VISUALIZATION OF CROWD FLOW IN LARGE-SCALE FACILITY USING AGENT-BASED SIMULATION[1]

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ABSTRACT: *To prevent crowd accidents in large-scale facilities that are available to the general public, it is important to share information on safety measures among organizers, the police, the fire department, and government officials. In this study, we present a crowd simulation system that is capable of sharing visual information on the estimated flow of the crowd and that can be used when the safety plan for a facility is being developed. The simulation is agent based and aims to reproduce the macroscopic phenomena of a crowd flow, especially in a queue, by modeling the microscopic interactions between the agents. This crowd behavior model is divided into three parts: route choice, crowd movement, and queue formation. Route choice is implemented using a simple graphical user interface (GUI); this enables the choice of an arbitrary route to guide each agent. Crowd movement is based on a social force model. In addition, we implement a queue formation model in which the route to a destination is changed according to the length of the queue in a specific area. The results are as follows. We calibrated the parameter of the simulation and reproduced the density of a crowd flow based on empirical observations. Queuing behavior was also verified for the emergence of the macroscopic phenomena of stop-and-go waves. Moreover, we applied this simulation to evaluate crowd safety for a special event held in a large-scale commercial facility. We propose a new method for safety experts and non-experts to share visual information about the flow of crowds.*

KEYWORDS: *Autonomous agents, crowd flow, visual simulation, large-scale facility*

1. INTRODUCTION

Safety measures to prevent crowd accidents have become increasingly important as the size of urban facilities and the frequency of mass events has increased. The incident on the Akashi pedestrian bridge that occurred on 21 July 2001 in Akashi, Hyogo, Japan killed 11 people and injured 247 people. This was due to the accumulation of the crowd on the pedestrian overpass that connects the site and the nearest railroad station. The resulting trial determined that the organizers of such an event were responsible for the safety of the crowd. Since that date, however, there have continued to be crowd accidents worldwide: the Baihe fireworks display disaster in China in 2004 (37 deaths, 37 injuries), the Duisburg Love Parade disaster in Germany in 2010 (37 deaths, over 500 injuries), and the Water Festival disaster in Cambodia in 2010 (348 deaths, over 600 injuries). An investigation pointed out that safety measures for high-density crowd flows were not always considered when planning mass events (Kaitsuji et al., 2010). To prevent crowd accidents in large-scale facilities that are available to the general public, it is important to share information on safety measures among organizers, the police, the fire department, and government officials.

To make an efficient plan for the prevention of crowd accidents, it is important to study past crowd accidents. Using individual trajectories to simulate crowds is an especially effective way to evaluate crowd flows and to share visual information. Many different models of human behavior have been proposed to reproduce the typical emergent phenomena of crowd flows in a simulation. Among these, agent-based approaches, which model the microscopic behaviors of individuals, are currently very common. Well-known examples are the social force models (Helbing et al., 2000), the cellular automaton models (Burstedde et al., 2001), and the rule-based models (Berg et al., 2008). Currently, one of the key areas for future research is simulating the behavior of groups. Lemercier et al. (2012) propose a realistic model of the following behavior in a queue by controlling the instantaneous tangential acceleration. However, the ability of this model to reproduce a high-density queue and dynamic queue formation have not yet been fully developed. Moreover, it has not been applied to a large-scale facility.

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This study develops an agent-based crowd simulation that reproduces the macroscopic phenomena of crowd flow, especially in the area of the queue in front of the entrance. Our simulation does this by modeling the microscopic interactions between agents. In addition, we apply this simulation to a large-scale facility that is currently under construction and provide visual information for the crowd flow that can be used when developing the safety plan for the facility.

2. METHOD

2.1 Development of Agent-based Crowd Simulation

We developed an agent-based simulation to evaluate the flow of the crowd in an urban facility. To reproduce the macroscopic phenomena of the crowd flow, especially in a queue, we propose a behavior model that is based on the social force model (Helbing et al., 2000). Behavior consists of three submodels: (1) route choice: each agent setting a destination and calculating the route; (2) crowd movement: agents approaching the destination and avoiding collisions; this section takes the entry queue into account; (3) queue formation: agents forming a queue in a specific area.

