Formation Control of Multiple Robot Fishes Based on Artificial Potential Field and Leader-follower Framework

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Abstract: Based on the artificial potential field, an approach is proposed for the formation control of multiple robot fishes, which overcomes the disadvantage that the collision avoidance is not satisfactorily solved in the leader-follower framework. In accessible areas, the formation of multiple robot fishes is maintained in the moving to target point by controlling the distance and angle between follower and leader. Under obstacle environment, robotic fish established expectations point to create artificial potential field by the order of priority. The simulation verifies the effectiveness of the method.

Key Words: Leader-follower, Artificial potential, Multiple robot fishes, Formation control

1 INTRODUCTION

With the continuous development of robotics industry, the mutual cooperation between multi-robot has become a hot research issue in the field of multi-agent. Robot formation control is an important aspect of the cooperation in multi-robot coordination and worthy of a detailed exploration. The so-called formation control is a control technology which requires that in the process of reaching the destination, the multiple robots maintain a certain formation, while at the same time have to adapt to environmental constraints. With the development of formation control, many control methods have been proposed [1, 2, 3, 4, 5]. Biomimetic robotic fish has attracted more and more attention as an effective tool for future unmanned exploration of the marine. Many scholars have studied the formation control of multiple robot fishes. For example, on the basis of leader-follower framework, the formation control was achieved in [6] by describing the positional relationship between robotic fish through coordinate curvature, where the description was carried out with respect to robotic fish geometry and mechanical shape restrictions. In [7], the Bezier curve between multiple robot fishes was established by estimation to realize the formation control, and the effectiveness of the method was verified by experiments. In [8], based on position feedback and graph theory methodology, a formation control strategy was introduced. The strategy makes each robotic fish adjust its position according to the feedback position information of the reference robotic fish. In this way, any formation can be realized for a multiple robot fishes system. However, this method cannot accurately control the formation of the robotic fish and is vulnerable to collision between the robotic fishes.

Leader-follower method has the advantage of simple control. Only leader's trajectory and the desired positional relationship between the leader and follower are needed to complete the formation control. The disadvantage of this approach is that the obstacle avoidance is not considered in the multi-robot system. The artificial potential field method was proposed in 1986 by Khatib. His main idea is to create a virtual artificial potential field. In the potential field, each robot will be affected by the attractive or repulsive force from different objects. The force is represented by potential function. The movement of the robot is eventually decided by the resultant of different abstract force suffered by the robot. Artificial potential field method is easy to understand. The associated control method is simple. It is commonly used in multi-robot collision avoidance. However, artificial potential field has local extremum problem. In [9] the methods to solve the local minimum problems were reviewed.

The paper proposes a formation control method for multiple robot fishes. The method combines leader-follower framework with artificial potential field. In obstacle-free environment, robotic fishes make formation movement under leader-follower framework. When the robotic fish fleet moves into obstacle area, multiple robot fishes system uses artificial potential field method to change the formation and avoid the obstacle. The control method has the advantages of both leader-follower framework and artificial potential field, which is simple, effective and easy to implement.

2 MODELING OF MULTIPLE ROBOT FISHES SYSTEM UNDER LEADER-FOLLOWER FRAMEWORK

The model of multiple robot fishes system is developed under leader-follower framework. The single robotic fish

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moves according to the following dynamic equation:

$$\begin{cases} \dot{x}_i = V_i \cos\theta_i \\ \dot{y}_i = V_i \sin\theta_i \\ \dot{\theta}_i = W_i \end{cases}$$

where (x_i, y_i) is the gravity coordinate of the ith robotic fish; V_i is the corresponding forward speed; θ_i is the heading angle and W_i is the angular velocity.

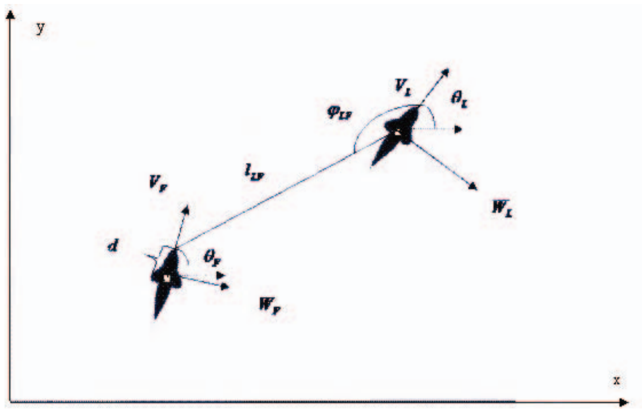

Figure 1: Multi-robotic fish fleet diagram

In multiple robot fishes system, each follower robotic fish moves with a fixed distance l_d and a fixed angle ϕ_d to follow the leader robotic fish. This is illustrated by Fig. 1, which implies the following equations:

