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Aggregation and leader following control of swarm robots: experimental results

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Abstract
Target tracking with a group of autonomous robots is of great importance in recent years. In this paper the control of a swarm robots in the aggregation and leader following missions has been considered. The swarm obey a third order dynamics and the control strategy is based on the potential function and sliding mode control theory. Each robot's sensor measures the relative distance and angle of others with respect to itself. These measurements have been used in the control law to calculate the velocities of the wheels of robots. The simulations and experimental results show the efficiency of the control strategy.

Keywords: swarm robots, potential function, sliding mode control, aggregation, leader following

Introduction

Target tracking with a group of autonomous robots is of great importance in recent years. Its application is in the fields of aerial vehicles such as satellites, military applications, explorations and etc.

Recent studies on the problem of tracking a target, can be found in [1], [2], where the authors considered the problem of tracking and capturing/enclosing a moving target with a swarm of fully actuated holonomic agents. In practice, most of the mobile agents (i.e., differentially driven robots, UAVs) have velocity constraints or they are under actuated and may not obey the model in [1], [2].

In [3], tracking a maneuvering target with autonomous differentially driven non-holonomic agents was considered and the results in [1] and [2] was extended. The authors assumed force and moment as control inputs and represented a five order dynamics for each agent. They used the artificial potential and sliding mode control based approach in [4] where a distributed control scheme for aggregation, foraging, and formation acquisition/ maintenance of swarms of non-holonomic agents was considered. The work in [3] was inspired by the earlier works of Guldner and Utkin on tracking the gradient of potential functions (potential fields) using sliding mode control [5-7].

In this paper we developed a control law based on the potential function and sliding mode control to our experimental robots for aggregation and leader following. Each robot has equipped with the infrared sensors that can measure the relative distance and angle of other robots with respect to itself.

This paper is organized as follows, first the dynamic model and the designed controller is presented, then the simulation and experimental results are shown. Finally the paper is concluded.

Swarm dynamics

Consider a system of non-holonomic mobile agents, e.g. robots, moving in R^2 that are labelled as $1,...i,...,N$. Assume that each agent has the configuration depicted in Figure **1** and the equations of motion given by:

$$\begin{aligned} \dot{p}_{xi} &= v_i \cos(\theta_i), \\ \dot{p}_{yi} &= v_i \sin(\theta_i), \\ \dot{\theta}_i &= \omega_i \end{aligned} \tag{1}$$

Where $x_i = \begin{bmatrix} p_{xi} & p_{yi} \end{bmatrix}^T$ is the vector position of i'th agent and θ_i is the steering angle. v_i and ω_i are the linear and angular speed, respectively.

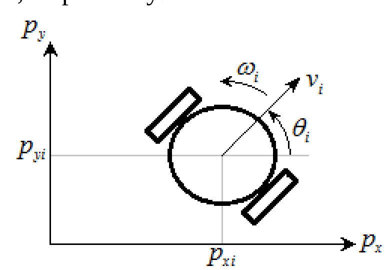

Figure 1. Agent schematic model

In fact this model is the same as the model that is presented in [3], with the difference that we considered the linear and rotational velocity as the control inputs. Eq. (1) presents a three order dynamics while in [3] each agent has a five order dynamics. The aim of this paper is to achieve the leader following and aggregation of the swarm agents.

Controller Design

According to [2] if the eq. (2) is satisfied, swarm robots can reach an aggregation.

$$\dot{\mathbf{x}}_i = -\nabla_{\mathbf{x}_i} J(\mathbf{X}) \tag{2}$$

Where $\mathbf{X}^T = \begin{bmatrix} \mathbf{x}_1^T & \mathbf{x}_2^T & \dots & \mathbf{x}_N^T \end{bmatrix}$, in which $\mathbf{x}_i$ is defined in eq. (1). $J(\mathbf{X})$ is the well-defined potential function that is selected by the control designer and one of the popular class of them has been introduced in [3]. Following is one of the most popular potential functions that has been used in this paper.

$$J(\mathbf{X}) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left[\frac{a}{2} \|\mathbf{x}_i - \mathbf{x}_j\|^2 + \frac{bc}{2} \exp\left(-\frac{\|\mathbf{x}_i - \mathbf{x}_j\|^2}{c} \right) \right] \tag{3}$$