2.1.1 Route-choice model

In the route choice model, each agent at each time step determines the direction vector towards the chosen destination. In this model, a plan of the target site or a floor plan is divided into a square grid and the direction vectors are set on each grid point, using a simple graphical user interface (GUI) route-editing tool (Fig.1). This tool enables us to set any direction for the vector at each grid point, just like painting. The direction vector at the grid point at which an agent stands is used for the next step of the route. The size of the grid is variable, but there are trade-offs between the accuracy of the plan and the calculation time. In this study, we set the grid size to 50 cm on a side in order to model individual agent in a large-scale facility.

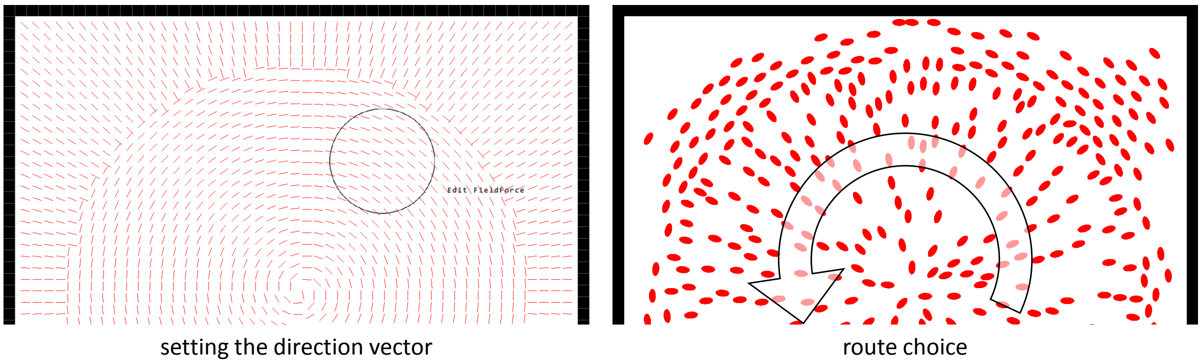

Fig. 1: Route choice based on direction vector and editing tool

2.1.2 Modeling the movement of a crowd in a queue

We used a social force model to approximate the microscopic movement behavior of a crowd. In the social force model, each agent is represented by a self-driven particle that is subject to both social and physical forces. Accordingly, agents i with a certain mass m_i like to move in a certain direction $\mathbf{e}_i^0$ at a certain speed v_i^0, adapting their velocity within a certain time period τ_i, while keeping their distance from other agents j and obstacles W. Therefore, the social forces consist of (1) an attracting force from a direction vector of the route choice model; (2) repulsive forces from other agents $\mathbf{f}_{ij}$; and (3) repulsive forces from walls and other obstacles $\mathbf{f}_{iW}$; as shown in Fig. 2. The mathematical representation of these forces is presented, in Eqs. 1. Each agent calculates the force and updates its walking speed once per time step. To restrict oscillation and numerical errors, a maximum walking speed is limited.

However, if we try to use the social force model to reproduce the behavior of a crowd in a queue, there are several issues. One is that the social force model cannot represent a high-density crowd in a queue because the shape of each agent is approximated by a circle. The other is that the social force model does not take into consideration the behavior of following in a queue. Because of this, we developed (1) ellipse-based collision detection and (2) velocity alignment parameters to model the following behavior in a queue, based on the social force model.

In the ellipse-based collision-detection process, the shape of each agent is approximated using an ellipse, and the collisions between them are detected. Specifically, the radius (r_i) of agent i is set the radius vector in the direction of the other agent j (see the right-hand side of Fig.2).

The velocity alignment parameter causes the velocity of each following agent to adapt to the velocity of the leading agent. If the distance between the following leading agents is less than D_i, the following agent is forced to adapt to the speed of the leading agent. If the distance is less than C_i, the following agent is forced to stop in order to avoid a collision (Eqs. 2).

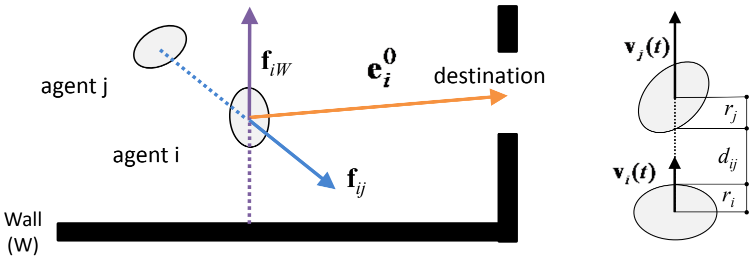

Fig. 2: Model of the social force between ellipses

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_{W} \mathbf{f}_{iW} \qquad (1)$$

