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Flexible and Scalable Formation for Swarm Systems

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Abstract

This paper presents a self-organizing scheme for multi-agent swarm systems based on coupled nonlinear oscillators (CNOs). In this scheme, unicycle robots self-organize to flock and arrange group formation through attractive and repulsive forces among themselves. The main result is the maintenance of flexible and scalable formation. It is also shown how localized distributed controls are utilized throughout group behaviors such as formation and migration. In the paper, the proposed formation ensures safe separation and good cohesion performance among the robots. Several examples show that the proposed method for group formation performs the group behaviors such as reference path following, obstacle avoidance and flocking, and the formation characteristics such as flexibility and scalability, effectively.

Key words : formation, potential function, path planning, local minimum, swarm systems

1. Introduction

In recent years, some of the studies have shown that many simple agents occupy one or two dimensional environments and are able to perform tasks such as pattern generation and self-organization [1]-[3]. A swarm is a distributed system with a large number of autonomous robots [7]. Self-organization in a swarm is the ability to distribute itself "optimally" for a given task, e.g., via geometric pattern formation or structural organization. The mechanisms for self-organization in swarms are studied in [7], [8]. It is generally believed that proper organization of swarms of cooperating mobile agents provides significant benefits over single unit approaches for various missions. For specific tasks, cooperating agents do not need to be sophisticated or expensive to compete with their advanced independent counterparts. In addition, the integrated multi-agent systems facilitate increased mobility, survivability, sensor coverage and information flows.

More recently much attention has been attracted on the behavior-based reactive systems [5], [22]. The behavior-based intelligences are motivated by natural species and can show great adaptability and robustness to the time-varying environment with relatively simple algorithms, as well as corresponding low computation cost during real-time operations [11]. Recent research results show that a variety of nonlinear systems can exhibit self-organization, reactive behavior to external stimulus and pattern formation [12], [13]. More specifically, the CNOs have been extensively studied for their simplicity to implement and exhibition of a wide variety of novel and complex spatiotemporal behaviors. In [15], it was reported that by using nonlinear oscillator scheme a sequence of basic behaviors such as random walking, obstacle avoidance and light following was able to coordinate in a single robot to achieve more complicated behavior. However, these behavior-based computational organizations lack insightful comprehension to the problems and sometimes exhibit unpredicted and undesirable performances. They need much time to be trained for selection of proper parameter values in different working environments [15]. It seems neither of those approaches can present a universal solution to the problem of designing cooperative mobile agents. These schemes should be combined in a certain trade-off and might be employed in different levels for different scenarios for the hierarchically architectural and multi-strategy adaptive intelligent system consisting of a swarm of homogeneous mobile agents.

Some research has been performed to investigate of flocking by autonomous mobile agents [16], [17]. [16] presented a simple flocking task and described a leaderless distributed flocking algorithm. However, off-line optimization is required to optimize the leaderless performance. [3] and [4] show that simple behaviors like avoidance, aggregation and dispersion can be combined to create an emergent flocking behavior. Other recent related papers on formation control include [5] and [6]. [6] simulates robots in a line-abreast formation navigating past way points to a final destination. Using the terminology introduced in this article, agents utilize a leader-referenced line formation. Although several attempts have been made to study a group of formation or behavior, there seems no developed study on the formation and migration among multi-agent groups.

The author presented a set of analytical guidelines for designing potential functions to avoid local minima for a

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number of representative scenarios based on the proposed framework for path planning by the angle distribution [26] and by the novel potential function compositions [27]. Specifically the following cases are addressed: 1) a non-reachable goal problem (a case that the potential of the goal is overwhelmed by the potential of an obstacle) , 2) an obstacle collision problem (a case that the potential of the obstacle is overwhelmed by the potential of the goal), and 3) a narrow passage problem (a case that the potential of the goal is overwhelmed by the potential of two obstacles). The example results for each cases show that the proposed scheme can effectively construct a path planning system in the capability of reaching a goal and avoiding obstacles despite possible local minima. However, the proposed method by the author is based on potential function utilization where only single robot is considered for path planning, not for multiple-robots for formation. As well, a moving particle named a point robot is used as a robot model such as the most popular path planning method [28] - [32], not a real robot model.

