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Optimization of Personal Distribution for Evacuation Guidance based on Vector Field

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Abstract— **It is an important issue to make a disaster reduction plans for overcrowded population in the urban cities. In this paper, we focus on evacuation guidance to prevent the damage from spreading. The personal navigation system cannot deal with evacuation guidance for the human crowd with large numbers of individuals because of time constraints and extraordinary communication error. An implicit guidance based on dynamical characteristic of swarm behavior is efficient and effective with a few guidance operators. We propose a modeling and control method of swarm based on vector field. The evacuee behavior model contains intention of evacuation, field of view, collision avoidance and evacuee group, which are represented by vector field. The guidance operator model contains indicating direction. By giving the desired vector field that indicates the safe route for evacuation, the position of guidance operators are optimally distributed. Moreover, the number of guidance operators is minimized based on the contribution index. The proposed modeling and control method is applied to the swarm robot and the effectiveness is evaluated by the experiments.**

I. INTRODUCTION

There are two types of countermeasures against disaster. One is disaster prevention, the other is disaster reduction. Because it is penetrated into the society that it is difficult to prevent disaster perfectly, the importance of disaster reduction method is focused on. Evacuation guidance for the human crowd with large number of individuals is one of important foci for disaster reduction. For evacuation guidance, it is an important issue to develop a guidance strategy that enables to maneuver many people to the safe route. Nakanishi et al. [1] developed a navigation system in which an operator gives indication to walkers using mobile-phone based on bird's-eye view. However, because of failure of communication system and evacuee's misreading of important information in panic, the explicit guidance sometimes causes confusion of crowds.

On the other hand, the implicit guidance like shepherding based on the dynamical behavior of swarm will be effective and some guidance strategies have been proposed so far. "The Follow Directions method" which is often utilized for evacuation guidance, means that a guidance operator indicates a safe exit with a loud voice and gestures. "The Follow Me method" means that a guidance operator evacuates with leading evacuees [2]. These methods are effective for small-scale swarm because the guidance operator evacuates with evacuees. Pelechano et al. [3] performed evacuation simulation from the building, and Helbing et al. [4] simulated panic situations in disasters. Watanabe et al. [5] performed evacuation simulation using routing panels which give the global disaster information. However, it is difficult to adjust the indication with respect to the changing environment. Rodriguez et al. [6] modeled human behaviors and simulated evacuation guidance. However, it's difficult to determine the behaviors of guidance operators using this model. Lien et al. [7][8] investigated ways to simulate shepherding behaviors.

We can interpret "swarm guidance" into "swarm control", and some methods to control swarm robot are proposed. Fink et al. [9] proposed cooperative manipulation method based on a potential field for swarm robot. Kerr et al. [10] proposed an effective search algorithm which imitates gaseous diffusion. Shimizu et al. [11] proposed a formation control method based on molecular dynamics and Navier-Stokes equation. Pimenta et al. [12] [13] proposed swarm control method using SPH (Smoothed Particle Hydrodynamics) method. These methods design a motion generative algorithm for swarm, however, are not appropriate for evacuation guidance because they are explicit control algorithm. Vaughan et al. [14] performed an experiment in which a sheep dog robot chases a flock of ducks. This method gives an implicit strategy considering the behavior of animals but involves heuristic ways.

In this paper, we propose an implicit evacuation guidance method by distributing guidance operators at appropriate points including direction of indication. Intention of evacuee is modeled by vector field as a macro model of swarm behavior. By modeling the operator's action by vector field, the distribution and indication of operators are optimized based on the superposition of vector field. By guiding a few individuals, the whole of swarm are guided according to the dynamical behavior of swarm. Because the proposed method is online algorithm, it copes with the changing environment. Moreover, as a quasi-human environment, the effectiveness of the proposed method is evaluated by guidance experiments using autonomous mobile robots including a radio controlled robot by a human.

