Formation Adaptation Control of Autonomous Robots in a Dynamic Environment

Anh Duc Dang and Joachim Horn

Abstract—**This paper presents a novel approach for the adaptive formation control of multi-agent systems to track a moving target in a dynamic environment. In this approach, while the swarm reaches the target position, if it detects obstacles on the way, its size will change in order to avoid these obstacles. In special cases, such as when the space between the obstacles is narrow, then the formation of the robots will automatically shrink into a smaller size. Hence, the swarm can easily pass through this space, while the swarm's connection is maintained. However, to avoid collisions among the robots, the swarm's size can only reduce to a minimum desired size. If the swarm's size is smaller than this minimum size, the swarm's structure will be broken, and then the robots become free to avoid obstacles. In order to handle these problems, the adaptive formation control algorithm is built based on the change of the desired distance between the neighboring robots. This desired distance depends on the sum of the repulsive forces from obstacles to the swarm. The effectiveness of the proposed approach has been verified in simulations.**

Keywords—**Formation control, obstacle avoidance, potential field, 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 recent years, the artificial potential field method has been widely studied and used to formation control of multi-agent systems to reach the position of the goal in a dynamic environment, see [1]-[4]. One of the main issues in the formation control of multi-agents to track a moving target is that all the member robots have to move together without collisions among them in an ordered swarm. Moreover, the whole swarm must avoid obstacles along its trajectory, which has a big influence on reaching the target. In order to solve these problems, the motion of each member robot is controlled by a total force field which includes the interactive forces between neighboring robots, the repulsive force from the obstacles of the environment and the attractive force to the target position. Under the effect of this total force, the formation of the swarm is stably maintained while the swarm reaches the target position in the free environment. In contrast, this stability is broken when the swarm avoids the obstacles of the dynamic environment. After the swarm has overcome the obstacles, its organization is redesigned; however, the formation of it is possibly changed, see [5], [6]. This problem can be resolved, if the swarm maintains its formation in a smaller size. This is an interesting topic that attracts the attention from researchers in recent years. A research result around this topic, 'Adaptive flocking of robot swarms: Algorithm and properties', is presented in [7]. In this approach, each agent can cooperatively learn the network's parameters to decide the size and the split of the network in a decentralized fashion so that the connectivity, formation and tracking performance can be improved when avoiding obstacles. Furthermore, in [8]- [11], the authors proposed another approach for adaptive flocking control. In this approach, when the swarm detects obstacles, the connection of the swarm is broken and each agent determines its direction toward the target position based on the width of the space among these obstacles.

In this paper, we propose a novel approach to adaptive formation control of a swarm of multi-robots which can quickly avoid obstacles to track a moving target. In addition, in a complex environment, such as when the space between obstacles is narrow, we suggest that the swarm's size can change so the swarm can easily pass through this space. In this case, the formation of the swarm is maintained while avoiding obstacles. However, when the swarm reaches a minimum desired size, at which the swarm cannot pass obstacles, its formation will be broken. The robots will split formation in order to avoid obstacles and collisions with each other. And then, the formation of these robots will be redesigned to reach the target. In other word, these robots will themselves find their swarm and they link to each other in a new formation, see [12], [13]. In our approach, the information, which is obtained from the changing environment, is concurrently sent to all robots in the swarm. Therefore, the swarm's size will quickly be adapted to changes of the environment.

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 swarm's adaptive control for avoiding obstacles is presented. Simulation results are presented in section V. Finally, section VI concludes this paper and proposes future research.

II. Problem Statement

In this section we consider a swarm of N robots ($N \geq 2$) that moves in a two-dimensional Euclidean space $\{R^2\}$ with M obstacles of the environment. Each robot's motion, which is assumed as a moving point in the space, is described by the dynamic model as follows:

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

Here $(p_i, v_i, u_i) \in \{R^2\}$ and m_i are the position, the velocity, the control input and the mass of the robot *i*, respectively.

