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A Leader-following Formation Control of Multiple Mobile Robots with Obstacle*

Jing Luo, Cheng-Lin Liu and Fei Liu

Key Laboratory of Advanced Process Control for Light Industry (Ministry of Education)
Institute of Automation, Jiangnan University, Wuxi, 214122, China

liucl@jiangnan.edu.cn

***Abstract* - By combining the Polar Histogram obstacle avoidance method, a leader-follower coordination formation control algorithm is proposed to solve the formation control problem of multiple mobile robots. Based on the formation control in leader-follower structure, a virtual-follower robot is introduced, and the formation control problem can be regarded as the follower robots tracking the virtual-follower robot. With the sensor technology, the corresponding path for robot movement strategy is provided in a simple or complicated environment so as to achieve the purpose of real-time navigation. With two-wheel differential robot Qbot as the investigation object, semi-physical simulation platform is built for simulation experiments. The simulation results show that the method can effectively achieve the coordination formation and obstacle avoidance control of multi-robot system.**

Index Terms* - *multiple mobile robots, leader-follower formation, obstacle avoidance.

I. INTRODUCTION

With the development of robot technology, network communication technology and automatic control technology, research on coordination control of multiple mobile robots system has attracted many researchers attention in recent years and shown its broad application prospect in the military, space exploration, traffic control, medical, service industry and other fields [1]. Formation control is one of the most basic and important research issues of coordinated control problems in multiple robots system. The so-called multiple robots formation control mean that the multiple robots maintain the desired formation and adapt to environmental constraints (such as the presence physical obstructions or space limitations) in the process of arriving at destination [2].

The robots in formation control mainly include: ground mobile robots [3-4], unmanned aerial vehicles [5-6], satellite [7] and autonomous underwater vehicles [8-9], etc. To realize the expected formation shape, effective control algorithms mainly include: behavior-based method [3-4], virtual-structure method [10-12] and leader-follower method [13-15]. In addition, for multiple mobile robots system, the obstacle avoidance problem is also an important problem considered in the formation. In the environment with obstacles, the obstacle avoidance control for formation control of multiple mobile robots becomes more complicated, because mobile robots not only maintain the overall formation, but also avoid obstacles reasonably. For the robot obstacle avoidance problem in a known environment, there are many effective solutions, such as potential field method, grid method, neural network method, etc. In [16] the avoidance control is designed according to the vehicle's acceleration limits to compensate for lags in the vehicle's reaction time, and the performance is evaluated and validated via simulation and experimental tests. A biologically inspired neural network approach to real-time complete coverage path planning of cleaning robots is proposed which is capable of autonomously planning collision-free paths for cleaning robots in a nonstationary environment [17]. A dynamic grids algorithm and a dynamic obstacle avoidance algorithm are proposed which include the position-forecasting and obstacle checking and controlling methods [18]. A feedback controller using potential functions is proposed that makes a two wheeled mobile robot converge to a desired point among obstacles such as a flat wall and a pillar [19]. Since the potential field method is simple and easy to achieve real-time control, the potential field method has been widely used, especially for handling obstacle avoidance problem. The design of potential field function is more difficult for the drawback in terms of local minimum points, which make the desired formation cannot be achieved [20].

Based on sensor technology of the mobile robot, a leader-follower coordination formation control algorithm is proposed to solve the formation control problem of multiple mobile robots. In addition, in order to make the formation and obstacle avoidance of multiple mobile robots successfully, we adopt a polar histogram obstacle avoidance algorithm, which searches for the safest direction of navigation using polar density of obstacles. The obstacle avoidance strategy effectively avoids the problem of local minimum points existing in the potential field method.