In this paper, a self-organizing scheme based on the CNOs for multi-agent swarm systems is proposed and explored. In this scheme, unicycle robots self-organize to flock and arrange group formation through attractive and repulsive forces among themselves. Aided by distributed controls, this approach enables robots to follow a moving target or a leader robot, while maintaining group formation and avoiding the obstacles that may appear on the path of the formation. While others have previously studied a target-following strategy [18], [19] , the purpose of this study is specifically to obtain the global behaviors such as migration and group formation by using simple local individual rules, as well as obstacle avoidance. Also, in contrast to much of this previous research, our research explicitly addresses issues of maintaining flexible and scalable formation while moving in a group.

This paper is organized as follows. Section 2 discusses the unicycle robot model and its control input. In Section 3, two kinds of potential function designs based on CNOs are proposed and analyzed for group formation. As well, the control formulation of the system for migration, group formation, and obstacle avoidance by the desired coordinate trajectory is presented. Section 4 describes overall behaviors such as reference path following, leader following and flocking, and shows the flexibility and scalability of formation through illustrative examples. Finally concluding remarks and further works are drawn in Section 5.

2. Problem Formulation

The phenomena of swarming in nature have inspired many interests about large-scale artificial swarms into electrical and mechanical engineers. A typical artificial swarm system is a large-scale fleet of cooperative robots. Each robot in such a robotic swarm can be viewed as an agent. And it will likely possess only basic capabilities and mission specific sensors. Direct communication between agents may or may not exist. The environment model is very "object-oriented" in its approach to agent construction. Sensors and behaviors are encapsulated when possible. This approach allows individual components to be added and/or removed from the model. We restrict the workspace to two-dimensional space where each agent moves in $[xy]$ plane.

2.1. Unicycle robot model

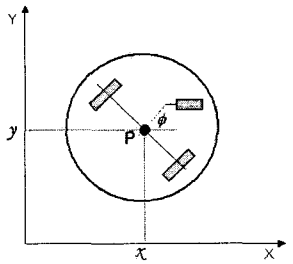

Fig. 1. Unicycle robot in a plane

Consider a unicycle robot depicted in Fig.1. Its configuration is completely described by a 3-vector $\mathbf{q}_i = (x_i, y_i, \phi_i)^T$ which defines the current position and orientation referred to an inertial reference frame. Assuming that the wheel of the robot does not slip on the plane the motion of the point $\mathbf{P}_i$ (whose position is controlled) for robot i is subjected to

$$\dot{x}_i \sin\phi_i - \dot{y}_i \cos\phi_i = 0 \tag{1}$$

where (x_i, y_i) is the center of gravity of the robot in the inertially fixed coordinate system, ϕ_i is its orientation. This natural constraint is nonintegrable, i.e., nonholonomic. The longitudinal velocity v_i and angular velocity w_i are given by

$$\begin{aligned} \dot{x}_i \cos\phi_i + \dot{y}_i \sin\phi_i &= v_i \\ \dot{\phi}_i &= w_i \end{aligned} \tag{2}$$

Hence, the kinematic model is given by

$$\mathbf{q}_i = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\phi}_i \end{bmatrix} = \begin{bmatrix} \cos\phi_i & 0 \\ \sin\phi_i & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix}. \tag{3}$$

2.2. Tracking control

Control algorithm for tracking [24] is given by

$$\begin{aligned} v_i &= \gamma \rho_i \cos\Delta\phi_i \\ w_i &= k\Delta\phi_i + \dot{\phi}_{di} \end{aligned} \tag{4}$$

where

$\rho_i = \sqrt{\Delta x_i^2 + \Delta y_i^2}, \Delta x_i = x_{di} - x_i, \Delta y_i = y_{di} - y_i,$

$\Delta\phi_i = \phi_{di} - \phi$, $\phi_{di} = atan2(\Delta y_i, \Delta x_i)$. and $k, \gamma > 0$.

$P_{di}(x_{di}, y_{di})$ is the desired coordinate trajectories. It can be the path of a virtual leader. We will specify $P_{di}(x_{di}, y_{di})$ in Section 3.3 considering group formation and obstacle avoidance.