Where *i* and *j* are the robot number and N is the number of the robots in the swarm. According to the eq. (2) the following equations has been concluded.

$$v_i = \left\| \nabla_{\mathbf{x}_i} J(\mathbf{X}) \right\| \tag{4}$$

$$\theta_{id} = \angle\left(-\nabla_{\mathbf{x}_i} J(\mathbf{X}) \right) \tag{5}$$

Using eq. (3 as potential function, the gradient will be as follows

$$\nabla_{\mathbf{x}_i} J(\mathbf{X}) = \sum_{j=1,\ j\neq i}^{N} (\mathbf{x}_i - \mathbf{x}_j) \left[a - b \exp\left(-\frac{\|\mathbf{x}_i - \mathbf{x}_j\|^2}{c} \right) \right] \tag{6}$$

Based on eq. (4), one of the control inputs of each agent is found. θ_{id} in eq. (5) is the desired steering angle of the ith agent. The steering angle error of the ith agent will be as follows

$$s_{\theta_i} = \theta_i - \theta_{id} \tag{7}$$

Since θ is the steering angle of the robot, we can bound the s_{θ_i} to $[-\pi \quad \pi)$. We defined the following sliding mode function for the ith agent.

$$s_i = \mathrm{mod}\left(s_{\theta_i} + \pi, 2\pi \right) - \pi \tag{8}$$

Similar to the approach that has been defined in [3], the second control input for each agent is designed as follows.

$$\omega_i = -K_i(\mathbf{X})\, sign(s_i) \tag{9}$$

where

$$K_i(\mathbf{X}) \geq \left| \dot{\theta}_{id} \right| + \varepsilon_i \tag{10}$$

ε_i defines the convergence time of reaching to the sliding surface.

According to the above mentioned potential function, an analytical upper bound can be found for $|\theta_{id}|$, but an easier approach is to set a fix value for $K_i(\mathbf{X})$ based on the maximum velocities of each agent. If the potential function calculated based on eq. (3), agents tend to aggregate in such a way that they will stay in an equilibrium distance as follows

$$d = \sqrt{c \ln(b/a)} \tag{11}$$

If the following potential function is used instead of eq. (3), swarm robots can achieve formation rather than an aggregation.

$$J(\mathbf{X}) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left[\frac{a_{ij}}{2} \|\mathbf{x}_i - \mathbf{x}_j\|^2 + \frac{b_{ij} c_{ij}}{2} \exp\left(-\frac{\|\mathbf{x}_i - \mathbf{x}_j\|^2}{c_{ij}} \right) \right] \tag{12}$$

With the above potential function, agents will form a configuration in which they will stay in an equilibrium distance of $d_{ij} = \sqrt{c_{ij} \ln\left(b_{ij} / a_{ij} \right)}$. In other words the equilibrium distance between different agents can be different.

In order to achieve the leader following, one of the agents should move as a swarm leader in a prespecified trajectory, and the others should follow its motion. For this purpose, eq. (4) and (5) should be modified as follows [3].

$$v_i = \left\| \alpha \times \nabla_{\mathbf{x}_i} J(\mathbf{X}) + \beta \times sign\left(\nabla_{\mathbf{x}_i} J(\mathbf{X}) \right) \right\| \tag{13}$$

$$\theta_{id} = \angle\left(-\alpha \times \nabla_{\mathbf{x}_i} J(\mathbf{X}) - \beta \times sign\left(\nabla_{\mathbf{x}_i} J(\mathbf{X}) \right) \right) \tag{14}$$

Existence of the sign function in the control input can lead to the unwanted chattering phenomena. In order to solve this problem, one can use approximation functions such as tangent hyperbolic or saturation. In the following, h_1 and h_2 are approximations of $sign(s_i)$.

$$\mathrm{h}_1(s_i) = \tanh(\sigma s_i)$$

$$\mathrm{h}_2(s_i) = sat(\sigma s_i) = \begin{cases} \sigma s_i & -\sigma \leq x \leq \sigma \\ sign(\sigma s_i) & else \end{cases} \tag{15}$$

Where σ is a constant.