II. TWO-WHEEL DIFFERENTIAL ROBOT MODEL

This paper studies Quanser's mobile robot named Qbot, which belongs to two-wheel differential robot. A differential drive mobile robot consists of two driving wheels, of which each wheel can be controlled independently to drive the robot either in forward or backward direction, an omni-directional wheel and a supporting wheel. When there exist differences between velocities of two driving wheels, the robot must rotate about a point that lies along the common left and right wheel axis. The point that robot rotates about is known as the ICC (Instantaneous Center of Curvature), as shown in Fig. 1. The trajectory of robot can be controlled by changing the velocities of two driving wheels. The robot states are

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represented by the left and right driving wheel midpoint coordinates (x, y) and the heading angle θ .The following equations establish a relation between the motion parameters of a differential drive mobile robot.

$$\begin{aligned} V_{\mathrm{r}} &= \omega(R + \mathrm{d}/2) \\ V_{\mathrm{l}} &= \omega(R - \mathrm{d}/2) \end{aligned} , \tag{1}$$

where d is the distance between the centers of two wheels, V_{r} and V_{l} are the velocities of right and left wheel along the ground, and R is the signed distance from the ICC to the midpoint between two driving wheels. ω is the rotation rate of robot about the ICC, and V is the robot's linear velocity.

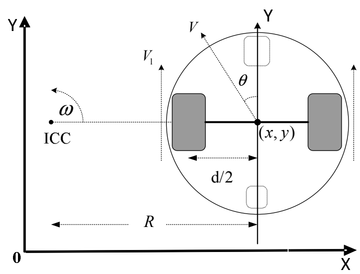


Fig. 1 Two-wheel differential robot

Equation 1 can be solved at any instance of time for R , ω and V as follows:

$$\begin{aligned} R &= \mathrm{d}(V_{\mathrm{r}} + V_{\mathrm{l}}) / 2(V_{\mathrm{r}} - V_{\mathrm{l}}) \\ \omega &= (V_{\mathrm{r}} - V_{\mathrm{l}}) / \mathrm{d} \\ V &= (V_{\mathrm{r}} + V_{\mathrm{l}}) / 2 \end{aligned} . \tag{2}$$

A. Robot's pose relative to its initial position

Robot's forward kinematics describes the relationship between velocities and position [21]. For a nonholonomic robot, motion equations of robot moving in a particular direction $\theta(t)$ with a given velocity $V(t)$ are described as:

$$\begin{aligned} x(t) &= \int_0^t V(t)\cos[\theta(t)]\mathrm{d}t \\ y(t) &= \int_0^t V(t)\sin[\theta(t)]\mathrm{d}t \\ \theta(t) &= \int_0^t \omega(t)\mathrm{d}t \end{aligned} . \tag{3}$$

Thus, the robot's pose at $t + \delta t$ is determined by:

$$\begin{bmatrix} x^* \\ y^* \\ \theta^* \end{bmatrix} = \begin{bmatrix} x + V\cos(\theta)\delta t \\ y + V\sin(\theta)\delta t \\ \theta + \omega\delta t \end{bmatrix} . \tag{4}$$

Where (x, y, θ) and (x^*, y^*, θ^*) are robot's pose at t and $t + \delta t$, respectively. For a differential driven robot, (4) becomes:

$$\begin{bmatrix} x^* \\ y^* \\ \theta^* \end{bmatrix} = \begin{bmatrix} x + (V_{\mathrm{r}} + V_{\mathrm{l}})\cos(\theta)\delta t / 2 \\ y + (V_{\mathrm{r}} + V_{\mathrm{l}})\sin(\theta)\delta t / 2 \\ \theta + (V_{\mathrm{r}} - V_{\mathrm{l}})\delta t / \mathrm{d} \end{bmatrix} . \tag{5}$$

(5) shows that the robot's trajectory is determined by the left and right wheels' velocities V_{l} and V_{r} . Hence, we achieve formation control by controlling V_{l} and V_{r} of the robot.

III. LEADER-FOLLOWER COORDINATION FORMATION CONTROL STRUCTURE

In the formation control of multiple mobile robots, selecting desired formation is very important, and reasonable formation play an important role on the efficiency of completing tasks. The basic formations of multiple mobile robots are column, line, triangle and wedge (see Fig. 2). Many other formations can be formed by the change of the several basic formations [22].

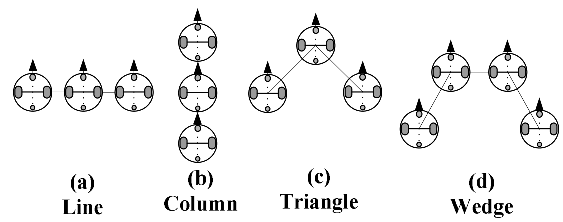


Fig. 2 Formations of multiple mobile robots

The leader-follower formation control method comes from Balch and Arkin, who designate one or more robots as the leader, other robots as followers tracking the navigation robot.