As long as P_{di} is bounded, it holds that

$$\lim_{t\to\infty} \rho_i(t) \le d$$

$$\lim_{t\to\infty} \| \Delta\phi_i \| \le \delta \quad (5)$$

for some $d, \delta > 0$ that can be made arbitrarily small with an appropriate choice of the control parameters k and γ. Proof is in [25].

3. The Proposed Algorithm

In this section, a self-organized swarm system controlled by the CNOs is proposed for group formation, and the formulation of a coordinate desired trajectory is presented for migration, group formation, and obstacle avoidance.

3.1. To keep group formation

The CNO that has simple interaction potential functions among the swarm robots to keep group formation is modeled as following. We propose two methods depending on how many neighboring robots each robot is affected by. In the first method, each robot is affected by only the nearest robot, which makes hardware implementation simple but the formation is loose. The second method is proposed that each robot is affected by the robots within its neighboring area, which makes the formation compact. But it requires more hardware burdens than the first method.

- The First Method

The potential function based on CNO for group formation is modeled as following.

$$U_i(k) = -c_a e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_a)} + c_r e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_r)} \quad (6)$$

where c_a, c_r, l_a, and l_r are the strengths and correlation distances of the attractive and repulsive force respectively, $\mathbf{P}_i$ is the position of an i-th robot, and $\mathbf{P}_j$ is the position of the nearest robot from the i-th robot.

The robot $\mathbf{P}_i$ uses the relative position to the nearest robot for group formation. For example, in Fig.2, the arrow between the robot 1 and the robot 3 implies that the robot 1 uses the information of the robot 3 and the robot 3 uses the information of the robot 1.

From (6) we obtain

$$F_i(k) = -\nabla U_i(k) = -2\frac{c_a}{l_a} e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_a)}(\mathbf{P}_i(k) - \mathbf{P}_j(k))$$

$$+ 2\frac{c_r}{l_r} e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_r)}(\mathbf{P}_i(k) - \mathbf{P}_j(k)). \quad (7)$$

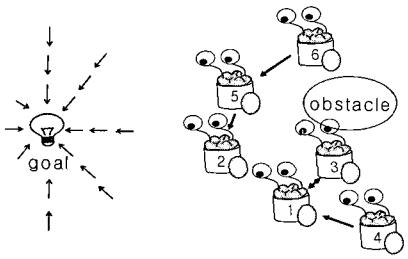

Fig. 2. The first method for group formation

Force function $F_i(k)$ is used to keep a formation among different robots and bounded. Fig.3 shows the attractive and repulsive force between two robots where $r = \|\mathbf{P}_i(k) - \mathbf{P}_j(k)\|$, $r_c = \sqrt{\frac{l_a l_r}{l_a - l_r} ln\frac{c_r l_a}{c_a l_r}}$, and $F_i(k)$ and $U_i(k)$ mean the force and potential, respectively. r_c is the desired distance between two robots. It is adjusted by design parameters l_a, l_r, c_a and c_r. s_d is the maximum distance that the robot is able to sense.

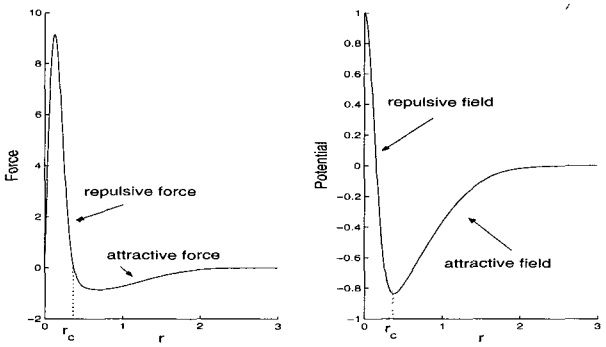

Fig. 3. The force and potential between two robots

Theorem 1: For $l_a > l_r$ and $(\frac{c_r l_a}{c_a l_r})^{\frac{l_a l_r}{l_a - l_r}} > 1$ in (6), each robot maintains the desired distance r_c from its nearest robot by the repulsive and attractive forces.

