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Intelligent Swarm-Finding in Formation Control of Multi-Robots to Track a Moving Target

Anh Duc Dang, Joachim Horn

Abstract**—**This paper presents a new approach to control robots, which can quickly find their swarm while tracking a moving target through the obstacles of the environment. In this approach, an artificial potential field is generated between each free-robot and the virtual attractive point of the swarm. This artificial potential field will lead free-robots to their swarm. The swarm-finding of these free-robots dose not influence the general motion of their swarm and nor other robots. When one singular robot approaches the swarm then its swarm-search will finish, and it will further participate with its swarm to reach the position of the target. The connections between member-robots with their neighbors are controlled by the artificial attractive/repulsive force field between them to avoid collisions and keep the constant distances between them in ordered formation. The effectiveness of the proposed approach has been verified in simulations.

Keywords**—**Formation control, potential field method, obstacle avoidance, swarm intelligence, multi-agent systems.

I. Introduction

FORMATION control of multi-robot systems has been one of the interesting research topics in the control community all over the world in recent years. Its potential applications in many areas, such as search and rescue missions, forest fire detection and surveillance, is the motivation and reason for this attraction.

In the formation control of multi-robot systems, the determination of the moving trajectory of member-robots and the control of the motion of them along this determined trajectory are crucial problems. Moreover, the swarm-finding of the robots and the integration of them into their swarm are also needful jobs in formation control. One of the effective and interesting methods to solve these problems is the artificial potential field method presented in [1]-[4]. In this method, the motion of the robots is controlled by artificial force fields, which consider the relative positions of the robots, target and obstacles of the environment. In recent years, the artificial potential field method has been widely studied and used to formation control of multi-agents to reach the position of the goal in a dynamic environment. Leader-following swarm, which is an application of potential field method for formation control, is easy to implement [5]-[7]. Robots can easily find their swarm under the conduction of the leader. However, any failures of this leader will influence the whole system. One other formation control method using also artificial potential field is to control all robots together to achieve a target position, in other words, all these robots take similar role [8], [9]. Using this control method the stability and robustness of the group are attained, but the quick swarm-approach of agents, which does not affect the moving trajectory of the swarm and the others, is not presented.

In this paper, the artificial potential field method is extended and applied to formation control of multi-robots to track a moving target. All robots have a general mission to observe and reach the target position. This work is driven by an attractive force field between these robots and the target. Each robot, which is not a singular member of swarm, is controlled by the attractive force field from a virtual attraction-point (VAP) of the swarm, so that this robot can easily reach its swarm. The VAP of the swarm, which is used to determine the current position of the swarm, is built as the center of the swarm. After robots integrate into their swarm, they link with their neighbors to avoid collisions in the swarm and attain a desired swarm-configuration. These connections are created by the attractive/repulsive force field between these member-robots and their neighbors.

This paper is organized as follows: The problem statement is given in the next section. Section III presents the background of the potential field method. In Section IV, the control algorithm for the swarm using the improved potential field is presented. The simulation results are presented in Section V. And finally, Section VI concludes this paper and proposes future research works.

II. Problem Statement

In this section we consider a swarm of N robots (N≥2) that moves in an n-dimensional Euclidean space (R^n) with the M obstacles of the environment. These robots are divided into two types: free-robots and member-robots. Each robot's motion, which is assumed as a moving point in the space, is described by the dynamic model as:

$$\begin{cases} \dot{p}_i = v_i \\ \dot{v}_i = \dfrac{1}{m} u_i \end{cases} \quad i = 1, \dots N. \tag{1}$$

Here $(p_i, v_i, u_i) \in R^n$ and m are the position vector, the velocity vector, control input and the mass of the robot i respectively.

The member-robots of a swarm are the robots that have stable positions in the swarm. They link with their neighbors

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to keep the constant distances among them in an ordered swarm (example in Fig. 1).