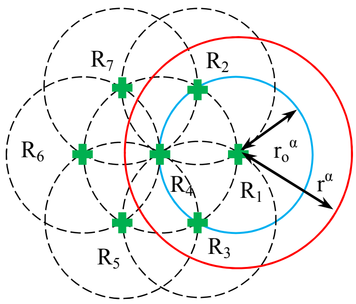

Fig.1 Configuration of a desired swarm of seven member-robots.

In a desired swarm, the neighboring robots have to link to each other to generate the constant distances among them (example in Fig.1). Let $N_i^\alpha(t)$ be the set of the α neighborhood of the robot *i* then the robot *j* at time *t*, which is the neighbor of the robot *i* ($j \in N_i^\alpha(t)$), is defined as follows:

$$N_i^\alpha(t) = \left\{ j, d_i^j \leq r^\alpha, j = 1,..N, j \neq i \right\}, \tag{2}$$

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

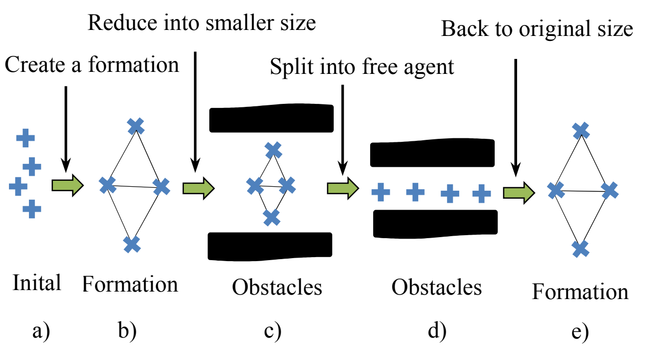

Fig.2 The description of adaptive formation control of a swarm while avoiding obstacles: The formation maintenance (c) and the formation splitting (d).

The idea for the adaptation to a complex environment to track a moving target is that when some robots in the swarm detect obstacles then the swarm's size will shrink oneself into smaller size so that the swarm can easily pass through these obstacles, but the formation of the swarm is maintained (example Fig.2c). However, in order to avoid collisions among robots in a swarm the swarm's size is only allowed to reduce to a minimum desired size. Each robot will split from its swarm to become a free robot to avoid obstacles in the direction toward the target (example Fig.2d). After the robots have overcome the obstacles, the swarm's structure will be redesigned in a desired swarm. The changing of the swarm's size to adapt to a complex environment is controlled by the desired distance r_0^α (see Fig.1) between the neighboring robots. The control algorithm for this adaption is given in section IV.

III. Potential Field Background

The artificial potential field is known in control technology as an effective method for robot's path planning. This potential field is the combination of the attractive force field to the target and the repulsive force fields away from the obstacles. In order to generate these control forces, some literatures, such as [1]-[4], gave 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, which is depicted in Fig.3a, is given by the negative gradient of this potential function shown in [2], [3] as:

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

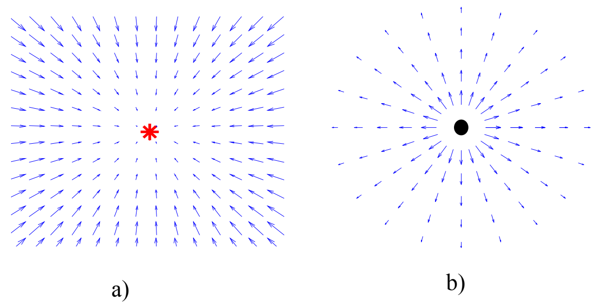

Fig.3 The attractive vector field F^t directed toward the target position (a) and the repulsive vector field F^o around the obstacle (b).

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:

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

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

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

In this equation, 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 in Fig.3b.