$$l_{LF} = \sqrt{(x_L - x_F - d\cos\theta_F)^2 + (y_L - y_F - d\sin\theta_F)^2} \tag{1}$$

$$\phi_{LF} = \begin{cases} \arcsin(\frac{y_L - y_F - d\sin\theta_F}{l_{LF}}) + \pi - \theta_L, & x_L > x_F \\ -\arcsin(\frac{y_L - y_F - d\sin\theta_F}{l_{LF}}) - \theta_L, & x_L < x_F \end{cases} \tag{2}$$

where l_{LF} represents the distance between leader and follower in the movement; ϕ_{LF} is the angle between the leader's velocity direction and the follower's head direction; and d represents the distance from the center coordinate of the follower to its head. After derivation calculus to (1) and (2), we get

$$\begin{aligned} \dot{l}_{LF} =& V_F \cos(\varphi_{LF} + \theta_{LF}) - V_F \cos\theta_{LF} \\ & - dW_F \sin(\varphi_{LF} + \theta_{LF}) \end{aligned}$$

$$\begin{aligned} \dot{\varphi}_{LF} =& \frac{1}{l_{LF}}[V_L \sin\varphi_{LF} - V_F \sin(\varphi_{LF} + \theta_{LF}) \\ & + dW_F \cos(\varphi_{LF} + \theta_{LF}) - W_L l_{LF}] \end{aligned}$$

where θ_{LF} represents the difference between the heading angle of leader and follower, i.e. $\theta_{LF} = \theta_L - \theta_F$. According to the above model of multi-robot fish system, the formation control can be achieved if the following conditions are satisfied.

1) $\lim_{t\to\infty} \| l_{LF} - l_d \| = 0$,

2) $\lim_{t\to\infty} \| \phi_{LF} - \phi_d \| = 0$.

3 DESIGN OF OBSTACLE AVOIDANCE

3.1 Obstacle model

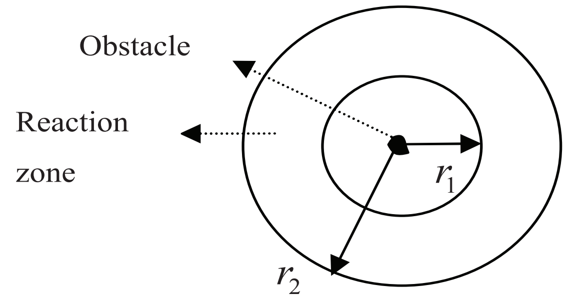

Figure 2: Obstacle model

As shown in Fig.2, set obstacle as the center and make two concentric circles with radius respectively r_1 and r_2 (normally, $r_2 > r_1$). Here, r_1 is the minimum turning radius of robotic fish, and $r_2 = r_1 + \partial r$, where ∂ is the proportionality coefficient whose size depends on that of r with r being the maximum radius of the formation of robotic fish. When the size of r exceeds a certain range, ∂ decreases with the increase of r. The value range of ∂ is 0 to 1.
Conditions for the obstacle avoidance of multiple robot fishes system: there is a robotic fish within the reaction zone of an obstacle. In this case, multiple robotic fish system may collide with an obstacle. The system needs to change the formation to avoid the obstacle. If all robotic fishes are not in the reaction zone of the obstacles, the obstructions certainly will not collide with any robotic fish. Under such circumstances, the multiple robot fishes system keeps moving with a fixed formation.

