Proceedings of the 38th Chinese Control Conference
July 27-30, 2019, Guangzhou, China

A Hybrid Formation Control Design for Multi-Robot System with Obstacle Avoidance

Shiguang Wu [1,2], Zezhi Sui [1,2], Jianqiang Yi [1,2], Zhiqiang Pu [1,2]

1. School of Artificial Intelligence, University of Chinese Academy of Sciences, Beijing 100049, China

2. Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China
E-mail: {wushiguang2017, suizezhi2015, jianqiang.yi, zhiqiang.pu}@ia.ac.cn

Abstract: The formation control of multi-robot systems in complex environments is a challenging problem, which needs to handle velocity estimation and obstacle avoidance problems. However, few researches considered these problems simultaneously in the literature. In this paper, a leader-follower hybrid formation control design for multi-robot system is proposed, which simultaneously solves leader-follower formation control problem, velocity estimation problem, and obstacle avoidance problem. First, based on the leader-follower architecture, formation control law is designed. Second, considering the difficulty of obtaining the whole accurate velocity information, a velocity estimator of the leader is designed, and the Lyapunov function is used to analyze the stability of the multi-robot system. In addition, the artificial potential field (APF) method is adopted to avoid obstacles in complex environments. Finally, an experimental platform of the multi-robot system is constructed, and simulation and experimental results verify the effectiveness performance of the leader-follower hybrid formation control design for the multi-robot system.

Key Words: multi-robot system, leader-follower, velocity estimator, artificial intelligence field

1 Introduction

In recent years, multi-robot systems have received increasing attention from researchers for its advantages, including strong robustness and high flexibility. they can reduce the complexity of a task for a single robot by decomposing the complex task to simple tasks. Even though one robot may encounter unexpected accidents, the rest of the robots can replace the abnormal robot immediately and continue to perform the task [1]. Besides, multi-robot systems include unmanned aerial vehicles (UAV), unmanned ground vehicles (UGV), and underwater vehicles [2], which have more potential in complex environments. Therefore, multi-robot systems have promising applications in different fields, such as surveillance [3], disaster rescue, object transportation, security patrols and so on.

Formation control is to realize that one robot can maintain a specific position with the other robots and accomplish given tasks, which is one of the most fundamental and critical problem in multi-robot systems. In general, there are three kinds of methods for formation control of multi-robot systems: leader-follower method, behavior-based method and virtual structure method [4]. Specifically, the behavior-based method [5] realizes distributed control, with which each robot takes actions derived by the weights of desired behaviors through clear feedbacks of the formation. However, the definition of the desired behavior cannot be described mathematically, and the stability of the formation system cannot be guaranteed. Besides, for the virtual structure method [6], the whole formation is regarded as a virtual rigid body, and the motion of each robot is determined by the relative position with the desired formation. However, the definition of a virtual rigid body

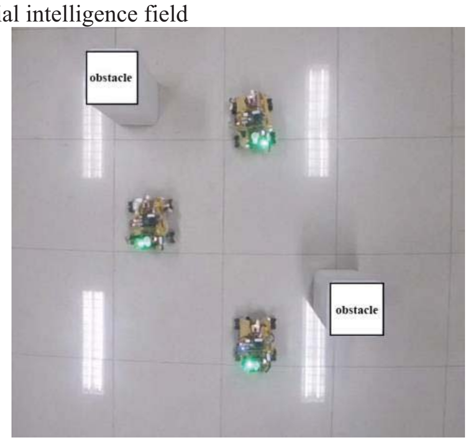


Fig. 1: Multi-robot formation

limits adaptive capacity of robots, especially in dynamic environments, which may further limit the scope of application. Moreover, with the leader-follower method [7], the followers keep a typical relative position with the leader. The formation can be determined clearly by the leader-follower method, and the stability of the formation system can be guaranteed. Therefore, the leader-follower method has been adopted by many researchers due to the advantages of simplicity and practicality.