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. ADAPTIVE FORMATION CONTROL

This section presents the swarm's adaptive control algorithm for a swarm of N robots, which pass through obstacles to track a moving target. The control law for each robot *i* is given as follows:

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

A. Obstacle-avoiding control

The first component f_i^o of (8) is used to control the obstacles avoidance for the member robots of the swarm while tracking a moving target. This component is proposed as:

$$f_i^0 = \sum_{o \in N_i^\beta} \left(F_i^o(p_i) - k_{iv}^o c_i^o (v_i - v_o) \right), \tag{9}$$

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

$$N_i^\beta(t) = \left\{ o, d_i^o \le r^\beta, o = 1,..M, o \ne j \right\}. \tag{10}$$

Here $r^\beta > 0$ is an obstacle detecting range and $d_i^o = \|p_i - p_o\|$ is the Euclidean distance. The scalar c_i^o, which is used to determine that an obstacle *j* is a neighboring obstacle of robot *i* or not, is defined as follows:

$$c_i^o = \begin{cases} 1 & \text{if } o \in N_i^\beta(t) \\ 0 & \text{if } o \notin N_i^\beta(\text{t}). \end{cases} \tag{11}$$

The repulsive force $F_i^o(p_i)$ is created around the obstacles to drive the robot *i* away from these obstacles. It is designed as:

$$F_i^o(p_i) = c_i^o \left(\left(\frac{1}{d_i^o} - \frac{1}{r^\beta} \right) \frac{k_{ip}^o}{(d_i^o)^2} - k_{ip}^\delta \left(d_i^o - r^\beta \right) \right) \mathrm{n}_i^o \tag{12}$$

In this equation, the positive constants $(k_{ip}^o, k_{ip}^\delta)$ are applied to control the fast obstacle avoidance. The unit vector from the obstacle to robot *i* is computed as $n_i^o = (p_i - p_o)/\|p_i - p_o\|$.

This gradient vector field is characterized by a respective potential function, which is developed based on the equations (3) and (5) as follows:

$$V_i^o(\mathrm{p}_i) = \frac{c_i^o}{2} \left(\left(\frac{k_{ip}^o}{d_i^o} - \frac{k_{ip}^o}{r^\beta} \right)^2 + k_{ip}^\delta \left(d_i^o - r^\beta \right)^2 \right) \tag{13}$$

B. Swarm-connection control

The second component f_i^j of (8) is used to control the connection of neighboring robots to avoid collisions and to keep the constant distances among them in an ordered swarm. This control component f_i^j is designed as:

$$f_i^j = \sum_{j=1, j \ne i}^{N} \left(F_i^j(p_i) - k_{iv}^j c_i^j (v_i - v_j) \right). \tag{14}$$

In this equation, the relative velocity ($v_i - v_j$) between the robot *i* and its neighbor *j* is used as damping term with the damping scaling factor k_{iv}^j. The scalar c_i^j is used to determine that the robot *j* is a neighbor of robot *i* or not. It is defined as:

$$c_i^j = \begin{cases} 1 & \text{if } j \in N_i^\alpha \\ 0 & \text{if } j \notin N_i^\alpha. \end{cases} \tag{15}$$

To create the attractive/repulsive force field $F_i^j(p_i)$ between the robot *i* and its neighbor *j,* a respective potential function is proposed as:

$$V_i^j(\mathrm{p}_i) = \frac{c_i^j}{2} \left(\left(\frac{k_{ip}^{1j}}{d_i^j} - k_d \right)^2 + k_{ip}^{2j} \left(d_i^j - r_1^\alpha \right)^2 \right) \tag{16}$$