$$\boldsymbol{v}_i^0(t) \begin{cases} |\mathbf{v}_i(t)|s + |\mathbf{v}_j(t)|(1-s) & (C_i \le d_{ij} < D_i) \\ 0 & (d_{ij} < C_i) \end{cases} \qquad s \begin{cases} \left(1 - \dfrac{d_{ij} - C_i}{D_i - C_i}\right)^2 & (|\mathbf{v}_i(t)| \ge |\boldsymbol{v}_j(t)|) \\ 0 & (|\mathbf{v}_i(t)| < |\boldsymbol{v}_j(t)|) \end{cases} \qquad (2)$$

2.1.3 Queue formation model

The queue formation model represents the creation of a queue near an entrance to a facility. Specifically, each agent is given a direction vector based on if the agent is standing in a queue area, a detour area, or another area. A queue area is where the agents stand in a queue. A detour area is where agents take a roundabout route to go to the rear of a queue (note that the location of the detour area changes as the queue forms and develops).

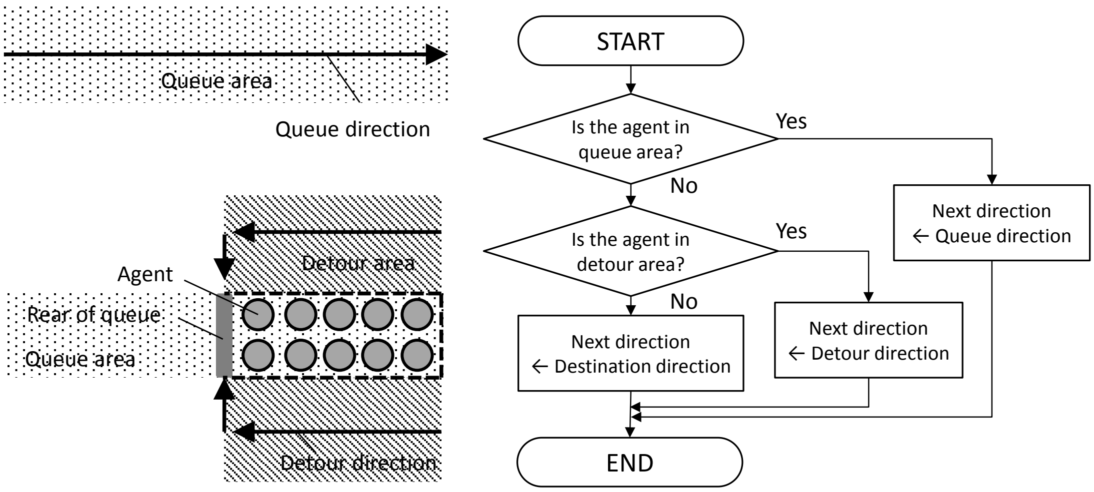

Fig. 3: Queue formation model

When an agent enters a queue area, the direction vector of the agent is set to the queue direction. This direction is distinguished from that of the route choice model. Figure 3 shows the directions in a queue area and a detour area. When an agent reaches the vicinity of a queue area, the agent tries to join the queue. However, if there is already a queue, the agent is directed to detour to the rear of the queue. A specific area around a queue and ahead of the rear of the queue is the detour area. If an agent reaches the end of the queue, the agent joins it. If a queue area is widened, a multi-line queue is formed by the action of force toward the queue direction and repulsive force from other agents. The agents in the queue are also made not to get out of the queue by repulsive force from the outside of a queue. The position of the rear of a queue moves in the direction opposite that of the queue if the density of the queue is greater than a specified value. The settings for the area and direction of the queue and the detour area can be changed by using an editing tool (Fig.4).