II. MACRO MODEL OF SWARM AND BEHAVIOR OF INDIVIDUALS

A. Environmental formulation and modeling of swarm intention

We consider the evacuation route as shown in figure 1-(a). This is a room with one entry and two emergency

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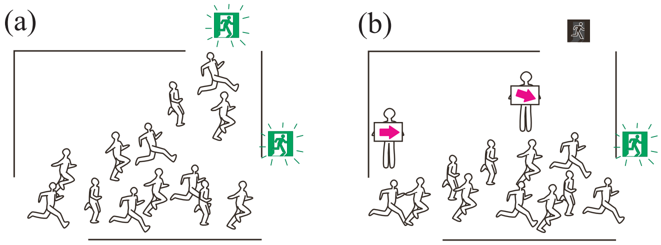

Fig. 1. Evacuation and non-available routes

exits. Though both exits are available usually, we assume that one of them changes to unavailable due to the fire or some accidents as shown in figure 1-(b). Our focus is on appropriate distribution of guidance operators so that all the evacuees are guided to the available exit. Here we assume that the evacuees come from the entry and go out the exit continuously. So far, we have proposed a macro modeling method of swarm behavior [15] in the exhibition space. The flow of the individuals touring the exhibition is represented by vector field. Same as the previous research, the evacuee's intention to seek the exit is modeled by vector field, which is a macro model of evacuee's behavior. On the other hand, Boid model [16] has three swarm behavior rules as follows:

(a) Collision Avoidance
(b) Velocity Matching
(c) Flock Centering

Our model of evacuee by vector field corresponds to rule (b). The rules (a) and (c) are discussed later.

B. Design of evacuation vector field

Vector field which represents evacuee's intention is represented by $\boldsymbol{v}_f = \boldsymbol{v}_f(\boldsymbol{x})$ at point $\boldsymbol{x}$ [15]. A polynomial of power of $\boldsymbol{x}$ is utilized for $\boldsymbol{v}_f$ as follows:

$$\boldsymbol{v}^f(\boldsymbol{x}) = \boldsymbol{a}_0 + \boldsymbol{a}_1\boldsymbol{x} + \boldsymbol{a}_2\boldsymbol{x}^2 + \boldsymbol{a}_3\boldsymbol{x}^3 \cdots \tag{1}$$

$$= \Theta\phi(\boldsymbol{x}) \tag{2}$$

$$\Theta = \left[\begin{array}{ccccc} \boldsymbol{a}_0 & \boldsymbol{a}_1 & \boldsymbol{a}_2 & \boldsymbol{a}_3 & \cdots \end{array} \right] \tag{3}$$

$$\phi(\boldsymbol{x}) = \left[\begin{array}{ccccc} 1 & \boldsymbol{x}^T & \boldsymbol{x}^{2T} & \boldsymbol{x}^{3T} & \cdots \end{array} \right]^T \tag{4}$$

where $\boldsymbol{a}_i (i = 0, 1, 2 \cdots)$ is a coefficient of polynomial and power of vector $\boldsymbol{x}$ is defined as follows:

$$\boldsymbol{x}^i = \left[\begin{array}{ccccc} x^i & x^{i-1}y & x^{i-2}y^2 & \cdots & y^i \end{array} \right]^T \tag{5}$$

$$\boldsymbol{x} = \left[\begin{array}{cc} x & y \end{array} \right]^T \tag{6}$$

$\boldsymbol{v}_f$ is designed particularly as follows. The routes from the entrance to the exits ξ_i^j(route number $j = 1, 2$)(data number $i = 1, 2, 3, \cdots$) is set as shown in figure 2. The point $\boldsymbol{x}_i$ near ξ_j^i are set and a vector at this point is defined by

$$\boldsymbol{v} = \xi_{i+1}^j - \boldsymbol{x}_i \tag{7}$$

By setting many points $\boldsymbol{x}_i$, a large number of pairs of $(\boldsymbol{v},\ \boldsymbol{x}_i)$ are obtained. By using the least square approximation, the coefficient matrix Θ is obtained. By using this method, the evacuation vector field for the evacuation routes in figure 2 is obtained as shown in figure 3.

