Distributed and Autonomous Control Method for Generating Shape of Multiple Mobile Robot Group

Hiroaki YAMAGUCHI and Tamio ARAI

The Department of Precision Machinery Engineering,
The Faculty of Engineering,
The University of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo 113, Japan
E-mail: yamaguch@prince.pe.u-tokyo.ac.jp

Abstract

This paper proposes a distributed and autonomous control method for generating the shape of a group that consists of multiple mobile robots. This control method is called Linear Autonomous System ("LAS"). With LAS, Controllability of Group Shape can be defined. This is because a decision of a shape of the group corresponds to designing a potential field that is spread on a space of relative distance between mobile robots. Since each mobile robot has parameter for designing the spread potential field, a shape of the group can be adapted to various situations by means of changing the parameters with respect to state of environment, for example, position of wall, a velocity of an obstacle and so on. Effectiveness of this control method is verified by a computer simulation. It means that a mobile robot is captured by a group that consists of multiple mobile robots.

Keywords: distributed and autonomous system, group, multiple mobile robots, Linear Autonomous System, Controllability of Group Shape

1. Introduction

In the natural world, living things achieve advantageous functions by making groups. For example, fish advance a rate of escaping from enemies by means of schooling. This is because an enemy can not decide which one to choose as a target among a fish school [1]. There are many other examples that show advantageous functions of groups. Recently, many researchers analyzed how group functions are generated from an engineering point of view.

In the field of robotic system, actualization of a function of a group that consists of multiple mobile robots was discussed. Beni pointed out important items for actualization of Distributed Robotic Systems("DRS") [2]. Wang proposed a distributed algorithm for establishment of a globally consistent order in a DRS [3]. Hara analyzed an effect of the size of a mobile robot group on an ability to search a target in a given space [4]. In these studies, there is no supervisor that controls the group of mobile robots. Each mobile robot decides its behavior with respect to behaviors of only neighboring mobile robots for generating a function of the group. Namely, a supervisor of the group does not exist and there are only interactions between mobile robots. Therefore, it is difficult to design decision manners of behaviors of mobile robots for generating a desired function of the group, i.e., a desired behavior of the group. This concerns with a relationship between behaviors of mobile robots and a behavior of the group. The relationship is important for designing a multiple mobile robot system.

Generation of a function of a group that consists of agents, for example, mobile robots and so on, was analyzed in another field. It is the field of Artificial Life. An important concept of Artificial Life is emergence of a function of the group. Emergence means that a function of the group can be generated only by interactions between agents. Therefore, it is considered that emergence of a function is important for designing a multiple mobile robot system. In the field of Artificial life, distributed problem solving was discussed [5][6][7]. It means that a task is completed by a function that emerges out of the group. Deneubourg discussed rules that govern behaviors of agents to produce a desired artifact [5]. Colorni solved the traveling salesman problem with many artificial ants using pheromone in a computer simulation [6]. Goss proposed a method to gather many targets distributed on a plane with the group [7]. From these studies, the following question occurs.

What kinds of agent behaviors are needed for emergence of a desired function of the group?

The question was also pointed out in [5]. It concerns with a relationship between behaviors of agents and a behavior of the group. However, there are few intentions to formalize the relationship on generating a function of the group.

This paper discusses the relationship between a mobile robot behavior and a generated shape of the group. A shape of the group has been regarded as one of important functions. For example, a line segment shape of the group can be utilized as a fence. Previously, generation of a shape of the group was discussed [8][9]. Sugihara and Suzuki proposed a method for generating a circle, a polygon and a line segment of the group in order to build a barricade or to surround a given object [8]. Gage expressed that a shape of the group achieves various functions, for example, a blanket, a barrier and a sweep

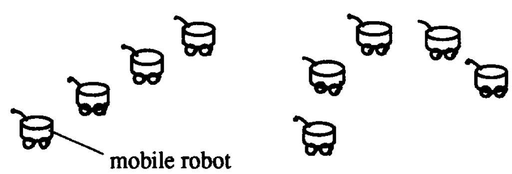
[9]. In these studies, a generated shape of the group depends on an initial distribution of mobile robots. The dependence is a hindrance for generation of a desired group shape. In this paper, since a decision of a shape of the group is attributed to designing a potential field that is spread on a space of relative distances between mobile robots, the shape does not depend on the initial distribution. With the potential field, Controllability of Group Shape can be defined. Since each mobile robot has a parameter for designing the potential field, a shape of the group can be adapted to various situations by means of changing the parameters with respect to a state of environment, for example, position of a wall, a velocity of an obstacle and so on. Effectiveness of the proposed method is verified by a computer simulation. It means that a mobile robot is captured by a group that consists of multiple mobile robots.