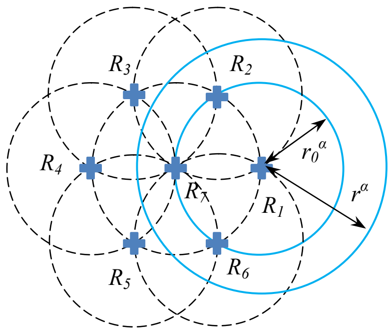


Fig. 1 Configuration of a desired swarm of seven member-robots

Let N_i^α be the set of the α neighborhood of the robot i. Robot j, which is the neighbor of the robot i ($j \in N_i^\alpha$), is defined as follows:

$$\left\{ j \in N_i^\alpha \right\} = \left\{ j, d_i^j \le r^\alpha, j = 1,..N, j \ne i, \right\}, \tag{2}$$

where r^α>0, o and $d_i^j = \left\| q_i - q_j \right\|$ are an interaction range (radius of neighborhood circle, show in Fig. 1), obstacle of the environment and the Euclidean distance, respectively. For example, in Fig. 1, the robot R_1 has three neighbors: R_2, R_3, R_4.

The free-robots must find their swarm to integrate into this swarm as other member-robots. For example, in Fig. 2, in a swarm of four robots, three member-robots R_1, R_2, R_3 only reach the target position. The free-robot R_4 is attracted by the attractive force field from the VAP, so that it will approach its swarm while it also tracks the target as other robots. After robot R_4 found its swarm, it can obtain one of the tree stable positions in the swarm, the positions A, B, C in Fig. 2. The control algorithm for this swarm-finding is given in Section III.

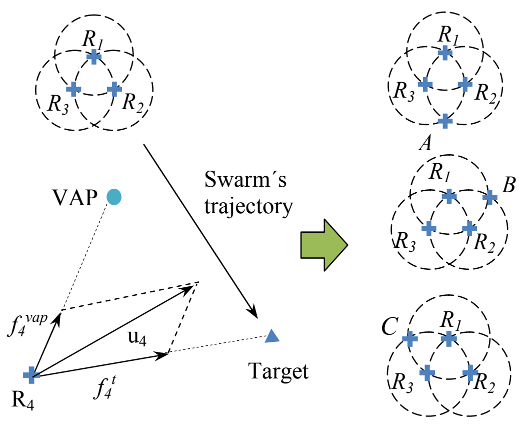


Fig. 2 The description of the swarm-finding of the robot R_4 in a swarm of four robots: f_4^{vap} and f_4^t are the attractive force filed of VAP and target, the trajectory of the robot is driven by a sum force field u_4

III. Potential Field Background

The approach of one robot to the target's position is controlled by an artificial force field that is the combination of the attractive force field to the target and the repulsive force fields away from the obstacles. In order to generate this control forces, some literatures such as [1]-[4] provide the method by using the negative gradient of the respective attractive/repulsive potential functions.

A. Attractive Potential Field

The attractive potential function used in [2], [3] is

$$V^t(p) = \frac{1}{2} k^t \ (p - p_t)^T (p - p_t), \tag{3}$$

where k^t is a positive scaling factor and (p - p_t) is a relative position vector between robot and target. The attractive force field is given by the negative gradient of this potential function shown in [2], [3] as

$$F^t(p) = -\nabla V^t(p) = -k^t \ (p - p_t). \tag{4}$$

This vector field is depicted in Fig. 3 (a).

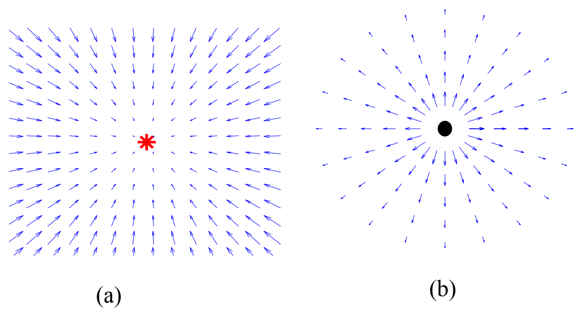


Fig. 3 The attractive vector field F^t directed toward the target position (a) and the repulsive vector field F^o around the obstacle (b)

