Collinear Formation Control of Autonomous Robots to Move Towards a Target Using Artificial Force Fields

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***Abstract*— In this paper, we propose a novel approach to control autonomous robots to achieve a desired linear formation during movement towards the target position. Firstly, one robot, which has the closest distance to the target, is selected as the leader of the swarm. The desired formation is built based on the relative position between this leader and the target. Secondly, the trajectory of the remaining robots towards the optimal positions in the desired formation is driven by the artificial force fields. These force fields consist of the local and global attractive potential fields surrounding each virtual node in the desired formation. Furthermore, an orientation controller is added in order to guarantee that the desired formation is always headed in the invariant direction to the target position. In addition, the local repulsive force fields around each robot and obstacle are employed in order to avoid collisions during movement. The stability of a swarm following a desired collinear formation in invariant direction towards the target is verified in simulations and experiments.**

***Keywords*: Formation control, swarm intelligence, collision avoidance, artificial vector fields**

I. INTRODUCTION

In recent years, formation control of multi-robot systems, such as formation of unmanned air vehicles (UAVs) see [15], autonomous underwater vehicles (AUVs) see [14], mobile sensor networks see [10]-[13], etc., has been an interesting research issue in the physical, cybernetic, control and automatic fields worldwide. The topic has attracted a lot of attention from researchers over the world, because its potential applications are very necessary in many practical areas, such as observing, tracking, search, and rescue missions.

There are many research directions on multi-robot systems, but the main aim is the member robots have to work together in order to achieve desired tasks, such as tracking and observing a moving target. Formation control is one of the necessary and important problems in the research field on the multi-robot systems. In this approach, member robots must connect to each other in a desired formation in order to avoid collisions and maintain a stable distance between them during movement. There are many methods to generate and control the formation of a swarm of mobile robots. Artificial potential field is known as a positive tool in order to control the coordination and the motion of a swarm towards the target position, see [1]-[5]. The success of the formation control method based on the random connections between neighboring members in a swarm is published in some literature, for example [6]-[13]. In this method, neighboring robots are linked to each other by the attractive/repulsive force fields between them to create the robust formation without collisions.

Fig.1 The collinear flying formation of aircraft (source: http://avioners.net/2013/03/breitling-acrobatics-team-using-l-39.html/)

Another approach for formation control is to control all robots to move together inside of a given dynamic framework, see [16], [17]. The published results in this approach have shown that robots are able to adjust the formation by rotating and scaling while moving together. Furthermore, formation control following desired shapes has also been a positive research direction. In this method, robots are controlled to achieve the optimal positions in desired formation, see [18], [19].

This paper considers a novel approach for the collinear formation control of autonomous robots (see Fig.1) while reaching the target position in a dynamic environment. This approach is built and developed based on the formation shape control method combined with the artificial vector field method [1]-[5]. One linear desired formation with the constant distances between virtual nodes is designed based on the relative position between the leader and the target. The leader is firstly chosen as the robot that has the shortest distance to the target. In this approach, the leader plays an important role to create and lead the desired formation towards the target in a stable direction. Hence, in many undesired cases, such as the leader is broken or trapped in obstacles (U-shape obstacle), one new leader is replaced in order to continue to lead the swarm towards the target. Under the effect of the artificial force fields, which are the global attractive force field to the free virtual nodes, the local attractive force field from the active virtual nodes, and the local repulsive force field around each robot, all free robots will automatically find their optimal position at virtual nodes in the desired formation without collision. In addition, the global attractive potential field from the target combined with the orientation controller will easily drive the formation of the robots towards the target position in a desired direction.

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The remaining sections of this paper are organized as follows: The problem formulation is presented in the next section. Section III gives the method in order to build the collinear desired formation. In section IV, the formation control algorithms are presented. Simulation results are discussed in section V. Finally, section VI concludes this paper and proposes the future research topic.

II. Problem Formulation

This section considers a swarm of N robots (N=2, 3, 4…) that has the mission to reach a target in a collinear formation in a two-dimensional Euclidean space. The direction of motion of this formation must be kept stable during movement. Let $p_i = (x_i, y_i)^T, v_i = (v_{ix}, v_{iy})^T$ and u_i be the position, velocity vector and control input of the robot i, respectively. The dynamic model of each robot i is described as follows:

$$\begin{aligned} \dot{p}_i &= v_i \\ \dot{v}_i &= u_i \qquad i = 1,..,N. \end{aligned} \tag{1}$$

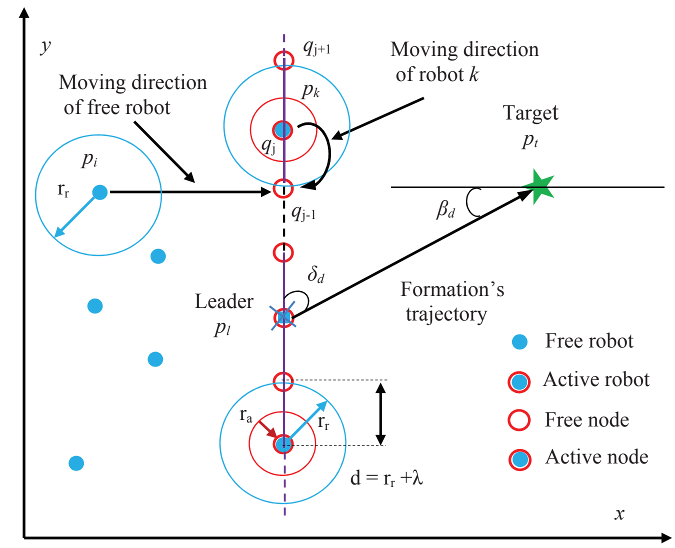

Fig.2 Formation control following the collinear desired formation.