2. Interactions between individuals for generating a shape

In this study, each individual interacts with other individuals for generating a shape. In this chapter, interactions between individuals are defined. Furthermore, the crowd is defined as a group with the interactions.

2.1 Individual

In the natural world, living things crowd and cooperate with each other for achievement of the purposes. For example, lions cooperate with each other for advancing a rate of capturing a prey. In this study, mobile robots crowd and generate a shape cooperatively, for example, a line segment or an arc (see Fig.1). Namely, a mobile robot plays a role of an individual in a crowd whose shape is utilized as a function. Therefore, a mobile robot is called "individual" from here on.



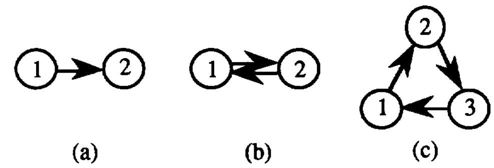
(a) Line segment shape of mobile robots

(b) Arc shape of mobile robots

Fig.1 Examples of a shape of a crowd that consists of mobile robots

2.2 Interactions between individuals

Since a shape is generated by interactions between individuals, the interactions are described in this section. In this study, each individual decides its behavior with respect to behaviors of neighboring individuals for generating a shape. Decisions of individual behaviors are symbolized by arrows (see Fig.2).



○ : individual

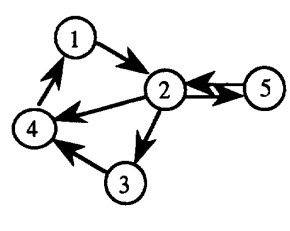
Fig.2 Expression of decisions of individual behaviors with arrows

Fig.2(a) means that individual 1 decides its behavior with respect to a behavior of individual 2. Fig.2(b) means that individual 1 and 2 decide their behaviors with respect to behaviors of each other. In Fig.2(c), individual 1 and 3 influence behavior of each other through individual 2, because individual 1 decides its behavior with respect to a behavior of individual 2 and individual 2 decides its behavior with respect to a behavior of individual 3 and furthermore, individual 3 decides its behavior with respect to a behavior of individual 1. In this paper, it is called "direct interaction" that two individuals influence their behaviors of each other in Fig.2(b). And it is called "indirect interaction" that two individuals influence their behaviors of each other through other individuals like Fig.2(c). Fig.2(a) does not mean an interaction. In the next section, a crowd of individuals is defined as a group with the interactions.

2.3 Definition of group

The definition of a group is "When direct or indirect interactions exist between two individuals that are selected arbitrarily among a crowd of individuals, the crowd is regarded as a group."

When a group is expressed by arrows that are used in the previous section, the expression of a group is regarded as "a strongly connected graph" from the graph theory point of view. An example of expression of a group is shown as follows.



○: individual

Fig.3 An example of expression of a group

In Fig.3, there are direct or indirect interactions between two arbitrary individuals. For example, there is an indirect interaction between individual 1 and 2, because individual 1 and 2 influence behaviors of each other through individual 4.

From the definition of a group, it is derived that individuals influence behaviors of each other directly or indirectly in a group. Generally, for generating a shape of a group, a supervisor is useful. In this case, a supervisor receives information about individual behaviors and individuals receive supervisor's commands that are decided with respect to the information. Namely, individuals influence behaviors of each other through a supervisor. Of course there is difference between a group with a supervisor and a group without a supervisor. However, in the proposed method, a shape of a group can be generated, though there is no supervisor and there are only interactions between individuals. Therefore, there is no fear of trouble which is caused by damage of a supervisor. The next chapter presents a decision manner of individual behaviors for generating a shape of a group.

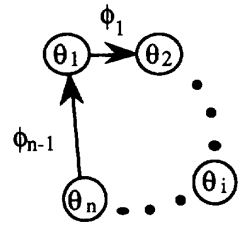
3. Decision manner of individual behavior for generating shape of group

In this study, each individual decides its behavior with respect to behaviors of neighboring individuals for generating a shape of a group. This chapter describes how an individual behavior is decided.

