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ADAPTIVE FORMATION CONTROL FOR DISTRIBUTED AUTONOMOUS MOBILE ROBOT GROUPS

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ABSTRACT

We present *adaptive formation control for distributed autonomous mobile robot groups*, envisioning mobile robots being used in *crime deterrence*. Our mobile robot group has a task to prevent a trespasser from passing along a way in a surveillance area by a group formation. To control the formation, each robot has a formation vector. In particular, the formation is controllable by the vectors. The group encounters various ways and each way has its own width. Moreover, the number of the robots in the group is changed when some of them are broken. However, the group in our control method can make a specified formation to achieve the task, adapting to variations of such conditions. In other words, we prove an existence of a distributed control method that enables the adaptation of the formation. The validity of our method is verified by computer simulations.

I. INTRODUCTION

Anyone has seen cooperative behaviors of living things, e.g., predators form a group to capture prey. Here, we are imagining that multiple mobile robots cooperate with each other in order to achieve given tasks which can not be done by a single robot [1][2][3]. As a control manner for the multiple mobile robots, we adopt a distributed autonomous control manner. We can not imagine that all the robots are controlled by a supervisor in a conventional (centralized) control manner. This is because the supervisor can not control all the robots simultaneously and furthermore, it is well known that a robotic system with the supervisor fails as it merely fails. Hence, distributed autonomous control manners are needed to realize cooperative behaviors of the multiple mobile robots [1]. The control manners are restricted as: each mobile robot senses only its surrounding environment; each mobile robot determines only its behavior; and there is no supervisor. Since some tasks can not be done without a centralized control manner, it is important to show that a given task can be done by a distributed autonomous control manner.

We envision the mobile robots being used in *crime deterrence*. To detect unusual situations: trespasses, gas leakage and fire occurrence, cameras and sensors are arranged in a surveillance area. The mobile robots have already been used to detect such unusual situations [4][5][6]. We may consider not only detection but also remedies of such situations. As a remedy, we give the mobile robot group a task to prevent a trespasser from passing along a way in the surveillance area. Specifically, we imagine that the mobile robot group obstructs the way by its group formation.

This paper presents adaptive formation control for distributed autonomous mobile robot groups. Each mobile robot in our control method has its own coordinate system and it moves, measuring its relative positions from other robots, in order to make a group formation. The robot also moves toward a landmark when it is visible. The landmarks are arranged, in order for the group to be located at a specified place. To control the formation, each robot has a formation vector. In particular, the formation is controllable by the vectors. Although each robot updates its formation vector by itself and there is no supervisor, the group makes a specified formation at a specified place, e.g., the group makes an arc formation between two landmarks, in order to obstruct a way. A landmark is located near each side of the way. The group encounters various ways and each way has its own width. Moreover, the number of the robots is changed when some of them are broken. However, the group in our control method can achieve this task, adapting to variations of such conditions. In other words, we prove an existence of a distributed autonomous manner that enables the adaptation of the group formation. The validity of our method is verified by computer simulations.

II. MODEL OF MOBILE ROBOT AND ADAPTATION OF ROBOT GROUP FORMATION

A. Model of Mobile Robot

We consider (n) mobile robots and (m) landmarks on a plane, and we assume that each mobile robot is free to move on the plane. We label each robot R_i, $i = 1, 2, \cdots, n$, and we also label each landmark LM_j, $j = 1, 2, \cdots, m$. However, these labels are not intrinsic to this method. Each robot does not need to know its own, other robot labels and landmark labels. We also assume that each robot measures its relative positions from other robots and from the landmarks when they are visible to it. We express the coordinate system of R_i as Σ_i. To express all the robot positions on a common coordinate system, we define a static coordinate system, Σ_0. We also define a coordinate system, Σ_i^0, whose origin is common to that of Σ_0 and whose orientation is common to that of Σ_i, (see Fig.1). These coordinate systems (Σ_i^0 and Σ_0) are unknown to R_i. Each R_i knows only its own coordinate system, Σ_i.