Definition 1. Robot i ($i=1,2,..,N$) is an active robot if the distance from this robot to any virtual node j ($j=1,2,..,N$) of the desired formation is smaller than the radius d_i^j<r_a ,(r_a=d/2), of the active circle around each virtual node, see fig.2. In other words, robot i is active if it lies inside of one active circle j. Otherwise, it is a free robot.

Definition 2. A virtual node j ($j=1,2,..,N$; $q_j=(x_j, y_j)^T$) of the linear desired formation is active if there is a robot i ($i=1,2,3…N$) in the active circle of this virtual node. In the case where there is no robot i in the active circle j, then the virtual node j is free.

Definition 3. The optimal position in the desired formation for robot ^{h} is a virtual node j at which $\lim_{t\to\infty}(p_i(t) - q_j(t)) = 0$ and the virtual node (j-1) is also active.

Remark 1. Consider a linear desired formation including N virtual nodes that are equally spaced with the desired distance $d = \|q_{j-1} - q_j\|$, and is related with vector (p_t -p_l) by a constant formation angle δ_d as shown in Fig.2. Robots have to find the optimal position in the desired formation. Firstly, each free robot i will pursue the closest free node in order to become an active robot. Secondly, if the position of the active robot k ($k=1,2,..,N$; $i\neq k$) at the active node j is not optimal, then this active robot will automatically move into virtual nodes (j-1) until it achieves a optimal position in the desired formation.

Remark 2. The motion of the formation depends on the relative position between the leader and the target. At initial time, one robot, which is closest to the target, is chosen as the leader, and it is saved in order to lead its formation towards the target. During movement, if this leader meets any risk, such as it is broken or hindered by the environment, a new leader is selected. This new leader will reorganize the formation and continue to lead the new formation towards the target in the desired direction β_d, see Fig.2.

III. Collinear Desired Formation

In this section, we present the method in order to build a collinear desired formation based on the relative position between the target and the leader combined with the coordinate system rotation and translation. Assume that the leader's position is determined at $q_l = (x_l, y_l)^T$. Now, in order to build the collinear desired formation including the virtual nodes, which are equally spaced with constant distance d, and deviating from the vector (p_t -p_l) at desired angle δ_d, one base node q_d is first generated with $((q_d - p_l),(p_t - p_l)) = \delta_d$, and $\|q_d - p_l\| = d$, see Fig.3. The coordinates of the node q_d on the coordinate system $x'y'$ ($q'_d = (x'_d, y'_d)^T$) are determined as follows:

$$\begin{pmatrix} x'_d \\ y'_d \end{pmatrix} = \|q_d - p_l\| \begin{pmatrix} \cos\delta_d \\ \sin\delta_d \end{pmatrix}. \tag{2}$$

By rotating and translating equation (2) according to coordinate systems $x''y''$ and xy, see [20], [21], we obtain the position of the desired node $q_d = (x_d, y_d)^T$on the coordinate system xy as follows:

$$q_d = p_l + Rq'_d\,. \tag{3}$$

In equation (3), the rotation matrix R depends on the rotation angle theta θ. If the angle theta θ rotates clockwise as described in Fig.3, then the rotation matrix is determined as $R = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$, and in contrast $R = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$ if the angle rotates counter-clockwise.

Secondly, from the base node q_d and the leader we obtain a unit vector $n_{ld} = (p_d - p_l)/\|p_d - p_l\|$ along the line connecting p_l to q_d. Now, a virtual node q_j ($j=1,2,3…N$-1; $q_j=(x_j, y_j)^T$; d_{jl}=$\|p_l - q_j\| = jd$) is determined by unit vector n_{ld} as follows:

$$(q_j - p_l) = jdn_{ld}\,. \tag{4}$$

The equation (4) can be rewritten as follows:

$$\begin{pmatrix} x_j \\ y_j \end{pmatrix} = (1-j)\begin{pmatrix} x_l \\ y_l \end{pmatrix} + j\begin{pmatrix} x_d \\ y_d \end{pmatrix}. \tag{5}$$

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The equation (5) shows that when j changes from value 1 to N, we get a formation of the virtual nodes that lie on the line through p_l and q_d , and are equally spaced. However, in this solution, the leader always has the outer position of the formation, so this situation is suitable for the row formation. For the parallel formation, the leader's position is selected as the center of the formation, so the algorithm to generate desired formation is redesigned as follows:

$$q_j = \begin{cases} jp_l - (j-1)q_d, & if\ j \le N/2+1 \\ (1-\xi)p_l + \xi q_d, & Otherwise, \end{cases} \tag{6}$$

where ξ is described as $\xi = j - floor(N/2) - 1$. Using this algorithm, the virtual nodes will be evenly distributed to both sides of the leader as depicted in Fig.3.

