Formation control of multi robot based on UWB distance measurement

Lv Qiang[1], Wei Heng[1], Lin Huican[1], Qin Shuqi[1], Duo Nanxun[1],Liang Bing[2]

1. Department of weapon control, Academy of Army Armored Forces, *Beijing* 100072, *China*

E-mail: wh_killer@foxmail.com

2. School of Information Engineering, Jiangxi University of Science and Technology, *Ganzhou 341000, China*

E-mail: lbwgs@126.com

Abstract: Robot formation control is the foundation of multi-mobile robot system. In view of the shortage of traditional formation control algorithm and the large network traffic of multi-robot, a formation control strategy based on state switching is proposed. The three kinds of traditional algorithms are compiled in a modular way, and then a state switching triggering mechanism based on composite information is designed. The reasonable selection of one or more formation control algorithms by the state of the robot and the surrounding environment and the timely triggering of the control law effectively reduce the complexity of the multi-robot formation control algorithm and reduce the communication burden on the robot. At the same time, a formation feedback mechanism based on UWB (Ultra Wide Band) ranging is proposed. UWB data structure is simple, which is convenient for processing on the micro-mobile robot and realizes the maintaining and feedback on the formation in real time. Finally, a multi-mobile robot platform is built, and the proposed strategy is applied to real robots. Multi-robot formation tracking and formation obstacle avoidance experiments are carried out, and the effectiveness and robustness of the proposed algorithm are verified.

Key Words: UWB, multi robot, Chinese Formation control, State switch

1 Introduction

In recent years, with the continuous development of computer technology and digital signal processing technology, it makes the function more and more strong, the micro processing chip processing speed more and more quickly, the development of automatic control technology and network communication technology makes the micro autonomous mobile robot has received extensive attention[1]. Because the multi mobile robot system has better stability, stronger fault tolerance and higher efficiency than single mobile robot, it has good application prospects and research value in the fields of investigation, patrol, rescue and environmental survey. The formation control of multi mobile robots is the basis of the multi mobile robot system, and has become a hot spot in the field of robotics [2].

In the design process of multi robot formation algorithm, we need to consider many problems such as robot model, external environment interference, algorithm control accuracy and different formation controllability [3]. The traditional multi robot formation control algorithms mainly include leader-follower algorithm [4], behavior based algorithm[5], graph based method[6], virtual structure method[7] and so on. The basic idea of leader-follower algorithm is to choose a robot as leader in the multi robot system. The other robots are follower, and we can control formation by adjusting the angle and distance between leader and follower. Literature [8] puts forward two kinds of formation control algorithms, $l\text{-}\varphi$ and $l\text{-}l$. $l\text{-}\varphi$ Algorithm controls formation by controlling the distance and angle between leader and follower, and $l\text{-}l$ algorithm keeps the formation through the distance between follower and adjacent robots. Literature [9] in order to prevent collisions between robots, proposed an improved $l\text{-}\varphi$ and $l\text{-}l$ algorithm based on the virtual gravitation. The Leader-follower algorithm is scalable, flexible and good motion strategies, but not between leader and follower algorithm in the formation of a stable and effective feedback, so the tracking error of follower with the interference of environment continues to expand, and when the leader fails, the whole multi robot system will not work. The basic idea of behavior based algorithm is to design basic behavior rules for each robot in multi robot system, such as obstacle avoidance, collision avoidance, target movement and formation. The algorithm can effectively reduce the complexity of the whole system of multi robot formation control algorithm, but its high requirements on sensor detection ability and the ability of communication between robots, and to the robot's behavior in the process of operation described accurately, it is difficult to guarantee the robustness of the system. The virtual structure method is first proposed by Lewis M A et al [10]. Its basic idea is to regard the whole multi robot system as a rigid whole. Each robot is regarded as a point on the rigid body. The advantage of the algorithm is that it is easy to design the formation behavior of multi robot system, and the formation retention rate is high. However, due to the constraint of rigid structure, the algorithm lacks flexibility in obstacle avoidance and formation transformation.