B. Repulsive Potential Field

The repulsive force field is created around obstacles to avoid the robot's collisions with these obstacles. The potential function of this force field is shown in [2], [3] as:

$$V^o(p) = \begin{cases} \frac{1}{2} k^o \left(\frac{1}{d} - \frac{1}{r^\beta} \right)^2, & 0 < d \le r^\beta \\ 0 & , \textit{otherwise}. \end{cases} \tag{5}$$

The negative gradient field of the potential function (see [2], [3]) is

$$F^o(p) = \begin{cases} k^o \left(\frac{1}{d} - \frac{1}{r^\beta} \right) \frac{1}{d^3} (p - p_o), & 0 < d \le r^\beta \\ 0 & , \quad \textit{otherwise}. \end{cases} \tag{6}$$

The magnitude of the relative position vector $(p - p_o)$ between robot and obstacle is $d = \|p - p_o\|$ (the Euclidean distance in the space) and k^o is a positive constant. This vector field is depicted as Fig. 3 (b).

Finally, in order to control the robot to reach the target position through M obstacles of the environment, the control law is given as

$$u = F^t(p) + \sum_{o=1}^{M} F^o(p). \tag{7}$$

IV. Formation Control

This section presents the control algorithm for a swarm of N robots to track a moving target under the hinder of the environment based on the improved potential field method. As we stated in Section II, the final aim of the free-robots is they find their swarm and integrate into their swarm as other member-robots. According to that, the control law for each robot *i* is given as:

$$u_i = f_i^{vap} + f_i^j + f_i^o + f_i^t. \tag{8}$$

A. Swarm-Finding Control

The first component of (8) f_i^{vap}, which is used to control the swarm-finding of the robot *i,* is given as:

$$f_i^{vap} = \begin{cases} F_i^{vap}(p_i) - k_{iv}^{vap}(v_i - v_{vap}), & if\ i\ is\ a\ free\text{-}robot, \\ 0 & , if\ i\ is\ a\ member\text{-}robot. \end{cases} \tag{9}$$

In this equation, the relative velocity vector $(v_i - v_{vap})$ between the robot *i* and the VAP is used as damping term, with the damping scaling factor k_{iv}^{vap}. The gradient vector field $F_i^{vap}(p_i)$ is described as:

$$F_i^{vap}(p_i) = \begin{cases} -2\dfrac{k_{ip}^{vap}}{r^\delta}(p_i - p_{vap}), & d_i^{vap} \le r^\delta \\ -\dfrac{r^\delta}{d_i^{vap}}(p_i - p_{vap}), & d_i^{vap} > r^\delta. \end{cases} \tag{10}$$

This gradient vector field is characterized by a potential function, which is developed based on (3) as:

$$V_i^{vap}(p_i) = \begin{cases} \dfrac{k_{ip}^{vap}}{r^\delta}(p_i - p_{vap})^T(p_i - p_{vap}) \\ r^\delta(p_i - p_{vap}) \end{cases}, \tag{11}$$

where k_{ip}^{vap}, r^δ are the positive factors used to regulate the fast approach of free-robots to the VAP. $d_i^{vap} = \|p_i - p_{vap}\|$ is the Euclidean distance. The position P_{vap} of the selected VAP, which is the center of the swarm, is calculated as

$$p_{vap} = \frac{1}{N}\sum_{i=1}^{N} p_i. \tag{12}$$

Let $N_i(t)$ be the amount of the neighbors of the robot *i* at time *t.* The robot *i* is the member-robot or the free-robot of a swarm of N robots, which depends on *N*, $N_i(t)$ and the connections of it with other robots. It is defined as follows:

- Case 1. $2 \le N \le 3$, robot *i* is a member-robot when $N_i(t) \ge 1$, otherwise it is a free-robot.
- Case 2. $4 \le N \le 5$, robot *i* is a member-robot when $N_i(t) \ge 2$, otherwise it is a free-robot.
- Case 3. $N \ge 6$, the definition for member-robots and free-robots is presented on the flow diagram as Fig. 4.

