions.

(a) The normal step size is 0.2m.

(b) We cannot let pedestrian collide with surrounding obstacles or pedestrians, so the step size is no more than nine tenth of the shortest distance from others.

(c) If the original calculated moving distance is larger than the retreat distance, the retreat distance is meaningless. So, the original distance is still taken.

Fig.4. When there're too many pedestrians blocking at the door, the comity model fails.

After the modification of the model, although part of the clogging problem had been solved, there were still some cases. As the original positions of pedestrians are very close, there is no space to step back. So, pedestrians would still block at the door like Fig.4. What's worse, this change would cause lots of pedestrians hovering during the evacuation. As a result, the comity model failed.

4.3.2 Attempt 2

We knew that $\boldsymbol{f}_e$ is the culprit that stops pedestrians getting out. However, people won't be afraid to hit the door frame when they want to go out. So, we tried setting $\boldsymbol{f}_e$ to zero. Unfortunately, it caused that the pedestrian near the doorframe can go into the door. But once he goes into the door, he is against the doorframe and will be bounced off the doorframe because of $\boldsymbol{f}_p$. What's worse, pedestrians may bump into the doorframe. Due to these, the attempt failed.

4.3.3 Attempt 3

People will avoid hitting the door but not approaching the doorframe. So, we tried only calculating the component force of $\boldsymbol{f}_e$ which is perpendicular to $\boldsymbol{f}_{self}$. This method not only allows the pedestrians to go out normally, but also preserves the pedestrians hitting the doorframe.

After the experiments again and again, we found the modified model could basically simulate the reality. By this model, we could observe following phenomenon in reality like Fig.5.

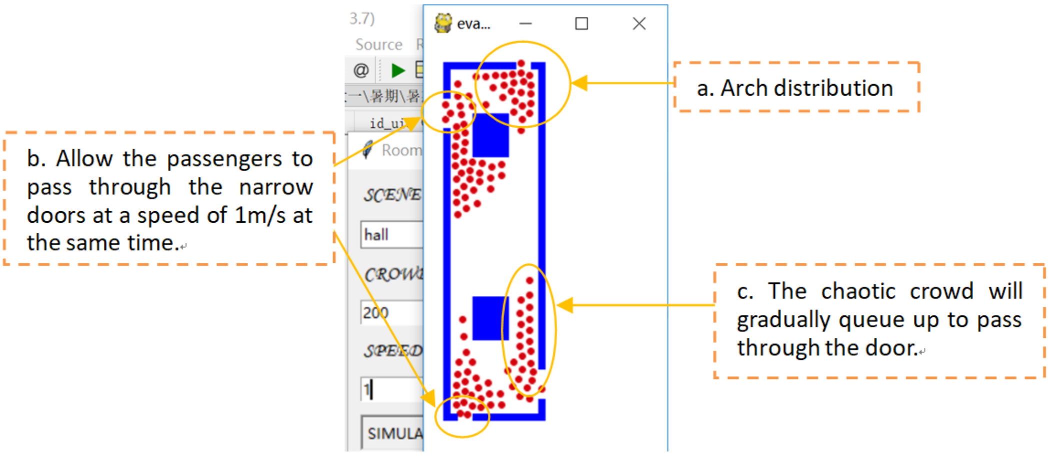


Fig.5. The phenomenon observed in the simulation of the modified model.

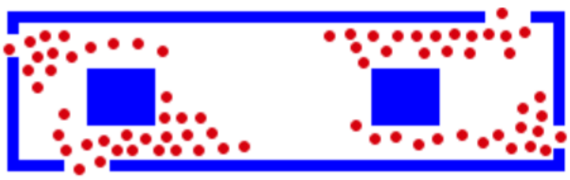
(a) It is obvious that the crowd in front of the door forms an arch distribution [2].
(b) Allow two pedestrians to go through together the door of 0.8 meters wide.
(c) Allow people at 0.8m/s to go out normally and this has included the cases at a very low speed.
(d) Pedestrians will generally queue up in front of the door.
(e) Everyone will eventually go out. There are almost no among anomalies.

So far, the Pedestrian stagnation problem had fundamentally got a proper solution.

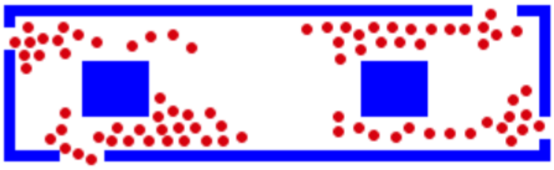
4.4 Distance between pedestrians

We found that while there are not too many pedestrians to leave, the queuing pedestrians keep others at a little big distance. This affects the speed of evacuation and is not realistic.

We thought $\boldsymbol{f}_{ij}$ may be set too large. So, we tried multiplying $\boldsymbol{f}_{ij}$ by a coefficient (l_v). Take the expected speed of 1m/s as an example. After many experiments, we found that when we took a new $\boldsymbol{f}_{ij}{}'$ which equals to $0.4 \cdot \boldsymbol{f}_{ij}$, the effect is better. The distance between pedestrians is smaller and pedestrians don't collide with each other, either, just like Fig.6.