Aiming at the deficiency of the traditional algorithm in formation control, the formation feedback mechanism of multi robot system based on UWB range finder is constructed, the relationship between robots is strengthened and the complexity of formation control algorithm is reduced, and the requirements for data processing capability

This work is supported by National Nature Science Foundation under Grant(61663014)

of a single robot are effectively reduced. At the same time, a formation control strategy based on state switching is proposed. It can flexibly use the advantages of all algorithms in different environments, effectively reduce the communication burden between multi robot systems, and reduce the complexity of formation control algorithm. Finally, the experiment was carried out based on the multi robot platform built in the laboratory [11] to verify the effectiveness and stability of the formation control strategy.

2 Formation feedback mechanism based on UWB distance measurement

Taking into account the UWB measuring system is cost-effective, low energy consumption, on the basis of laboratory has been done in the work of UWB, at the same time as the UWB data structure is simple and conducive to real-time processing in the micro mobile robot, designed formation feedback mechanism based on UWB distance measurement, the schematic diagram is shown in Figure 1.

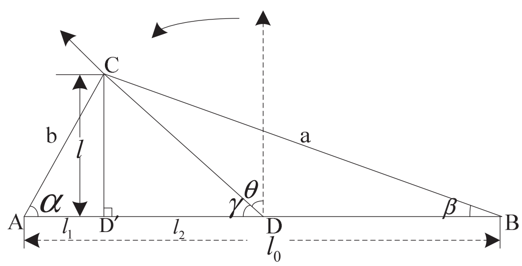

Fig 1. Schematic diagram of formation feedback mechanism based on UWB distance measurement

Let A and B be the two UWB modules on the robot 1, D as the center of mass, C as the UWB module on other robots, l_0 as the baseline, l is the vertical distance from robot 1 to robot 2, and θ is the angle between the orientation of the robot 1 and the robot 2. From Figure 1, it can be obtained:

$$\alpha = \arccos[(b^2 + l_0^2 - a^2) / 2bl_0] \tag{1}$$

$$\beta = \arccos[(a^2 + l_0^2 - b^2) / 2al_0] \tag{2}$$

$$l_2 = \frac{l_0}{2} - l_1 = b\cos\alpha \tag{3}$$

$$l = b\sin\alpha \tag{4}$$

$$\theta = \frac{\pi}{2} - \gamma = \frac{\pi}{2} - \arctan\frac{l}{l_2} \tag{5}$$

The distance and angle between the various robots in the multi robot system can be obtained by the formula (4) and the formula (5), thus the whole formation is fed back. The above formula is that when the current robot in the counterclockwise direction of the rear robot, when the current robot in the clockwise direction of the rear robot, the formula (3) and the formula (4) become the following:

$$l_2 = \frac{l_0}{2} - l_1 = a\cos\beta \tag{6}$$

$$l = a\sin\beta \tag{7}$$

The above is the basic schematic of formation feedback mechanism based on UWB distance measurement. When the number of UWB modules ≥ 3, the multi robot system can complete the cooperative positioning. Each robot can figure out its position relative to the location of other robots. Thus maintain and feedback the entire formation. The algorithm flowchart is shown in Figure 2.

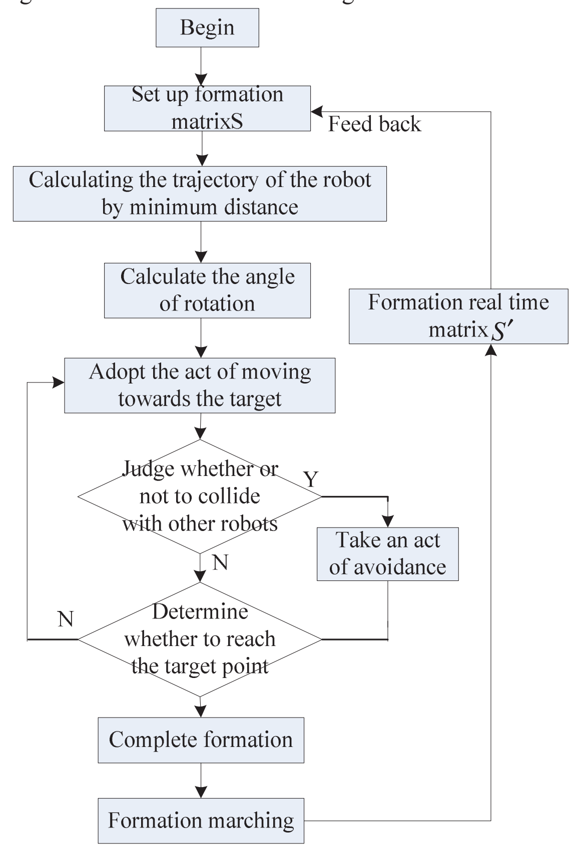

Fig 2. Algorithm flow chart of formation feedback mechanism based on UWB distance measurement