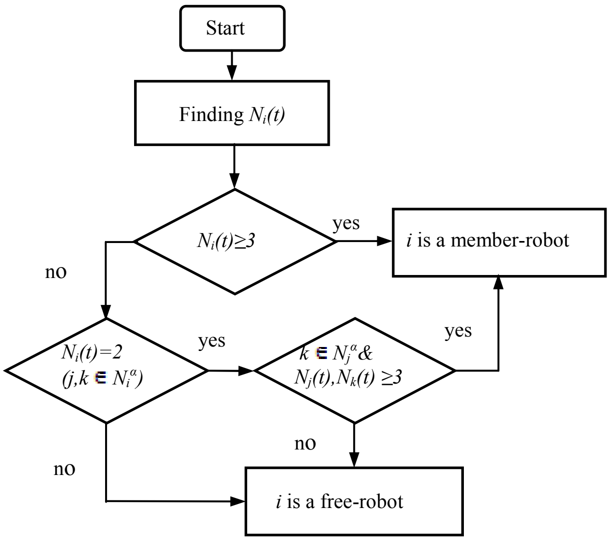


Fig. 4 The flow diagram for the definition of the robots in a swarm of N robots ($N \ge 6$)

B. Swarm-Connection Control

The second component f_i^j of (8) is used to control the connection of member-robots with their neighbors to avoid collisions and to keep the constant distances among them in an ordered swarm. However, the free-robots can also link with their neighbors and then they can together reach the position of the swarm. The control component f_i^j is designed as:

$$f_i^j = \begin{cases} \sum_{j=1}^{N_i(t)} F_i^j(p_i) - \sum_{j=1}^{N_i(t)} k_{iv}^j(v_i - v_j), & j \in N_i^\alpha \\ 0 \quad , & j \notin N_i^\alpha. \end{cases} \tag{13}$$

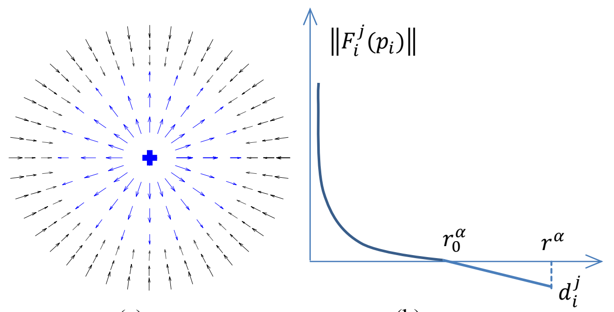
Similar to (9), in (14) the damping term $(v_i - v_j)$ with a positive factor k_{iv}^j is also appointed. To create the attractive/repulsive force field $F_i^j(P_i)$ between the robot *i* and its neighbor *j,* a potential function is proposed as

$$V_i^j(\mathrm{p}_i)=\begin{cases}\frac{1}{2}k_{ip}^{1j}\left(\frac{r_0^\alpha+k_{ip}^{2j}}{d_i^j+k_{ip}^{2j}}-1\right)^2 & ,0<d_i^j<r_0^\alpha\\ k_{ip}^{3j}\left(d_i^j-r_0^\alpha\right)^2 & ,\ r_0^\alpha<d_i^j\le r^\alpha\\ 0 & ,\ otherwise.\end{cases}\quad(14)$$

Taking the negative gradient of (14) at p_i we obtain the attractive/repulsive force, which is described in Fig. 5, as follows:

$$F_i^j(\mathrm{p}_i)=\begin{cases}k_{ip}^{1j}\left(\frac{r_0^\alpha+k_{ip}^{2j}}{d_i^j+k_{ip}^{2j}}-1\right)\frac{\left(r_0^\alpha+k_{ip}^{2j}\right)}{\left(d_i^j+k_{ip}^{2j}\right)^2}n_i^j & ,0<d_i^j<r_0^\alpha\\ -2k_{ip}^{3j}\left(d_i^j-r_0^\alpha\right)n_i^j & ,\ r_0^\alpha<d_i^j\le r^\alpha\\ 0 & ,\ otherwise,\end{cases}\quad(15)$$