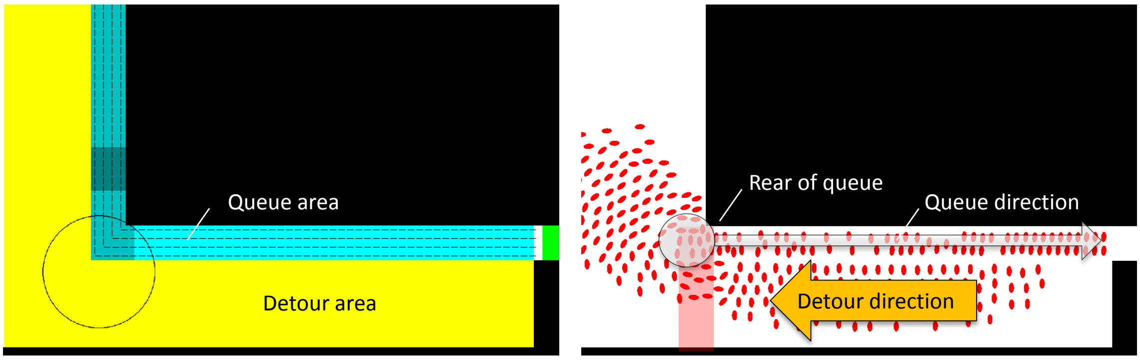

Fig. 4: Queue-editing tool

2.2 Verification of Crowd Behavior in Queues

To verify the reproducibility of crowd behavior in a queue by using our crowd simulation, we evaluated (1) the way in which the parameter choice changed the linear density, (2) how the simulated crowd flow compared with observation data, and (3) the way in which the process of formation of a queue depends on the shape of the queue area.

Specifically, we measured the changes in the linear density due to the size of the ellipse that represents the exclusive area of an agent, and compared this with the linear density observed in previous research (Kanao at el., 1992). As for the crowd flow, we compared the characteristics of the simulation with observation data at a soccer stadium. We extracted data on the trajectories of pedestrians from a video of queues in front of the entrance. From the observation data, we determined that the queue had a high density where individuals were standing and a low density where they were moving. For a single queue, our crowd simulation reproduced the density and this characteristic crowd flow.

We measured the formation of a queue for three types of areas: straight, corner, and winding (Fig.5). In our simulation, 200 agents were distributed at random, and then they all moved toward the queue area. After all agents were in the queue, the entrance was opened, and we measured the flow of the crowd as they entered.

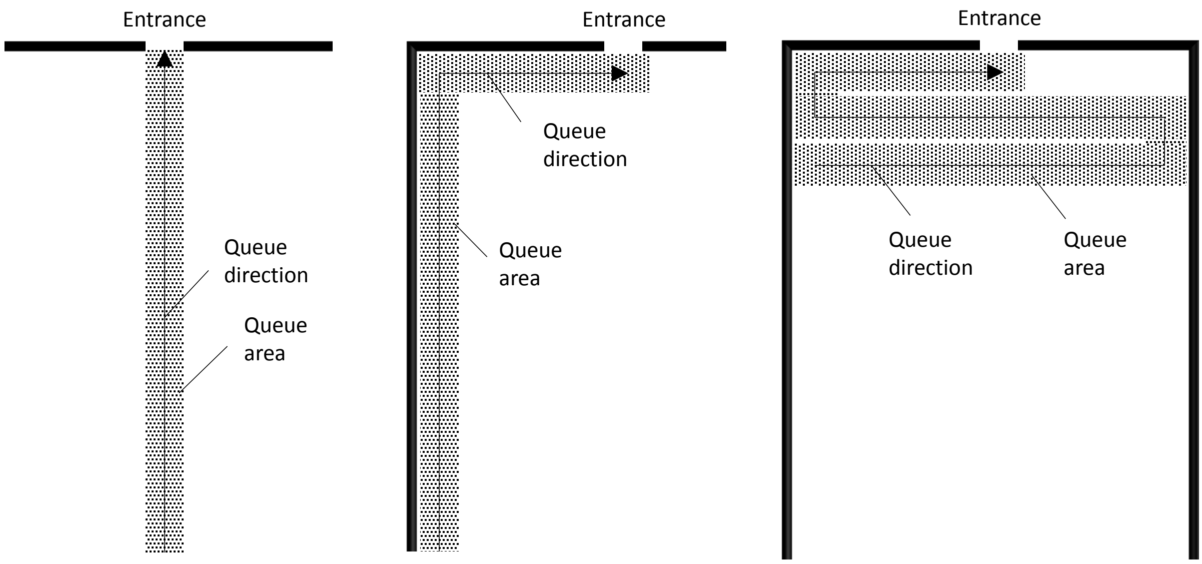

Fig. 5: Three types of queue formations

2.3 Application to a Large-scale Facility

We applied the crowd simulation to a large-scale commercial facility that is currently under construction, in order to evaluate crowd safety during a special event. The entire site covers an area of approximately 38,000 square meters. The number of visitors is estimated to be 10,000 people, and the time is from 7:00 (3 hours before opening) to 11:00 (1 hour after opening). The six routes are based on the existing public transportation in this area, and the proportion of individuals on each route is based on transport planning figures. We considered the queue areas in front of each of the four entrances. The shapes of the queue areas include straight, corner, and winding, as needed to adapt to the surrounding environment (Fig.6).