3.1 Representation of individual behavior

In this paper, an individual behavior is defined as an individual position on a plane. The plane has a Cartesian coordinate that has two axes, the x axis and the y axis. An individual position is represented by a vector that has two elements, the x value and the y value. In the presented method, the x value and the y value of an individual don't correlate with each other and decision manners of the x value and the y value are the same on generating a shape of a group. Therefore, each value is called "state value" and one of two values is discussed from here on. Representation of state values is shown as follows.

A state value of an individual is represented by the variable θ_i and a difference of state values between two individuals is represented by the variable ϕ_j. When there are n individuals in a group, state values of all individuals are represented by the vector θ whose dimension is n and differences of state values are represented by the vector ϕ whose dimension is n-1 and whose elements are linear independent. A representation of state values and differences of state values is shown in Fig.4. In Fig.4, an arrow expresses that an individual decides its state value with respect to a state value of another individual.



$\phi_1 = \theta_2 - \theta_1$

$\phi_{n-1} = \theta_1 - \theta_n$

$\theta = (\theta_1, \theta_2, \cdots, \theta_n)^t$

$\phi = (\phi_1, \phi_2, \cdots, \phi_{n-1})^t$

θ_i : state value of individual i

ϕ_j : difference of state values between two individuals

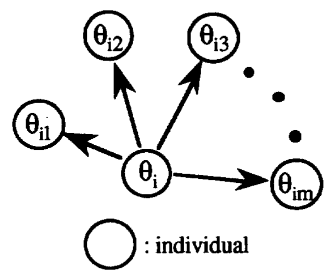
Fig.4 A representation of state values and differences of state values between individuals

3.2 Decision manner of individual behavior

Each individual decides its state value with respect to state values of other neighboring individuals with the following equation autonomously. The equation (1) is named Linear Autonomous System ("LAS") in this paper.

$$\frac{d\theta_i}{dt} = \sum_{k \in L_i} \tau_i (\theta_k - \theta_i) + d_i, \qquad (1)$$

where τ_i is a time constant that influences a settling time of state values, d_i is a variable for changing a group shape and L_i is a set of individuals to that arrows are drawn from individual i, i.e., L_i is a set of individuals that influence a state value of individual i directly. An example of L_i is shown as follows.



$(\theta_{i1}, \theta_{i2}, \cdots, \theta_{im}) = L_i$

Fig.5 An example of L_i

The equation (1) means that each individual decides its state value with utilization of differences of state values between itself and other neighboring individuals.

The next section discusses a group shape that is generated by individual behaviors that are decided by the equation (1).

3.3 Group shape generated by individual behavior

This section analyzes a relationship between a group shape and individual behaviors that are decided by the equation (1). An expression manner of a group shape is introduced for the analysis. Since an individual behavior is defined as an individual position and it is represented by the variable θ_i with respect to an axis, a relative distance between two individuals is represented by the variable ϕ_j with respect to the axis. Therefore, a group shape is expressed as a point that is located on a relative distance space with respect to each axes, the x axis and the y axis. An expression of a group shape is shown as follows.

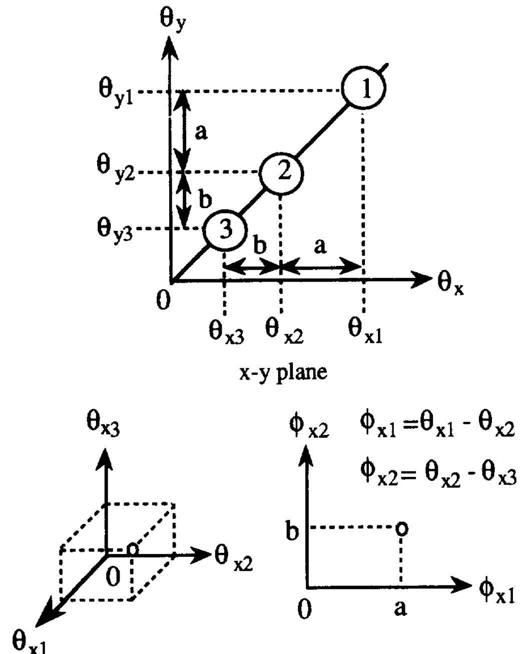


Fig.6 An expression of a group shape

A group has a line segment in Fig.6. The group shape is expressed as a point on a relative distance space with respect to the x axis in Fig.6.