3 Formation control strategy based on state switching

Aiming at the advantages and disadvantages of leader-follower algorithm, behavior-based algorithm and virtual structure method in traditional formation algorithm, this paper proposes formation control strategy based on state switching, and flexibly utilizes the advantages of each algorithm in different environments to avoid it shortcomings, effectively reduce the complexity of formation control algorithm and reduce the communication burden and data processing capacity between multi-robot systems.

In the design, using the top-down design scheme, the state switching mechanism based on composite information is designed first, and then the robot control part is designed. The control section is divided into the inner loop control and the outer loop control. The outer loop control mainly writes into three traditional formation control algorithms, and the inner loop control is the underlying control algorithm of the mobile robot. When the sensor information and the robot state reach a trigger condition, the state switching mechanism automatically selects and triggers the corresponding formation control algorithm of the robot, and then controls the bottom of the mobile robot to complete the formation control. The modular design divides the whole system into three parts: the underlying control, formation algorithm and triggering mechanism are connected to each other without interference, which makes the application more flexible and convenient for subsequent expansion of the system. In the experiment, different mobile robots were used, and the control strategies were verified in different environments.

Suppose a multi-robot system is:

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ u_i(t) = \mathrm{F}(\dot{v}_i(t)), i = 0,1,\cdots,N \end{cases} \tag{8}$$

In the above formula, $x_i(t) \in R^n$ represents robot i position, $v_i(t)$ represents robot i speed, $u_i(t)$ represents robot i control input, and robot i control strategy is as shown in Figure 3.

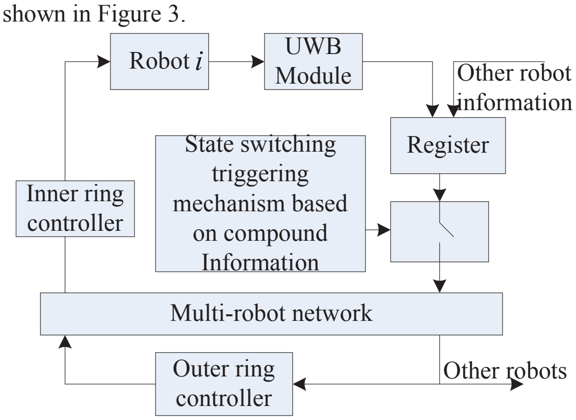

Fig 3. Robot i control strategy

Assuming that the weight a_{ij} of the connection between the robot i and the robot j network changes with time, the topology of the multi-robot system can be expressed as $G(t) = \mathrm{F}_1(A(t))$, $A(t) = [a_{ij}(t)] \in R^{N\times N}$ is a weighted graph adjacency matrix with a Laplacian matrix $L(t) = [l_{ij}(t)] \in R^{N\times N}$, if $i \neq j, l_{ij}(t) = -a_{ij}$,if $i \neq j, l_{ij}(t) = -a_{ij}, l_{ii}(t) = \sum_{j=1}^{N} a_{ij}(t)$. Assumptions:

$$L(t) = \hat{L}(t) - C(t) \tag{9}$$

$$\hat{L}(t) = \sum_{p=1}^{m} \eta_p(t)\hat{L}_p \tag{10}$$

In the above formula, $\hat{L}_p$ is a known constant matrix, $m > 0$, $\eta_p(t) > 0$, $\sum_{p=1}^{m} \eta_p(t) = 1$.The design of the formation control strategy function is as follows:

$$u_i(t) = -k_1\delta_{ix}(t_{ki}^i - \tau) - k_2\delta_{iv}(t_{ki}^i - \tau) \tag{11}$$