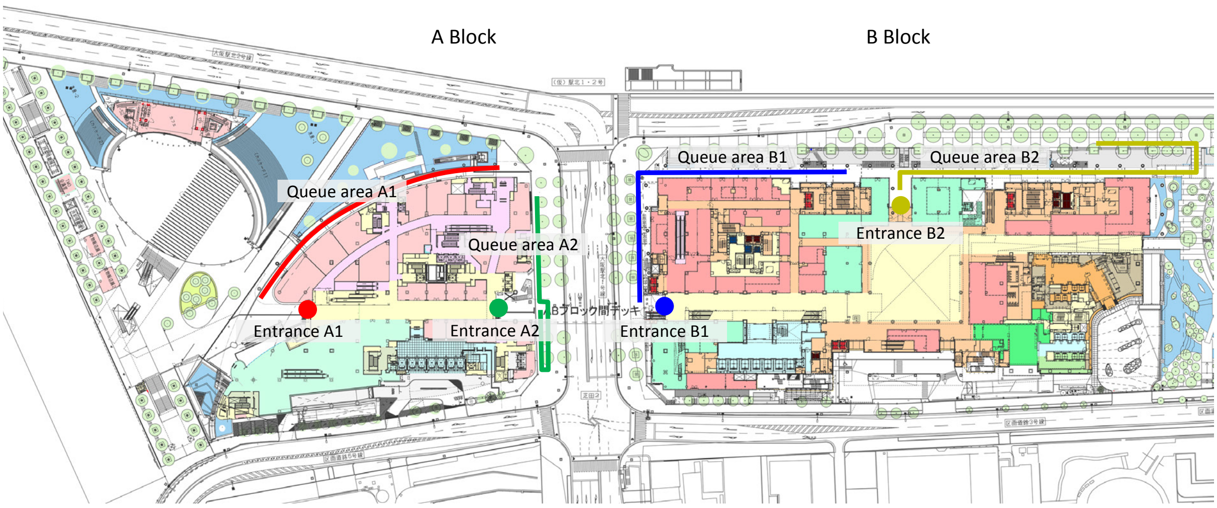

Fig. 6: Large-scale commercial facility

3. RESULT AND DISCUSSION

3.1 Linear Density in the Queue

In our model of crowd movement in a queue, we used an ellipse instead of a circle so that we could consider the difference of shoulder width and body thickness. We consider this shape is exclusive to the agent. When the shoulder width is fixed at 60 cm and the body thickness is changed in increments of 5 cm, ranging from 25 cm to 60 cm, changes in the linear density of the queue are shown in Fig. 7. According to the previous observation data

(Kanao at el., 1992), 77.6% of linear densities for a single queue are distributed between 1.6 and 2.4 people/m. The average is approximately 2.0 people/m and the standard deviation is approximately 0.4 people/m. In our model, if the body thickness is 30 cm, the linear density is approximately 2.0 people/m. However, it is appropriate to change the linear density depending on the conditions, and our model enables the density to be calibrated by adjusting the shape of the ellipse.