Proof:

- the case of a repulsive force

In Fig.4, we suppose that $\mathbf{P}_i(k)$ and $\mathbf{P}_j(k)$ are located in (x_1, y_1) of a top-left plane and (x_2, y_2) of (0, 0), respectively. If we assume $r < r_c$, (x_1, y_1) of $\mathbf{P}_i(k)$ gets a repulsive force to $F_{xi}(k) < 0$ and $F_{yi}(k) > 0$ where $F_i(k) = [F_{xi}(k)\ F_{yi}(k)]$.

Considering x and y in (7) separately gives

$$F_{xi} = -2\frac{c_a}{l_a} e^{-(x_1-x_2)^2/l_a}(x_1 - x_2) + 2\frac{c_r}{l_r} e^{-(x_1-x_2)^2/l_r}(x_1 - x_2) < 0,$$

$$F_{yi} = -2\frac{c_a}{l_a} e^{-(y_1-y_2)^2/l_a}(y_1 - y_2) + 2\frac{c_r}{l_r} e^{-(y_1-y_2)^2/l_r}(y_1 - y_2) > 0. \quad (8)$$

$x_1 - x_2 < 0$ and $y_1 - y_2 > 0$ give $\frac{c_r}{l_r} e^{-(x_1-x_2)^2/l_r} > \frac{c_a}{l_a} e^{-(x_1-x_2)^2/l_a}$ and $\frac{c_r}{l_r} e^{-(y_1-y_2)^2/l_r} > \frac{c_a}{l_a} e^{-(y_1-y_2)^2/l_a}$, respectively.

Using natural logarithm gives $\frac{l_a l_r}{l_a - l_r} \ln(\frac{c_r l_a}{c_a l_r}) > (x_1 - x_2)^2$, $\frac{l_a l_r}{l_a - l_r} \ln(\frac{c_r l_a}{c_a l_r}) > (y_1 - y_2)^2$, respectively. Combining both equations gives

$$\sqrt{\frac{l_r l_a}{l_a - l_r}\ln\left(\frac{c_r l_a}{c_a l_r}\right)} > \left\|\mathbf{P}_i(k) - \mathbf{P}_j(k)\right\| \quad (9)$$

i.e. $r_c > r$. Thus, when $r < r_c$, (x_1, y_1) of $\mathbf{P}_i(k)$ gets the repulsive force between two robots of (x_1, y_1) and (x_2, y_2). Using the same procedure, we can prove whether (x_1, y_1) of $\mathbf{P}_i(k)$ is located on top-right, bottom-left or bottom-right plane.

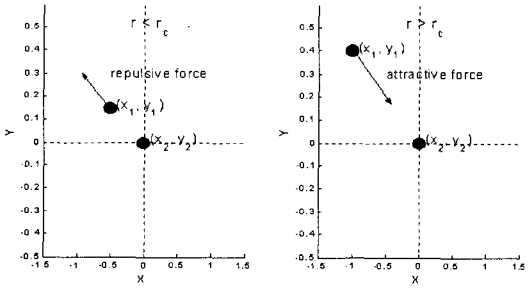

Fig. 4. The repulsive and attractive forces between two robots

- the case of a attractive force

If we assume $r > r_c$, (x_1, y_1) of $\mathbf{P}_i(k)$ gets an attractive force to $F_{xi}(k) > 0$ and $F_{yi}(k) < 0$. Considering x and y separately gives

$$F_{xi} = -2\frac{c_a}{l_a}e^{-(x_1-x_2)^2/l_a}(x_1 - x_2) + 2\frac{c_r}{l_r}e^{-(x_1-x_2)^2/l_r}(x_1 - x_2) > 0,$$

$$F_{yi} = -2\frac{c_a}{l_a}e^{-(y_1-y_2)^2/l_a}(y_1 - y_2) + 2\frac{c_r}{l_r}e^{-(y_1-y_2)^2/l_r}(y_1 - y_2) < 0. \quad (10)$$

$x_1 - x_2 < 0$ and $y_1 - y_2 > 0$ give $\frac{c_r}{l_r}e^{-(x_1-x_2)^2/l_r} < \frac{c_a}{l_a}e^{-(x_1-x_2)^2/l_a}$ and $\frac{c_r}{l_r}e^{-(y_1-y_2)^2/l_r} < \frac{c_a}{l_a}e^{-(y_1-y_2)^2/l_a}$, respectively.