Nevertheless, most of leader-follower formation control methods assume that the followers can obtain the velocity information of the leader [8]. In practice, there exists one problem that the velocity information of the leader is unobtainable. Therefore, how to design a velocity estimator of the leader should be taken into consideration. [9], [10] considered the velocity estimation of the formation system. [11] considers the movement of the formation in distance-based control, and proposes a distance-based adaptive formation control law for the leader-follower system, under the condition that the leader moves with a constant reference velocity in horizontal plane.

In addition, for better performance in complex environments, multi-robot systems should be able to avoid obstacles while keeping desired formations. Therefore, obstacle avoidance of multi-robot systems should be

*This work was supported in part by the National Natural Science Foundation of China under Grant 61421004, Grant 61603383, and Grant 61603384, and in part by the Beijing Advanced Innovation Center of Intelligent Robots and Systems under Grant 2016IRS23

considered. Many methods have been developed for obstacle avoidance such as trajectory planning [12], fuzzy logic [13], artificial potential field (APF) [14] and so on. Trajectory planning requires that the system needs to obtain the environmental information in advance, which may be time-consuming and burdensome in practice. Fuzzy logic is able to correct and reduce the robot motion direction errors, however, due to the difficulty in defining suitable fuzzy rules, the generated paths are not smooth enough at turning and traversing. APF realizes obstacle avoidance with resultant force, including the attractive force and repulsive force, which is simple and easy to achieve real-time control. Therefore, APF has been widely used for multi-robot systems to handle obstacle avoidance in unknown environments.

To the best of our knowledge, few researches simultaneously focus on the leader-follower formation control, velocity estimation, and obstacle avoidance problems in complex situations. Thus, in this paper, to simultaneously deal with the problems, a leader-follower hybrid formation control design is proposed. In other words, the robots switch different control methods, according to different states and environments. In particular, the leader navigates autonomously, and the followers hold desired positions with the leader. Based on this, a velocity estimator of the leader for each follower is designed, which solves the problem that the velocity information of the leader may not be acquired. Besides, to enhance the adaptive capacity of the robots, the APF method is applied to avoid obstacles. Finally, as shown in Fig. 1, here, a layered experimental platform of multi-robot system is constructed, and validates the availability of the leader-follower hybrid formation control design.

The rest of paper is organized as follows: formation control problem is given in Section 2. In Section 3, a leader-follower hybrid formation control design is presented. Afterwards, a platform and experimental results are presented in Section 4. Finally, we give the conclusions.

2 Formation Control Problem

In a general leader-follower formation architecture, there are two roles including the leader and the followers. The leader navigates autonomously, and the followers are supposed to maintain expected formation while tracking the trajectory of the leader by obtaining the states information of the leader.

In this paper, it is supposed that the motion model of each robot is a single integrator. Considering the multi-robot system with N robots, the dynamics of the i-th follower in two dimensions can be described as follows:

$$\dot{\boldsymbol{X}}_i = \boldsymbol{U}_i, i = 1, \cdots, N, \tag{1}$$

where $\boldsymbol{X}_i \in \mathbb{R}^2$ and $\boldsymbol{U}_i \in \mathbb{R}^2$ are the position vector of the follower and the control input vector of the follower, respectively. In addition, $\boldsymbol{X}_l \in \mathbb{R}^2$ and $\boldsymbol{U}_l \in \mathbb{R}^2$ are the position vector of the leader and the control input vector of the leader, respectively.

The control objective of this paper is to design a formation tracking law for each follower such that the norm of the formation error $\boldsymbol{E}_i = \boldsymbol{X}_l - \boldsymbol{X}_i - \boldsymbol{H}_i$, where $\boldsymbol{H}_i \in \mathbb{R}^2$ being a vector of the expected formation for each follower, can converge to a small neighborhood of zero, which leads to a successful formation tracking for the multi-robot system.

3 A Leader-Follower Hybrid Formation Control Design

For a complex formation control problem, it needs to simultaneously deal with leader-follower formation control, velocity estimation, and obstacle avoidance problems. Here, a leader-follower hybrid formation control design is proposed to solving the above problems.