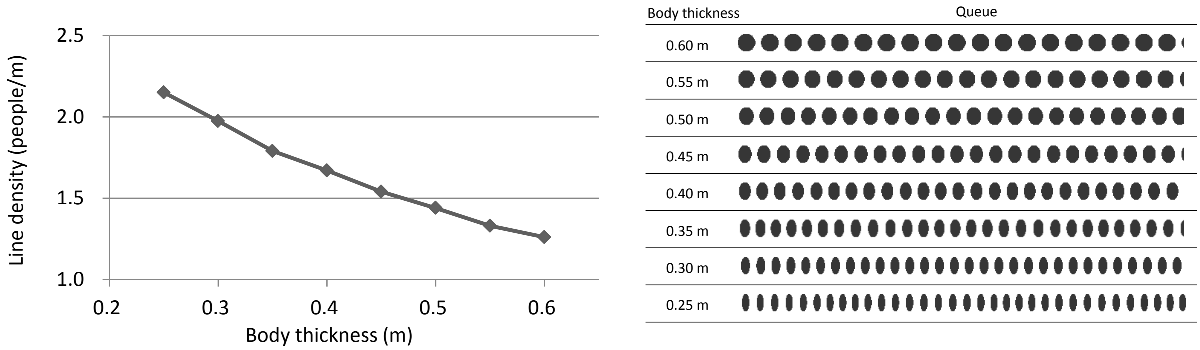

Fig. 7: Changes of linear density by parameter

3.2 Reproduction of Crowd Flow in a Queue

To reproduce a pattern observed in the flow of crowds in a queue, we modeled the situation in which a pedestrian towards the front of a queue temporarily stops. This changes the queue which then consists of high-density standing parts and low-density moving parts. Over time, the high-density parts move backward in the queue. This phenomenon is called a stop-and-go wave.

The upper left-hand side of Fig. 8 shows a stop-and-go wave observed in the queue formed in front of the entrance of a soccer stadium. The upper right-hand side of Fig. 8 shows a stop-and-go wave reproduced by our simulation. The lower part of Fig. 8 compares the distribution of pedestrians as observed with that of the simulation. In the observation data, the queue was formed by one or two rows, whether they were a group or not. The linear density of the moving pedestrians is 1.5 people/m and that of the standing pedestrians is 3.2 people/m. On the other hand, the queue of the simulation is formed by a single row. The linear density of the moving pedestrians is 0.9 people/m and that of the standing pedestrians is 2.0 people/m. Because the number of rows is different between the observation and the simulation, a simple comparison is impossible. However, the ratios between the density of moving pedestrians and that of standing pedestrians are almost the same. Moreover, the propagation speed of the high-density part in the observed queue is reproduced by calibrating the parameters of C_i and D_i in our crowd movement model.

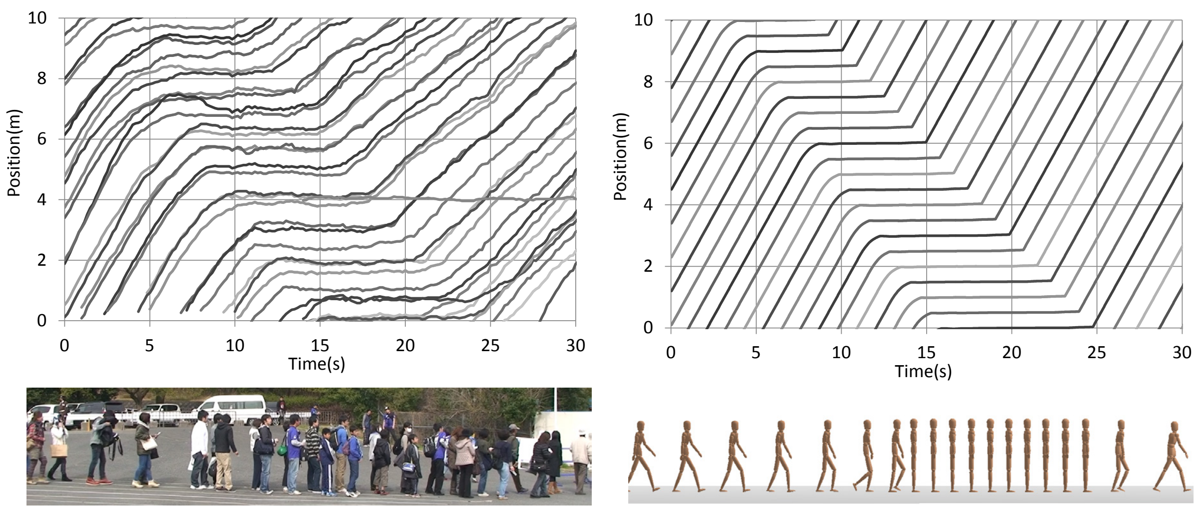

Fig. 8: Reproduction of crowd flow in a queue

3.3 Comparison of Queue Formation Process

Figure 9 shows the results of the queue formation and entry processes for the three types of queue areas. At first, agents are distributed at random positions, and the agents near the entrance move to the queue area. As the queue is formed, the agents who want to join a queue move toward the rear of the queue, where the agent can join the queue.