There are two kinds of kinematics model for leader-follower formation, i.e., $l - l$ and $l - \varphi$ [23]. The $l - l$ method requires at least three robots in which the following robots follow the two navigation robots with a fixed distance and maintain the desired formation. The $l - \varphi$ formation means that the followers track the leader robot with a certain distance and angle to implement the desired formation control.

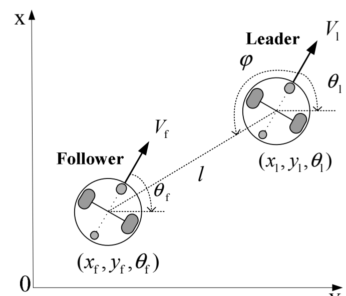


Fig. 3 Leader-follower formation structure model

As shown in Fig. 3, the aim of $l - \varphi$ formation control is to make $\lim_{t\to\infty}(l_d - l) = 0$ and $\lim_{t\to\infty}(\varphi_d - \varphi) = 0$, where l_d and φ_d are the desired values of the separation and relative bearing between the leader and follower robots. l and φ stand for the measured values of l_d and φ_d respectively.

Hence, if the position and direction of leading robot is given and l and φ are known, the position of following robots are determined.

In this paper, the virtual-following robot is introduced based on the $l - \varphi$ formation control and the virtual-following robot maintain the desired structure with the leading robot. Therefore, the desired formation can be achieved, as long as the following robot moves to the virtual-following robot's position. In Fig. 4, $(x_{\mathrm{l}}, y_{\mathrm{l}}, \theta_{\mathrm{l}})$ and $(x_{\mathrm{f}}, y_{\mathrm{f}}, \theta_{\mathrm{f}})$ denote the poses of leader and follower, respectively. l and φ are the distance and relative bearing between the follower and the leader, and we can get the virtual-following robot pose (x_v, y_v, θ_v) as:

$$\begin{aligned} x_v &= x_l + l\cos(\theta_l + \varphi) \\ y_v &= y_l + l\sin(\theta_l + \varphi) \\ \theta_v &= \theta_l \end{aligned} \quad . \tag{6}$$

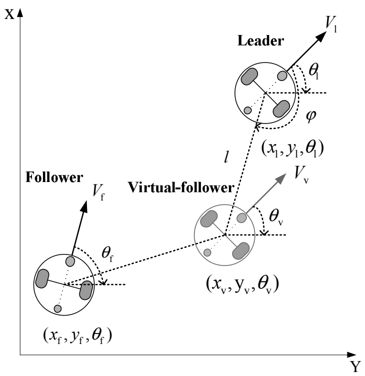


Fig. 4 Leader-virtual follower formation structure model

By introducing virtual-following robot, the formation control problem is converted to a tracking control problem that the follower robot tracks the virtual-follower robot.

IV. Selection of Obstacle Avoidance Algorithm

The motion environment of multiple mobile robots often changes in real time, so robots need to rely on sensors to sense the external environment and their own position information, and communicate with each robot for avoiding obstacles to reach the destination ultimately. The obstacle avoidance method based on sensors behavior can make timely response to the unknown obstacle environment. Now, the popular obstacle avoidance algorithm is based potential field method.

A. Potential field method and its problems

Potential field method employs virtual force fields generated by the obstacles and the target. Each obstacle point within the sensory perception exhibits a repulsive force and the target produces an attractive force. Hence, the weighted vector summation of the force fields generates the desired navigation heading.

For the traditional potential field method, the local minimum problem and repeated oscillation problem near the obstacles may occur [20]. Some reasons lead to these problems. On the one hand, when the robot coincides with obstacles and the target point in a straight line at some point, there may be attractive and repulsive force balance, and the trend of robot's movement cannot be sure. Robots will remain stationary and get trapped in local minimum at this moment. On the other hand, if the resultant force is out of balance, the repeated oscillation of robot occurs and robot hits obstacles eventually. The above problems will influence the success of desired formation convergence of multiple mobile robots.