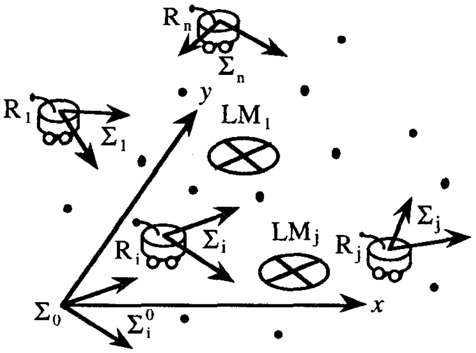

Fig.1 Mobile robots and landmarks

B. Adaptation of Robot Group Formation

Let us consider (n) mobile robots in a configuration which is called strongly connected, and we assume that the configuration is static, (see Fig.2). A mobile robot at the start of an arrow tries to keep a relative position from another robot at the end of the arrow, in order to make a group formation. We call these mobile robots a *mobile robot group*, and we imagine a task of the group as shown in Fig.2. The group makes an arc formation, in order to prevent a thief from passing along a way. Since, as we have assumed, each mobile robot senses only its local area and the way is wide enough, any robot can not sense both the sides of the way simultaneously. In other words, any robot can not sense how wide the way is. The group, of course, encounters various ways and each way has its own width. Moreover, the number of the robots in the group is changed when some of them are broken. Therefore, the group has to change its formation in order to obstruct the way, adapting to variations of the conditions: the width of the way and the number of the robots in the group, without knowing these conditions.

In order to inform the end robots, R_1 and R_7, of the positions in which they should be located, we put two landmarks, LM_1 and LM_2, (see Fig.2). R_1 senses and approaches to LM_1. R_7 senses and approaches to LM_2. Even if R_1 and R_7 arrive at the landmarks, how can we guarantee that the group makes an arc formation? How does the group make other formations? Each mobile robot in our control method has its own vector to control the group formation. In particular, the formation is controllable by the vectors. Moreover, the obstruction of the way is achieved by adjusting the vectors in a distributed autonomous manner.

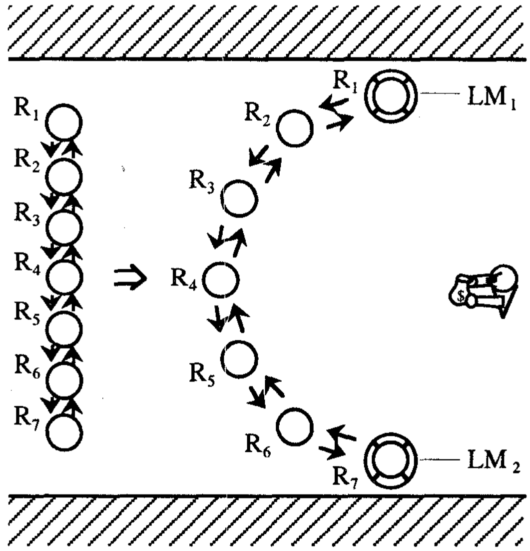

Fig.2 Obstruction of way by a mobile robot group

III. ROBOT CONTROL

A. Control Strategy

As we have assumed in Subsection II-A, (n) mobile robots form a strongly connected configuration. Hence, at least one arrow goes from a robot to another. We denote with L_i the set of the robots to which arrows go from R_i. Each R_i tries to keep its relative positions from the robots in L_i, in order to make a group formation. As we have described in Subsection II-B, we put the landmarks to inform the robots of the positions of the way sides. Since each robot can sense only its local area, some of the robots can sense the landmarks, while some of them can not. We denote with H the set of the robots that can sense the landmarks. The robot tries to arrive at the landmark which is nearest to itself. We denote with $LM_{j\in R_i}$ the landmark at which R_i tries to arrive. To obstruct the way by the group formation, we make a physical assumption that the dynamics of R_i is affected linearly by the relative position from $R_j \in L_i$. The dynamics is also affected linearly by the relative position from $LM_{j\in R_i}$. In addition, we assume that the formation is controlled by a *formation vector* that is available to R_i. Formally, we express the control strategy as Eq.(1):

$$\begin{pmatrix} \dot{\theta}^i_{xi} \\ \dot{\theta}^i_{yi} \end{pmatrix} = \sum_{j\in L_i} \tau_{ij} \begin{pmatrix} \theta^i_{xj} \\ \theta^i_{yj} \end{pmatrix} + \tau_i \begin{pmatrix} \theta^i_{xt_i} \\ \theta^i_{yt_i} \end{pmatrix} + \begin{pmatrix} d^i_{xi} \\ d^i_{yi} \end{pmatrix}, \quad (1)$$