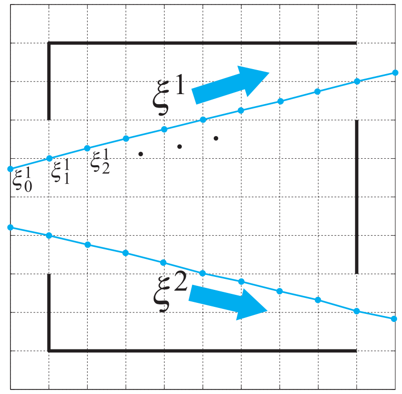

Fig. 2. Defined evacuation route

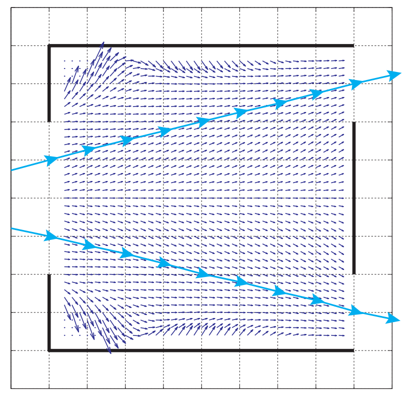

Fig. 3. Obtained evacuation vector field

C. Design of vector field for collision avoidance with obstacles and other individuals

Individuals in the swarm avoid collision with obstacles or others. These behaviors are modeled by vector field considering the traveling direction of individuals. The avoidance vector will be large for the close obstacles and small for the far one, which corresponds to the rule (a) in Boid model. The individual at $\boldsymbol{x}_j = [x_j\ y_j]^T$ yields the collision avoidance vector $\boldsymbol{v}_j^p$ at point $\boldsymbol{x}$ as follows:

$$\boldsymbol{v}_j^p(\boldsymbol{x}) = -\frac{c^p}{1 + \exp\left\{a^p\left(\|\boldsymbol{r}_j^p\| - b^p\right)\right\}} \frac{\boldsymbol{r}_j^p}{\|\boldsymbol{r}_j^p\|} \tag{8}$$

$$\boldsymbol{r}_j^p = \boldsymbol{x}_j - \boldsymbol{x} \tag{9}$$

where a^p and c^p are constant. b^p is defined considering the traveling direction of individual at $\boldsymbol{x}$ as follows:

$$b^p(\Delta\theta_j^p) = \frac{\gamma^p}{1 + \exp\left\{\alpha^p(\Delta\theta_j^p - \beta^p)\right\}} + \delta^p \tag{10}$$

$$\Delta\theta_j^p = \left| \left\{ \tan^{-1}\left(\frac{y_j - y}{x_j - x}\right) - \theta^p \right\} \right| \tag{11}$$

where α^p, β^p, γ^p and δ^p are constant. The larger b^p yields the larger $\boldsymbol{v}^p$ which conveys the individual faster. θ^p is defined as the angle between the traveling direction $\boldsymbol{v}^f$ of individual at $\boldsymbol{x}$ and horizontal direction. $\Delta\theta_j^p$ represents the angle between θ^p and $\boldsymbol{r}_j^p$ which is the direction of $\boldsymbol{x}_j$. These parameters are defined as figure 4. Arc tangent in equation (11) is defined

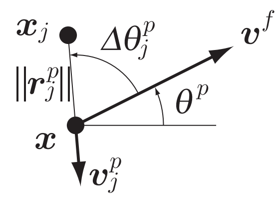

Fig. 4. Parameter definition for collision avoidance

in 0 to π. β^p is set as $\pi/3$ because it is known that the human ability for stereoscopic is about $2\pi/3$ field of front view [17]. Because the wall is a static object, the vector field for collision avoidance with the wall is set as follows:

$$\boldsymbol{v}^w(\boldsymbol{x}) = -\frac{c^w}{1+\exp\{a^w(\|\boldsymbol{r}^w\| - b^w)\}}\frac{\boldsymbol{r}^w}{\|\boldsymbol{r}^w\|} \tag{12}$$

where a^w, b^w and c^w are constant. $\boldsymbol{r}^w$ is the vector from the individual to the nearest point on the wall. To define a^p and c^p in equation (8), γ^p in equation (10), a^w, b^w and c^w in equation (12), we observe the human behavior.

Figure 5 shows the photograph of human flow. The top

Fig. 5. Human flow with the symmetrical dispersion

right corner is the entry and the bottom left corner is the exit. When the population density is low, the human goes straight to the exit, and when the population density is high, the human flow broadens symmetrically as shown in figure 5. On the other hand, the human does not keep distance from the static obstacle as shown in the bottom left of figure 5. To represent these behaviors, the parameters are set appropriately. For example, $\boldsymbol{b}^p$ represents personal space, which is obtained from the observed data.

D. Grouping of evacuees

Mawson [18] proposes "Affiliative model" of human behavior in emergency. In this model, evacuees in panic approach to familiar people or places. This model is introduced to our evacuee model as rule (c) in Boid model. To group the familiar evacuees, the affiliative vector $\boldsymbol{v}_i^a$ is introduced as follows:

$$\boldsymbol{v}_i^a(\boldsymbol{x}) = c^a \boldsymbol{r}_i^a \tag{13}$$

$$\boldsymbol{r}_i^a = \boldsymbol{x} - \boldsymbol{x}_i^a \tag{14}$$

where $\boldsymbol{x}_i^a$ is a center of the group. c^a is constant.