A relationship between a group shape and individual behaviors is analyzed with the expression manner of a group shape as follows. When one of two individuals decides its state value with respect to a state value of the other, the other always decides its state value with respect to a state value of one. Namely, when there is an arrow between two individuals, there is always another arrow that has inverse direction between the two individuals (see Fig.2(b)). In this case, a potential field is spread on a relative distance space utilizing the equation (1) for decision of individual behaviors. The spread potential field has a quadratic curved shape regardless of the number of individuals in a group (see [10]). And furthermore, the time differential of the vector ϕ is represented by the following equation with a spread potential field V (see [10]).

$$\frac{d\phi}{dt} = -\mathrm{grad}V = g(\phi), \qquad (2)$$

where a spread potential field V is a function of only vector ϕ (see [10]). An example of a spread field V is shown as follows.

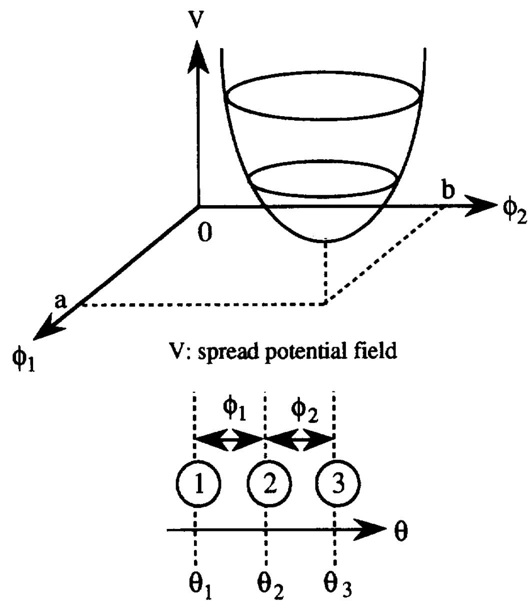


Fig.7 An example of a spread potential field

The equation (2) means that a group shape converges into the shape that is expressed as the point that is located on one of local minimums of a spread potential field V. Since a spread potential field V has a quadratic curved shape, i.e., it has no local minimum and has a global minimum on the relative distance space, a generated group shape always converges into the shape that is located on the global minimum. Therefore, a generated group shape is independent of an initial distribution of individuals. Consequently, a decision of a group shape is attributed to designing a spread potential field V. In the utilization of the equation (1) for generating a group shape, a relationship between a group shape and individual behaviors is clear. The next section presents Controllability of Group Shape.

3.4 Controllability of Group Shape

The previous section shows that a decision of a group shape is attributed to designing a spread potential field V. This section shows that a group shape can be controlled by changing the variable d_i that is used in the equation (1).

The vector representation of the equation (1) is shown as follows.

$$\frac{d\theta}{dt}=B\theta+d, \qquad (3)$$

where the vector θ represents state values, B is a $n\times n$ matrix, the variable d_i is an element of the vector d. The following equation is an example of the equation (3) that is used for the group shown in Fig.7.

$$\frac{d\theta}{dt}=\begin{pmatrix} -\tau_1 & \tau_1 & 0 \\ \tau_2 & -2\tau_2 & \tau_2 \\ 0 & \tau_3 & -\tau_3 \end{pmatrix}\theta+d.$$

And furthermore, the following vector Φ is introduced.

$$\Phi=F\theta, \qquad (4)$$

$$\Phi=(\phi_1,\phi_2,\cdots,\phi_{n-1},\hat{\phi})^t,\ \hat{\phi}=\theta_1+\theta_2+\cdots+\theta_n,$$

$$F=\begin{pmatrix} 1 & & 0 & -1 \\ & 1 & & -1 \\ & & \cdot & \cdot \\ 0 & & 1 & -1 \\ 1 & 1 & \cdot\ \cdot & 1 \end{pmatrix},$$

where F is a regular matrix, ϕ_i $(i=1,2,\cdots,n-1)$ and $\hat{\phi}$ are linear independent. Time differential of Φ is derived from the equation (3) and (4) as follows.

$$\frac{d\Phi}{dt}=FBF^{-1}\Phi+Fd, \qquad (5)$$

The equation (2) means that a time differential of ϕ is a function of only ϕ, i.e., it is independent of $\hat{\phi}$. And a time differential of $\hat{\phi}$ is independent of $\hat{\phi}$, because $\hat{\phi}$ is a summation of θ_i whose time differential is a function of only ϕ that is independent of $\hat{\phi}$ (see equation (1),(2)). Therefore, the nth column of FBF^{-1} is zero in the equation (5). The equation (5) is rewritten as the following equation.

$$\frac{d\Phi}{dt}=\begin{pmatrix} A & 0 \\ a & 0 \end{pmatrix}\Phi+Fd, \qquad (6)$$

where A is a $n-1\times n-1$ matrix that is derived by removal of nth line and nth column of FBF^{-1}. The following equation (7) is derived from the equation (6).

$$\frac{d\phi}{dt}=A\phi+Pd, \qquad (7)$$

where P is a $n-1\times n$ matrix that is derived by removal of nth line of F.