$$\tau_i = \begin{cases} \tau, & i \in H \\ 0, & i \notin H \end{cases},$$

where $\left(\dot{\theta}^i_{xi}, \dot{\theta}^i_{yi}\right)^T$ is the velocity of R_i in the coordinate system, Σ^0_i, whose orientation is common to that of Σ_i and whose origin is common to that of Σ_0; $\left(\theta^i_{xj}, \theta^i_{yj}\right)^T$, $j \in L_i$, is the position of $R_j \in L_i$ in Σ_i, i.e., the relative position of $R_j \in L_i$ from R_i in Σ_i; $\left(\theta^i_{xt_i}, \theta^i_{yt_i}\right)^T$ is the position of $LM_{j \in R_i}$ in Σ_i, i.e., the relative position of $LM_{j \in R_i}$ from $R_i \in H$ in Σ_i; $\left(d^i_{xi}, d^i_{yi}\right)^T$ is the formation vector that is available to R_i; $\tau_{ij}(>0)$, $j \in L_i$, is the attraction coefficient of R_i to $R_j \in L_i$; τ_i is the attraction coefficient of $R_i \in H$ to $LM_{j \in R_i}$; and $\tau_i = \tau > 0$, $R_i \in H$, and $\tau_i = 0$, $R_i \notin H$. Physically, $\tau_{ij}\left(\theta^i_{xj}, \theta^i_{yj}\right)^T$ in the first term of Eq.(1) means that R_i is attracted to $R_j \in L_i$. The second term means that $R_i \in H$ is attracted to $LM_{j \in R_i}$. The third term means that R_i is pulled in the direction of $\left(d^i_{xi}, d^i_{yi}\right)^T$. Since, as we described here, $R_i \in H$ is attracted to both $LM_{j \in R_i}$ and $R_j \in L_i$, $R_i \in H$ can not arrive at $LM_{j \in R_i}$ solely by Eq.(1). Hence, $R_i \in H$ updates its formation vector, $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i \in H$, in order to arrive at $LM_{j \in R_i}$. Of course, each robot senses only its local area. Updating the formation vector has to be executed by $R_i \in H$, using only information in its local area. In other words, the formation vector has to be updated in a distributed autonomous manner.

B. Updating Formation Vector

Let us consider an updating manner of the formation vector to make $R_i \in H$ arrive at $LM_{j \in R_i}$. Here, we give a Lyapunov function as Eq.(2):

$$V = \frac{1}{2}\sum_{i \in H}\left\{\begin{pmatrix}\dot{\theta}^i_{xi}\\ \dot{\theta}^i_{yi}\end{pmatrix} - \tau_i\begin{pmatrix}\theta^i_{xt_i}\\ \theta^i_{yt_i}\end{pmatrix}\right\}^T \left\{\begin{pmatrix}\dot{\theta}^i_{xi}\\ \dot{\theta}^i_{yi}\end{pmatrix} - \tau_i\begin{pmatrix}\theta^i_{xt_i}\\ \theta^i_{yt_i}\end{pmatrix}\right\}. \quad (2)$$

To describe the physical meaning of Eq.(2), we transform all the vectors in Eq.(2) into vectors in the static coordinate system, Σ_0, as Eq.(3):

$$V = \frac{1}{2}\sum_{i \in H}\left[\begin{pmatrix}\dot{\theta}_{xi}\\ \dot{\theta}_{yi}\end{pmatrix} - \tau_i\left\{\begin{pmatrix}\theta_{xt_i}\\ \theta_{yt_i}\end{pmatrix} - \begin{pmatrix}\theta_{xi}\\ \theta_{yi}\end{pmatrix}\right\}\right]^T \left[\begin{pmatrix}\dot{\theta}_{xi}\\ \dot{\theta}_{yi}\end{pmatrix} - \tau_i\left\{\begin{pmatrix}\theta_{xt_i}\\ \theta_{yt_i}\end{pmatrix} - \begin{pmatrix}\theta_{xi}\\ \theta_{yi}\end{pmatrix}\right\}\right], \quad (3)$$

where $\left(\dot{\theta}_{xi}, \dot{\theta}_{yi}\right)^T$ is the velocity of $R_i \in H$ in Σ_0; $\left(\theta_{xt_i}, \theta_{yt_i}\right)^T$ is the position of $LM_{j \in R_i}$ in Σ_0; $\left(\theta_{xi}, \theta_{yi}\right)^T$ is the position of $R_i \in H$ in Σ_0. If $V = 0$ is satisfied, from Eq.(3), we derive Eq.(4):

