Flexible and Scalable Formation for Unicycle Robots

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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. 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, unicycle robots, swarm systems

I. Introduction

Recently much attention has been attracted on the behavior-based reactive systems [1], [2]. 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 [3]. Recent research results show that a variety of nonlinear systems can exhibit self-organization, reactive behavior to external stimulus and pattern formation [4], [5]. 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 [6], 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 [6]. 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.

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 [7], [8] , 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.

II. Problem Formulation

2.1. Unicycle robot model

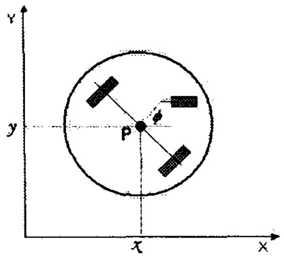

Fig. 1. Unicycle robot in a plane

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

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

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 [9] is given by

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

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

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

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 [10].

III. 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.

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

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

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.2 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 (6) we obtain

$$F_i(k) = -\nabla U_i(k) = \sum_{j\ne i} \{-2\frac{c_a}{l_a} e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_a)}(\mathbf{P}_i(k) - \mathbf{P}_j(k))$$
$$+ 2\frac{c_r}{l_r} e^{(-\|\mathbf{P}_i(k)-\mathbf{P}_j(k)\|^2/l_r)}(\mathbf{P}_i(k) - \mathbf{P}_j(k))\}. \tag{7}$$

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

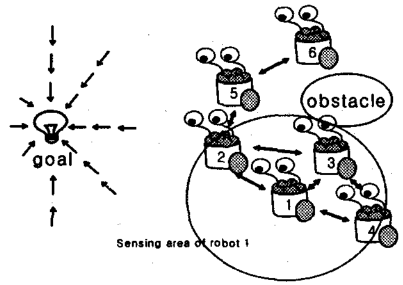

Fig. 2. The proposed method for group formation

Theorem 1: 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: The details are omitted on account of limited space.

For the illustrative example of theorem 1, let a robot start from different initial positions (gray ○) in Fig.7 where $0 < x < 1.7, -1.7 < y < 0$. Three neighboring robots (◊) in Fig.3 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 ○ in Fig.3) finally, and consequently maintains a constant distance for the three neighbor robots.

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

$$\begin{bmatrix} x_{oi} \\ y_{oi} \end{bmatrix} = \begin{bmatrix} cos\theta_{oi} & sin\theta_{oi} \\ -sin\theta_{oi} & cos\theta_{oi} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \tag{8}$$

where

$$\theta_{oi} = \{ \begin{matrix} random[2,2\pi] & \text{if meet an obstacle} \\ 0 & \text{otherwise} \end{matrix} \tag{9}$$

The relatively simple technique for obstacle avoidance is adopted. As well, diverse obstacle avoidance or random walking techniques can be employed [11]. 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.

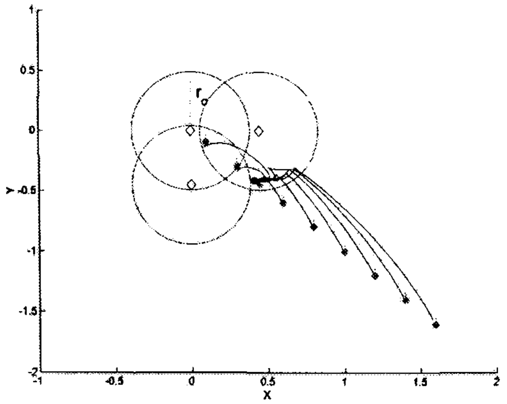

Fig. 3. the illustrative example of theorem 1 (gray ○: the initial position of a robot, black ○: the final position of a robot, ◊ : the other robots)

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 $P_{di}(x_{di}, y_{di})$:

$$\begin{aligned} x_{di} &= x_r + \alpha_1 F_{xi} + s_{oi}\alpha_2 x_{oi} \\ y_{di} &= y_r + \alpha_1 F_{yi} + s_{oi}\alpha_2 y_{oi} \end{aligned} \tag{10}$$

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

$$s_{oi} = \{ \begin{matrix} 1 & \text{if meet an obstacle} \\ 0 & \text{otherwise} \end{matrix} \tag{11}$$

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 (10) is bounded, since F_{xi}, F_{yi}, x_{oi} and y_{oi} are bounded, as long as P_r is chosen to be bounded.

IV. 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.4, 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. In Fig.4, it is shown that each robot follows the reference path and the leader, respectively, in a good way while maintaining formation.

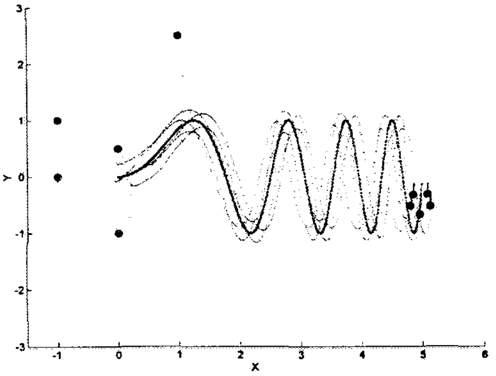

Fig. 4. Reference path following (bold line: reference path)

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.5 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 ○ indicates the initial configuration of robots and the black ○ 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 [12]. 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.6 shows the proposed self-organized swarm robots go through a tunnel, where each robot changes formation flexibly, not fixed formation.

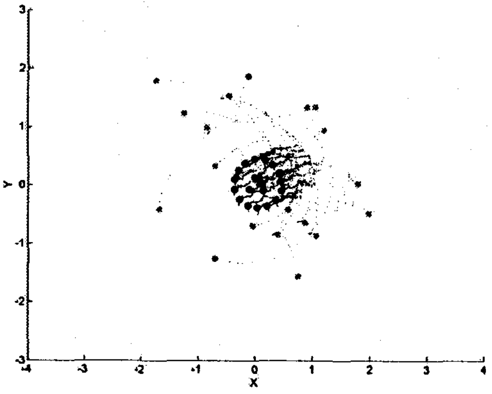

Fig. 5. Flocking (gray ○ : initial robots)

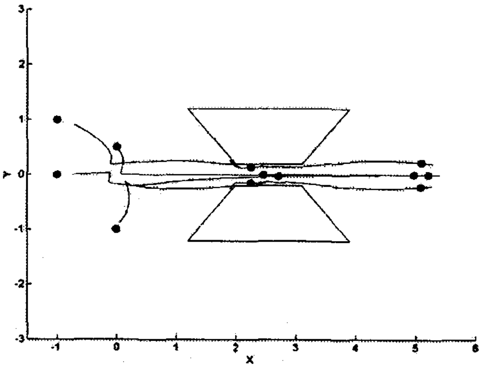

Fig. 6. 5 robots going through tunnel

V. Conclusions

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.

Acknowledgement

This work was financially supported by MOCIE through IERC program.

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