With the equation (7), Controllability of Group Shape is shown from here on. For clarification of a stability of ϕ, eigenvalues of A are analyzed. A characteristic equation of FBF^{-1} is derived from the equation (5) and (6) as follows.

$$\det(sI-FBF^{-1})=s\det(sI-A)=0, \qquad (8)$$

where s is a complex number, I is unit matrix. And furthermore, the equation (8) is rewritten as follows.

$$\det(sI-FBF^{-1})=\det(sI-B)=0. \qquad (9)$$

The equation (8) and (9) mean that all of eigenvalues of A correspond to eigenvalues of B except one eigenvalue that is located on the origin of the complex plane. There are the following two theorems that concern with eigenvalues of B as follows.

(Theorem 1)" Eigenvalues of B are located on the left-half complex plane that does not contain the imaginary axis but the origin regardless of the number of individuals in a group."

Theorem 1 is shown by Gerschgorin's theorem.

(Theorem 2)" B has only one eigenvalue that is located on the origin of the complex plane."

Theorem 2 is shown by Perron-Furobenius theorem.

It is derived from theorem 1 and 2 that real parts of all eigenvalues of A are lower than zero, i.e., A is an asymptotically stable matrix. Therefore, ϕ converges a vector that depends on a vector Pd (see the equation (7)).

It is shown that a group shape is controllable with changing a vector d as follows. A desired group shape is represented by ϕ_d and furthermore, a deviation of a group shape from a desired group shape is represented by $\tilde{\phi}=\phi-\phi_d$ from here on. The equation (7) thereby is rewritten as follows.

$$\frac{d\tilde{\phi}}{dt}=A\tilde{\phi}+A\phi_d+Pd. \qquad (10)$$

When the following equation (11) is satisfied, the equation (10) is rewritten as the equation (12).

$$A\phi_d+Pd=0. \qquad (11)$$

$$\frac{d\tilde{\phi}}{dt}=A\tilde{\phi}, \qquad (12)$$

where A is an asymptotically stable matrix, $\tilde{\phi}$ therefore converges into zero, i.e., it is achieved that a group shape converges into a desired group shape. Whether a group shape converges into a desired group shape depends on a satisfaction of the equation (11). It is shown as follows that the equation (11) can be satisfaction with changing a vector d that is used in the equation (3). The first term of the equation (11), $A\phi_d$, is rewritten as $PBF^{-1}(\phi_d^t,\hat{\phi})^t$ (see the equation (5),(6),(7)). Both the first term and the second term of the equation (11) therefore are images of a liner transform of P. A condition for a satisfaction of the equation (11) is derived as follows.

$$BF^{-1}(\phi_d^t,\hat{\phi})^t+d=0, \qquad (13)$$

Since d is a vector whose elements are changeable, equation (11) can be satisfied by changing the vector d. Consequently, the group shape can be controlled. Changing the vector d corresponds to a transfer of a spread potential field on a relative distance space. An example of a transfer of a spread potential field is shown as follows.

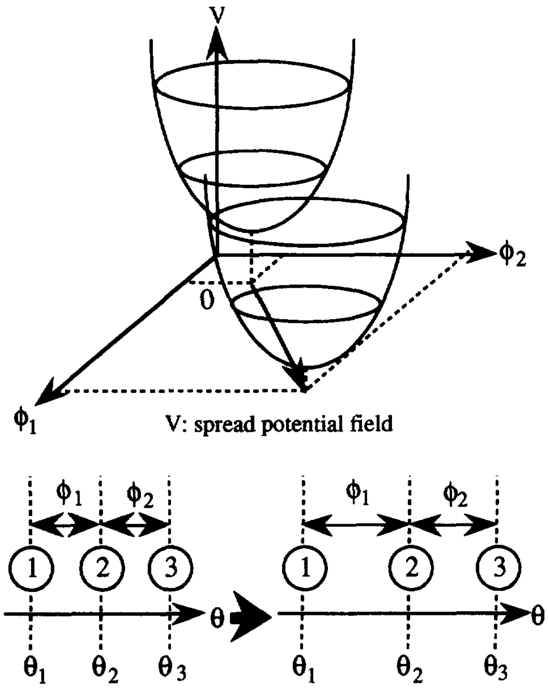


Fig.8 An example of a transfer of a spread potential field with changing a vector d

This section shows Controllability of Group Shape ("CGS") on Linear Autonomous System. The next chapter shows effectiveness of utilization of CGS with a computer simulation.