3.2 Artificial potential field design of leader robotic fish

In subsequent arguments, the multiple robot fishes system uses artificial potential field method for obstacle avoidance under leader-follower framework. In the multiple robot fishes system, the robotic fish leader is driven by the repulsive and attractive force which are respectively generated from the obstacle and target point. This enables the leader to avoid obstacle while moving to the target point. The robotic fish begins to be affected by the repulsive force when it comes into the reaction zone of the obstacle. The repulsive force increases with the reduced distance to the obstacle and becomes maximum when the robotic fish reaches a circle with radius r_1. The repulsive potential field suffered by robotic fish is defined as follows:

1) when $r_1 < \| R^o_{L_i} \| \leq r_2$, the repulsive potential field is

$$V^o_{L_i} = A(e^{\frac{r_2 - \| R^o_{L_i} \|}{L_o^2(\| R^o_{L_i} \| - r_1)}} - 1);$$

2) when $r_1 > \parallel R^o_{L_i} \parallel$, the repulsive potential field takes the maximum value; when $r_2 \leq \parallel R^o_{L_i} \parallel$, its value is zero,

where $\parallel R^o_{L_i} \parallel$ is the distance of the robotic fish to the obstacle i. A and L_o are constant parameters. Robotic fish is subjected to the action of the repulsive force while also subject to the gravitational pull of the target point. The farther the robotic fish away from the target point the greater the gravitational force acted upon it. Define the gravitational potential field as follows:

1) when $0 \leq \parallel R^g_L \parallel < r_g$, the gravitational force field is

$$V^g_L = B(e^{\frac{\parallel R^g_L \parallel}{L^2_g(r_g - \parallel R^g_L \parallel)}} - 1);$$

2) when $r_g < \parallel R^g_L \parallel$, the gravitational force field takes the maximum value,

where $\parallel R^g_L \parallel$ is the distance from robotic fish to the target point. B, L^2_g and r_g are constant parameters and r_g is the gravity action boundary. The gravitation acted upon robotic fish reaches its maximum value when the distance from robotic fish to the target distance is not less than r_g.
The total potential field acted upon robotic fish is

$$\begin{aligned} & V_L \\ =& \sum_i^N V^o_{L_i} + V^g_L \\ =& A\sum_i^N (e^{\frac{r_2 - \parallel R^o_{L_i} \parallel}{L^2_o(\parallel R^o_{L_i} - r_1 \parallel)}} - 1) + B(e^{\frac{\parallel R^g_L \parallel}{L^2_g(r_g - \parallel R^g_L \parallel)}} - 1). \end{aligned} \tag{3}$$

The above (3) is differentiated to yield

$$\begin{aligned} F_L =& B\frac{r_g - 2R^g_L}{L^2_g(r_g - 2R^g_L)^2} e^{\frac{\parallel R^g_L \parallel}{L^2_g(r_g - \parallel R^g_L \parallel)}} \\ & - A\sum_i^N \frac{2R^o_{L_i} - r_1 - r_2}{L^2_o(R^o_{L_i} - r_1)^2} e \frac{r_2 - \parallel R^o_{L_i} \parallel}{L^2_o(\parallel R^o_{L_i} \parallel - r_1)} \end{aligned}$$

The direction and size of the force exerted on robotic fish determines, respectively, its motion direction and speed.

3.3 Artificial potential field design of follower robotic fish

Obstacle avoidance of multiple robot fishes system is realized by changing the formation. Common configurations in the formation control of multiple robot fishes systems are single line, triangle and diamond-shaped. By [10], the general mathematical model of these three basic formations is

$$\begin{cases} x_i = x_0 - M \times \gamma + (-1)^{(G\times i + Q)\times K} \times (\frac{i+1}{2})^P \\ \qquad \times \gamma \times \cos(\beta + H \times \alpha) \\ y_i = y_0 - (-1)^{i\times K} \times (\frac{i+1}{2})^P \times \gamma \times \sin(\beta + H \times \alpha), \end{cases}$$

where (x_0, y_0) is the coordinate of leader robotic fish. (x_i, y_i) is the coordinate of ith robotic fish. M, G, Q, K, P, H are governor parameters of the formation. α and β are the direction angle and angle of the formation, respectively. γ is the distance between the robots. When robotic fish avoids obstacle, the expectation point of the robotic fish can be determined according to the above formula. Accordingly the gravitational potential field corresponding to the desired point can be obtained for each follower robotic fish i. Follower robotic fish is also affected by the repulsion that comes from obstacles and other robotic fishes in order to prevent collisions. The repulsive potential field that each robotic fish generates to others can be defined as

1) when $0 < \parallel R_{ij} \parallel \leq r_d$, the repulsive potential field is

$$V_{ij} = B(e^{\frac{r_d - \parallel R_{ij} \parallel}{L^2_d \parallel R_{ij} \parallel}} - 1)$$