Using natural logarithm gives $\frac{l_r l_a}{l_a - l_r}\ln\left(\frac{c_r l_a}{c_a l_r}\right) < (x_1 - x_2)^2$, $\frac{l_r l_a}{l_a - l_r}\ln\left(\frac{c_r l_a}{c_a l_r}\right) < (y_1 - y_2)^2$, respectively. Combining both equations gives

$$\sqrt{\frac{l_r l_a}{l_a - l_r}\ln\left(\frac{c_r l_a}{c_a l_r}\right)} < \left\|\mathbf{P}_i(k) - \mathbf{P}_j(k)\right\| \quad (11)$$

i.e. $r_c < r$. Thus, when $r < r_c$, (x_1, y_1) of $\mathbf{P}_i(k)$ gets the attractive force between two robots of (x_1, y_1) and (x_2, y_2). Using the same procedure, similarly we can prove whether (x_1, y_1) of $\mathbf{P}_i(k)$ is located on top-right, bottom-left or bottom-right plane. Fig.5 shows the illustrative example of theorem 1 for a robot located to different position, respectively when the other robot is located in $(x_2, y_2) = (0, 0)$. The robot starting from different positions maintains the distance r_c for the other robot.

Thus, if the robot is far from its nearest robot on the basis of r_c, the robot is drawn to its nearest robot by attractive force. On the other hand, if the distance between two robots is shorter than r_c, they keep a certain distance not to be close by repulsive force. Thus, each robot possesses the characteristic of flocking to keep group formation while ensuring safe separation between swarm robots.

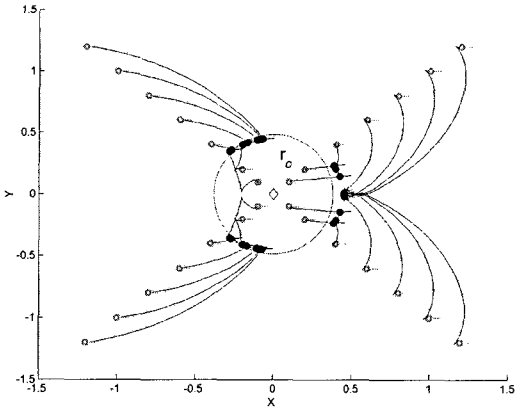

Fig. 5. The illustrative example of theorem 1 (gray o: the initial position of a robot, black o: the final position of a robot, ◊ : the other robot)

- The Second Method

The potential function based on CNO for group formation is modeled as following.

$$U_i(k) = -\sum_{j \neq i}\{c_a e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_a)} + c_r e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_r)}\} \quad (12)$$

where $\mathbf{P}_j$ is the position of each robot within sensing distance s_d around the i-th robot.

The robot $\mathbf{P}_i$ uses the relative position to the robots within sensing distance s_d around the i-th robot. Fig.6 illustrates the robot 1 uses the information of the robot 2, 3 and 4 that is located within the sensing area of robot 1.

From (12) we obtain

$$F_i(k) = -\nabla U_i(k) = \sum_{j \neq i}\{-2\frac{c_a}{l_a}e^{(-n\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|n^2/l_a)}(\mathbf{P}_i(k) - \mathbf{P}_j(k)) + 2\frac{c_r}{l_r}e^{(-n\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|n^2/l_r)}(\mathbf{P}_i(k) - \mathbf{P}_j(k))\}. \quad (13)$$

$F_i(k)$ is constructed by the influence of the repulsive and attractive force from the robots that is within the sensing area around i-th robot.

