Potential Energy Field based Pedestrian Behavior Model for Crowd Evacuation Simulation in Airport Terminal

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Abstract. The crowd evacuation simulation in airport terminal is an important method to improve the efficiency of the emergency evacuation decision. Different from traditional pedestrian simulation, the evacuation simulation in airport terminal should fully consider the layout of the terminal building and the characteristics of passenger behavior. This paper proposes a pedestrian behavior model based on potential energy field. On the one hand, the spatial region is modeled by fine grid, so as to model the pedestrian’s body type, pose and decision in airport terminal more realistically; on the other hand, the potential energy field mechanism fully considers following factors’ influence on the pedestrian behavior, including the shortest path to the destination, obstacles, other pedestrians and sudden events. Based on the model, this paper simulates the evacuation process on a certain airport terminal, and evaluates the evacuation ability of the building. Based on the simulation of evacuation time under different number of people and different utilization of building space, the quantitative emergency measures and building optimization recommendations are given. This research can provide advance scientific guidance for pedestrian organization, terminal building design, and emergency plan.

1. Introduction

With the rapid development of civil aviation transportation, the number of persons and stranded passengers in the airport increases significantly. For example, in 2018, the passenger throughput of Beijing Capital International Airport had exceeded 100 million, and the daily flow of people was about 300,000[1]. Therefore, the pressure of emergency evacuation in the terminal building is also increasing. The terminal building is large in scale and complex in structure. Taking the T3 terminal of Beijing Capital Airport as an example, its construction area is over 900,000 square meters. Therefore, the emergency evacuation should fully consider the factors such as passenger density and behavior characteristics, spatial layout and organization. The crowd evacuation simulation of the terminal building will help to understand the function and efficiency of the terminal emergency system more accurately, and provide quantitative guidance for pedestrian organization, terminal building design and emergency plan.

The research on pedestrian simulation can be divided into the macro simulation and the micro simulation. The macro pedestrian simulations take the whole pedestrian flow as the research object, and compare the pedestrian flow to gas or fluid, so that the models of gas dynamics and fluid mechanics are applied to pedestrian simulation [2-5]. Macro pedestrian simulations include gas dynamics models, flow models, queuing network models and so on, but such models have few descriptions for individual and their behaviors, so that the results of the simulation are rough. The
micro pedestrian simulations take a single pedestrian as the research object, consider the differences of the individual attributes of the pedestrians, and aggregate the individual behaviors to obtain the behavior of the crowd. Micro pedestrian simulations include models based on "force", Cellular Automaton (CA) models, discrete selection models and so on [6-8]. Since micro pedestrian simulations can describe the interaction between pedestrians and the interaction between pedestrians and internal facilities in a more detailed way, they have been widely used in urban traffic, emergency and pedestrian simulation in recent years. For the crowd evacuation simulation of civil aviation airport, most of the research still stay in the formulation of emergency plans and the calculation of disaster time, the application of computer quantitative simulation is few. The existing simulation research are mostly based on general-purpose simulation tools, such as SimPed, EXODUS, MYRIAD, PAXPOR and Legion [9], which have few descriptions of the characteristics and behaviors for the particular group of airport passengers, as well as the simulation of the specific spatial structure of the airport terminal. This paper proposes a potential energy field based crowd evacuation simulation model in airport terminal, which can model the pedestrian’s body type, pose and decision in airport terminal more realistically and fully consider different factors’ influence on pedestrian behavior. Based on this model, we take simulation evaluation experiments on data of the Beijing Capital International Airport, and give quantitative recommendations for emergency measures and building optimization.

2. Potential Energy Field based Pedestrian Behavior Model

One the one hand, the model performs fine meshing on the building plane, which divides the airport building plane into uniform cell grids with a minimum cell size of 10cm×10cm. Each cell has three states: occupied by obstacles, occupied by pedestrians, and blank state. In order to describe the behavior of pedestrians more accurately, we set the plane space occupied by each pedestrian to 50cm×30cm. With reference to the direction of advancement, pedestrians can be in both forward and lateral orientations, as shown in figure 1. For example, when the pedestrian finds that the advance width allowed to pass is less than 50cm but more than 30cm, he/she can advance in the lateral orientation.

On the other hand, we propose potential energy field based method to model the pedestrian behaviour. The basic idea is that introducing the potential energy field function to describe the geometric structure of walking space, and completing the route planning by searching the negative gradient direction of the potential energy field. According to the influencing factors of pedestrian behavior, the potential energy field function consists of four parts: the destination potential function, the obstacle potential function, the pedestrian potential function, and the sudden event potential function.

The first part is the destination potential function. The most basic feature of a person’s walking behavior is to select the shortest route to reach the destination, so that we use the destination potential function to describe the attractive effect of the destination on the pedestrian. Each cell (i, j) in the walking area is assigned a potential energy value: $U_{ij}^{\text{dest}} = f(d_{ij}-g_{\text{goal}})$, where (i, j) is the current
position; \( d_{ij-goal} \) is the shortest geometric distance between the current position (i, j) and the destination considering the obstacle blocking.