To solve the problems existing in potential field method, we introduce polar histogram obstacle avoidance method using polar density of obstacles [24].

B. Polar histogram obstacle avoidance method

This method searches for the safest direction of navigation by using polar density of obstacles. For example, the polar density of obstacles can be determined by taking weighted average of the inverse of range data (i.e., distance to the obstacles) at each orientation of the sensors. We select the direction of the minimum density as the safest navigation direction of robot. The following figure demonstrates an example where Fig. 5(a) shows the range data obtained from sensors directed at 0^o, 45^o, 90^o, 135^o, and 180^o.

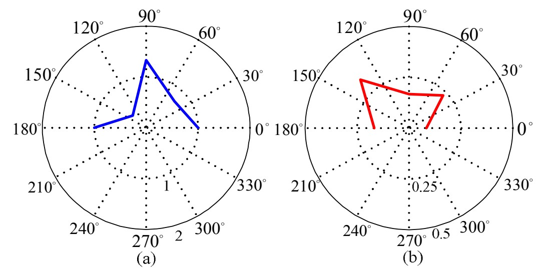


Fig. 5 Polar plots of range data and obstacle density

Fig. 5(b) shows the corresponding polar obstacle density (POD), which is calculated as:

$$\begin{aligned} POD_i &= w_1 f(d_{i-1}) + w_2 f(d_i) + w_3 f(d_{i+1}) \\ f(d_i) &= [1 - \min(d_{th}, d_i)/d_{th}]^2 \end{aligned} \quad , \tag{7}$$

$$\hat{i} = \arg\min POD_i, i = 1, \ldots, 5 \ . \tag{8}$$

Where, $i = 1, \ldots, 5$ denotes the i^{th} sensor, which is directed at $(i-1)\times 45^o$ and d_i denotes the obstacle distance obtained from the i^{th} sensor. The maximum sensor range is defined by d_{th}. $f(d_i)$ denotes obstacle density obtained from the i^{th} sensor. w_1, w_2 and w_3 denote weight factors ($w_1 + w_2 + w_3 = 1.0$), and $w_2 > w_1, w_2 > w_3$ means that the obstacle density value in a certain direction is affected by the sensor obstacle density value on this direction is greater than that on the other two directions. Equation (8) signifies that the direction of $(\hat{i}-1)\times 45^o$ is the safest direction of robot navigation. Here, $\hat{i}$ is equal to the value of i, when POD_i is the minimum value. Equation (7) uses $w_2 = 0.6667$, $w_1 = w_3 = 0.1667$, $f(d_0) = f(d_6) = 0$ and $d_{th} = 1.5\text{m}$. Hence, the robot finds 0^o as the safest direction to navigate through obstacles. Without obstacles, the robot moves towards the target location. According to the above description, this method can effectively avoid the local minimum and repeated oscillation problems occurred in potential field method.

V. The Simulation Results and Analysis

To validate the actual effectiveness of the algorithm, this paper takes Qbot developed by iRobot Create robotic platform as the research object. There are five infrared sensors mounted on the 0^o, 45^o, 90^o, 135^o and 180^o directions of the Qbot, as shown in Fig. 6. We build Quanser unmanned vehicle systems (UVS) simulation platform and conduct semi-physical simulation experiment.

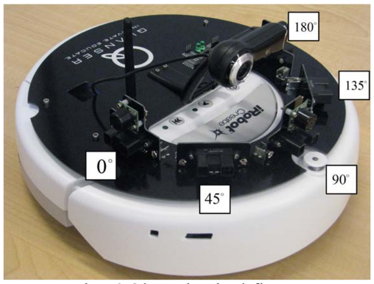


Fig. 6 Qbot physical figure

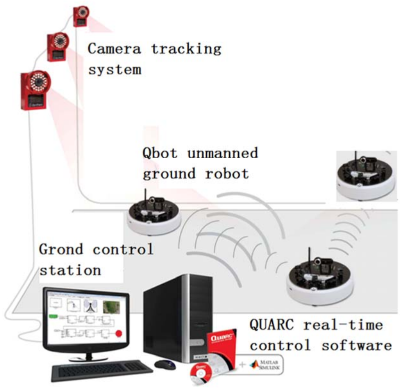


Fig. 7 Quanser Unmanned Vehicle Systems

A. *Quanser unmanned vehicle systems*

Quanser unmanned vehicle systems in Fig. 7 consist of: Qbot unmanned ground robot, ground control station, camera tracking system, QUARC real-time control software and multi-agent task development system.