$$\begin{pmatrix}\dot{\theta}_{xi}\\ \dot{\theta}_{yi}\end{pmatrix} = \tau_i\left\{\begin{pmatrix}\theta_{xt_i}\\ \theta_{yt_i}\end{pmatrix} - \begin{pmatrix}\theta_{xi}\\ \theta_{yi}\end{pmatrix}\right\}, \quad (4)$$

where $i \in H$. Eq.(4) means that $\left(\theta_{xi}, \theta_{yi}\right)^T$ converges to $\left(\theta_{xt_i}, \theta_{yt_i}\right)^T$, namely, $R_i \in H$ arrives at $LM_{j \in R_i}$. Hence, let us consider $\partial V / \partial\left(d^i_{xi}, d^i_{yi}\right)^T$ as Eq.(5):

$$\frac{\partial V}{\partial\left(d^i_{xi}, d^i_{yi}\right)^T} = \left\{\begin{pmatrix}\dot{\theta}^i_{xi}\\ \dot{\theta}^i_{yi}\end{pmatrix} - \tau_i\begin{pmatrix}\theta^i_{xt_i}\\ \theta^i_{yt_i}\end{pmatrix}\right\}^T \frac{\partial\left(\dot{\theta}^i_{xi}, \dot{\theta}^i_{yi}\right)^T}{\partial\left(d^i_{xi}, d^i_{yi}\right)^T}. \quad (5)$$

From Eq.(1), the partial differential of $\left(\dot{\theta}^i_{xi}, \dot{\theta}^i_{yi}\right)^T$ by $\left(d^i_{xi}, d^i_{yi}\right)^T$ is given as Eq.(6):

$$\frac{\partial\left(\dot{\theta}^i_{xi}, \dot{\theta}^i_{yi}\right)^T}{\partial\left(d^i_{xi}, d^i_{yi}\right)^T} = \begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}. \quad (6)$$

We give an updating manner for the formation vector as Eq.(7):

$$\begin{pmatrix}\dot{d}^i_{xi}\\ \dot{d}^i_{yi}\end{pmatrix} = -\left\{\begin{pmatrix}\dot{\theta}^i_{xi}\\ \dot{\theta}^i_{yi}\end{pmatrix} - \tau_i\begin{pmatrix}\theta^i_{xt_i}\\ \theta^i_{yt_i}\end{pmatrix}\right\}, \quad (7)$$

where $i \in H$. In this case, $\dot{V} < 0$ $(V \neq 0)$ is satisfied and V converges to zero. We can see that $R_i \in H$ can execute Eq.(7), using only information in Σ_i. In other words, $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i \in H$, can be updated in a distributed autonomous manner.

C. Stability Analysis

As we have described in Subsection III-B, using the updating manner of the formation vector shown in Eq.(7), $R_i \in H$ arrives at $LM_{j \in R_i}$. We have to consider where $R_i \notin H$ is located. We transform all the vectors in Eq.(1) into vectors in the static coordinate system, Σ_0, in order to analyze stability.

$$\begin{pmatrix}\dot{\theta}_{xi}\\ \dot{\theta}_{yi}\end{pmatrix} = \rho_i\begin{pmatrix}\dot{\theta}^i_{xi}\\ \dot{\theta}^i_{yi}\end{pmatrix} = \sum_{j \in L_i}\tau_{ij}\rho_i\begin{pmatrix}\theta^i_{xj}\\ \theta^i_{yj}\end{pmatrix} + \tau_i\rho_i\begin{pmatrix}\theta^i_{xt_i}\\ \theta^i_{yt_i}\end{pmatrix}$$

$$+\rho_i \begin{pmatrix} d_{xi}^i \\ d_{yi}^i \end{pmatrix} = \sum_{j \in \mathrm{L}_i} \tau_{ij} \left\{ \begin{pmatrix} \theta_{xj} \\ \theta_{yj} \end{pmatrix} - \begin{pmatrix} \theta_{xi} \\ \theta_{yi} \end{pmatrix} \right\}$$