The second part is the obstacle potential function. Since pedestrians have a tendency to avoid obstacles and maintain a certain distance from them during walking, we use the obstacle potential function to describe the repulsive effect of the obstacle on the pedestrian. Considering that the pedestrian will not be affected when the distance from the obstacle is beyond a certain value, we define the obstacle potential function as follows:

\[
U_{ij}^{rep} = \begin{cases} 
\alpha (d_{ij} - d_{obs}) & d_{ij} \leq d_{obs} \\
0 & d_{ij} > d_{obs}
\end{cases}
\]

where \( \alpha \) is the parameter to be determined; \( d_{ij} \) is the distance between the cell (i, j) and the boundary of the obstacle; \( d_{obs} \) is the distance influenced by the obstacle, beyond which \( U_{ij}^{rep} = 0 \).

The third part is the pedestrian potential function. Pedestrians are also affected by other pedestrians nearby during walking, such as the blocking effect of pedestrians in front and the crowding effect of lateral pedestrians. We use the pedestrian potential function to describe the influence of other pedestrians. The potential energy field generated by each pedestrian in the cell (i, j) is as:

\[
U_{ij}^{ped} = \begin{cases} 
\beta (d_{ped} - d_{ij}) & d_{body} \leq d_{ij} \leq d_{ped} \\
0 & d_{ij} > d_{ped}
\end{cases}
\]

\( \beta \) is the parameter which indicates whether the pedestrian’s effect on decision maker is attractive or repulsive. If the angle between the movement direction of the pedestrian and the decision maker in the previous time step is acute, then \( \beta < 0 \), indicating that the pedestrian’s effect is attractive; otherwise, \( \beta > 0 \), indicating that the pedestrian’s effect is repulsive. \( d_{ped} \) is the distance influenced by the pedestrian; \( d_{body} \) is the body size of the pedestrian; \( d_{ij} \) is the distance between the pedestrian and the cell (i, j). When \( d_{ij} > d_{ped} \), the influence of the pedestrian is negligible and \( U_{ij}^{ped} = 0 \).

The fourth part is the sudden event potential function. The potential energy field generated by the sudden event needs to be defined according to its specific influence mechanism and space-time evolution law. In this paper, fire disaster is taken as an example, and the fire potential energy field is generated according to the fire simulation software FDS (Fire Dynamic Simulator). The potential function is as follows:

\[
U_{ij}^{sud} = \varphi U_{smoke} + \phi U_{Temp},
\]

\( U_{sud} \) is the fire potential energy field which describes fire’s effects on pedestrian behavior; \( U_{smoke} \) is the smoke potential energy field generated by fire; \( U_{Temp} \) is the temperature potential energy field generated by fire; \( \varphi, \phi \) are the controllable parameters.

By superposing above-mentioned potential functions, we get composite potential energy field in the scene:

\[
U_{ij} = aU_{ij}^{att} + bU_{ij}^{rep} + c \sum U_{ij}^{ped} + d U_{ij}^{sud}.
\]

Note that since the pedestrian may be affected by several other pedestrians nearby, the pedestrian potential function in the formula is the accumulation of potential energy generated by all the other pedestrians in the neighborhood.

During the simulation process, we set that the distance each pedestrian can travel at each step does not exceed a certain value, so that the feasible domain of the pedestrian in the simulation process can be determined. For each pedestrian in the simulation scene, it will always follow the negative gradient direction of the integrated potential energy field \( U_{ij} \). In each simulation step, the walking path from the position with high potential energy to the position with low potential energy is the shortest path to the exit. The execution flow of the model is shown in figure 2.

3. Experiments for Crowd Evacuation Simulation in Airport Terminal based on the Model

Based on the above model, this paper selects the real data of the Beijing Capital International Airport terminal for crowd emergency evacuation simulation experiments.

Firstly, combined with the actual firefighting drawings of the terminal building, the static potential energy field is simulated by considering the attractive effects of escape exits, the repulsive effects of obstacle blocking and the effects of fire disaster. Taking the check-in area in T1 terminal building as an example, the generated static potential energy field is shown in figure 3.
3.1. Evacuation simulation of the fire scene in the terminal building

Taking the T1 terminal check-in area as an example, during the simulation process, we randomly distribute 737 passengers (the number of passengers in the peak period of this area) in the area, set the pedestrian speed uniformly distributed within 7-10 cells/time step (equivalent to 1.4~2.0 m/s), and place the fire source in the middle of the area. There are 11 exits in this scenario. When opening different exits, the simulation of pedestrian evacuation trajectory is shown in figure 4.