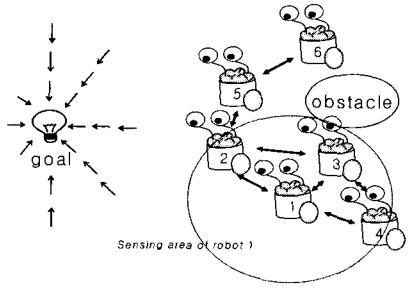

Fig. 6. The second method for group formation

Theorem 2: For $l_a > l_r$ and $(\frac{c_r l_a}{c_a l_r})^{\frac{l_r l_a}{l_a - l_r}} > 1$ in (6), each robot maintains a constant distance from the robots within the sensing area around it by the repulsive and attractive forces.

Proof:

Since we have proven that the robot can keep a distance from its nearest robot by the repulsive and attractive forces in theorem 1, the position of the robot in the second method is determined by adding all of the repulsive and attractive forces from the neighboring robots within its sensing area.

We suppose that $\mathbf{P}_i(k)$ and $\mathbf{P}_j(k)$ are located in (x_1, y_1) and (x_j, y_j), respectively. Considering x and y in (13) separately gives

$$F_{xi} = \sum_{j \neq i} \{-2\frac{c_a}{l_a} e^{-(x_1 - x_j)^2 / l_a}(x_1 - x_j) + 2\frac{c_r}{l_r} e^{-(x_1 - x_j)^2 / l_r}(x_1 - x_j)\},$$

$$F_{yi} = \sum_{j \neq i} \{-2\frac{c_a}{l_a} e^{-(y_1 - y_j)^2 / l_a}(y_1 - y_j) + 2\frac{c_r}{l_r} e^{-(y_1 - y_j)^2 / l_r}(y_1 - y_j)\}. \quad (14)$$

$F_{xi} > 0$ and $F_{xi} < 0$ cause x_1 to move toward the right and left side on the basis of Cartesian coordinate, respectively. Also, $F_{yi} > 0$ and $F_{yi} < 0$ cause y_1 to move toward the top and bottom side on the basis of Cartesian coordinate, respectively.

For the illustrative example of theorem 2, let a robot start from different initial positions (gray o) in Fig.7 where $0 < x < 1.7, -1.7 < y < 0$. Three neighboring robots (◊) in Fig.7 are located in $(x_2, y_2) = (0,0)$, $(x_3, y_3) = (0.45, 0)$ and $(x_4, y_4) = (0, -0.45)$, respectively. The robot starting from different initial positions arrives a point around (0.5,0.5) (black o in Fig.7) finally, and consequently maintains a constant distance for the three neighbor robots. In Section 4, the second method to maintain group formation is adopted since the second method exhibits compact formation than the first method.

3.2. Obstacle Avoidance

During the process of migration, if a robot meets an obstacle, a collision avoidance technique that leads to the collision-free movement is applied. In the proposed control strategy, the velocity direction is adjusted randomly in the direction of the reference path after meeting an obstacle, that is

$$\begin{bmatrix} x_{oi} \\ y_{oi} \end{bmatrix} = \begin{bmatrix} cos\theta_{oi} & sin\theta_{oi} \\ -sin\theta_{oi} & cos\theta_{oi} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \quad (15)$$

where

$$\theta_{oi} = \begin{cases} random[2, 2\pi] & if\ meet\ an\ obstacle \\ 0 & otherwise \end{cases} \quad (16)$$

The relatively simple technique for obstacle avoidance is adopted. As well, diverse obstacle avoidance or random walking techniques can be employed [26], [27]. However, the development of obstacle avoidance technique for swarm robots is not included on our focus. Note that our main concern is on group formation for swarm robots.

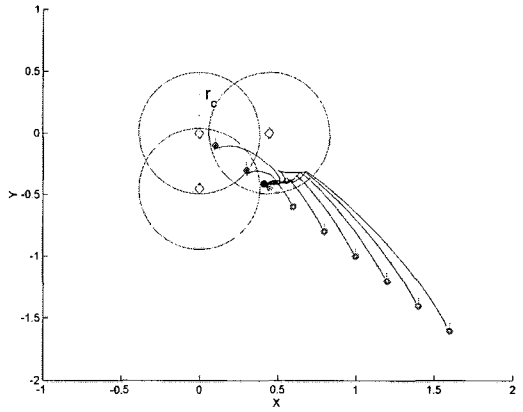

Fig. 7. the illustrative example of theorem 2 (gray o: the initial position of a robot, black o: the final position of a robot, ◊ : the other robots)