3.1 Leader-Follower Formation Control Design

For a leader-follower formation control, the followers need to maintain expected relative positions with the leader based on obtaining the information of the leader. Since the formation control law for different dimensions is the same, here, only one-dimensional design is described. Therefore, to fascinate the formation maintaining, the formation control law for the i-th follower in one dimension can be designed as following:

$$u_i = k_{1i} e_i + \dot{x}_l - \dot{h}_i, \tag{2}$$

where k_{1i} is a positive constant, x_l , e_i and h_i are the position vector of the leader, the formation error for i-th follower, the expected formation for the i-th follower, respectively.

Consider the following Lyapunov function to analyze the stability of the formation system:

$$V = \frac{1}{2} e_i^2, \tag{3}$$

which is continuously differentiable.

Then the derivative of V with respect to time t can be easily computed as follows:

$$\dot{V} = -k_{1i} e_i^2 \le 0. \tag{4}$$

From (3) and (4), it is clear that the Lyapunov function is lower bounded and positive definite, and the derivative of V with respect to time t is negative semi-definite and uniformly continuous. By referring to Barbalat's lemma [15], $\dot{V} \to 0$ as $t \to \infty$ can be realized. Furthermore, the formation error $e_i \to 0$ as $t \to \infty$ also can be realized. Therefore, the formation can be realized by the proposed formation control law.

3.2 Velocity Estimation

In the previous section, it is assumed that the followers are capable of getting the velocity information of the leader. However, in practice, the followers may not acquire the velocity information of the leader. Therefore, a velocity estimator of the leader should be designed so that the followers can hold the desired formation while tracking the trajectory of the leader. Here, it is assumed that the leader moves with a constant velocity. In each dimension for the leader to move in v_0 , the leader-follower formation control law and the velocity estimator of the leader for the followers are given as:

$$u_i = k_{2i} e_i + \hat{v}_l - \dot{h}_i, \tag{5}$$

$$\dot{\hat{v}}_l = e_i, \tag{6}$$

where k_{2i} is a positive constant, $\hat{v}_l$ is the velocity estimator of the leader.

Consider the Lyapunov function to analyze the stability of the formation system:

$$V=\frac{1}{2}e_i^2+\| v_0-\hat{v}_l \|^2, \tag{7}$$

which is continuously differentiable.

Then the derivative of V with respect to time t can be easily computed as follows:

$$\dot{V}=-k_{2i}e_i^2 \le 0. \tag{8}$$

Based on (7) and (8), a similar result to the one in subsection can be obtained, which indicates that the velocity estimator of the leader $\hat{v}_l \to v_0$ as $t \to \infty$ and the formation error $e_i \to 0$ as $t \to \infty$ can be realized. That is to say, the velocity of the leader can be estimated and the formation can be implemented by the proposed formation control law.

3.3 Obstacle Avoidance

In the formation control, the robots need to keep the expected formation, while they should be capable of avoiding obstacles. Thus, obstacle avoidance should be taken into consideration. In detail, for the leader, it should take action to avoid obstacles when it meets obstacles, and the followers should change the relative positions with the leader when they encounter obstacles. Besides, after passing the area of obstacles successfully, the followers should reconstruct the desired formation. To handle the problem, the APF method is used to realize obstacle avoidance.

The APF [14] method is an effective method to solving obstacle avoidance. As shown in Fig. 2, the APF method is made up of the attractive force field and the repulsive force field. The attractive field is a guide for the robots to reach the destination, while the repulsive force field is adopted to avoid obstacles. Under the two fields influence, the robots are able to move to the destination without collision.

The attractive potential field $U_{att}(q)$ and the attractive force $F_{att}(q)$ to the robot q can be defined as：

$$U_{att}(q)=\frac{1}{2}\xi d^2(q,g), \tag{9}$$

$$F_{att}(q)=\xi d(q,g), \tag{10}$$

where $d(q,g)$ is the distance between the robot and the target g , ξ is an accommodation coefficient for attractive force.