QUARC real-time control software is a rapid control development environment with Matlab/Simulink that provides interfaces to Qbot. The UVS is operated from a single PC or laptop, also known as the ground control station, which can implement positioning and control of the robots. Qbot is autonomous mobile robot developed by iRobot Create robotic platform. The Qbot has five infrared sensors, which can be used to detect obstacles, and the maximum detection range is 150cm. Camera tracking system consists of eight infrared cameras connected to the ground control station. The system allows robots workspace positions to be accurately measured, which is critical for autonomous navigation and control.

B. *experimental principles*

The system uses Host-Target mode to carry out real-time control. The controllers are developed in Simulink with QUARC on the host computer, and then downloaded and compiled into executables on the mobile robot target to realize real-time control. Hence, the host can control multiple robot targets simultaneously. Each mobile robot is equipped with three markers reflecting infrared light which are visible to infrared cameras mounted on the wall. The infrared cameras can capture the position and orientation of the robot, and then the pose (x, y, θ) can be transmitted to each mobile robot through wireless network in real time. To achieve desired formation, the followers track the leader at a pre-specified distance with the pre-designed algorithm. The leader robot detects obstacles and uses polar histogram avoidance control strategy to avoid obstacles.

C. *algorithm steps*

The first step, the tracking path of the leader robot is designed on the host, and wireless local area network is established.

The second step, the host sends poses information captured by camera tracking system to the leader and follower robots in real time, and the tracking path command pre-designed on the host is sent to the leader robot.

The third step, the leader robot receiving the pose measurements and the tracking path pre-designed on the host runs to the target point. When the obstacles are detected by infrared sensors of the robot, the leader uses the designed algorithm of obstacle avoidance to avoid obstacles, and then continues to run to the target point after passing obstacles. At the same time, the leader robot is responsible for generating virtual-follower robot trajectory for the follower robot to follow according to the $l-\varphi$ control method.

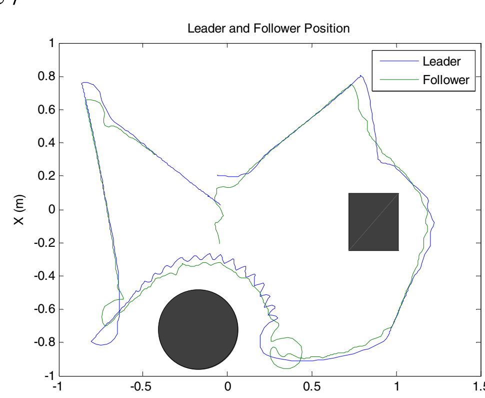
The fourth step, the follower robot receives pose measurements from the host and the virtual-follower robot trajectory from the leader robot in real time. The follower robot will follow the leader robot along the virtual-follower robot trajectory and realize the formation control.

D. *simulation experiment and result analysis*

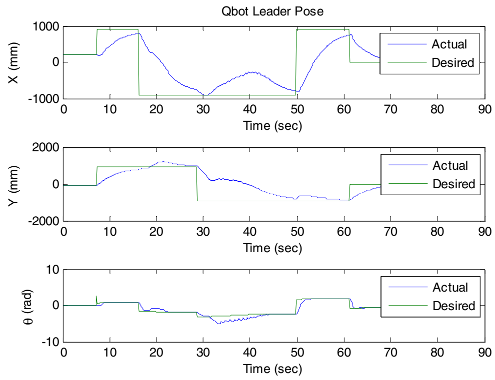
The simulation environment with $3\text{m}\times 3\text{m}$ experimental workspace is constructed. We perform two robots obstacle avoidance control experiment of column formation and three robots triangle formation experiment to avoid obstacles by transforming the formation, respectively. We set the Qbot's infrared sensor detection range $d_{\text{th}} = 0.4\text{m}$, control cycle T=0.1s, and the distance between the two driving wheels of Qbot d=252.5mm.