E. Simulation of evacuation behavior

By considering all the vectors of evacuee, the behavior of an individual is represented as follows:

$$\boldsymbol{x}_i[k+1] = \boldsymbol{x}_i[k] + \boldsymbol{v}_i(\boldsymbol{x}_i[k])T \tag{15}$$

$$\boldsymbol{v}_i = \boldsymbol{v}^f + \sum_{j\neq i}^{n} \boldsymbol{v}_j^p + \sum_{j=1}^{\ell} \boldsymbol{v}_j^w + \boldsymbol{v}_i^a \tag{16}$$

where k is the timestep, T is a sampling time, n is the number of individuals in the swarm and ℓ is the number of walls. Using equation (15), evacuation simulation is performed. As shown in figure 6-1, a square room is set with one entry on the left wall, two exits on the right wall. Individuals come into the room from the entry continuously

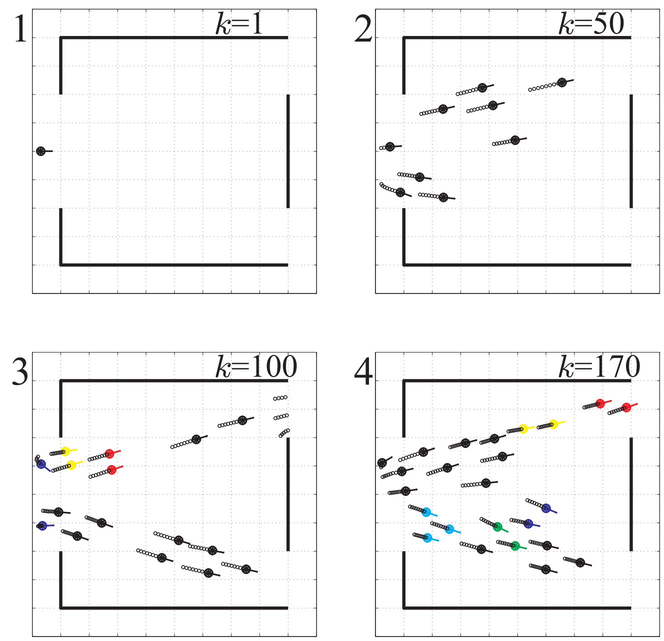

Fig. 6. Simulation result of swarm behavior

and move based on equation (15). The simulation result is shown in figure 6. • represents a position of an individual, the arrow represents the direction of individual (velocity $\boldsymbol{v}_i$) and small ◦ represents the trajectory of the individual in the latest 8 steps. The individuals which painted the same color except black belong to the same group to represent "Affiliative model". All the individuals evacuate along the evacuation route with furcating two exits and gathering the same group member. The simulation result shows the effectiveness of the proposed modeling method of evacuee.

III. Swarm Guidance

A. Modeling of guidance operator

The purpose of evacuation guidance is to shepherd the evacuee to the safe route by moving the guidance operators. The proposed method employs (a) modeling of operator's action to evacuee by vector field and (b) optimization of operator's distribution based on superposition of vector field.

Suppose that the guidance operator indicates a particular direction at particular position. The operator's action $\boldsymbol{v}^g$ is modeled by the following equation.

$$\boldsymbol{v}^g(\boldsymbol{x}) = \frac{c^g}{1+\exp\{a^g(\|\boldsymbol{r}^g\| - b^g)\}} R(\theta^g) \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (17)$$

$$\boldsymbol{r}^g = \boldsymbol{x}^g - \boldsymbol{x} \quad (18)$$

where $\boldsymbol{x}^g$ is the position of the operator, $\boldsymbol{x}$ is the position of evacuee, a^g and c^g are constant. b^g is set as follows:

$$b^g(\Delta\theta^g) = \frac{\gamma^g}{1+\exp\{\alpha^g(\Delta\theta^g - \beta^g)\}} \quad (19)$$

$\Delta\theta^g$ represents the angle between the traveling direction $\boldsymbol{v}_i$ of individual at $\boldsymbol{x}$ and $\boldsymbol{r}^g$. α^g, β^g and γ^g are constant. Rotation matrix $R(\theta)$ is defined by:

$$R(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \quad (20)$$

θ^g is the indicating direction of operator. $R(\theta)$ makes $\boldsymbol{v}^g$ in equation (17) turn to the indicating direction. These parameters are represented as shown in figure 7. By considering