Simulation

In this section we have done two simulations. As stated before, we have consider two missions which are aggregation and leader following. In the simulation we have six agents randomly distributed in the 2D space. Each agent follows the three order dynamics which is stated in eq. (1).

In the aggregation, the controller on agents are the same as each other and they try to reach at the equilibrium distance from each other. The linear velocity of each agent computed from eq. (4) in which the potential function of eq. (3) is used with the parameters that are shown in Table **1**.

Table 1. controller parameters

Parameters	**a**	**b**	**c**	α	β
Value	0.08	1.8	10000	1	1

With the $\mathrm{h}_1(s_i)$ of eq. (15) as the $sign(s_i)$ in sliding mode control law introduced in eq. (9), the angular velocity of each robot is computed. In this equation, a constant $K_i(\mathbf{X})$ is considered for all the agents.

$$\omega_i = -5 \tanh(s_i) \tag{16}$$

Eqs. (4) and (16) as control laws and $T_s = 0.25s$ (sampling time) has been used in the simulations and the results are shown in Figure 2 and Figure 3.

Figure 2 shows the aggregation of swarm and its agents' path to aggregate. It shows the Initial position of each agent in blue and the final in red and their path in solid blue lines.

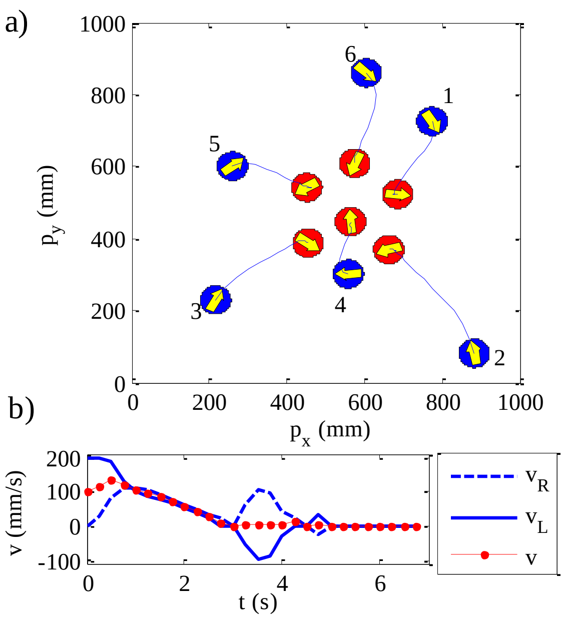

Figure 2. Aggregation. a) agents' trajectories b) agent 1 velocities

According to eq. (11) and the parameters which has been stated in Table 1, robots equilibrium distance should be equal to 176mm which is obvious in Figure 2. Figure 2 shows the linear velocities of the right and left wheels and the center of mass of agent one. The aggregation is achieved successfully and the velocities of the agents get zero eventually. As we know there is a dead zone and saturation in the velocity characteristics of the DC motors. In the simulation the velocities lower than 20mm/s is mapped to zero and velocities upper than 200mm/s is mapped to 200mm/s.