For a straight queue, it took 2 minutes 30 seconds until all the agents had joined a double-row queue. The maximum linear density was 3.92 people/m, and the length of the queue was 51 m. The corner queue took 3 minutes 58 seconds to finish forming; it was also in two rows. The maximum linear density was 3.74 people/m, and the length of the queue was 53.5 m. The winding queue took 4 minutes 29 seconds to finish forming a double queue. The maximum linear density was 3.60 people/m, and the length of the queue was 55.5 m. These results indicate that the differences in the linear density and the lengths of the queues are not significant, but the difference in the time it took to finish forming the queue was large. The time depends on the environment of the queue area, such as if a straight queue has walls on either side, or if a corner or winding queue can only be accessed from one side.

While the queue was being formed, the entrance was closed. When the queue was finished forming, every agent was in the queue, and the linear density was maximized, the entrance was opened. The graph of Fig. 9 shows the number of agents in the queue after the entrance was opened. The entrance time for the straight queue is shortest. The time was 135.9 seconds, and the average rate of flow at the entrance opening was 0.98 people/m/s. Because the width of the opening and the that of the queue were the same, the flow rate maintained a high value compared with other queues. However, the flow rate was smaller than the empirical flow rate at a simple opening (1.5 people/m/s). The flow rate of 2.22 people/s (1.49 people/m/s) was approximately reproduced by our model when using a 1.5 m opening (Fig.9: the graph of 'None'). The delay occurred when an agent in a queue started to move behind the agent in front of him, but was delayed by the model of following behavior. The second shortest entrance time was measured with the corner queue. The time was 157.1 seconds, and the average flow rate at the entrance opening was 0.85 people/m/s. The three right-angle corners reduced the flow. The longest entrance time was measured with the winding queue. The time was 180.3 seconds, and the average flow rate at the entrance opening was 0.74 people/m/s. The crowd flow with the winding queue was less than that of the corner type due to the three corners that turned it back 180 degrees.

From this comparison, we see that the crowd flow increases if the queue is as wide as the opening. However, the flow rates for every type of queue were less than the empirical flow rates with a simple opening (1.5 people/m/s). Moreover, we note that the number of corners in a queue also reduces the flow rate.

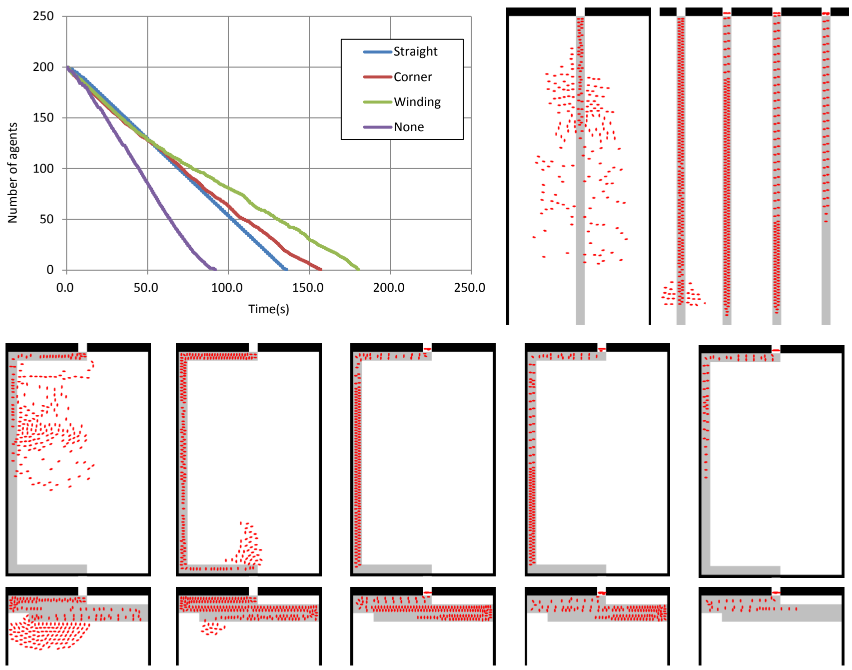

Fig. 9: Entrance time and queue formation process

3.4 Application to a Large-scale Facility

Figure 10 shows the application of our simulation to a large-scale facility that is currently under construction. The person in charge of crowd security uses a simulation movie to explain the specific queue areas and the expected flow of visitors. Safety measures are shared among the organizers when a special event is going to be held. A method that uses visual information assists non-experts, for whom numerical information may not be useful, to imagine the crowd flow.