![Figure 4. Simulation of pedestrian trajectory when open different number of doors.](image)

We open different numbers of exits under different personnel densities, and run simulation tests 10 times separately to calculate the average of the results, the results are shown in table 1. According to GB50016-2014 (the China's current building fire protection design standard): for crowded public buildings, the accident evacuation time of the platform should be no more than 6 minutes. From each line of table 1, it can be observed that the more exits are opened, the shorter the pedestrian evacuation time is. However, considering the security costs of the airport, we need to open smaller number of exits on the premise of ensuring safety. The bold and italic area in table 1 is the situation which is more than the safe evacuation time (6 minutes), so more exits are needed to ensure evacuation safety. For example, for the T1 terminal check-in area, when the number of people exceeds 2300, the evacuation time is more than 6 minutes with only one exits opened, so one or more exits need to be opened to ensure that the evacuation is completed within 6 minutes.

| number of people | time of 1 exit opened (s) | time of 2 exits opened (s) | time of 3 exits opened (s) | time of 4 exits opened (s) | time of 5 exits opened (s) | time of all exits opened (s) |
|------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|-----------------------------|
| 500              | 120.60                   | 107.50                   | 102.30                   | 98.30                    | 90.80                    | 85.50                       |
| 737              | 124.36                   | 120.75                   | 118.05                   | 117.00                   | 116.15                   | 115.30                      |
| 900              | 155.70                   | 145.30                   | 134.70                   | 131.70                   | 129.4                    | 120.80                      |
3.2. Evaluation of evacuation capability based on simulation experiments

Based on the proposed model, we take the crowd evacuation simulation of the fire scene according to the number of passengers in the peak period of different areas in each terminal building, and determine the approximate evacuation time, so that the evacuation capability of the terminal building can be evaluated in advance during the terminal design stage. This paper takes evaluation experiments of evacuation capability on the three terminals of Beijing Capital International Airport (T1, T2 and T3). The experimental results are shown in table 2, which show that the three terminals of the Beijing Capital International Airport have reached the safe evacuation time mentioned above (6 minutes).

| Terminal | Area                  | Peak hours       | Number of People | Simulated evacuation time (s) when all exits opened |
|----------|-----------------------|------------------|------------------|----------------------------------------------------|
| T1       | Check-in area         | 16:00-17:00      | 737              | 115.3                                              |
|          | Security check area   | 7:30             | 2735             | 181.35                                             |
|          | Arrival area          | 1:00-2:00        | 300              | 55.25                                              |
| T2       | Check-in area         | 16:00-17:00      | 849              | 113.95                                             |
|          | Security check area   | 7:30             | 361              | 65.25                                              |
|          | Arrival area          | 1:00-2:00        | 756              | 133.95                                             |
| T3       | Check-in area         | 16:00-17:00      | 930              | 168.65                                             |
|          | Security check area   | 7:30             | 839              | 121.45                                             |
|          | Arrival area          | 1:00-2:00        | 539              | 68.65                                              |

3.3. Simulation-based evacuation bottleneck optimization

A typical area of the Beijing Capital International Airport T3 terminal (shown in figure 5) was selected for simulation experiments. During the simulation, the initial positions of 456 people were randomly distributed in the area.

The space utilization of the evacuation process can be observed according to trajectories of pedestrian as shown in figure 5. It can be seen that in both routs to the escape stairs the longer one has less utilization while the shorter one has the more utilization, which shows that one of the evacuation bottleneck of this area is unbalanced space utilization. So we can set guidance signs to lead pedestrians to the route with lower utilization so that to help balancing the crowd.

Another evacuation bottleneck of this area is the gates near the escape stairs. There are three gates in the densest part of pedestrian trajectory. From the perspective of architecture design, the quantitative assessment of evacuation efficiency can be performed at the design stage to modify the original design and enhance evacuation efficiency. For the above-mentioned evacuation bottleneck, we increase the width of the three gates by 0.8 meters and compare the evacuation simulation results under the original design and modified design. We take experiments on 21 sets of data with different personnel densities, starting from 100 people and up to 500 people with an increasing speed of 20
people each time. Each group of data is simulated 5 times with two design scenarios, and the average value is taken as the evacuation time, which is shown in figure 6. We can observe that, when the number of people is small (100~220), the difference of evacuation time under two designs is small; when there are a large number of people, the difference is obvious. When the number is between 400 and 500, the evacuation time is shortened by about 30 seconds under the modified design. In practical applications, such simulation comparison can be taken for different design schemes so that to give quantitative recommendations for terminal building design.

![Pedestrians trajectories](image1.png)  
**Figure 5.** Pedestrians trajectories.  
![Evacuation time under original and modified design](image2.png)  
**Figure 6.** Evacuation time under original and modified design.

### 4. Conclusions

As an important public building, the safety management of terminal building is very important. This paper proposes a potential energy field based crowd evacuation simulation model in airport terminal, which can model the pedestrian’s body type, pose and decision more realistically and fully consider different factors’ influence on pedestrian behavior by the potential energy field mechanism. By applying the model on real terminal building data, quantitative emergency measures and building optimization recommendations can be given. It can provide scientific guidance for pedestrian organization, terminal building design, and emergency plan.

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