Taking the negative gradient of this potential function at p_i, we obtain the attractive/repulsive force, which is described in Fig.4a, as follows:

$$F_i^j(\mathrm{p}_i) = c_i^j \left(\left(\frac{k_{ip}^{1j}}{d_i^j} + k_d \right) \frac{k_{ip}^{1j}}{(d_i^j)^2} - k_{ip}^{2j} \left(d_i^j - r_1^\alpha \right) \right) n_i^j \tag{17}$$

where $n_i^j = (p_i - p_j)/\|p_i - p_j\|$ is a unit vector along the line connecting p_i *to* p_j, d_i^j is the Euclidean distance shown in equation (2). The positive constants ($k_{ip}^{1j}, k_{ip}^{2j},$) are used to regulate the fast collision avoidance, and the stability in the set of the α neighborhood of the robot *i*. The distance r_1^α is a minimum desired distance at which the attractive/repulsive forces balance. The positive factor k_d is used as an adaptive control element to control the balance position between the attraction and the repulsion. Hence, when the swarm's size changes the formation of the swarm will be maintained.

By equating $\left(\left(k_{ip}^{1j}/d_i^j + k_d \right) k_{ip}^{1j}/(d_i^j)^2 - k_{ip}^{2j} \left(d_i^j - r_1^\alpha \right) \right) = 0$, one can find a value $d_i^j = r_k^\alpha$ at which the sum of the attractive force and the repulsive is zero. In other words, if there is a given value $r_k^\alpha \geq r_1^\alpha$ and the line $-k_{ip}^{2j}\left(d_i^j - r_1^\alpha\right)$ is not changed, then the adaptive control element k_d is determined as a function of the r_k^α. This function is described as

$$k_d = \frac{k_{ip}^{2j}\left(r_k^\alpha - r_1^\alpha\right)\left(r_k^\alpha\right)^2}{k_{ip}^{1j}} - \frac{k_{ip}^{1j}}{r_k^\alpha}. \quad (18)$$

The equation (18) shows that when the desired distance r_k^α changes from the maximum desired value r_0^α to the minimum desired value r_1^α then the adaptive control element k_d will change in order to find the balance position, at which the connection between robot j and i is stable (see Fig.4a). When $0 < d_i^j < r_k^\alpha$, then the robots i and j repel each other to avoid the collisions between them. Otherwise, when $r_k^\alpha < d_i^j \leq r^\alpha$, then they attract each other to achieve the equilibrium position $(d_i^j = r_k^\alpha)$ in the set of α neighborhood of robot i. When $d_i^j > r^\alpha$ there is no interaction between these members.

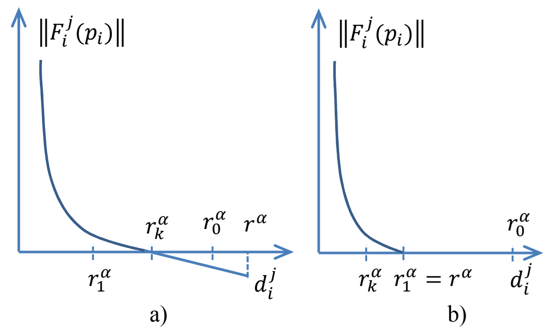

Fig.4 The amplitude of the force of robot j acts on robot i when $r_1^\alpha \leq r_k^\alpha \leq r_0^\alpha$ (a) and when $r_k^\alpha < r_1^\alpha$ (b).

From Fig.1 we see that the swarm's size depends on the links between neighboring robots in the ordered swarm. Hence, when changing these links, that is, changing the desired distance r_k^α, the swarm's size will also change. Furthermore, the formation of the swarm has to shrink into a smaller size in order that the swarm can easily pass through the obstacles. Therefore, the desired distance r_k^α is designed by an adaptive control force that is the average of the sum of repulsive forces from obstacles to the swarm. This desired distance is described as:

$$r_k^\alpha = r_0^\alpha - c_o \sum_{i=1}^{N} \sum_{o \in N_i^\beta} \left\|F_i^o\left(p_i\right)\right\|. \quad (19)$$