2) when $r_d \leq \parallel R_{ij} \parallel$, the repulsive potential field takes zero,

where B, L_d are governor parameters. r_d is the expected distance between two robotic fishes. $\parallel R_{ij} \parallel$ is the actual distance between two robotic fishes. The repulsion increases gradually with the decrease of $\parallel R_{ij} \parallel$ when $\parallel R_{ij} \parallel$ is smaller than r_d. The total artificial potential field of the follower robotic fish can be written as

$$\begin{aligned} V_{F_i} =& V^g_{F_i} + \sum_j^M V_{ij} + \sum_k^N V^o_{F_ik} \\ =& B(e^{\frac{\parallel R^g_{F_i} \parallel}{L^2_g(r_g - \parallel R^g_{F_i} \parallel)}} - 1) + B\sum_j^M (e^{\frac{r_d - \parallel R_{ij} \parallel}{L^2_d \parallel R_{ij} \parallel}} - 1) \\ & + A\sum_k^N (e^{\frac{r_2 - \parallel R^o_{F_ik} \parallel}{L^2_o(\parallel R^o_{F_ik} - r_1 \parallel)}} - 1) \end{aligned} \tag{4}$$

where $\parallel R^g_{F_i} \parallel$ is the distance from the follower robotic fish to its expected position. $\parallel R^o_{F_ik} \parallel$ is the distance between follower robotic fish i and obstacle k. M is the number of robotic fishes which generate repulsion to follower robotic fish i in a moment. N is the number of obstacles which generate repulsion to follower robotic fish i in a moment. Other parameters have the same meaning as defined above. Make derivation calculus to (4), one has

$$\begin{aligned} F_{Fi} =& B\frac{r_g - 2R^g_{F_i}}{L^2_g(r_g - R^g_{F_i})^2} e^{\frac{\parallel R^g_{F_i} \parallel}{L^2_g(r_g - \parallel R^g_{F_i} \parallel)}} \\ & + B\sum_j^M \frac{r_d - 2R_{ij}}{L^2_d R_{ij}} e^{\frac{r_d - \parallel R_{ij} \parallel}{L^2_d \parallel R_{ij} \parallel}} \\ & + A\sum_k^N \frac{r_1 + r_2 - 2R^o_{F_ik}}{L^2_o(R^o_{F_ik} - r_1)^2} e^{\frac{r_2 - \parallel R^o_{F_ik} \parallel}{L^2_o(\parallel R^o_{F_ik} \parallel - r_1)}} \end{aligned}$$

3.4 Algorithm flow of obstacle avoidance of multiple robot fishes system

The priority of each robotic fish can be determined by the length of distance between obstacles and follower robotic fishes to prevent collisions between robotic fishes when robotic fish formation avoids obstacles.The closer the distance, the higher the priority. The expectations point of each robotic fish can be determined by different priority according to the principle of proximity and high to low.

1) Follower robotic fishes follow leader to the target with a certain distance and angle.
2) Judge whether robotic fish formation has entered the obstacles region, if yes, proceed to the next step; if not, perform step 5
3) The corresponding expectation points of each robotic fish can be determined by the length of distance between obstacles and follower robotic fish and then the corresponding potential field can be obtained also.
4) Judge whether obstacle avoidance is finished, if yes, proceed to the next step; if not, continue performing step 3.
5) Restoring the formation and moving to the goal.

4 SIMULATION

Taken three robotic fishes as an example, simulation has been done to validate the feasibility of the algorithm. Three robotic fishes keep a triangle formation moving to goal and avoid obstacles during the process. The initial positions of the three robotic fishes are respectively leader (-150,-100), follower1 (-200,-50), follower2 (-200,-150). The radius of reaction zone is 40 and the goal of the leader is (290,-100). The simulation results are illustrated by Figures 4-7.

Figure 4 shows that the multiple robot fishes system changes formation to avoid obstacle 2 and obstacle 3. multiple robot fishes system keeps triangle formation moving to target at the beginning. Then, the multiple robot fishes system began changing formation to avoid obstacles since the system is affected by the repulsion of obstacle 1 and obstacle 2 after entering the reaction zone of obstacles. At this time, the priority of follower 1 is higher than the priority of follower 2 because it is nearer to obstacles than follower 2. Follower robotic fishes track leader robotic fish to move to the goal.