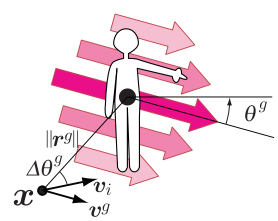

Fig. 7. Vector field via guidance operator

the influence of operators, the behavior of evacuee in (16) is rewritten as follows:

$$\boldsymbol{v}_i = \boldsymbol{v}^f + \sum_{j\neq i}^{n} \boldsymbol{v}_j^p + \sum_{j=1}^{\ell} \boldsymbol{v}_j^w + \sum_{j=1}^{m} \boldsymbol{v}_j^g + \boldsymbol{v}_i^a \quad (21)$$

where m is the number of operators.

B. Optimization of guidance operator distribution

To achieve the evacuation guidance, the safe route that leads the evacuee to the desired exit is set and modeled by vector field $\widehat{\boldsymbol{v}}^f$. By the same way as shown in section II-A, $\widehat{\boldsymbol{v}}^f$ is represented by

$$\widehat{\boldsymbol{v}}^f(\boldsymbol{x}) = \widehat{\Theta}\phi(\boldsymbol{x}) \quad (22)$$

and obtained as shown in figure 8. When the vector field of evacuee behavior $\boldsymbol{v}_i$ in (21) and the desired vector field $\widehat{\boldsymbol{v}}^f$ in (22) satisfy

$$\boldsymbol{v}_i = \widehat{\boldsymbol{v}}^f \quad (23)$$

all the evacuees are shepherded to the safe route.

To optimize the distribution of guidance operator, the objective function J

$$J = \sum_{j=1}^{n} \left\| \widehat{\boldsymbol{v}}^f(\boldsymbol{x}_j^r) - \boldsymbol{v}_i(\boldsymbol{x}_j^r) \right\|^2 \quad (24)$$

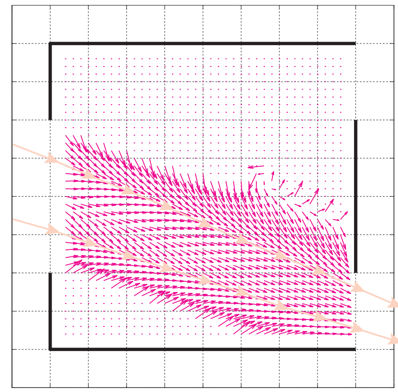

Fig. 8. Definition of modified evacuation routes

is set with respect to the representative point $\boldsymbol{x}_j^r$, and design parameters $\boldsymbol{x}^g$ (position of the operator), θ^g (pointing direction) are calculated so that J is minimized. To develop an online optimization that copes with the changing environment, $\boldsymbol{x}_j^r$ is selected as the position of evacuee, and the design parameters are online optimized by the following gradient method.

$$\boldsymbol{x}^g \leftarrow \boldsymbol{x}^g - \left(\frac{\partial J}{\partial \boldsymbol{x}^g}\right)^T \delta x \quad (25)$$

$$\theta^g \leftarrow \theta^g - \left(\frac{\partial J}{\partial \theta^g}\right) \delta\theta \quad (26)$$

where δx and $\delta\theta$ are constant. Because $(\partial J/\partial \boldsymbol{x}^g)$ and $(\partial J/\partial \theta^g)$ are locally effective around the operator, knowledge of evacuees only near the operator are considered. This algorithm means that

- The position and indicating direction of the operator locally minimize J around the position of operator, which means the behavior of the operator is determined by the local information of the operator.
- Only a few evacuees are directly guided by the operator, and behavior of the others are decided by the dynamical interaction of evacuees, which means the operator works like a sheepdog.