$$+ \tau_i \left\{ \begin{pmatrix} \theta_{xt_i} \\ \theta_{yt_i} \end{pmatrix} - \begin{pmatrix} \theta_{xi} \\ \theta_{yi} \end{pmatrix} \right\} + \begin{pmatrix} d_{xi} \\ d_{yi} \end{pmatrix}, \tag{8}$$

$$\tau_i = \begin{cases} \tau, & i \in \mathrm{H} \\ 0, & i \notin \mathrm{H} \end{cases},$$

where ρ_i is a rotation matrix. We rewrite Eq.(8) as:

$$\begin{pmatrix} \dot{\theta}_x \\ \dot{\theta}_y \end{pmatrix} = \begin{pmatrix} B-\Delta & 0 \\ 0 & B-\Delta \end{pmatrix} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix} + \begin{pmatrix} \Delta\theta_{xt} \\ \Delta\theta_{yt} \end{pmatrix} + \begin{pmatrix} d_x \\ d_y \end{pmatrix}, \tag{9}$$

$$\theta_x = (\theta_{x1}, \theta_{x2}, \cdots, \theta_{xn})^T,\ \theta_y = (\theta_{y1}, \theta_{y2}, \cdots, \theta_{yn})^T,$$

$$\theta_{xt} = (\theta_{xt_1}, \theta_{xt_2}, \cdots, \theta_{xt_n})^T,\ \theta_{yt} = (\theta_{yt_1}, \theta_{yt_2}, \cdots, \theta_{yt_n})^T,$$

$$d_x = (d_{x1}, d_{x2}, \cdots, d_{xn})^T,\ d_y = (d_{y1}, d_{y2}, \cdots, d_{yn})^T,$$

$$\Delta = \mathrm{diag}(\tau_1, \tau_2, \cdots, \tau_n),$$

where B is a $n \times n$ matrix and its components are defined as: $b_{ij,i\neq j} = \tau_{ij\in \mathrm{L}_i} > 0$; $b_{ij,i\neq j} = \tau_{ij\notin \mathrm{L}_i} = 0$; and $b_{ii} = -\sum_{j=1,j\neq i}^{n} b_{ij}$. As we have defined in Subsection II-B, the mobile robot group has a strongly connected configuration. Hence, $b_{ii} < 0$, $i = 1, 2, \cdots, n$. Since the diagonal components of B are negative and the non-diagonal components are not negative, B is a *compartment matrix*. Moreover, $(B-\Delta)v_1 \leq 0$, $v_1 = (1, 1, \cdots, 1)^T$. Therefore, $(B-\Delta)$ is asymptotically stable. In Eq.(9), $|\Delta\theta_{xt}|$ and $|\Delta\theta_{yt}|$ are finite, because $(\theta_{xt_i}, \theta_{yt_i})^T$ is the position of $\mathrm{LM}_{j\in \mathrm{R}_i}$ in Σ_0. As we have described in Subsection III-B, using Eq.(7), V converges to zero. When $V = 0$ is satisfied, $(\dot{d}_{xi}^i, \dot{d}_{yi}^i)^T = 0$, $i \in \mathrm{H}$. In other words, $(d_{xi}^i, d_{yi}^i)^T$, $i \in \mathrm{H}$, converges and its norm is finite. We will design $(d_{xi}^i, d_{yi}^i)^T$, $i \notin \mathrm{H}$, in Subsection III-C, satisfying that its norm is also finite. In this case, θ_x and θ_y are stable. They are determined by $(d_{xi}^i, d_{yi}^i)^T$, $i \notin \mathrm{H}$, and the positions of the landmarks. Since $(B-\Delta)$ is asymptotically stable, the group formation is controllable by $(d_{xi}^i, d_{yi}^i)^T$, $i = 1, 2, \cdots, n$. Therefore, updating $(d_{xi}^i, d_{yi}^i)^T$, $i \in \mathrm{H}$, by Eq.(7), $\mathrm{R}_i \in \mathrm{H}$ can arrive at $\mathrm{LM}_{j\in \mathrm{R}_i}$, and the location of $\mathrm{R}_i \notin \mathrm{H}$ is determined by $(d_{xi}^i, d_{yi}^i)^T$, $i \notin \mathrm{H}$.