3.3. Desired coordinate trajectory

We can formulate the control of a whole system for the combination of migration, group formation and obstacle avoidance by using following desired coordinate trajectory $P_{di}(x_{di}, y_{di})$:

$$x_{di} = x_r + \alpha_1 F_{xi} + s_{oi}\alpha_2 x_{oi}$$

$$y_{di} = y_r + \alpha_1 F_{yi} + s_{oi}\alpha_2 y_{oi} \quad (17)$$

where $P_r(x_r, y_r)$ is a reference path for migration or a target position. α_1 and α_2 are positive constants called the adaptation gain for group formation, and

$$s_{oi} = \begin{cases} 1 & if\ meet\ an\ obstacle \\ 0 & otherwise \end{cases} \quad (18)$$

If the robot is in collision-free region, the system is again switched to the main controller including only migration and group formation.

Remark 1: It can be simply checked that P_{di} in (17) is bounded, since F_{xi}, F_{yi}, x_{oi} and y_{oi} are bounded, as long as P_r is chosen to be bounded.

4. Formation of the Self-organized Swarm Using CNOs

4.1. Reference path following and leader following

First, our task is to show the performance of reference path following using the proposed self-organized scheme. In Fig.8, the 5 robots are randomly initialized on the left side of the simulation environment, then direct to proceed to the right side of the frame. The reference path is $P_r = (t, \sin t^2)$.

Next task is a leader-referenced approach addressing a simple leader following application while maintaining self-organized formation. Each robot determines its position for formation, in relation to the leader robot that does not keep the

formation. Fig.9 illustrates robots migrating with the leader-referenced approach. In Fig.9, the robots were randomly initialized on the top-left side of the simulation environment, then directed to proceed to the lower center of the frame. After the formation was established, a 90° turn to the left was initiated. In Fig.8 and 9, it is shown that each robot follows the reference path and the leader, respectively, in a good way while maintaining formation.

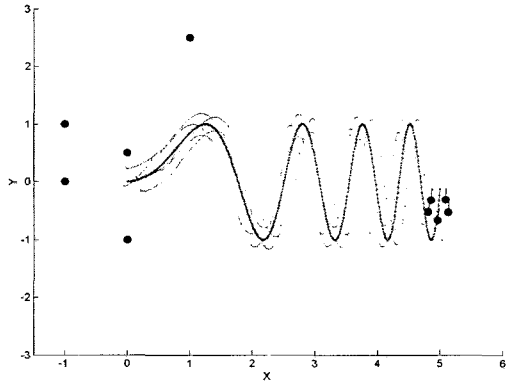

Fig. 8. Reference path following (bold line: reference path)

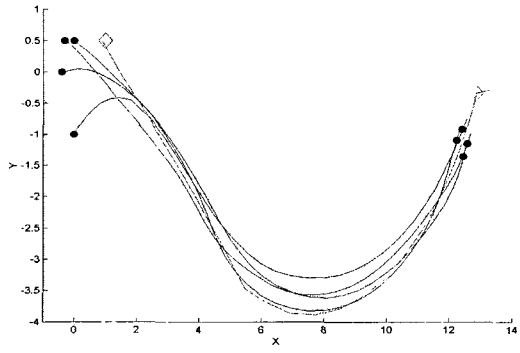

Fig. 9. Leader-referenced following for a 90° turn ($\Diamond$: a leader)

4.2. Flocking

The loose or tight formation can be adjusted by using design parameters l_a, c_a, l_r and c_r. Fig.10 illustrates flocking at $(0,0)$ when $l_a = 1, c_a = 1, l_r = \frac{1}{10}$ and $c_r = 1$. Initially, 20 robots randomly spread out among all. The gray o indicates the initial configuration of robots and the black o indicates the configuration of robots in formation after $t = 10$. This plot shows that randomly initialized 20 robots flock by the attractive force, and arrange by the attractive and repulsive force.