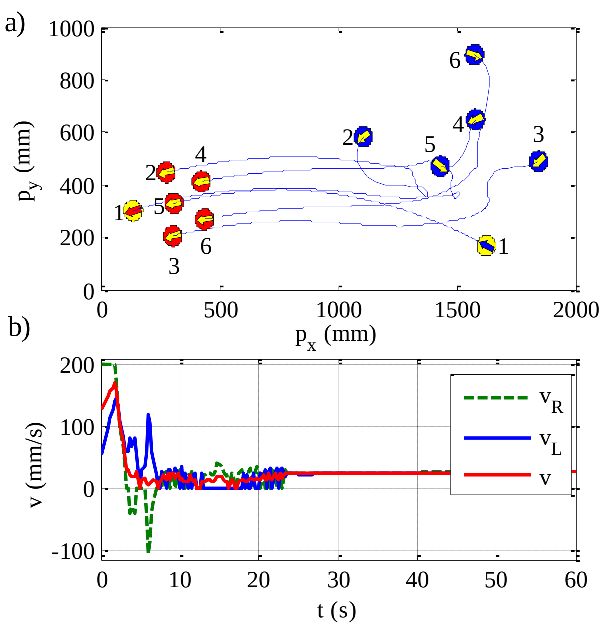

Figure 3. Leader following. a) agents' trajectories b) agent 2 velocities

Figure 3 shows the leader following simulation results. In this simulation, the agent one has to move in a pre-specified circular path. In this way, the right and left wheels should have different velocities. In this simulation these velocities are equal to 26mm/s and 25mm/s, respectively. Therefore the radius of the generated path will become approximately 2 meters. Other agents try to follow its motion and to keep their equilibrium distance from others. In Figure 3 the agents and their trajectories in the 2D space are depicted. Figure 3 shows the linear velocities of the wheels and center of mass of the second agent.

Experimental Results

In this section the mentioned missions has been applied to the swarm robots designed and fabricated in the control laboratory of mechanical department of Sharif University of Technology [8] (Figure 4).

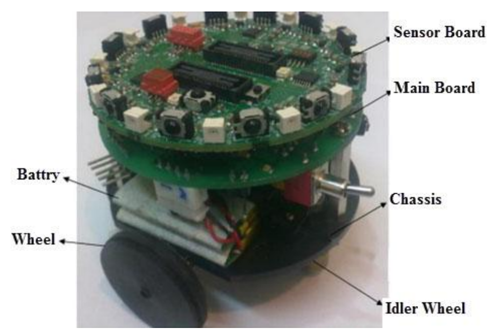

Figure 4. View of swarm robots' agent

The angular velocities of the right and left wheels of robots can be calculated as follows

$$\omega_{R_i} = \frac{v_i}{r} + \frac{d}{2r}\omega_i \qquad (17)$$
$$\omega_{L_i} = \frac{v_i}{r} - \frac{d}{2r}\omega_i$$

Where r is the wheels' radius and d is the axel length.

The robots has equipped with two electronic boards that have a connection with each other. The dSPIC30F6014a microcontroller as the main processor and an e-puck range and bearing sensor [9] are used to calculated the relative distance d_j and relative angle β_j of jth agent with respect to itself via infrared signals as shown in Figure 5.

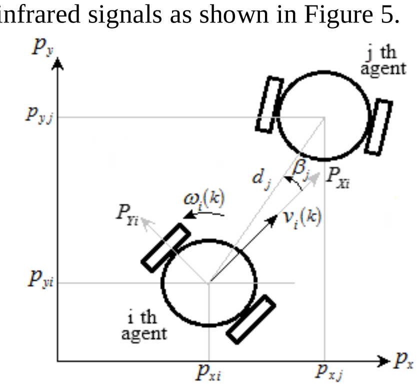

Figure 5. Robots sensor measurement and relative coordinates

P_{Xi} and P_{Yi} are relative coordinates of the ith robot and k is number of sample time. In this relative coordinates:

$$\nabla_{\mathbf{X}_i} J = -\sum_{j=1, j\neq i}^{N} d_j \times \begin{bmatrix} \cos\beta_j \\ \sin\beta_j \end{bmatrix}^T \left[a - b\exp\left(-\frac{d_j^2}{c} \right) \right] \tag{18}$$

$$v_i(k+1) = \left\| \nabla_{\mathbf{X}_i} J \right\| \tag{19}$$

$$s_{\theta_i} = -\angle\left(-\nabla_{\mathbf{x}_i} J(\mathbf{X}) \right) \tag{20}$$

$$s_i = \mathrm{mod}\left(s_{\theta_i} + \pi, 2\pi \right) - \pi \tag{21}$$

$$\omega_i(k+1) = -K_i \tanh\left(s \times s_i \right) \tag{22}$$

Gradient of potential function with respect to relative coordinates of the ith robot compute from eq. (18). Error of steering angle and sliding mode function for the ith robot compute from eqs. (20) and (21) respectively. Velocity and angular velocity of each robot in the next sample time computed from eqs. (19) and (22).

The control algorithm is coded with MPLAB software to the microcontroller of the robots and the experiments show satisfactory results. Figure **6** shows the aggregation of the robots and their successful reaching to the equilibrium condition.