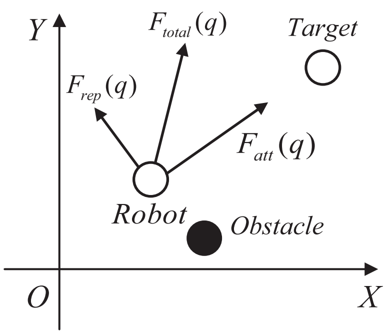


Fig. 2. Model of artificial potential field

The repulsive potential field $U_{rep_j}(q)$ and the repulsive force $F_{rep_j}(q)$ of the robot are defined as :

$$U_{rep_j}(q)=\begin{cases}\frac{1}{2}\eta(\frac{1}{d(q,obs_j)}-\frac{1}{d_0})^2 & if\, d(q,obs_j)\le d_0\\ 0 & if\, d(q,obs_j)>d_0\end{cases}, \tag{11}$$

$$F_{rep_j}(q)=\begin{cases}\eta(\frac{1}{d(q,obs_j)}-\frac{1}{d_0})^2\frac{1}{d^2(q,obs_j)} & if\, d(q,obs_j)\le d_0\\ 0 & if\, d(q,obs_j)>d_0\end{cases}, \tag{12}$$

where obs_j is the j -th obstacle, $d(q,obs_j)$ is the Euclidean distance between the robot q and the j -th obstacle, η is an accommodation coefficient for repulsive force, d_0 is a positive constant denoting the effective distance of the APF method.

From the above, the APF method combines the attractive force and the repulsive force to realize obstacle avoidance. Thus, the resultant force of the robot q in the APF is:

$$F_{total}(q)=F_{att}(q)+\sum_{j=1}^{m}F_{rep_j}(q), \tag{13}$$

where m is the numbers of obstacles. To use the APF method to avoid obstacles, the output of the formation control need to be regarded as the attractive force to guide the followers. Meanwhile, for the leader, it should track the reference trajectory.

3.4 Leader-Follower Hybrid Formation Control Design

Combining the above three subsections, the leader-follower hybrid formation control design is proposed, aiming to solve the formation control in complex environments. The proposed design handles leader-follower formation control, velocity estimation, and obstacle avoidance problems. Fig. 3 depicts the leader-follower hybrid formation control design. The robots can adjust their control laws accordingly due to different input states. In detail, first, under the situation that the velocity of the leader can be obtained for the followers, the leader-follower formation control only consists of the leader-follower formation controller (2). Secondly, when the velocity of the leader cannot be acquired, the velocity estimation controller is used to estimate the velocity of the leader so that the leader-follower formation control (5) can be realized. Finally, if the robots are in complex environments, the APF method is used to implement obstacle avoidance in the leader-follower formation control, whatever the velocity of the leader can be obtained or not. Therefore, by integrating the three parts, the leader-follower hybrid formation control can be achieved.

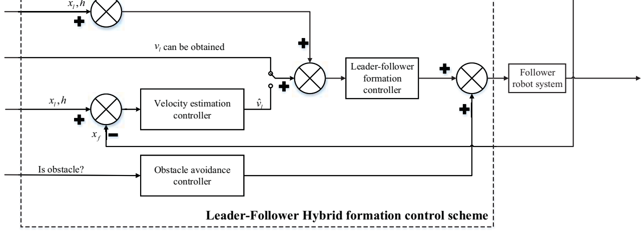


Fig. 3. Leader-follower hybrid formation control design

4 Experimental Platform and Results

In this section, the effectiveness of the leader-follower hybrid formation control design is verified by the experimental platform of the multi-robot system with simulation and experimental results. Here, the multi-robot system considers one leader and two followers.

4.1 Experimental Platform

In this section, four-wheel omnidirectional mobile robots are constructed to demonstrate the performance of the control design, which has the capacity of flexible movement. As shown in Fig. 4, (x_x, x_y, θ) denotes the robot's attitude. (x_x, x_y) presents the position of the robot in the global coordinate. θ is the heading angle of the robot. (v_x, v_y) and ω are the robot's velocity and angular velocity, respectively in the body coordinate of the robot. a and b are the distances between the center of the robot and the center of the wheel on x-axis and y-axis, respectively. v_1, v_2, v_3, v_4 are the linear speeds of the four wheels, respectively. The kinematical model is given as following:

$$\begin{aligned} v_1 &= v_y - v_x - \omega(a+b) \\ v_2 &= v_y + v_x - \omega(a+b) \\ v_3 &= v_y - v_x + \omega(a+b) \\ v_4 &= v_y + v_x + \omega(a+b). \end{aligned} \tag{14}$$