IV. Simulation of Evacuation Guidance

A. Effectiveness of the proposed method

In the same environment as section II-E, the simulation based on the proposed method is performed. The number and initial positions of operators are selected randomly. The evacuees come into the room from the entrance with constant time interval. Each individual moves by equation (15) and (21) and positions and indicating directions of the operators are optimized by equation (25) and (26). Collision avoidance is applied between operators by the same way as equation (8). The trajectories of individuals and the positions and indicating direction of operators are shown in figure 9. $\bullet$ is a position of an individual and the arrow represents $\boldsymbol{v}_i$. Small $\circ$ represents the trajectory of the individual. $\circ$ is a position of an operator and its arrow represents the pointing direction. These result shows that the operators are

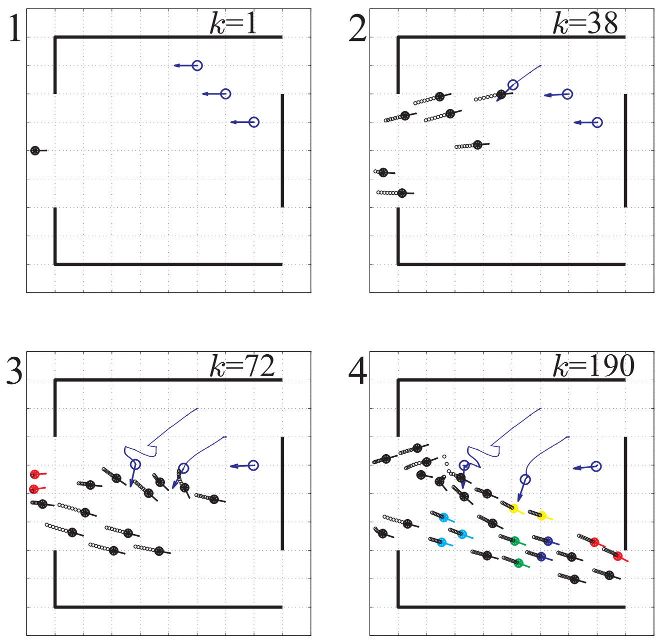

Fig. 9. Positional and directional optimization of guidance operators

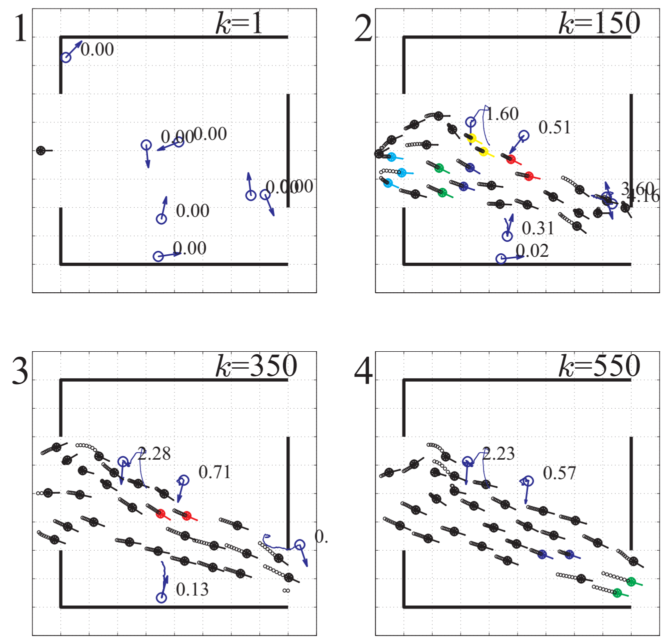

Fig. 10. Optimization of position, direction, number of guidance operators

distributed optimally and the evacuees are guided to the safe route.

B. Optimization of the number of guidance operators

The number of guidance operators is optimized by relieving the operator who has low contribution for guidance. An operator's contribution W is defined by the summation of indicating vectors norm as follows:

$$W = \sum_{i=1}^{n} \frac{c^g}{1 + \exp\{a^g(\|\boldsymbol{r}_i^g\| - b^g)\}} \tag{27}$$

The operator whose W is the smallest is relieved and the number is reduced within the extent of possible guidance. The simulation result is shown in figure 10. The index of $\circ$ represents the operator contribution W. In all of the simulations with seven operators initialized randomly, two operators are remained at the same position and indicating direction as shown in figure 10-4, which means the distribution, indicating direction and number of operators as shown in figure 10-4 are optimized solutions. However, when all the operators are distributed in the left bottom corner of the room initially, any operators cannot reach to the optimized position across the evacuee flow exceptionally, which means there are local minima of the objective function J from topological point of view. It is necessary that the operators are distributed initially all over the room.