Experiment 1: two Qbots obstacle avoidance control experiment of column formation.

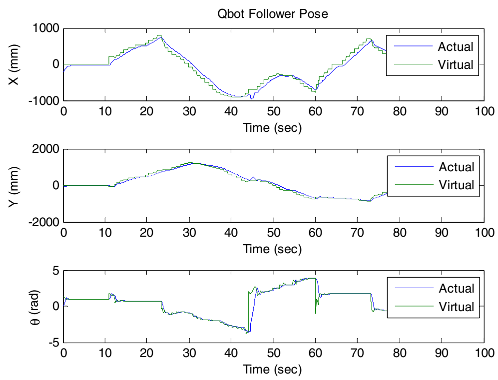
On host computer, we design trajectory that the leader robot R_1 move from any initial position, via intermediate points (0.9, 0.9), (-0.9, 0.9), (-0.9, -0.9) and (0.9, -0.9) to the target point (0, 0). The circular and rectangular obstacles are placed in the path. The follower robot R_f tracks the leader robot R_1 with the desired separation $l = 0.4\text{m}$ and relative bearing $\varphi = 180^\circ$ in column formation.



(a) Formation trajectories



(b) Qbot leader pose



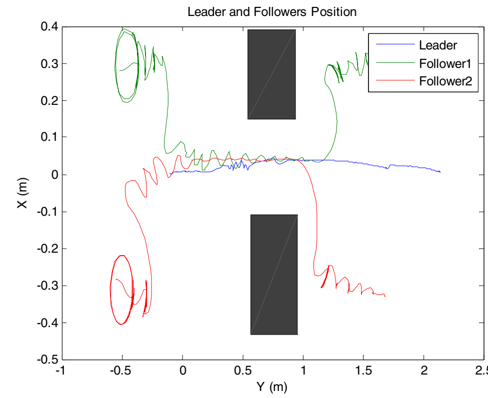
(c) Qbot follower pose

Fig. 8 Two robots column formation control experiment

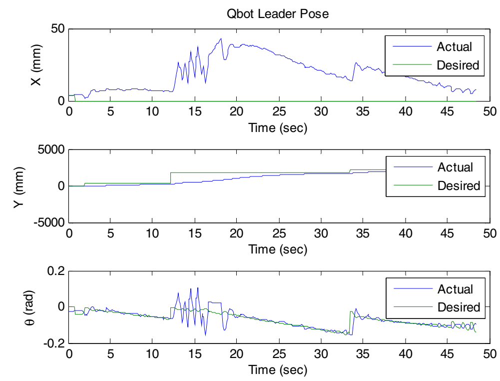
Formation trajectories are shown in Fig. 8(a). The follower robot R_f follows the leader robot R_l to avoid obstacles and reach the target point successfully. The leader robot trajectory is the desired trajectory for the follower robot to follow. The pose of leader robot R_l is shown in Fig. 8(b), and the leader robot R_l tracking points (0.9, 0.9), (-0.9, 0.9), (-0.9, -0.9) and (0.9, -0.9) eventually reaches the target point (0, 0). There is error when encountering obstacles, but with the formation of forward, tracking error tends to zero. The pose of follower robot R_f is shown in Fig. 8(c). The follower robot R_f tracks virtual-follower robot trajectory generated by the leader robot R_l with smaller error and completes the trajectory tracking control.

Experiment 2: 3 robots triangle formation experiment to avoid obstacles by transforming the formation.