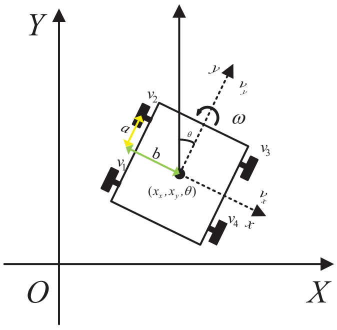


Fig. 4. Geometry of omnidirectional mobile robot

Due to the four-wheel omnidirectional mechanical structure, the formation control method with the model of a single integrator can be complemented easily in the omnidirectional robot.

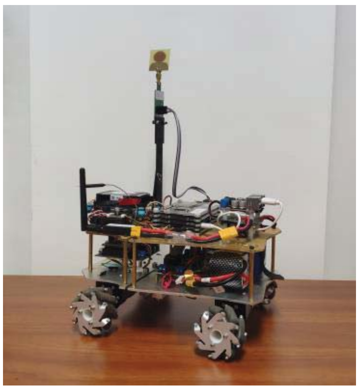


Fig. 5. Omnidirectional mobile robot.

As shown in Fig. 5, each robot is equipped with an Ultra Wideband(UWB) tag, which is used to get the position of the robot in the coordinate of the UWB. In addition, all of the robots have the same size of 20cm ×20cm ×30cm. The Mecanum wheels of 3cm-radius are mounted on a chassis, and the motors of 12-V rated voltage drive the wheels with rated torque 1N/m at 500 r/min. In each motor, there is one incremental encoder, which is used to calculate the speed of the wheels, aiming to realize the close-loop control of the robot.

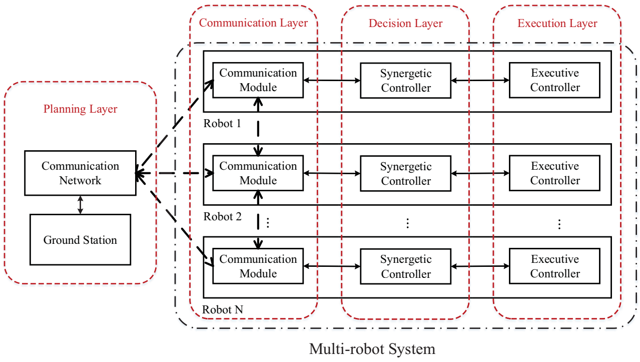


Fig. 6. The control platform structure of multi-robot system

The experimental platform consists of the omnidirectional mobile robots, the ground station, the communication links, and the control platform. The control platform is designed hierarchically with planning layer, communication layer, decision layer, and execution layer, aiming to realize the formation control and enhance the scalability and universality of the multi-robot system. The execution layer is in charge of the attitude, the position, and the velocity control of the omnidirectional mobile robot.

Fig. 6 shows the structure of the control platform of the multi-robot system. In particular, the arrows show the data links between different layers. The planning layer generates the corresponding commands to the decision layer, and the input of the planning layer is determined by the type of the task, which is implemented by the ground station. The communications between different robots and station are guaranteed by the communication layer, which realizes the information interactions between different robots through the wireless network. The decision layer is distributed decisions accomplished by the Companion computer –Raspberry, which handles the information of the commands and the velocities, the positions and the states of the robots, while, generating relevant instructions to the execution layer. After receiving the orders from the decision layer, the execution layer processes the information of the sensors, actuates the omnidirectional mobile robot to desired states, and returns corresponding information to the decision layer. The functions of the decision layer are achieved by the Pixhawk controller. In addition, the real-time location and navigation of the multi-robot system are provided by the Ultra Wideband (UWB) location system.