where $n_i^j=\frac{\left(p_i-p_j\right)}{\left\|p_i-p_j\right\|}$ is a unit vector along the line connecting p_i to p_j, d_i^j is the Euclidean distance shown in (2). The positive constants ($k_{ip}^{1j},k_{ip}^{2j},k_{ip}^{3j},$) are used to regulate the fast collision avoidances, and the stability in the set of the *α* neighborhood of the robot *i*. The desired distance, at which the attractive/repulsive forces balance, is $\left\|q_i-q_j\right\|=r_0^\alpha$ (see Fig. 5).



(a) (b)

Fig. 5 The vector field (a) and the amplitude (b) of the force of robot *j* acts on robot *i*.

The interaction ranges ($r_0^\alpha, r^\alpha>0$, shown in Fig. 1) describe the influence of the force F_i^j on the robot *i*. When $0<d_i^j<r_0^\alpha$, then the robots *i* and *j* repel each other to avoid the collisions between them. Otherwise, when $r_0^\alpha<d_i^j\le r^\alpha$, then they attract each other to achieve the equilibrium position ($d_i^j=r_0^\alpha$) in the set of *α* neighborhood of robot *i*. When $d_i^j>r^\alpha$ there is no interaction between these members.

C. Obstacle-Avoiding Control

The third component f_i^o of (8), which is the total of repulsive forces of the obstacles, is created around the obstacles to drive the robot *i* to avoid these obstacles. Based on (6) this component is proposed as:

$$f_i^o=\sum_{o\in N_i^\beta}F_i^o\left(p_i\right)-\sum_{o\in N_i^\beta}k_{iv}^o\left(v_i-v_o\right),\quad(16)$$

where the relative velocity vector ($v_i - v_o$) between the robot *i* and its obstacle is used as a damping term with the damping scaling factor k_{iv}^o. The set of *β* neighborhood of the robot *i* is N_i^β. The neighbor-obstacle (*o)* of the robot *i* ($o\in N_i^\beta$), which the robot *i* must avoid, is defined similar to (2) as:

$$\left\{o\in N_i^\beta\right\}=\left\{o,d_i^o\le r^\beta,o=1,..M,o\ne j\right\}.\quad(17)$$

Here $r^\beta>0$ is an obstacle detecting range and $d_i^o=\left\|q_i-q_o\right\|$ is the Euclidean distance.

The negative gradient field of the potential function that is proposed as

$$V_i^o(\mathrm{p}_i)=\begin{cases}k_i^o\left(\frac{\left(r^\beta+k_i^\delta\right)}{\left(d_i^o+k_i^\delta\right)}-1\right)^2 & ,0<d_i^o<r^\beta\\ 0 & ,\ d_i^o\ge r^\beta\end{cases}\quad(18)$$

is calculated as follows:

$$F_i^o(p_i)=\begin{cases}k_{ip}^o\left(\frac{r^\beta+k_{ip}^\delta}{d_i^o+k_{ip}^\delta}-1\right)\frac{\left(r^\beta+k_{ip}^\delta\right)}{\left(d_i^o+k_{ip}^\delta\right)^2}\mathrm{n}_i^o & ,0<d_i^o<r^\beta\\ 0 & ,\ d_i^o\ge r^\beta.\end{cases}\quad(19)$$

The positive constants (k_{ip}^o,k_{ip}^δ) are applied to control the fast obstacle avoidance, n_i^o is a unit vector from the obstacle to robot *i*.