4.3. Flexibility of formation

Use of the CNOs makes maintaining formation very flexible. While maintaining the characteristic of swarm, the robot wanders about flexibly, i.e., it has a nature of self-organized flocking that the robots make formation dynamically without explicit reorganization contrary to [23]. Since the proposed approach does not explicitly use the alignment of other group members, individual robots were not commanded to be located to any positions for alignment. Also if they encounter with obstacles, they reorganize their formation to avoid the obstacle without external command. For example, if their formation encounters a tunnel, they change their maintenance to a kind of line as themselves while keeping a formation. Fig.11 shows the proposed self-organized swarm robots go through a tunnel, where each robot changes formation flexibly, not fixed formation.

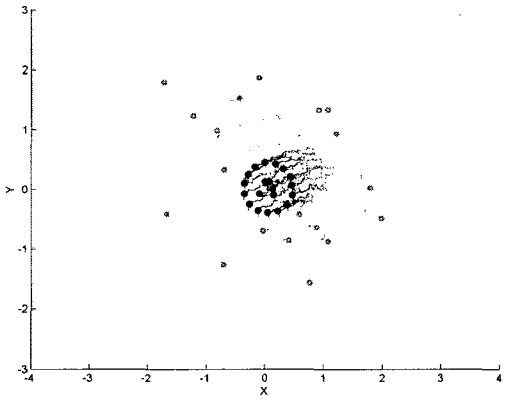

Fig. 10. Flocking (gray o: initial robots)

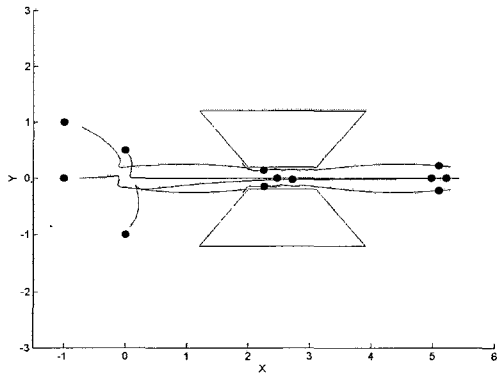

Fig. 11. 5 robots going through tunnel

4.4. Scalability of formation

This approach has a good scalability which adds or removes any number of robots easily. As an example, consider the group of 20 robots in the existence of a triangle-shaped obstacle, illustrated in Fig.12. The robots start on the left side of the field and move to the right around the obstacle in the middle of the field. After the formation splits around the obstacle, each robot comes together. This example shows that the proposed formation ensures safe separation and good cohesion performance among the robots.

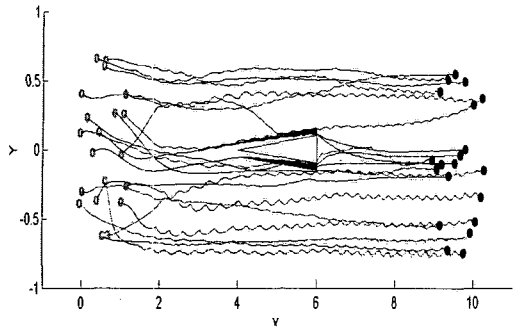

Fig. 12. 20 robots negotiating a group of obstacles in the middle of the field (gray o: initial robots)

5. Conclusion and Further Works

In this paper, a swarm robot system design based on the CNOs for multiple unicycle robots is proposed and studied. One of the main contributions in this method is the flexibility of formation. The formation of swarm robots based on the CNOs splits in the existence of obstacles while migrating, makes the robots rejoin in the area out of obstacles. It is on the ground that the proposed approach does not require specified formation, which makes each robot self-organize for group formation according to given environment. As well, it is important that, in the proposed method, global behaviors such as migration and group formation is obtained based on simple local individual interactive rules. Initial arrangement for group formation is not required since each robot has its own group formation behavior. Thus, the framework is fully scalable for the distributed control that operates independently of the number of robots. The simulation examples show that the proposed scheme can effectively construct a self-organized swarm system with the capability of group formation and migration in the presence of obstacles. With the proposed concept and system structure, more scenarios through cooperation in the more complicated environment can be further studied.

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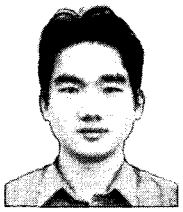

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