In the above formula, k_1, k_2 is the design of the control function coefficient,

$$\delta_{ix}(t) = \sum_{j\in N_i(t)} [a_{ij}(t)((x_i(t) - x_{d_i}) - (x_j(t) - x_{d_i})) + c_{i0}(x_i(t) - x_0(t) - x_{d_i})] ,$$

$$\delta_{iv}(t) = \sum_{j\in N_i(t)} [a_{ij}(t)((v_i(t) - v_j(t)) + c_{i0}(v_i(t) - x_0(t))]$$

is compound information, h is the time taken by the UWB module to refresh once, τ ($0 \le \tau \le h$)is time delay, $C(t) = \mathrm{diag}[c_{10}(t), c_{20}(t), \cdots, c_{N0}(t)]$, $\{t_k\}(k = 0, 1, \cdots)$ is trigger time list, $t_{k_i}^i = \max\left\{t^i \,\middle|\, t^i \in \{t_l^i, l = 0,1,\cdots\}, t^i \le t\right\}$ is robot i last trigger moment. The next trigger time by the trigger mechanism to determine:

$$f_{ix}(t) = \|e_{ix}(t)\| - \alpha\|\delta_{ix}(t_{k_i}^i)\| \tag{12}$$

$$f_{iv}(t) = \|e_{iv}(t)\| - \beta\|\delta_{iv}(t_{k_i}^i)\| \tag{13}$$

In the above formula, $\alpha, \beta > 0$ is design the trigger threshold, $e_{ix}(t) = \delta_{ix}(t) - \delta_{ix}(t_{k_i}^i)$, $e_{iv}(t) = \delta_{iv}(t) - \delta_{iv}(t_{k_i}^i)$. If $t = t_{k_i}^i$, $e_{ix}(t) = 0, e_{iv}(t) = 0$. When either $f_{ix}(t)$ or $f_{iv}(t)$ has any one greater than zero, the status of the robot i will be transmitted to the multi-robot network, and the zero-order retainer will be used to maintain its status when not transmitting:

$$t_{k_i+1}^i = \inf\{t : t > t_{k_i}^i, f_{ix}(t) > 0 \,\|\, f_{iv}(t) > 0\} \tag{14}$$

Available from formula (8) and formula(11), robot i formation status error is:

$$\begin{cases} \bar{x}_i(t) = x_i(t) - x_0(t) - x_{d_i} \\ \bar{v}_i(t) = v_i(t) - v_0(t) \end{cases} \tag{15}$$

The robot i can be expressed as:

$$\begin{cases} \dot{\bar{x}}_i(t) = \bar{v}_i(t) \\ \dot{\bar{v}}_i(t) = -k_1 \sum_{j\in N_i(t)} a_{ij}(t)(\bar{x}_i(t-\tau) - \bar{x}_j(t-\tau)) - \\ \qquad k_2 \sum_{j\in N_i(t)} a_{ij}(t)(\bar{v}_i(t-\tau) - \bar{v}_j(t-\tau)) \\ \qquad - k_1 c_{i0}(t)\bar{x}_i(t-\tau) - k_2 c_{i0}(t)\bar{v}_i(t-\tau) \\ \qquad + k_1 e_{ix}(t-\tau) + k_2 e_{ix}(t-\tau) \end{cases} \tag{16}$$

4 Simple obstacle avoidance strategy

About multi-mobile robot formation obstacle avoidance algorithm is not in the scope of this article, however, in order to fully verify the validity and robustness of the proposed state-switching formation control strategy, a simple obstacle avoidance strategy is designed for the leader to see whether other robots can effectively trigger the state switching based on the leader state to complete the obstacle avoidance and maintain the team shape. at the same time to verify the number of state switching and formation control effect. The leader in the design is equipped with a rplidar laser sensor. When an obstacle appears near the robot and its distance is less than the safety distance, the given task does not change, but a control reverse to the obstacle is added to it. The closer the distance to the obstacle, the reverse Control the more intense, thus completing the obstacle avoidance, the algorithm flow chart is shown in Figure 4.

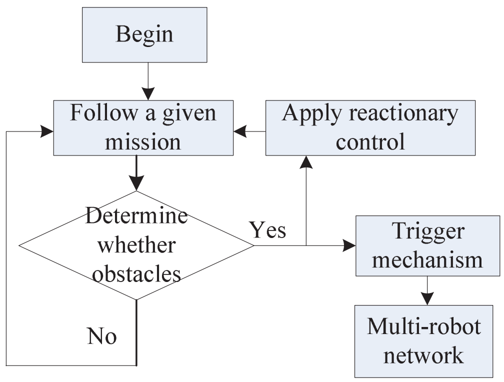

Fig 4. Leader obstacle avoidance strategy

5 Experiment

Based on the lab-built multi-robot network architecture, experiments were conducted on self-designed 3-wheel omni-directional robot and UWB ranging module. The kind is shown in Figure 5. Three sets of experiments were carried out to verify the effectiveness and robustness of the algorithm. In the experiment, a UWB positioning system was set up to measure the trajectory of the robot, and the error was compared with the expected trajectory.