4. Computer simulation

This chapter shows effectiveness of utilization of the proposed control method with a computer simulation. A computer simulation implemented in this chapter is a Japanese children's game. It is called "Tetunagi-oni". The game means that a thief is captured by a group that consists of polices.

4.1 Outline of computer simulation

"Tetunagi-oni" is the following game. A number of polices link up each other with hands to generate a group that has a line linkage and the group pursues a thief and furthermore, the group captures it (see Fig.9). In this game, the group encloses a thief with utilization of its line shape and furthermore, the group presses the thief close with shrinking the size of the group. Enclosing a thief and pressing it close are achieved by utilization of the proposed control method. In the next section, a concrete manner for capturing a thief is presented.

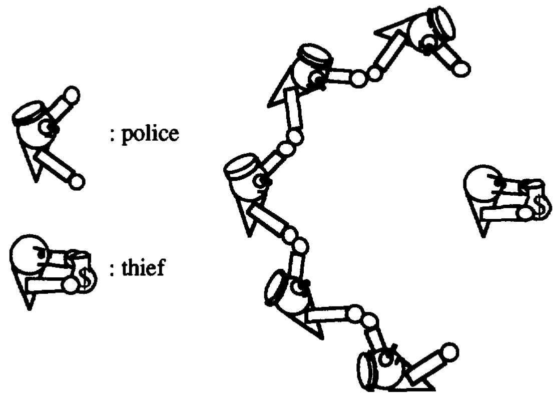


Fig.9 "Tetunagi-oni" game

4.2 Control manner of group shape for "Tetunagi-oni"

Preconditions are given as follows. An individual has only two virtual hands, the right hand and the left hand, to link up another individual and a linkage is allowed only with the right hand and the left hand between two individuals (see Fig.10(a)). A linkage means that there is a direct interaction between two individuals (see Fig.10(a)). And furthermore, several individuals are linked up each other for generation of line linkage in advance (see Fig.10(b)). A distributed and autonomous algorithm is utilized for generation of a line linkage. Since the algorithm is heuristic, explanation of the algorithm is omitted in this paper. In these preconditions, a thief is captured with utilization of the proposed control method.

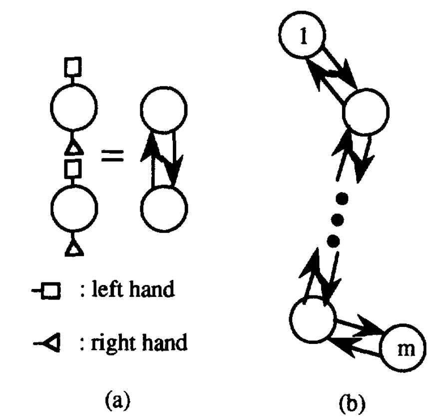


Fig.10 A linkage between two individuals and a group that has a line linkage

There are two individuals whose one hand is free in a group that has a line linkage. Individual 1 and m correspond to these two individuals in Fig.10(b). For generating an arc shape of a group, individual 1 whose left hand is free has two variables, d_{x1} and d_{y1}. Each variable corresponds to d_1 that is used in the equation (1) for determination of θ_{x1} and θ_{y1} respectively. A determination manner of d_{x1} and d_{y1} is represented as follows. A vector D_1 is utilized for determination of d_{x1} and d_{y1}. The vector D_1 whose two elements correspond to $-d_{x1}$ and $-d_{y1}$ respectively points to a direction. The direction is turned clockwise ninety degrees from a line that is drawn from individual 1 to a thief (see Fig.11). Similarly, individual m whose right hand is free has the vector D_m that points to a direction. The direction is turned counter-clockwise ninety degrees from a line that is drawn from individual m to a thief (see Fig.11). The other individuals don't have such kind of the vector. A vector norm of D_1 is equal to one of D_m. In this case, an arc shape is generated. The arc shape is utilized for enclosing a thief.