Figure 5 shows that the multiple robot fishes system avoids obstacle 3. The force which is composed of the repulsion of obstacle 3 and the attraction of target makes the leader robotic fish move to the target while avoiding obstacle. Follower robotic fish is affected by the repulsion of obstacles while tracking leader robotic fish.

Figure 6 shows that follower robotic fish track robotic fish leader to move to the goal after the multiple robot fishes system avoids all the obstacles.

Figure 7 shows that multiple robot fishes system restores formation and reaches target point. The simulation experiment verifies the effectiveness of the method.

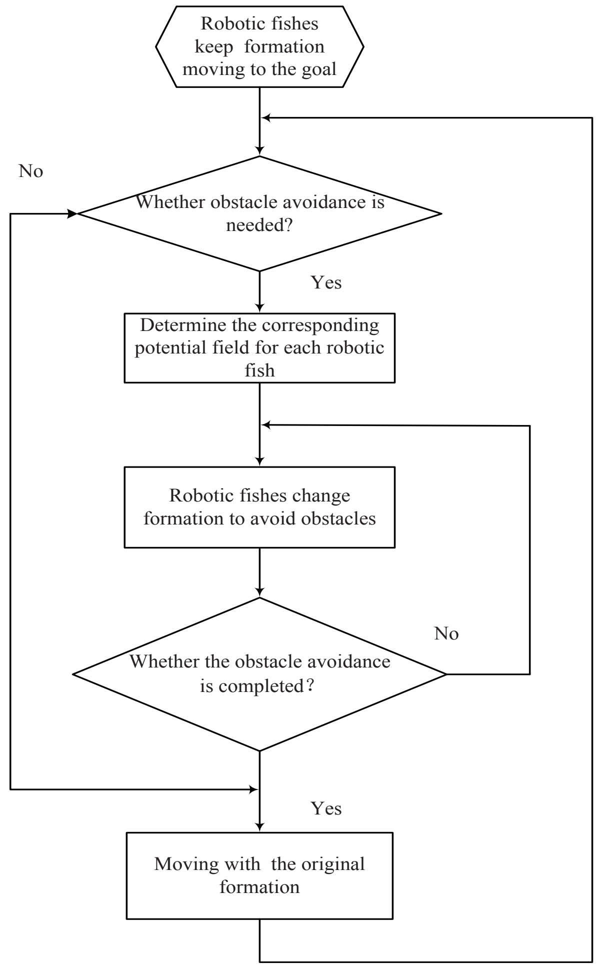

Figure 3: The flowchart of obstacle avoidance of multiple robot fishes system

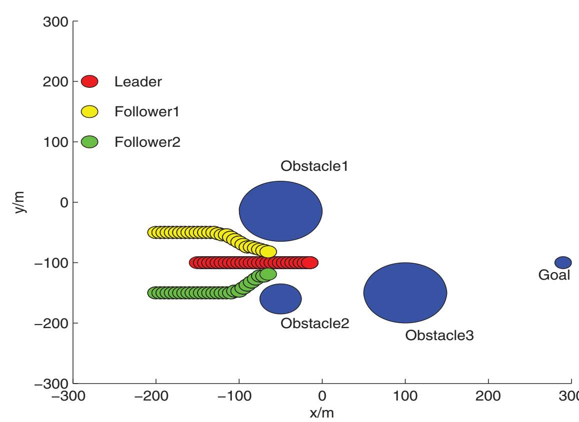

Figure 4: Multiple robot fishes system transforms formation to avoid obstacles

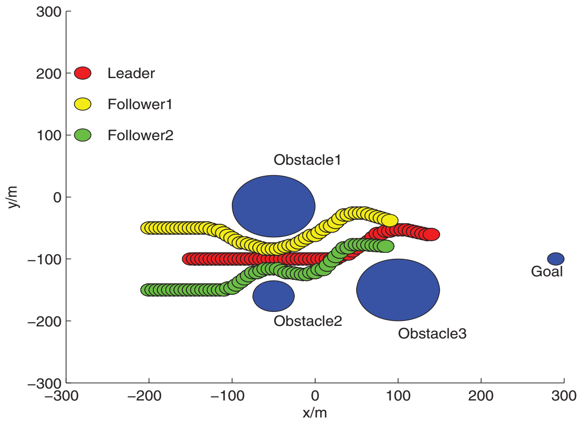

Figure 5: Multiple robot fishes system avoids obstacle 3

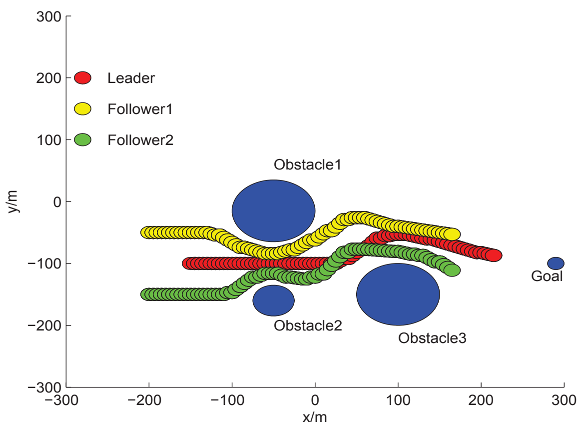

Figure 6: The formation of robotic fishes completes obstacle avoidance

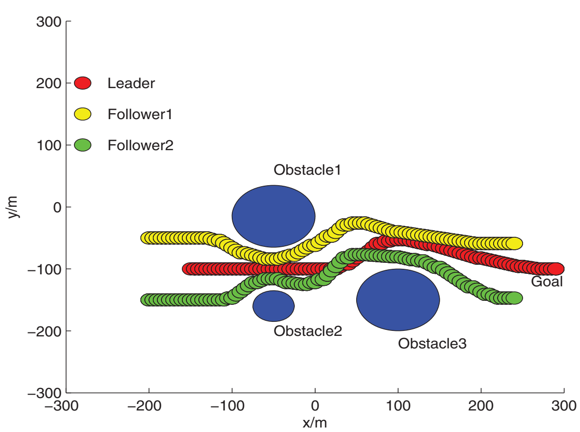

Figure 7: Multiple robot fishes system restores formation and reaches target

5 CONCLUSIONS

In the paper, the model of formation control of multiple robot fishes system was established under leader-follower framework. Then artificial potential field function was designed for multiple robot fishes system which was adopted to avoid obstacles by changing formation. The combination of these two methods makes full use of their corresponding advantages. It should be noted that the singularity is prone to appear because the extremum problem was ignored when establishing the artificial potential field function. Accordingly, the algorithm still needs to be further improved.