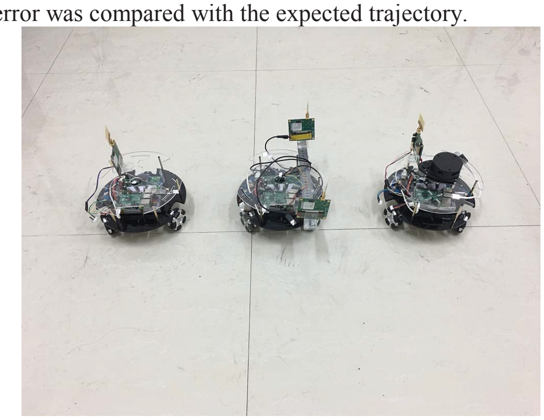

Fig 5. Multi-robot system

Experiments 1 and 2 respectively completed the multi-robot formation tracking circular trajectory and formation tracking sinx trajectory, the results shown in Figure 6, Figure 7 and Table 1, Table 2 below. Experiments 1 and 2 respectively completed the multi-robot formation tracking circular trajectory and formation tracking sinx trajectory, the results shown in Figure 6, Figure 7 and Table 1, Table 2 below. The experimental results show that the multi-robot system can effectively form a formation. The formation formation remains stable and the trajectory tracking is in good condition. Only a few state transitions are needed to complete the formation tracking control. Under the premise of ensuring formation control precision, the communication burden and data processing pressure between multiple robots are effectively reduced, which proves the effectiveness and robustness of the proposed control strategy.

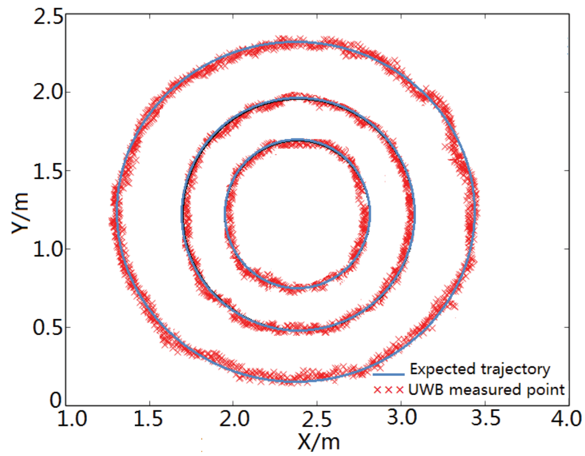

Fig 6. Formation tracking circular trajectory experimental results

Table 1 formation tracking circular trajectory experimental results

	State switching times (times)	Root mean square error (m)
Robot 1	6	0.124
Robot 2	8	0.119
Robot 3	9	0.131

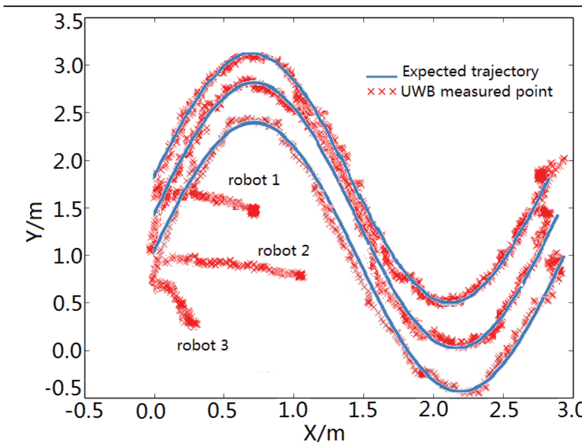

Fig 7. Formation tracking sinx trajectory experimental results

Table 2 Formation tracking sinx trajectory experimental results

	State switching times (times)	Root mean square error (m)
Robot 1	12	0.132
Robot 2	14	0.137
Robot 3	16	0.134

Experiment 3 completed obstacle avoidance, the results shown in Figure 8 and Table 3. Experimental results show that multi-robot can effectively avoid obstacle avoidance and resume formation after obstacle avoidance; formation control strategy based on state switching can meet the requirements of real-time and stability of multi-robot formation control.