D. Target-Tracking Control

In order to control the robot *i* reach the target position the fourth component f_i^t in (8) is proposed as:

$$f_i^t=F_i^t\left(p_i\right)-k_{iv}^t\left(v_i-v_t\right).\quad(20)$$

This component is similar to (4) in section III, but here the relative velocity ($v_i - v_t$) among the robot *i* and the target is added with a positive constant k_{iv}^t. Under the effect of the attractive force of the target, the robot *i* will always track the target until it approaches this target position. The attractive force is proposed as follows:

$$F_i^t(\mathrm{p}_i)=\begin{cases}-\dfrac{k_{ip}^t}{r^\tau}(\mathrm{p}_i-\mathrm{p}_t)\,, & d_i^t<r^\tau\\ -k_{ip}^t\dfrac{(\mathrm{p}_i-\mathrm{p}_t)}{\|\mathrm{p}_i-\mathrm{p}_t\|}, & d_i^t\geq r^\tau.\end{cases} \quad (21)$$

Here $r^\tau>0$ is the target-position approaching range, and the magnitude of the relative position vector $(\mathrm{p}_i-\mathrm{p}_t)$ between robot *i* and the target is $\mathrm{d}_i^t=\|\mathrm{p}_i-\mathrm{p}_t\|$.

V. Simulation Results

This section presents the results of the simulations of the swarm-finding control algorithm in formation control of multi-robots in a dynamic environment. For the simulations, we assume that the initial velocities of the robots and target are set to zero, and obstacles of the environment are stationary. All robots know the position of other robots as well as the position of obstacles and target. The general parameters of the simulations are listed in Table I.

First of all, we test the control algorithm for a swarm of four robots that tracks a moving target. The target moves along the trajectory $p_t=(0.3t+200,-0.2t+480)^T$.

TABLE I
Parameter Values

Parameter	Definition	Value
r^δ	Distance of swarm-approach	10 m
$k_{ip}{}^{vap}$	Constant for fast swarm-approach	2,4
$k_{iv}{}^{vap}$	Damping factor for fast swarm-approach	0,9
$r_0{}^\alpha$	Desired distance for neighbors	20 m
r^α	Radius of neighborhood circle	30 m
$k_{ip}{}^{1j}$ $k_{ip}{}^{2j}$ $k_{ip}{}^{3j}$	Constants for fast link between neighbors to balance position	50 1,2 1,8
$k_{iv}{}^{j}$	Damping factor for approach to balance position	1
r^β	Obstacle detecting range	30 m
$k_{ip}{}^{o}$ $k_{ip}{}^{\delta}$	Constants for fast obstacle avoidance	100 1
r^τ	Distance of approach to target position	50 m
$k_{ip}{}^{t}$	Constant for fast approach to target position	1,6
$k_{iv}{}^{t}$	Damping factor for approach to target position	0,9

The simulation case for the robust connections of the member-robots in an ordered swarm is depicted in Figs. 6 and 7. For this simulation, the initial positions of robots and obstacle are chosen as follows:

$$\mathrm{p}_1=(10,50)^\mathrm{T},\ \mathrm{p}_2=(20,160)^\mathrm{T},\ \mathrm{p}_3=(100,30)^\mathrm{T},\ \mathrm{p}_4=(40,120)^\mathrm{T},\mathrm{p}_\mathrm{o}=(200,250)^\mathrm{T}.$$

The results of the simulations in Figs. 6 and 7 show that the formation of the member-robots is always maintained while their swarm tracks a moving target. At initial time, all robots move free, but after a short time of circa 200s (see Fig. 6) they link themselves together to reach the stable positions in the swarm. These connections are always kept until the swarm meets the obstacle at time t=800s. The connection of the swarm is broken while avoiding this obstacle, and then it is quickly redesigned in the robustness of a desired swarm while following the trajectory of the target.