4.2 Experimental results

(a) Leader-Follower Formation Control Law

In this section, it is assumed that the followers are able to obtain the velocity information of the leader. The leader-follower formation control is verified from a triangle formation maintaining and a circular formation maintaining. Specifically, the goal formation is a triangle, the displacements of the desired formation between the followers and the leader are set as: $(-0.6, -0.6)$ for follower

1, $(0.6,-0.6)$ for follower 2, and $k_{1i}=1$. The experimental results are presented by Figs.7-8. Fig. 7 shows that the formation trajectory of the three robots in a horizon plane. The leader moves along a straight line, and the followers keep the desired triangle formation, where, the dotted line represents the triangle formation. Fig. 8 depicts the formation tracking errors on X-axis and Y-axis for the followers under the leader-follower formation control law. The formation tracking errors converge to a small neighborhood of zero, which is in the range of 0 to 0.1m. in addition, the formation tracking errors are mainly caused by the location errors brought from the location system of the UWB, which still satisfy the practical requirements.

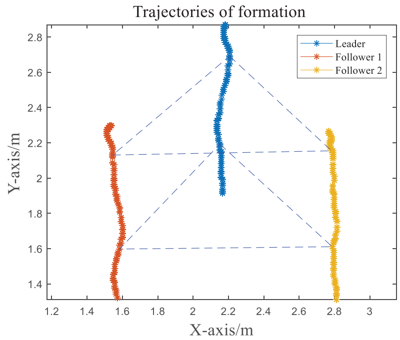
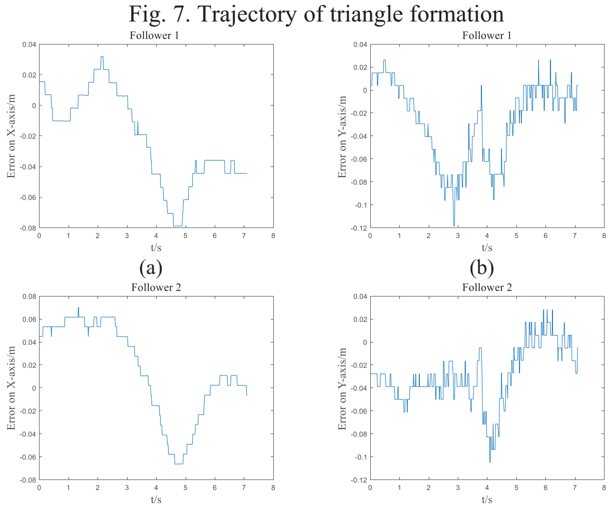


Fig. 7. Trajectory of triangle formation



(a) (b)
(c) (d)
Fig. 8. Errors of triangle formation

For circular formation maintaining, the followers should circle with the leader simultaneously and maintain the desired formation. The displacements and parameters of the formation are the same with the triangle formation. Fig. 9 shows that the circular formation trajectory of the three robots. The followers are capable of tracking the varying velocity of the leader, which shows the effective performance of the leader-follower formation control. As show in Fig. 10, the circular formation maintaining errors are in the range of 0 and 0.2m, especially, the errors have the periodical variation, due to the varying velocity and the location errors of the UWB location system, which still satisfy the practical requirements. To sum up, the desired formation can be implemented by the leader-follower formation control.

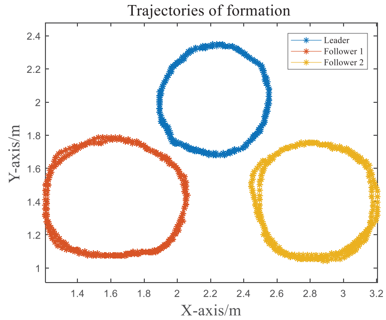
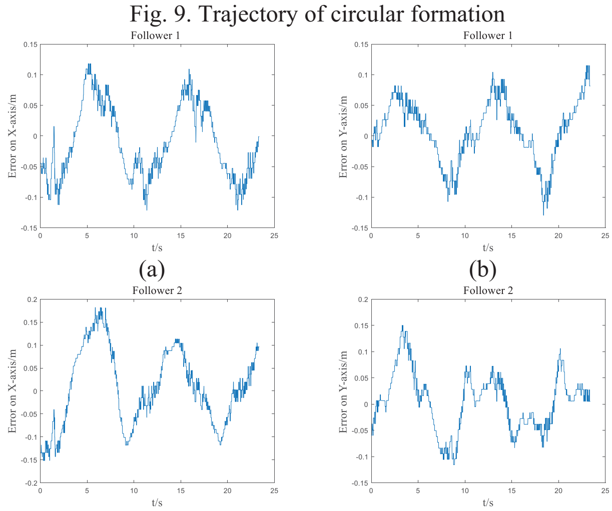