The component c_o is defined as $c_o = c \Big/ \sum_{i=1}^{N} \sum_{o \in N_i^\beta} c_i^o$, here c is a positive constant. The repulsive force $F_i^o\left(p_i\right)$ from the obstacle o $(o=1...M)$ to the robot i is presented in (12).The equation (19) shows that when the swarm does not detect the obstacles (that is, $c_o \sum_{i=1}^{N} \sum_{o \in N_i^\beta} \left\|F_i^o\left(p_i\right)\right\| = 0$) then $r_k^\alpha = r_0^\alpha$ (the original size of the swarm is not changed). If this adaptive control force increases, that is, the swarm is hindered more, then the r_k^α will decrease into the smaller size until the swarm can pass through these obstacles. However, if $r_k^\alpha < r_0^\alpha$, then the connection of the swarm must be broken to avoid the collisions between the robots in the swarm. The member robots will split from the swarm to avoid obstacles. Therefore, to solve these problems, the radius of neighborhood circle r^α is chosen as:

$$r^\alpha = \begin{cases} \frac{3}{2} r_k^\alpha, & \text{if } r_1^\alpha \leq r_k^\alpha \leq r_0^\alpha \\ r_1^\alpha, & \textit{otherwise}, \end{cases} \quad (20)$$

and the adaptive control element k_d *is also* redesigned as follows:

$$k_d = \begin{cases} \frac{k_{ip}^{2j}\left(r_k^\alpha - r_1^\alpha\right)\left(r_k^\alpha\right)^2}{k_{ip}^{1j}} - \frac{k_{ip}^{1j}}{r_k^\alpha}, & \text{if } r_1^\alpha \leq r_k^\alpha \leq r_0^\alpha \\ -\frac{k_{ip}^{1j}}{r_1^\alpha}, & \textit{otherwise.} \end{cases} \quad (21)$$

Finally, from equations (17), (20), (21) we see that when r_k^α reduces from r_0^α to r_1^α, then the swarm's size also shrinks into a smaller, but the robust connections between the neighboring robots are further maintained (see Fig.4a). Otherwise, when $r_k^\alpha < r_1^\alpha$, then the link of the swarm is broken, there is only the repulsive force between the neighboring robots to avoid the collisions among them (see Fig.4b).

C. *Target-tracking control*

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

$$f_i^t = F_i^t\left(p_i\right) - k_{iv}^t\left(v_i - v_t\right). \quad (22)$$

This component is similar to equation (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. This attractive force is proposed as follows:

$$F_i^t(\mathrm{p}_i) = \begin{cases} -\frac{k_t}{r^\tau}(\mathrm{p}_i - \mathrm{p}_t), & \text{if } d_i^t < r^\tau \\ -k_t \frac{(\mathrm{p}_i - \mathrm{p}_t)}{\left\|\mathrm{p}_i - \mathrm{p}_t\right\|}, & \textit{otherwise.} \end{cases} \quad (23)$$

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 $d_i^t = \left\|p_i - p_t\right\|$. In order to adaptively control a swarm that can better avoid obstacles, this attractive force plays an important role too. The magnitude of this force is decided by the control factor k_t, which is proposed as follows:

$$k_t = \begin{cases} \dfrac{k_{ip}^t}{r_k^\alpha}, & \text{if } r_1^\alpha \le r_k^\alpha \le r_0^\alpha \\ \dfrac{k_{ip}^t}{r_1^\alpha}, & \text{if } r_k^\alpha < r_1^\alpha \end{cases} \quad (24)$$

The equation (24) shows that when the adaptive control force increases, that is, the desired distance r_k^α decreases, then the attractive force of the target is also increased. However, when $r_k^\alpha < r_1^\alpha$, the gain of this attractive force is limited by a maximum desired value that corresponds to $k_t = k_{ip}^t / r_1^\alpha$, so the swarm will avoid damage.

V. Simulation Results

This section presents the results of the simulations of the adaptive formation control algorithm of multi-robots while avoiding obstacles. 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 for the simulations are listed in table I.