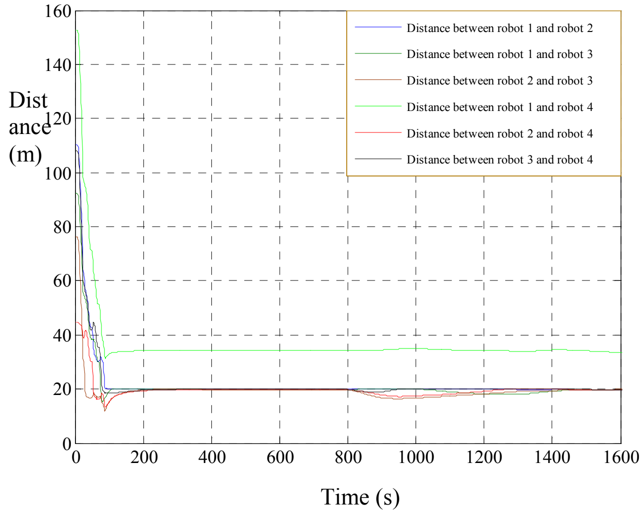


Fig. 6 Distance between robots in swarm at time *t*

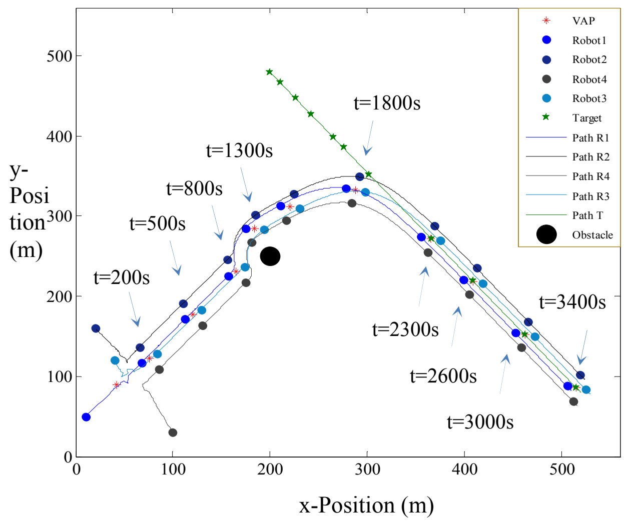


Fig. 7 The robust connection of a swarm of four member-robots is maintained while tracking a moving target

The simulation case for the swarm-finding of the free robots is presented in Figs. 8 and 9. The initial positions of the robots and obstacles are selected as:

$$\mathrm{p}_1=(10,200)^\mathrm{T},\ \mathrm{p}_2=(30,210)^\mathrm{T},\ \mathrm{p}_3=(60,220)^\mathrm{T},\ \mathrm{p}_4=(400,10)^\mathrm{T},$$
$$\mathrm{p}_{o1}=(230,150)^\mathrm{T},\ \mathrm{p}_{o2}=(300,100)^\mathrm{T}.$$

The simulation results in Figs. 8 and 9 show that three robots (R_1, R_2, R_3) have quickly approached their swarm and become member-robots at time t=200s (see Fig. 8). Their motion to the target position is not affected by the attractive force of the VAP. Under the effect of the attractive force from VAP, the free robot R_4 passes through obstacles to achieve its swarm (see Fig. 9). This robot approaches its swarm and becomes a member in swarm at time t=650s and then it is linked with other members in the stability of swarm while tracking the moving target.