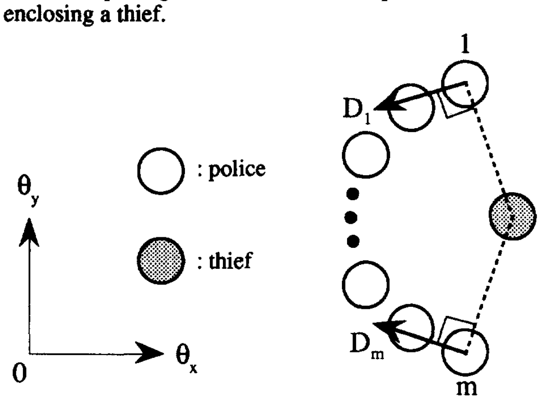


Fig.11 A group that has an arc shape

For pursuing a thief and pressing it close, a term is added to the equation (3) as the following equation.

$$\frac{d\theta}{dt}=B\theta+d+\begin{pmatrix}\tau(\theta_t-\theta_1)\\ \tau(\theta_t-\theta_2)\\ \cdot\\ \tau(\theta_t-\theta_m)\end{pmatrix}, \quad (14)$$

θ_t : coordinate of a thief,

τ : positive constant,

where the third term means that all of individuals move to a thief. When the third term is added to the equation (3), two questions occur. One question is whether stability of θ is guaranteed. The other question is whether Controllability of Group Shape is guaranteed. It is shown as follows that both the stability and Controllability of Group Shape are guaranteed. The equation (14) is rewritten as follows.

$$\frac{d\theta}{dt}=(B-\tau I)\theta+d+\tau\theta_t v_1, \quad (15)$$

$$v_1=(1,1,\cdots,1)^T,$$

where the matrix $B-\tau I$ is asymptotically stable. It is shown with Gerschgorin's theorem. Therefore, θ is stable. In this case, the relative distances with respect to x axis and y axis between mobile robots and a thief are derived from the equation (15) as follows.

$$\frac{d\tilde{\theta}}{dt}=(B-\tau I)\tilde{\theta}+d-\dot{\theta}_t v_1, \quad (16)$$

$$\tilde{\theta}=\theta-\theta_t v_1.$$

And furthermore, Controllability of Group Shape is analyzed as follows. When the vector Φ is utilized for the analysis, the dynamics of ϕ is derived as the following equation.

$$\frac{d\phi}{dt}=(A-\tau I)\phi+Pd, \quad (17)$$

where the matrix $A-\tau I$ is asymptotically stable. It is shown with Gerschgorin's theorem. Therefore, Controllability of Group Shape is guaranteed, though the dynamics of θ is the equation (14). Of course there is difference between the equation (7) and (17). However, when τ is sufficiently small compared with τ_i, the arc shape that is expressed with the equation (7) is almost same as one which is expressed with the equation (17).

With the equation (16) and (17), the position of the group from a target and the shape of the group can be calculated. Thereby, it is shown that the proposed determination manner of d_{x1}, d_{y1} and d_{xm}, d_{ym} is effective in capture of a thief. The effectiveness of the manner is verified with the following simulation result.

In the simulation, Runge-Kutta-Gill method is utilized. The sampling time is 0.001 [sec]. Parameters are decided as follows. $\tau_i=5.0$ $(i=1, 2, \cdots, 8)$, each norm of D_1 and D_8 is 4.0, $\tau = 5.0$. The simulation result is shown in Fig.12. The target stays on the position whose coordinate is (18.0, 0.0). In the initial situation, the group has a straight line shape. In this situation, the group begins capture of a thief. Directly after the beginning of the capture, since the group is far from a target, the vector D_1 and D_8 face each other. Therefore, the group has an almost straight line shape. However, when the group approaches to a target, it takes a arc shape and capture of a thief is achieved. Consequently, the effectiveness of the proposed method is verified by this computer simulation.