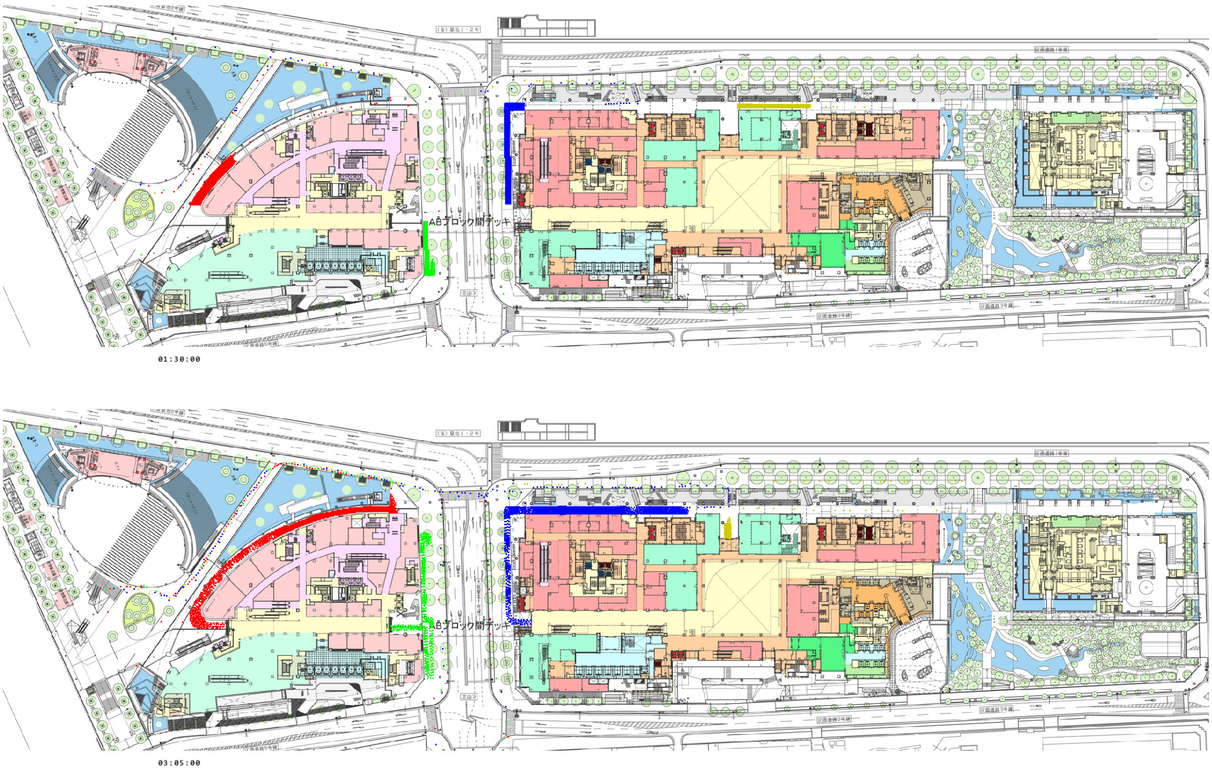

Fig. 10: Application to a large-scale facility

4. CONCLUSION

This study modeled the microscopic interactions between agents to develop an agent-based crowd simulation that enables the reproduction of the macroscopic phenomena of the flow of a crowd in a queue. In addition, we applied the simulation to a large-scale facility that is currently under construction and share visual information about the crowd flow that can be used when a safety plan for the facility is determined. The results are as follows.

To reproduce the crowd flow in high-density queue, we implemented an ellipse-based collision detection process based on the social force model. In consequence, if the body thickness was 30 cm, the linear density was approximately 2.0 people/m. We also reproduced a feature of queues called stop-and-go waves. By comparing the simulation with observed data, we determined that the ratios between the densities of moving and stationary pedestrians were almost same. Moreover, the propagation speed of the high-density part of the observed queue was reproduced by calibrating the parameters. The shape of the queue area was also determined to affect the flow of the crowd. However, the flow rates for every type of queue were less than the empirical flow rates at a simple opening because of behavior when following. The number of corners in a queue also reduced the crowd flow.

As a result of the application of this method to the simulated crowd at a large-scale urban facility, safety measures can be shared among the organizers when a special event is going to be held. A method such as this, which uses visual information, enables crowd flow to be imagined even by non-experts, for whom numerical information may not be useful.

5. ACKNOWLEDGEMENT

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