C. Determination of Formation Vector

We have already assumed that R_i determines its formation vector, $(d_{xi}^i, d_{yi}^i)^T$, in Σ_i. $\mathrm{R}_i \in \mathrm{H}$ updates $(d_{xi}^i, d_{yi}^i)^T$, $i \in \mathrm{H}$, by using Eq.(7). We also make an assumption that $\mathrm{R}_i \notin \mathrm{H}$ determines its formation vector, $(d_{xi}^i, d_{yi}^i)^T$, $i \notin \mathrm{H}$, solely according to its surrounding environment, e.g., according to the formation vector of $\mathrm{R}_j \in \mathrm{L}_i$ that is sensed by $\mathrm{R}_i \notin \mathrm{H}$. We give two examples of the determination of $(d_{xi}^i, d_{yi}^i)^T$, $i \notin \mathrm{H}$.

Eq.(10) means that $\mathrm{R}_i \notin \mathrm{H}$ updates $(d_{xi}^i, d_{yi}^i)^T$, $i \notin \mathrm{H}$, to make it converge to the average of the formation vectors among the robots in L_i.

$$\begin{pmatrix} \dot{d}_{xi}^i \\ \dot{d}_{yi}^i \end{pmatrix} = \sum_{j \in \mathrm{L}_i} \left\{ \begin{pmatrix} d_{xj}^i \\ d_{yj}^i \end{pmatrix} - \begin{pmatrix} d_{xi}^i \\ d_{yi}^i \end{pmatrix} \right\}, \tag{10}$$

where $i \notin \mathrm{H}$; and $(d_{xj}^i, d_{yj}^i)^T$ is the formation vector of $\mathrm{R}_j \in \mathrm{L}_i$ which is expressed in Σ_i. To execute Eq.(10), $\mathrm{R}_i \notin \mathrm{H}$ has to know $(d_{xj}^j, d_{yj}^j)^T$. It also has to know the relative orientation of Σ_j from Σ_i in order to transform $(d_{xj}^j, d_{yj}^j)^T$ to $(d_{xj}^i, d_{yj}^i)^T$. Since $\mathrm{R}_i \notin \mathrm{H}$ and $\mathrm{R}_j \in \mathrm{L}_i$ sense their relative positions of each other in our group configuration, (see Fig.2), they can calculate the relative orientation between Σ_i and Σ_j, informing their relative positions: one is sensed by $\mathrm{R}_i \notin \mathrm{H}$; and the other is sensed by $\mathrm{R}_j \in \mathrm{L}_i$. Hence, in the case of Eq.(10), we assume that $\mathrm{R}_j \in \mathrm{L}_i$ informs $\mathrm{R}_i \notin \mathrm{H}$ of $(d_{xj}^j, d_{yj}^j)^T$ and the relative position of $\mathrm{R}_i \notin \mathrm{H}$ from $\mathrm{R}_j \in \mathrm{L}_i$ which is sensed by $\mathrm{R}_j \in \mathrm{L}_i$ in Σ_j.

Fig.3 means that $\mathrm{R}_i \notin \mathrm{H}$ has $(d_{xi}^i, d_{yi}^i)^T$ whose orientation is that of $(d_{xj}^i, d_{yj}^i)^T$ rotated α in Σ_i and whose norm is $\beta\left|(d_{xj}^i, d_{yj}^i)^T\right|$. The formation vector, $(d_{xj}^i, d_{yj}^i)^T$, is $(d_{xj}^j, d_{yj}^j)^T$ transformed in Σ_i by $\mathrm{R}_i \notin \mathrm{H}$ which calculates the relative orientation of Σ_j from Σ_i, in the same manner as in the case of Eq.(10). $\mathrm{R}_j \in \mathrm{L}_i$, of course, informs $\mathrm{R}_i \notin \mathrm{H}$ of its formation vector, $(d_{xj}^j, d_{yj}^j)^T$.

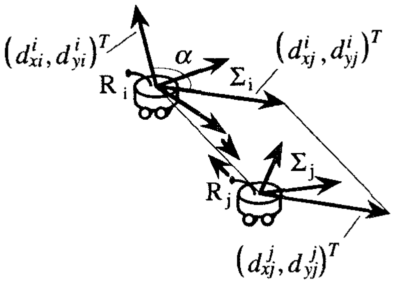

Fig.3 Determination of $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i \notin \mathrm{H}$

$\left(d^i_{xi}, d^i_{yi}\right)^T$, in the cases of Eqs.(7,10) and Fig.3, is independent of Σ_i. Hence, $\left(d^i_{xi}, d^i_{yi}\right)^T$ is invariant, even if R_i changes its orientation. In other words, the formation is invariant under the rotations of R_i. We can, of course, consider $\left(d^i_{xi}, d^i_{yi}\right)^T$ to depend on Σ_i. In such cases, the orientation of R_i will be one of formation control elements and it will be investigated in future work.