TABLE I. Parameter Values

Parameter	Definition	Value
r_1^α	Minimum desired distance for neighbors	10
r_0^α	Maximum desired distance for neighbors	20
k_{iv}^j	Damping factor for approach to balance point	1
k_{ip}^{1j}	Constants for fast link between neighbors to balance position	50
k_{ip}^{2j}		1,2
r^β	Obstacle detecting range	30
k_{ip}^o	Constants for fast obstacle avoidance	100
k_{ip}^δ		1
r^ε	Distance of approach to target position	50
k_{ip}^t	Constant for fast approach to target position	1,6
k_{iv}^t	Damping factor for approach to target position	0,9

Firstly, we test the control algorithm for the robust connections in a swarm of four robots, which avoids the obstacles while tracking a moving target. The target moves along the trajectory $p_t = (0.3t + 400, -0.2t + 300)^T$. For this simulation, the initial positions of robots and obstacle are chosen as follows:

$p_1=(40,70)^T$, $p_2=(30,50)^T$, $p_3=(80,10)^T$, $p_4=(20,30)^T$, $p_{o1}=(250,140)^T$, $p_{o2}=(250,250)^T$, $p_{o3}=(400,160)^T$, $p_{o4}=(400,230)^T$.

The results of the simulations in Fig.5 and Fig.6 show that the formation of a swarm is maintained while the swarm tracks a moving target. At initial time, all robots move freely, but after a time of circa 50s they link to each other to reach the stable positions in a desired swarm. The swarm's size is kept until the swarm meets the obstacle. At time t=125s until t=220s the swarm's size is shrunk into a smaller size to avoid obstacle, but the formation is not broken. After overcoming obstacle the swarm's size is immediately recovered, and further maintained in an original size while tracking a moving target.

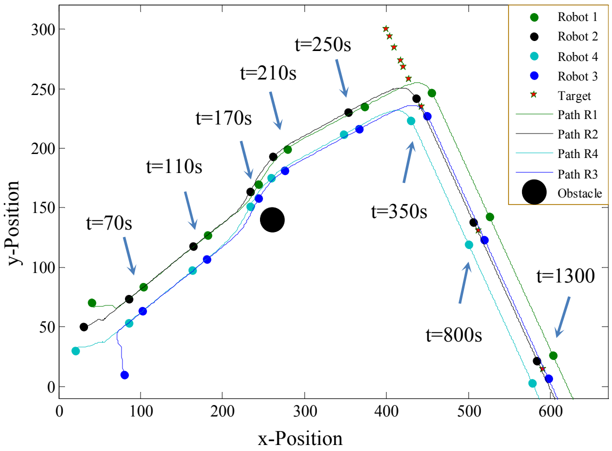

Fig.5 The robust connection of a swarm of four robots is maintained while tracking a moving target.

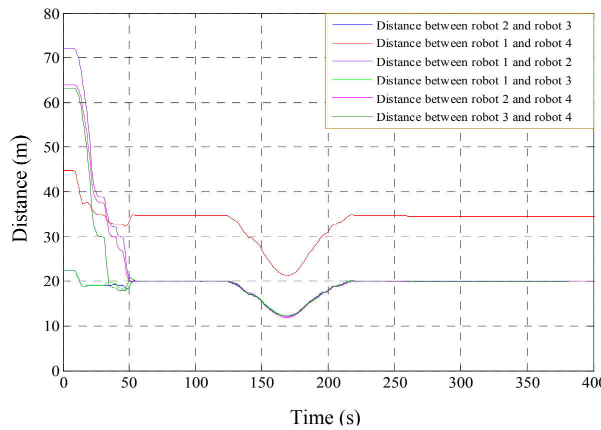

Fig.6 The size of a swarm in Fig 6 changes at time *t*.