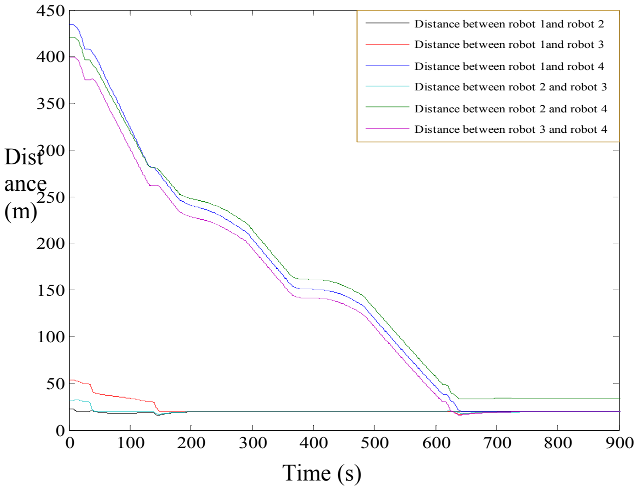


Fig. 8 Distance between robots in the swarm at time *t*

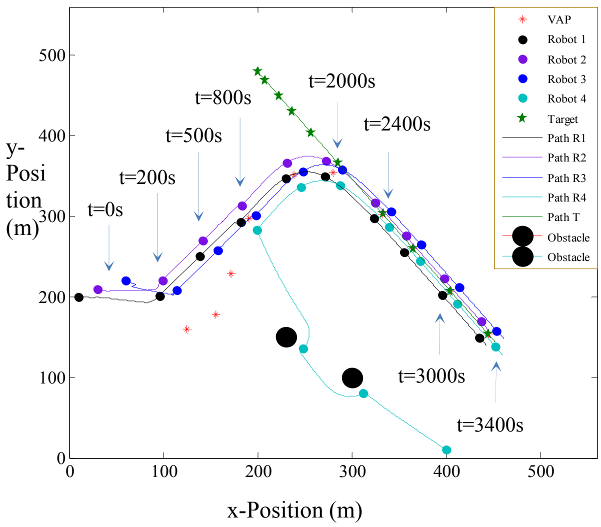


Fig. 9 The swarm-finding and the position-reach in swarm as other member of the robot R_4 in a swarm of four robots

Secondly, we test the control algorithm for the swarm-finding of free robots while they track a target that moves along the trajectory $p_t = (0.06t + 200, -0.08t + 480)^T$. For this simulation, the initial positions of the robots and obstacle are selected as:

$$p_1=(10,20)^T, p_2=(20,10)^T, p_3=(30,20)^T, p_4=(40,50)^T, p_5=(5,80)^T$$
$$p_6=(300,10)^T,\ p_7=(450,10)^T, p_{o1}=(350,100)^T,\ p_{o2}=(280,200)^T.$$

The simulation results depicted in Fig. 10 show that the swarm-finding of two robots (R_6 and R_7) is successfully achieved, and this swarm-finding does not change the general trajectory of swarm. At initial time all robots are directed to the VAP position. The free-robots $R_{1...5}$ quickly find their neighbors, and immediately they connect together to become the first member-robots of a basic swarm. The approach of the robot R_6 into this basic swarm is not difficult. Robot R_7 has also successfully reaches the basic-swarm, although it is hindered by some obstacles of the environment. The organization of the swarm is changed when the free-robots R_6 and R_7 become member-robots. The constant distances between member-robots are always maintained while these robots track the moving target.

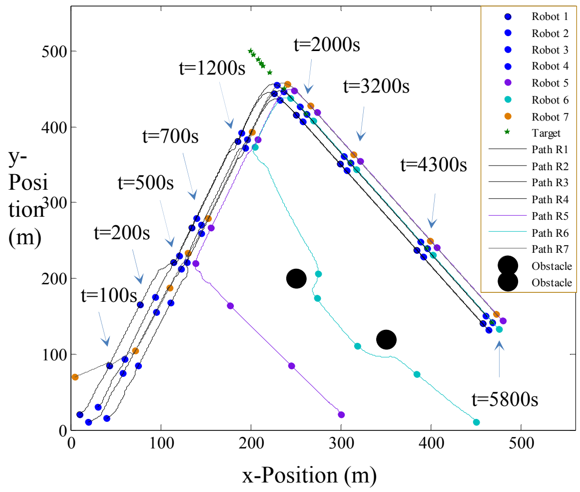


Fig. 10 The swarm-finding and the position-reach in swarm as other member of the robot R_6, R_7 in a swarm of seven robots

VI. Conclusion

This paper has presented an approach of swarm-finding control of free-robots while they track a moving target based on the potential field method. These proposed control algorithms were verified by simulations. The results of the simulations have shown that this approach is one of the control methods that can be applied to control the swarm-finding of multi-robots in formation control. Using the virtual attractive field from the center of swarm, the free-robots can easily find their swarm, and then these free-robots will become member-robots as other member-robots in the swarm. The velocity of the free-robots when reaching the swarm can be easily controlled by changing the control-factor k_{ip}^{vap}. The combination of this method with the adaptive formation control in dynamic environment is an interesting topic for our future research.

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