(a) When we take the expected speed as 1m/s, l_v as 1, the evacuation time is 24.87s.



(b) When we take the expected speed as 1m/s, l_v as 0.4, the evacuation time is 22.89s.

Fig.6 The comparison between different k in the same conditions.

However, this value of l_v doesn't fit other speeds because there may be different degrees of collision. The preliminary analysis is l_v should be related to the expected speed, because $\boldsymbol{f}_{self}$ is different under different expected speed, and its degree of influence to $\boldsymbol{f}_{ij}$ is also different. What's more, our update time is also set related to the expected speed. However, due to time and conditions, the specific formula cannot be given and is reserved for subsequent research.

4.5 The way to choose the exit

Firstly, we considered pedestrians will choose the nearest door as their exits. But in fact, we knew if there are too many pedestrians in front of certain pedestrian going to the same door, or the door is too narrow to go through several pedestrians at the same time, this pedestrian may change another door as exit. According to the pertinent literature we had read, we used the following equation to estimate the evacuation time for certain pedestrian to the certain door [3].

$$T_i = \frac{d_{id}}{v_i^0(t)} + \frac{n_{id}}{2 \cdot w}$$

Among this equation, we used the Manhattan distance to estimate the distance between door and pedestrian (d_{id}). When we calculated the number of the pedestrians in front of this pedestrian going to the same door, we firstly distributed the doors for every pedestrian only according to distance. If the door was the distributed one, we regarded n_{id} as the number of pedestrians who was distributed to the uniform door and was not farther from the door. Otherwise, n_{id} was the number of pedestrians who was distributed to this door. After this modification, in a great part of the cases the final distribution of the doors is more reasonable and the evacuation time is shorter. We took 100 pedestrians and the expected speed of 1.5m/s as an example just like what shows in Fig.7.

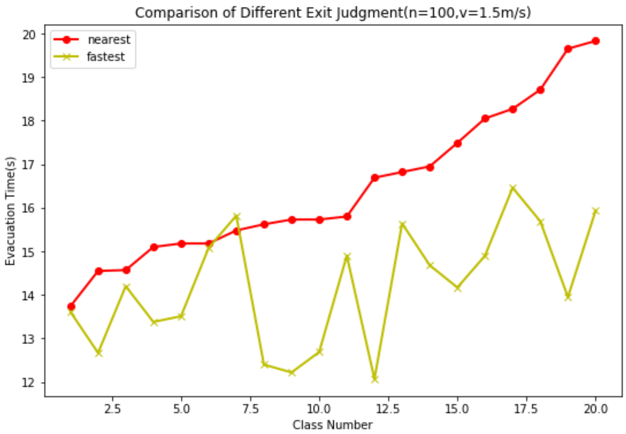


Fig.7 The comparison of different exit judgment.

5 Conclusions

(a) The Social Force model and the A*algorithm can be the basic model to simulate the pedestrian evacuation.
(b) The Social Force model has some flaws, but we can modify it based on the reality and make it fit the reality better. Besides, fundamental speed-density diagrams like Fig.8 and Fig.9 can be drawn to show its feasibility [4]. We selected an area of 0.8m*0.8m at the door, whose population density was the most concentrated, to draw the speed-density diagrams and compared it with Weidmann empirical formula. They all show the normal phenomenon in the real life that the higher density is, the lower mean speed is. So, it gets the conclusion that “faster is slower” and can prove the rationality of our model.
(c) According to the simulation, we can observe some phenomenon during the evacuation. For example, it is obvious that the crowd in front of the door forms an arch distribution [2] and the pedestrians will generally queue up in front of the door. These are important when we use our model to analyze the pedestrian evacuation for further research.

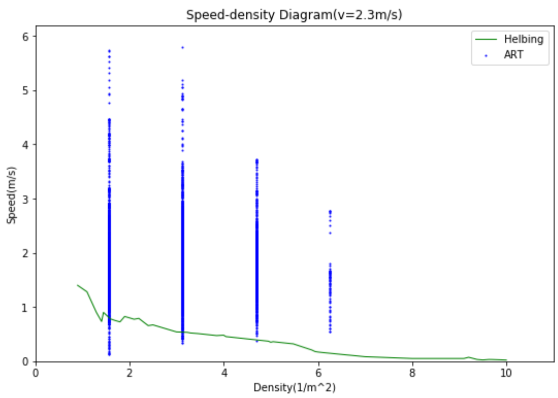


Fig.8. The faster speed condition

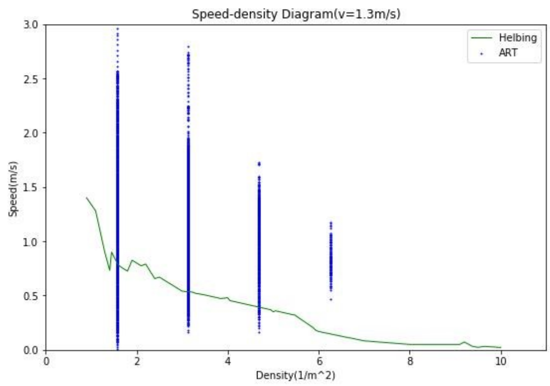


Fig.9. The lower speed condition

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