Fig. 9. Trajectory of circular formation



(a) (b)
(c) (d)
Fig. 10. Errors of circular formation

(b) Velocity Estimation

In practice, the followers may not obtain the velocity of the leader, therefore, a velocity estimator of the leader should be designed. The velocity estimator of the leader is verified with the simulation and experiment results. Specifically, the displacements of the desired formation are set as: $(-0.6,0.6)$ for follower 1, $(-0.6,-0.6)$ for follower 2. The velocity vector of the leader is set as: $(0,0.2)$. As shown in Fig. 11, at the beginning, the followers are in random positions, then the followers estimate the velocity of the leader and maintain the desired formation, where, the dotted line represents the formation. Fig. 12 shows the curve of the errors of velocity estimation, which demonstrates that the errors of the velocity estimation converge to zero. In addition, as show in Fig. 13, the formation errors also converge to zero, which shows the effectiveness of the estimator and formation control. Moreover, the experimental result is shown in Fig. 14, the result indicates that the formation can be realized. In conclusion, the velocity estimation is effective, and the desired formation can be accomplished.

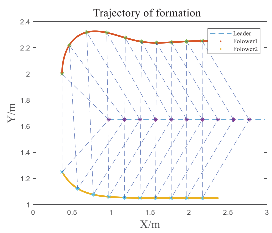


Fig. 11 Trajectory of estimation

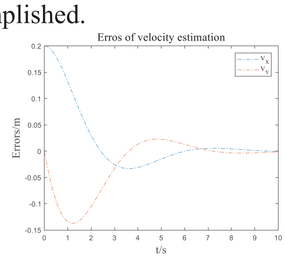


Fig. 12 Errors of velocity estimation

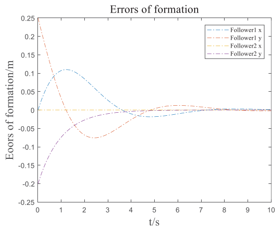


Fig. 13 Errors of formation

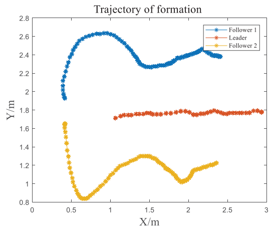


Fig. 14 Trajectory of formation

(c) Obstacle Avoidance

In this section, the robots maintain the desired formation, meanwhile, the robots are able to avoid obstacles with the APF method in complex environments. In particular, the radius of obstacles is 0.2m. the positions of the obstacles are $Obs1:(1.55,1.8)$, $Obs2:(2.7,0.95)$ for simulation. Fig. 15 shows the trajectory of formation with obstacle avoidance. The black circle, the red rectangle, the blue rectangle, and the green rectangle represent the obstacles, the leader, the follower 1, and the follower 2, respectively. In addition, at the beginning, the leader navigates autonomously. Then, the leader avoids obstacles when it encounters the obstacles. The followers can effectively avoid the obstacles and reconstruct the desired formation after passing the obstacles. Besides, the experimental result of formation with obstacle avoidance is shown in Fig. 16, the robots are capable of avoiding the obstacles and maintaining the desired formation. Therefore, the simulation and experimental results demonstrate the effective performance of the leader-follower hybrid formation control design.