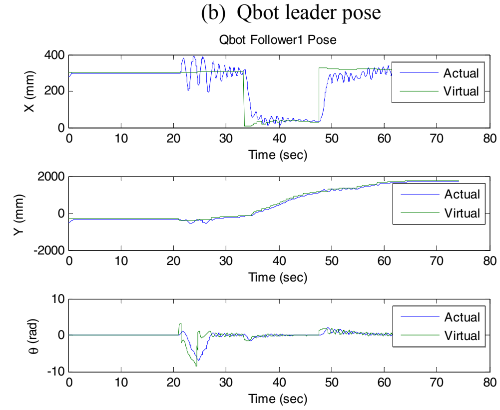
We design the leader robot R_l from the initial position (0, 0), via intermediate points (0, 0.6) and (0, 1.6) and eventually reach the target point (0, 2.2). The virtual-follower robots R_{v1} and R_{v2} are introduced to maintain desired distances 0.4m, 0.4m and desired angle 135^0, -135^0 with respect to the leader R_l. The follower robots R_{f1} and R_{f2} track virtual-follower robots R_{v1} and R_{v2}, respectively.



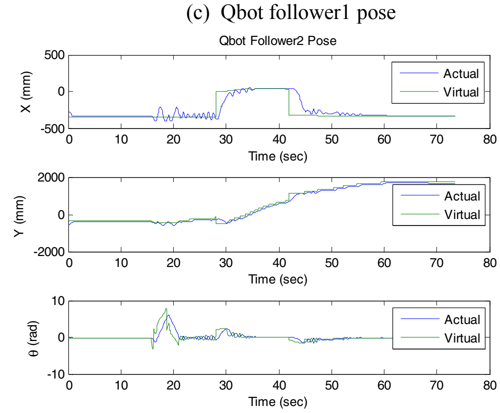
(a) Formation trajectories



(b) Qbot leader pose



(c) Qbot follower1 pose



(d) Qbot follower2 pose

Fig. 9 Three robots triangle formation control experiment

Formation trajectories are shown in fig. 9(a). The initial formation of robots is triangle formation, and then changes into column formation when the leader robot R_1 detects obstacles. After completing obstacle avoidance, formation returns to the previous triangle formation reaching the target point (0, 2.2). The pose of the leader robot R_1 is shown in Fig. 9(b). The leader robot R_1 tracks points (0, 0.3) and (0, 1.8) and eventually reaches the target point (0, 2.2). The leader robot deviates from the track points, while detecting obstacles, but tracking error converge to zero along the time coordinate. The poses of follower robots R_{f1} and R_{f2} as shown in Fig. 9(c) and (d), the follower robots R_{f1} and R_{f2} track the trajectories of the virtual-follower robots R_{v1} and R_{v2} with smaller tracking error and complete the trajectory tracking control.

From the above experiments, the robots' team autonomously transforms formation according to environmental constraints, and then restore to the initial formation after obstacle avoidance to complete formation control of multiple mobile robots.

VI. Conclusion

In this paper, we propose a formation control algorithm for multiple mobile robots in obstacle environment with two-wheel differential robots as the research object. The proposed method through infrared sensors equipped on the leader autonomous perception for external environment information uses the leader–follower approach and polar histogram obstacle avoidance approach to guide the robots' team to avoid obstacle intelligently, and realizes the obstacle avoidance control of multiple mobile robots formation. The semi-physical simulation experiments of the column formation and triangle formation have been conducted on Quanser unmanned vehicle systems. Simulation results demonstrate the effectiveness of the proposed method. To complete formation control of multiple mobile robots, evidently, the robots' team not only keeps the formation, but also transforms formation to avoid obstacles according to the external obstacles.

References

[1] A. Farinelli, L. Locchi , and D. Nardi, "Multirobot systems: A classification focused on coordination," *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, vol. 34, no. 5, pp. 2015-2028, October 2004.

[2] T. Arai, E. Pagello, and L. Parker, "Guest editorial advances in multirobot systems," *IEEE transaction on Robotics and Automation*, vol. 18, no. 5, pp. 655-661, October 2002.

[3] B. Tucker and C. Ronald, "Behavior-based formation control for multirobot teams," *IEEE Transactions on Robotics and Automation*, vol. 14, no. 6, pp. 926-939, 1998.

[4] F. Yang, S. Liu, and D. Dong, "Robot behavior and service-based motion behavior structure design in formation control," *Robot*, vol. 34, no. 1, pp. 120-128, January 2012.

[5] M. Song, R. Wei, and D. Shen, et al, "UAV formation control based on nonlinear dynamic inversion," *Control and Decision*, vol. 26, no. 3, pp. 448-452, March 2011.