Thus, we are considering two mappings. One is S_i, the mapping from the surrounding environment of R_i to $\left(d^i_{xi}, d^i_{yi}\right)^T$. Specifically, Eq.(7) is $S_{i\in H}$, and Eq.(10) and Fig.3 are examples of $S_{i\notin H}$. The other is T, the mapping from the locations of $LM_{j\in R_i}$, $i \in \mathrm{H}$, and $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i \notin \mathrm{H}$, to the group formation. We can put LM_j anywhere and we can design various kinds of $S_{i\notin H}$. $R_i \in \mathrm{H}$, using Eq.(7), arrives at $LM_{j\in R_i}$ and the location of $R_i \notin \mathrm{H}$ is determined by $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i \notin \mathrm{H}$, which is given by $S_{i\notin H}$. However, no one can say that we can find out a suitable design of $S_{i\notin H}$ in any application, because $R_i \notin \mathrm{H}$ determines $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i \notin \mathrm{H}$, only according to its own surrounding environment. Hence, even though the formation is controllable by $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i = 1, 2, \cdots, n$, we can not say that any formation can be generated, as long as $R_i \notin \mathrm{H}$ determines $\left(d^i_{xi}, d^i_{yi}\right)^T$, $i \notin \mathrm{H}$, in Σ_i.

IV. SIMULATIONS

We consider the case in Fig.4. The group which consists of seven robots tries to make an arc formation between two landmarks: LM_1 and LM_2. We assume that only end robots in the group look for the landmarks. R_1 and R_7 are the ends in Fig.4. The robot in the group can recognize whether it is an end or not, because an end robot senses only one robot, while a non-end robot senses two robots, in order to make a group formation. We also make an assumption that R_1 can sense LM_1 and R_7 can sense LM_2. They update their formation vectors by using Eq.(7). Other robots, i.e., the non-end robots, determine their formation vectors as the following rules: (i) the non-end robots (which are the neighboring robots of the end robots), i.e., R_2 and R_6, determine their formation vectors as shown in Fig.3; and (ii) the non-end robots (which are not the neighboring robots of the end robots), i.e., R_3, R_4 and R_5, update their formation vectors by using Eq.(10). The rotating angle of the formation vector in the case of R_2 is α, while it in the case of R_6 is $-\alpha$, (see Fig.4). The landmark has the sign of the angle. LM_1 has (+) and LM_2 has (−). The plus sign, (+), is transmitted from LM_1 to R_2 through R_1. The minus sign, (−), is transmitted from LM_2 to R_6 through R_7. The attraction coefficient of R_i to R_j is given as: $\tau_{ij} = \tau_{ji} = 20.0$, $j = i+1$, $i = 1, 2, \cdots, 6$. The other parameters are given as: $\tau = 5.0$, $\alpha = 2\pi/3$ [rad] and $\beta = 0.5$. Simulations are executed by the Runge-Kutta-Gill method. The sampling time is 0.001[sec].