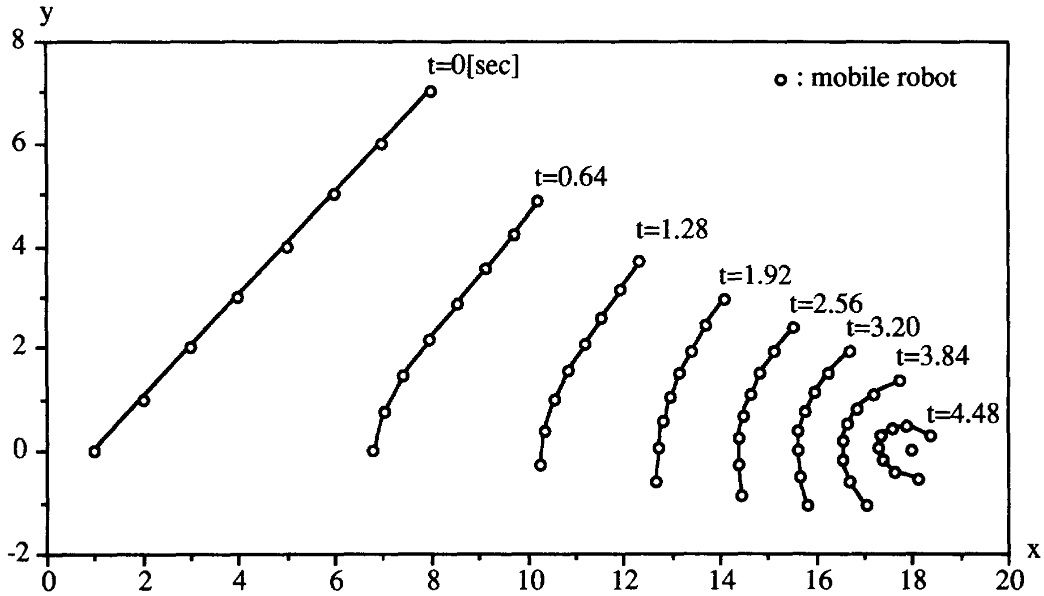


Fig.12 Simulation results of "Tetunagi-oni"

5. Conclusion

This paper proposes a distributed and autonomous control method for generating a shape of a group that consists of multiple mobile robots. In the proposed control method, a decision of a shape of the group is attributed to designing a potential field that is spread on a space of relative distance between mobile robots. With the potential field, Controllability of Group Shape can be defined. Since each mobile robot has parameter for designing the spread potential field, a shape of the group can be adapted to various situations by means of changing the parameters with respect to state of environment, for example, position of wall, a velocity of an obstacle and so on. Effectiveness of this control method is verified by a computer simulation.

Reference

[1]Brain L. Pattridge, " The Structure and Function of Fish Schools", Scientific American, June, pp.90-99(1982)

[2]G. Beni and J. Wang, "Theoretical Problems for the Realization of Distributed Robotic Systems", Proceedings of the IEEE International Conference on Robotics and Automation, pp.1914-1920(1991)

[3]J. Wang, "Establish A Globally Consistent Order of Discrete Events in Distributed Robotic Systems", Proceedings of the IEEE International Conference on Robotics and Automation, pp.853-858(1993)

[4]F. Hara and S. Ichikawa, "Effects of Population Size in Multiple-Robots Cooperative Behaviors", Proceedings of International Symposium on Distributed Autonomous Robotic Systems, Wako, Saitama, Japan-Sep.21-22, pp.3-9(1992)

[5]J. L. Deneubourg, G. Theraulaz and R. Beckers, "Swarm-Made Architectures", Toward a Practice of Autonomous Systems Proceedings of the First European Conference on Artificial Life, MIT Press, pp.123-133(1992)

[6]A. Colorni, M. Dorigo and V. Maniezzo, "Distributed Optimization By Ant Colonies", Toward a Practice of Autonomous Systems Proceedings of the First European Conference on Artificial Life, MIT Press, pp.134-142(1992)

[7]S. Goss, J. L. Deneubourg, "Harvesting By A Group of Robots", Toward a Practice of Autonomous Systems Proceedings of the First European Conference on Artificial Life, MIT Press, pp.195-204(1992)

[8]K. Sugiura and I. Suzuki, "Distributed Motion Coordination of Mutiple Mobile Robots", Proceedings of the 5th IEEE International Symposium on Intelligent Control, pp.138-143(1990)

[9]D. W. Gage, "COMMAND CONTROL FOR MANY-ROBOT SYSTEMS", Unmanned Systems Magazine, Vol.10, No.4, pp.28-34(1992)

[10] H. Yuasa and M. Ito, "A theory on structures of decentralized autonomous systems", Trans. Soc. Instrum. Control Engin.(SICE in Japanese), Vol. 25, pp.1355-1362(1989)