[6] S. Li, Y. Chen, and Z. Yang, et al, "Formation fight control of multi-UAVs with communication delay," *Information and Control*, vol. 41, no. 2, pp. 142-146, April 2012.

[7] J. Wu , K. Liu, and D. Han, et al, "Optimized tracking control for attitude and orbit of satellite formation flying using dual quaternion," *Control Theory & Applications*, vol. 30, no. 9, pp. 1069-1078, September 2013.

[8] Y. Wang, W. Yan, and J. Li, "Passivity-based formation control of autonomous underwater vehicles," *IET Control Theory & Applications*, vol. 6, no. 4, pp. 518-525, March 2012.

[9] Y. Wang and W. Yan, "Consensus formation tracking control of multiple autonomous underwater vehicle systems," *Control Theory & Applications*, vol. 30, no. 3, pp. 379-384, July 2013.

[10] R. Wei and S. Nathan, "Distributed coordination architecture for multirobot formation control," *Robotics and Autonomous Systems*, vol. 56, no. 4, pp. 324-333, April 2008.

[11] G. Jawhar, M. Hasan, and S. Maarouf, "Formation path following control of unicycle-type mobile robots," *Robotics and Autonomous Systems*, vol. 58, no. 5, pp. 727-736, May 2010.

[12] M. Hasan, G. Jawhar, and S. Maarouf, "Nonlinear coordination control for a group of mobile robots using a virtual structure," *Mechatronics*, vol. 21, no. 7, pp. 1147-1155, October 2011.

[13] C. Luca, M. Fabio, and P. Domenico, "Leader-follower formation control of nonholonomic mobile robots with input constraints," *Automatica*, vol. 44, no. 5, pp. 1343-1349, May 2008.

[14] J. Shao, G. Xie, and L. Wang, "Leader-following formation control of multiple mobile vehicles," *IET Control Theory and Applications*, vol. 1, no. 2, pp. 545-552, March 2007.

[15] L. Yang, Z. Cao, and M. Tan, "Dynamic formation control for multiple robots in uncertain environments," *Robot*, vol. 32, no. 2, pp. 283-288, February 2010.

[16] E J Rodríguez-Seda, C Tang, and M W Spong, et al. "Trajectory tracking with collision avoidance for nonholonomic vehicles with acceleration constraints and limited sensing," *The International Journal of Robotics Research*, vol. 33, no. 12, pp. 1569-1592, August 2014.

[17] S. Yang and C. Luo, "A neural network approach to complete coverage path planning," *IEEE Transactions on Systems, Man, and Cybernetics Part B: Cybernetics*, vol. 34, no. 1, pp. 718-725, February 2004.

[18] P. Tang, Q. Zhang, and Y. Yang, "Studying on path planning and dynamic obstacle avoiding of soccer robot," in *Proceedings of the 3rd World Congress on Intelligent Control and Automation*, Hefei, China, 2000, pp. 1244-1247.

[19] U. Takateru, O. Kenji, and T. Yukio, "Feedback control of a two wheeled mobile robot with obstacle avoidance using potential functions," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sendai, Japan, 2004, pp. 2428-2433.

[20] T. Yang, Z. Liu, and H. Chen, "Formation control of mobile robots: state and open problems," *CAAI Transactions on Intelligent Systems*, vol. 2, no. 4, pp. 21-27, April 2007.

[21] G. Dudek and M. Jenkin, *Computational Principles of Mobile Robotics*, Cambridge university press, 2010.

[22] R. Zhang, S. Li, and Q. Chen, et al, "Formation control for a kind of nonholonomic mobile robots," *Control and Decision*, vol. 28, no. 11, pp. 1751-1755, November 2013.

[23] J. Desai, J. Ostrowski, and V. Kumar, "Controlling formations of multiple mobile robots," in *Proceedings of IEEE International Conference on Robotics and Automation*, Leuven, Belgium, 1998, pp. 2864-2869.

[24] I. Ulrich and J. Borenstein, "VFH+: Reliable obstacle avoidance for fast mobile robots," in *Proceedings of IEEE International Conference on Robotics and Automation*, Leuven, Belgium, 1998, pp. 1572-1577.