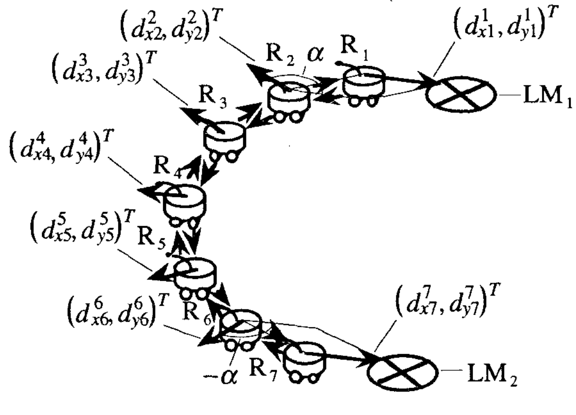

Fig.4 A mobile robot group

Fig.5 shows a simulation result. LM_1 is located in $(8.0, 9.0)^T$ and LM_2 is located in $(8.0, 1.0)^T$. At the beginning, all the robots are located on the line: $x = 2.0$ at an interval of 1.0. The initial values of the formation vectors are given as: $\left(d_{x1}, d_{y1}\right)^T\Big|_{t=0} = (0.0, 20.0)^T$; $\left(d_{x7}, d_{y7}\right)^T\Big|_{t=0} = (0.0, -20.0)^T$; $\left(d_{xi}, d_{yi}\right)^T\Big|_{t=0} = (0.0, 0.0)^T$, $i = 3, 4, 5$; and $\left(d_{xi}, d_{yi}\right)^T\Big|_{t=0}$, $i = 2, 6$, is determined as shown in Fig.4. The end robot, R_1 (which senses LM_1) is attracted and moves toward LM_1 by the second term in Eq.(1). Moreover, R_1 arrives at LM_1, updating its formation vector by using Eq.(7). Similarly, R_7

arrives at LM_2. We can see that the group makes an arc formation between LM_1 and LM_2.

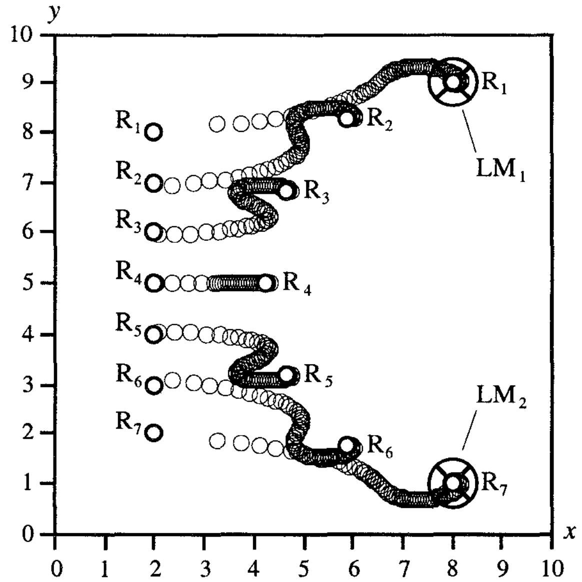

Fig.5 Simulation result

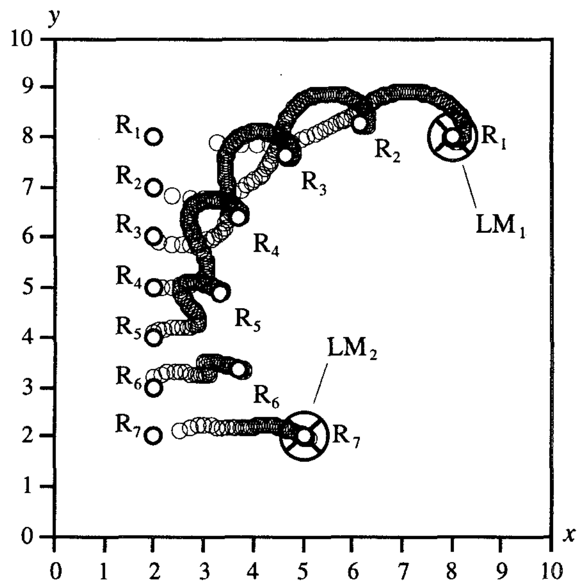

Fig.6 Simulation result

Fig.6 shows a simulation result of another case. The locations of the landmarks are changed, while other conditions remain the same as in Fig.5. LM_1 is located in $(8.0, 8.0)^T$ and LM_2 is located in $(5.0, 2.0)^T$. In this case, R_1 and R_7 also arrives at LM_1 and LM_2 respectively, and the group makes an arc formation. This formation has a similar figure of the formation in Fig.5, while its size is smaller. This is because the group formation is linearly controlled by the formation vectors. We can see that the mobile robot group in our control method adapts to the variation of the distance between the landmarks and it achieves its task.

V. CONCLUSIONS

This paper has presented *adaptive formation control for distributed autonomous mobile robot groups*. The mobile robot group has a task to obstruct a way in a surveillance area by a group formation. Each robot in our control method has its own coordinate system and it senses only its local area. To control the formation, the robot has a formation vector. In particular, the formation is controllable by the vectors. Although each robot is localized and there is no supervisor, the group can achieve the task, adapting to variations of the conditions: the width of the way and the number of the robots in the group. In other words, we have proven an existence of a distributed control manner that enables the adaptation of the group formation. The validity of our control method has been verified by the computer simulations.

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