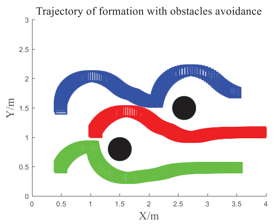


Fig.15. Simulation of obstacle avoidance

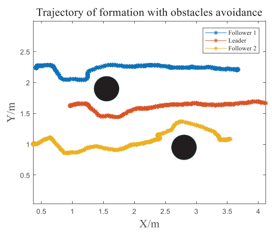


Fig. 16. Experimental result of obstacle avoidance

5 Conclusion

In this paper, we present a hybrid formation control design. It solves simultaneously the leader-follower formation control, velocity estimation, and obstacle avoidance problems. Besides, for the followers, a velocity estimator of the leader is designed so that the followers maintain the desired formation and track the leader, and the stability of formation system is analyzed by the Lyapunov function. Furthermore, the APF method is adopted for obstacles avoidance, which demonstrates the effective performance of obstacle avoidance. Moreover, an experimental platform is constructed to verify the performance of the leader-follower hybrid formation control design with the simulation and experimental results.

However, the velocity of the leader is required as a constant in velocity estimation. In the future work, the time-varying velocity of the leader for velocity estimation will be taken into consideration.

References

[1] P. Schillinger, M. Bürger and D. V. Dimarogonas, Auctioning over Probabilistic Options for Temporal Logic-Based Multi-Robot Cooperation Under Uncertainty, *in Proceedings of IEEE International Conference on Robotics and Automation*, 2018: 7330-7337.

[2] A. Rucco, P. B. Sujit, A. P. Aguiar, J. B. de Sousa and F. L. Pereira, Optimal Rendezvous Trajectory for Unmanned Aerial-Ground Vehicles, in IEEE Transactions on Aerospace and Electronic Systems, 54(2): 834-847, 2018.

[3] R. Mur-Artal, J. M. Montiel, and J. D. Tardos, Orb-slam: a versatile and accurate monocular slam system， *IEEE Transactions on Robotics*,31(5):1147–1163, 2015

[4] Z. Hu, J. Liang, L. Chen, and B. Wu, Survey on the formation control of multi-agent system, *Proceedings of the 31st Chinese Control Conference*, 2012: 6092-6098.

[5] B. Tucker and C. Ronald, Behavior-based formation control for multirobot teams, *IEEE Transactions on Robotics and Automation*, 14 (6): 926-939, 1998.

[6] M. Hasan, G. Jawhar, and S. Maarouf, Nonlinear coordination control for a group of mobile robots using a virtual structure, *Mechatronics*, 21(7) :1147-1155, 2011.

[7] Z. Han, K. Guo, L. Xie and Z. Lin, Integrated Relative Localization and Leader–Follower Formation Control, IEEE Transactions on Automatic Control, 64(1): 20-34, 2019.

[8] L. Krick, M. E. Broucke, and B. A. Francis, Stabilisation of infinitesimally rigid formations of multi-robot networks, *International Journal of Control*, 82 (3):423–439, 2009

[9] J. Guo, G. Yan, and Z. Lin, Local control strategy for moving-target enclosing under dynamically changing network topology, *Systems & Control Letters*, 59(10): 654–661, 2010.

[10] G. Lafferriere, A. Williams, J. Caughman, and J. Veerman, Decentralized control of vehicle formations, *Systems & control letters*, 54 (9): 899–910, 2005.

[11] S. Kang, M. Park, B. Lee and H. Ahn, Distance-based formation control with a single moving leader, *American Control Conference*, 2014: 305-310.

[12] A. Richards, J. P. How, Aircraft trajectory planning with collision avoidance using mixed integer linear programming, *American Control Conference*, 2002:1936-1941.

[13] Y. Fu and S. Y. T. Lang, Fuzzy logic based mobile robot area filling with vision system for indoor environments, *in Proceedings of IEEE Intelligent Symposium on Computational Intelligence in Robotics and Automation*, 1999:326–331.

[14] O. Khatib, Real-Time Obstacle Avoidance for Manipulators and Mobile Robots, *in Proceedings of IEEE International Conference on Robotics and Automation*, 1985:500-505.

[15] H. K. Khalil and J. W. Grizzle, Nonlinear systems. Prentice hall Upper Saddle River, 2002, vol. 3.