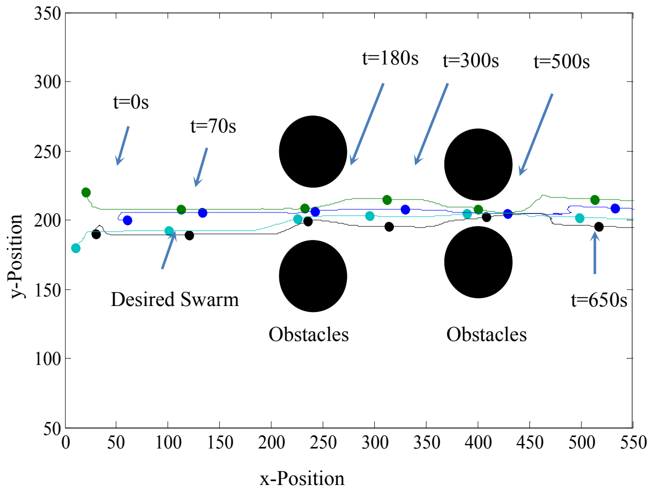

Fig.7 The adaptation of a swarm of four robots when the space between obstacles changes.

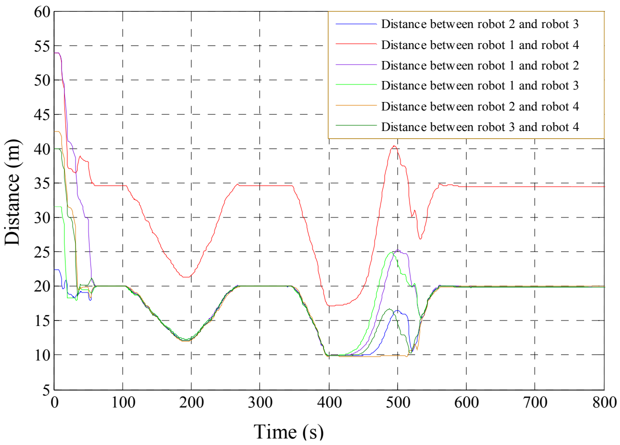

Fig.8 The size of a swarm in Fig 8 changes at time *t*.

Secondly, the adaptive formation control is tested while a swarm passes through the different narrow spaces between obstacles. Fig.7 and Fig.8 depict the results of the simulations for a swarm of four robots. During the period from 100s to 260s the distances between neighboring robots are reduced to smaller values (see Fig.8). Hence, the swarm can easily overcome the space between these obstacles, while the swarm's structure is maintained. From t=400s to t=560s the swarm's link is broken and the robots become free robots in order to avoid obstacles. In this case, the obstacle avoidance of the free robots is successful and there are no collisions among robots (the smallest distance between neighbors is $d_i^j = r_1^\alpha$, see Fig.9).

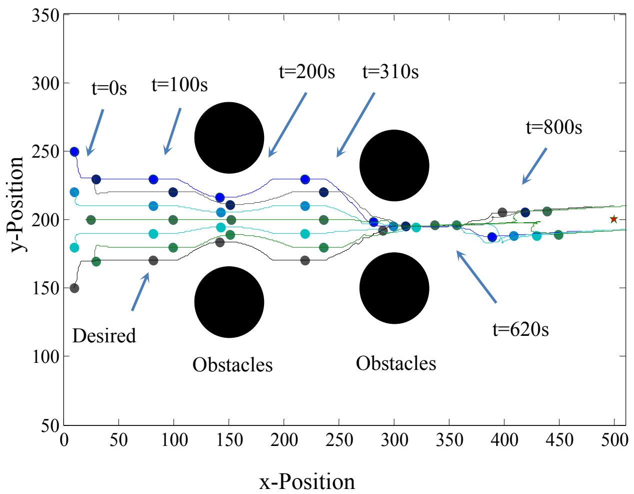

Fig.9 The adaptation of a swarm of seven robots when the space between obstacles changes.

Similar to the case for a swarm of four robots, Fig.9 shows that a swarm of seven robots adapts to the changing environment while reaching the position of the target. At time t=200s, the formation is shrunk in order to pass through the narrow space between obstacles, and then it is recovered as the original formation at t=200s. At time t=620s the formation is broken, and then it is redesigned in a different stable structure in order to further move towards the target.