REFERENCES

[1] M. A. Lewis, K. H. Tan, High precision formation control of mobile robots using virtual structures, Autonomous robots, Vol.4, No.4, 387-403, 1997.

[2] T. Balch, R. C. Arkin, Behavior-based Formation Controlfor Multi-robot Teams, IEEE Trans on Robotics and Automation, Vol.14, No.6 1-15, 1998

[3] M. L. Minsky, Theory of neural analog reinforcement systems and its application to the brain model problem, New Jensey, USA: Princeton University ,1954.

[4] A. Jadbabaie, J. Lin, A. S. Morse, Coordination of groups of mobile autonomous agents using nearest neighbor rules, IEEE Trans on Automatic Control, Vol.48, No.6, 988-1001, 2003.

[5] P. K. C. Wang, Navigation strategies for multiple autonomous mobile robots moving in formation, J of Robotic Systems, Vol.8, No.2, 177-195, 1991.

[6] J. Y. Shao, J. Z. Yu, L. Wang, Formation Control of Multiple Biomimetic Robotic Fish, Intelligent Robots and Systems, No.9, 2503-2508, 2006.

[7] Z. Wei, Y. H. Hu, L. Wang, Leader-following formation control of multiple vision-based autonomous robotic fish, Decision and Control, 579-584, 2009.

[8] S. Liu, M. Yu, G. M. Xie, Formation Control of multiple robot fishes Based on Position Feedback, Ordnance Industry Automation, Vol.30, No.12, 75-78, 2011.

[9] H. J. Fang, R. Wei, Research of Artificial Potential Field Theory in Motion of Multi-robots, Control Engineering of China, Vol.14, No.2, 115-150, 2007.

[10] J. H. Liang, Motion control strategy for mobile robot formation, Journal of Computer Applications , Vol.31, No.12, 3312-3314, 2011.