V. Experimental evaluation using swarm robot

A. Autonomous mobile robot

To evaluate the proposed method, the guidance experiments are performed using autonomous mobile robot. The experiments simulate the quasi-human environment. Figure 11 shows the autonomous mobile robot. It has a microcontroller (SH-2), Li-Po battery, position and orientation measurement system (StarGazer) and infrared range sensors. It communicates with a server PC through wireless LAN. There are three geared motors with omnidirectional wheel which enables omnidirectional movement. However, we set the front direction in these experiments. From the information of the position measurement system and range sensors, the evacuee robot calculates $\boldsymbol{v}^f$ and $\boldsymbol{v}^p$ respectively by the microcontroller. Five range sensors are distributed in the front position with $\pm 60°$ area. However, unfortunately, the robot cannot measure the indicating direction of the operator robots, and its information is sent from the server PC to the evacuee robot. Besides one evacuee robot is radio controlled by a human to simulate the quasi-human environment.

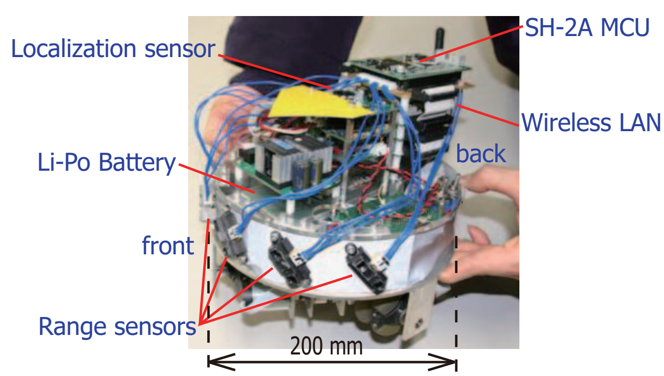

Fig. 11. Appearance of swarm robot

B. Experimental results of evacuation guidance

10 evacuee robots and 2 operator robots are utilized for the experiment. Figure 12 shows the experimental result. The white lines represent the wall of room. There are one entry in the left hand side and two exits in the right hand side.

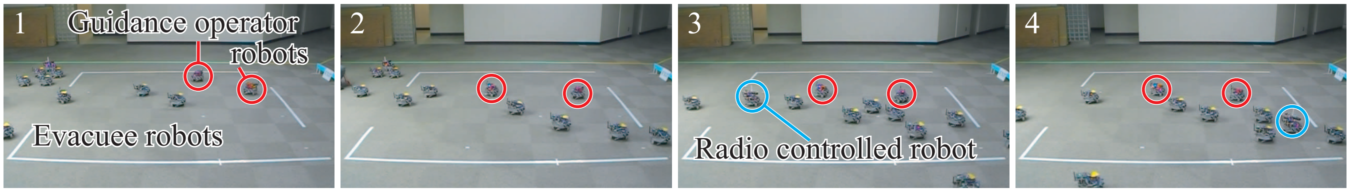

Fig. 12. Guidance experiment with 10 evacuees and 2 guidance operators

Same as the simulation in the previous section, we assume that the upper exit is unavailable and all the evacuees have to be shepherded to the lower exit. In figure 12-1, one evacuee goes to the upper exit, however, because of the action of the operator, it smoothly changes the direction and guided to the safe exit. This result shows that

- By using the proposed method, all the evacuees including the radio controlled evacuee are shepherded to the safe route, which shows the effectiveness of the proposed method.
- The operators are distributed at the same position as shown in figure 9, which means the obtained positions are optimized solutions.

We note that there are some robots out of the room (white line). These robots return to the entry after finishing the evacuation because of the small number of the robots. They have to be omitted. The attached movie shows the experimental result of the evacuation guidance.

VI. Conclusions

In this paper, we focus on the disaster reduction and proposed optimization method of position, indicating direction and number of operators for implicit evacuation guidance. The results are as follows:

1) Based on the evacuation route, the intention of the evacuee is modeled by vector field.
2) Based on the human characteristics, the evacuee behavior is modeled including interaction of individuals, affinity model and field of view.
3) The action of the operator is modeled by vector field considering indicating direction.
4) Based on the superposition of the vector fields, the optimization method of distribution and indicating direction of the operator is proposed. Because the proposed method is online method, it copes with the changing environment.
5) By using the autonomous mobile robots, the proposed method is evaluated in the quasi-human environment using a radio controlled robot by a human.

The proposed method uses local information of the guidance operators and does not require the supervisor with bird's-eye view, which means the proposed method utilize micro phenomenon spreading to the macro characteristic of the swarm. We can conclude that the proposed method is implicit strategy for large-scale swarm.

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