VI. Conclusion

This paper has presented an approach for the adaptive formation control of a swarm of autonomous robots that pass through the obstacles of the dynamic environment to reach the target position. The adaptation of a swarm to the environment is built based on the change of the desired distance between the neighboring robots in the swarm. This desired distance is inversely proportional to the sum of the repulsive force from obstacles to the swarm. Information about obstacles, which each member robot detects from the environment, will be sent to all other member robots in the swarm. Therefore, the swarm's size will immediately change to adapt to the changing environment. The results of the simulations have shown that under the proposed adaptive control algorithm, a swarm of autonomous robots can easily escape obstacles of the environment in order to reach the target. The development of this approach for application in more complex environments, in which a swarm must confront moving obstacles and influence of noises, is an interesting topic for our future research.

References

[1] Frank E. Schneider and Dennis Wildermuth, " A potential field based approach to multi robot formation navigation", *Proc. of the 2003 IEEE Intl. Conf. on Robotics, Intelligent System and Signal Processing, pp. 680-685,October 2003.*

[2] Shi and Yiwen Zhao, "An efficient path planning algorithm for mobile robot using improved potential field", *Proc. of the 2009 IEEE Intl. Conf. on Robotics and Biomimetics, pp. 1704-1708, December 2009.*

[3] S. S. Ge and Y. J. Cui, "New potential functions for mobile robot path planning", *IEEE Trans. on Robotics and Automation, vol. 16, no.5, pp. 615-620,October 2000.*

[4] Simon János and István Matijevics, "Implementation of potential field method for mobile robot navigation in greenhouse environment with WSN support", *IEEE 8th Intl. Symp. on Intelligent Systems and Informatics, pp. 319-323, September 2010.*

[5] Jia Wang, Xiao-Bei Wu and Zhi-Liang Xu, "Decentralized formation control and obstacles avoidance based on potential field method", *Proc. of the Fifth Intl. Conf. on Machine Learning and Cybernetics, pp. 803-808,August 2006.*

[6] Xiu-juan Zheng, Huai-yu Wu, Lei Cheng, Yu-Li Zhang, "Multiple nonholonomic mobile robots formation coordinated control in obstacles environment", *Proc. of 2011 Intl. Conf. on Modeling, Indentification and control, pp. 122-126, June 2011.*

[7] G. Lee and N.Y. Chong , "Adaptive flocking of robot swarms: Algorithms and properties", *IEICE Trans. on Communications, vol. E91-B, no.9, pp.* 2848–2855, *September 2008.*

[8] Y. Yang, N. Xiong, N. Y. Chong and X. Défago, "A decentralized and adaptive flocking algorithm for autonomous mobile robusts", *IEEE 3th Intl. Conf. on Grid and Pervasive Computing-Workshops, pp. 262-268, 2008.*

[9] Y. Dai, K. S. Choi and S. G. Lee "Adaptive formation control and collision avoidance using a priority for nonholonomic mobile robots", *Intl. Jour. of Advanced Robotics System, vol. 10, , pp.* 1–14, *2013.*

[10] Dong Eui Chang, Shawn C. Shadden, Jerrold E. Marsden and Reza Olfati-Saber, " Collision avoidance for multiple agent systems", *Proc. of the 42nd IEEE Conf. on Decision and control, pp. 539-543, December 2003.*

[11] Wenwu Yu and Guanrong Chen, "Robust adaptive flocking control of nonlinear multi-agent systems", *IEEE Intl. Sym. on Computer-Aided Control system Design, pp. 363-367, September 2010.*

[12] Anh Duc Dang and Joachim Horn "Intelligent swarm-finding in formation control of multi-robots to track a moving target", *Intl. Journal of Computer, Information Science and Engineering, Vol.8, No. 4, pp.12-18,2014.*