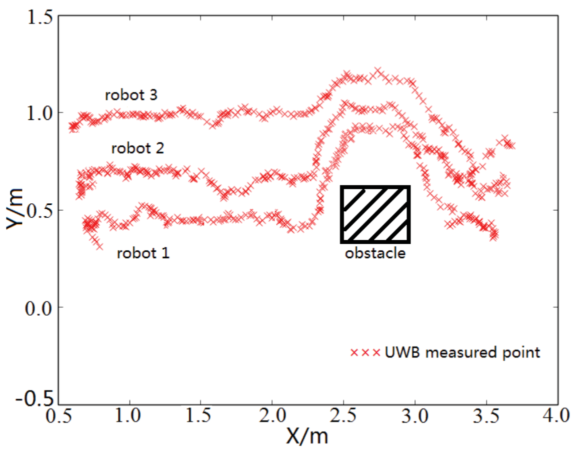

Figure 8 formation obstacle avoidance experiment results

Table 3 Formation obstacle avoidance test results

	State switching times (times)
Robot 1	4
Robot 2	4
Robot 3	5

6 Experiment

Aiming at the advantages and disadvantages of the traditional leader-follower algorithm, behavior-based algorithm and virtual structure method, this paper proposes a formation control strategy based on state switching based on UWB ranging. While giving full play to the advantages of each formation algorithm, the disadvantages of each algorithm are abandoned as much as possible, which reduces the complexity of formation control algorithm and reduces the communication burden of the robot and the data processing ability. At last, the validity and robustness of the proposed strategy are verified by constructing a multi-robot platform.

REFERENCES

[1] NELSON E, CORAH M, MICHAEL N. Environment model adaptation for mobile robot exploration[J]. Autonomous Robots, 2017(5):1-16.

[2] YI Guo, MAO Jianxu, WANG Yaonan, et al. Distributed control for leader-follower formation tracking of multiple nonholonomic vehicles[J]. Chinese Journal of Scientific Instrument, 2017(9)..

[3] CUI Mingyue, LIU Hongzhao, LI Yongfu, et al. Adaptive Formation Control of Uncertain Wheeled Mobile Robot Based on Virtual Team Leader[J]. Control and Decision, 2017, 32(7):1203-1209.

[4] WANG H, GUO D, LIANG X, et al. Adaptive Vision-Based Leader-Follower Formation Control of Mobile Robots[J]. IEEE Transactions on Industrial Electronics, 2017, PP(99):1-1.

[5] CUNNINGHAM A G, EUSTICE R M, OLSON E et al. Multipolicy decision-making for autonomous driving via changepoint-based behavior prediction: Theory and experiment[J]. Autonomous Robots, 2017, 41(6):1-16.

[6] LIU C, ZONG Q, DOU L Q. Generation and Control of Wheeled Robots Formation Based on Persistent Graph Theory[J]. Control Engineering of China, 2017.

[7] PAN Wuwei, JIANG Dapeng，PANG Yongjie, et al. A Multi-AUV Formation Algorithm Combining Artificial Potential Field and Virtual Structure[J]. Acta Armamentarii, 2017, 38(2):326-334.

[8] DESAI J P, OSTROWSKI J, KUMAR V. Controlling Formations of Multiple Mobile Robots.[C]// IEEE International Conference on Robotics and Automation, 1998. Proceedings. DBLP, 1998:2864-2869.

[9] TAKAHASHI H, NISHI H, OHNISHI K. Autonomous decentralized control for formation of multiple mobile robots considering ability of robot[J]. IEEE Transactions on Industrial Electronics, 2004, 51(6):1272-1279.

[10] LEWIS M A, TAN K H. High Precision Formation Control of Mobile Robots Using Virtual Structures.[J]. Autonomous Robots, 1997, 4(4):387-403.

[11] LV Q, WEI H, LIN H, et al. Design and implementation of multi robot research platform based on UWB[C]// Control and Decision Conference. IEEE, 2017:7246-7251.