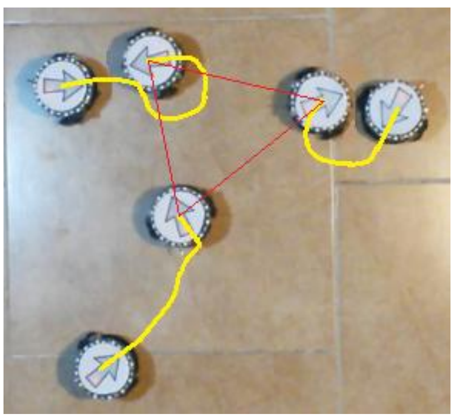

Figure 6. Aggregation of three robots

Figure **7** and Figure **8** shows the leader following of two and three robots, respectively. Trajectory of the leader is shown in red and the others in yellow. These trajectories show that this mission is done successfully.

Figure 7. Leader following of the two robots

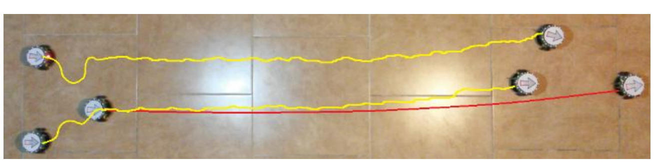

Figure 8. Leader following of the three robots

It should be noted that the unacceptable transient behavior of the follower robots at the beginning is due to the sensors misreading at a few first sample times.

Conclusion

In this paper the aggregation and leader following missions of a swarm robots has been considered and a control algorithm has been designed. The control algorithm is based on the potential function and sliding mode control theory. The main idea behind the control algorithm is to force the robots to move in such that the total amount of the potential function decreases. The results shows the satisfactory behavior both in simulation and experiments.

References

[1] Gazi, Veysel, and Raúl Ordónez. "Target tracking using artificial potentials and sliding mode control." International Journal of Control 80, no. 10 (2007): 1626-1635.

[2] Yao, Jingyi, Raul Ordonez, and Veysel Gazi. "Swarm tracking using artificial potentials and sliding mode control." Journal of Dynamic Systems, Measurement, and Control 129, no. 5 (2007): 749-754.

[3] Koksal, M. I., Veysel Gazi, Barıs Fidan, and Raúl Ordónez. "Tracking a maneuvering target with a non-holonomic agent using artificial potentials and sliding mode control." In 16th Mediterranean Conference on Control and Automation, pp. 1174-1179. 2008.

[4] Gazi, Veysel, Bariş Fİdan, Y. Sinan Hanay, and İlter Köksal. "Aggregation, foraging, and formation control of swarms with non-holonomic agents using potential functions and sliding mode techniques." Turkish Journal of Electrical Engineering & Computer Sciences 15, no. 2 (2007): 149-168.

[5] Guldner, Jurgen, and Vadim I. Utkin. "Sliding mode control for an obstacle avoidance strategy based on an harmonic potential field." In Decision and Control, 1993., Proceedings of the 32nd IEEE Conference on, pp. 424-429. IEEE, 1993.

[6] Guldner, Jurgen, and Vadim I. Utkin. "Stabilization of non-holonomic mobile robots using Lyapunov functions for navigation and sliding mode control." In Decision and Control, 1994., Proceedings of the 33rd IEEE Conference on, vol. 3, pp. 2967-2972. IEEE, 1994.

[7] Guldner, Jürgen, and Vadim I. Utkin. "Sliding mode control for gradient tracking and robot navigation using artificial potential fields." Robotics and Automation, IEEE Transactions on 11, no. 2 (1995): 247-254.

[8] Shahsavari, B. " Design and fabrication of two agents of swarm robots." BSc diss., Sharif University of Technology, 2011 (In Persian).

[9] Gutiérrez, Álvaro, Alexandre Campo, Marco Dorigo, Jesus Donate, Félix Monasterio-Huelin, and Luis Magdalena. "Open e-puck range & bearing miniaturized board for local communication in swarm robotics." In Robotics and Automation, 2009. ICRA'09. IEEE International Conference on, pp. 3111-3116. IEEE, 2009.