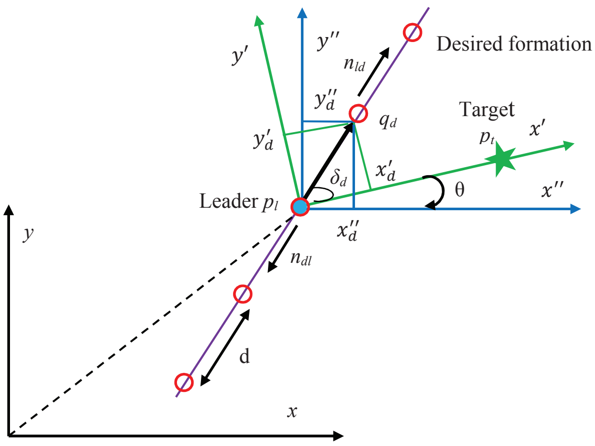

Fig.3 The description of the method to build the collinear desired formation.

IV. Control Algorithms

This section presents the formation algorithms for control wherein all robots will automatically find the optimal position in the desired formation. While reaching the target position, the stability of the formation must be maintained, and guarantee that there are no collisions between members. Furthermore, after avoiding obstacles robots have to automatically find their swarm and continue with their formation to reach the target. In addition, the movement direction of the formation towards the target position is kept stable in the given orientation.

A. Collision avoidance between robots

In order to avoid collision between robots i and k ($i,k=1,2,..,N$; $i\neq k, i\neq l$) during movement, the local repulsive force field is created around each robot within the repulsive radius r_r ($r_r = d - \lambda$, λ is a positive constant), see Fig.2. This vector field is given as follows:

$$F_i^k(p_i) = \left(\left(\frac{1}{d_i^k} - \frac{1}{r_r} \right) \frac{k_{i1}^k}{(d_i^k)^2} - k_{i2}^k \left(d_i^k - r_r \right) \right) c_i^k n_i^k . \tag{7}$$

Here k_{1i}, k_{2i}, $n_i^k = (p_i - p_k)/\|p_i - p_k\|$, and $d_i^k = \|p_i - p_k\|$ are the positive factors, the unit vector along the line from robot k to robot i, and the Euclidean distance between k and i, respectively. The scalar c_i^k is defined as:

$$c_i^k = \begin{cases} 1 & if\ d_i^k \le r_r \\ 0 & otherwise. \end{cases} \tag{8}$$

The control algorithm for collision avoidance is built based on the repulsive vector field combined with the relative velocity vector $k_{iv}^k(v_i - v_k)$ between k and i as follows:

$$f_i^k(p_i) = \sum_{k=1,k\neq i}^{N} \left(F_i^k(p_i) - k_{iv}^k c_i^k (v_i - v_k) \right). \tag{9}$$

B. Attractive forces from virtual nodes

Around the virtual nodes of the desired formation, the artificial attractive force fields are created. Under the effect of these vector fields, robots are driven to achieve the optimal position in the desired formation. The attractive forces of the virtual nodes, which affect robot i, are built as follows:

Algorithm 1: Reach the optimal position at the virtual nodes in the desired formation

Consider: a robot p_i and virtual nodes q_j ($i,j=1,..,N$, $i\neq l$).
Determine the shortest distance from p_i to all the virtual nodes q_j and the scalar factor c_i^j as follows:

$$d_i^{j\,m1} = \min\left\{ d_i^j = \|p_i - q_j\|, j = 1,..,N \right\}, \quad c_i^j = \begin{cases} 1 & if\ q_j\ is\ active \\ 0 & if\ q_j\ is\ free. \end{cases}$$

if $d_i^{j\,m1} \le r_a$ & $c_i^{j\,m1-1} = 1$ **then**

$$f_i^j(p_i) = -k_{i1}^j(p_i - q_{j\,m1}) - k_{iv}^j(v_i - v_{j\,m1})$$

else if $d_i^{j\,m1} \le r_a$ & $c_i^{j\,m1-1} = 0$ **then**

$$f_i^j(p_i) = -k_{i2}^j(p_i - q_{j\,m1-1}) - k_{iv}^j(v_i - v_{j\,m1-1})$$

else if $d_i^{j\,m1} > r_a$ **then**

if $c_i^{j\,m1} = 0$ **then**

$$f_i^j(p_i) = -k_{i3}^j \frac{(p_i - p_{j\,m1})}{\|p_i - p_{j\,m1}\|} - k_{iv}^j(v_i - v_{j\,m1})$$

else

Determine the shortest distance from p_i to the free virtual nodes q_j in the desired formation as:

$$d_i^{jm2} = \min\left\{ d_i^j = \|p_i - q_j\|, c_i^j = 0, j = 1,..,N \right\}$$

$$f_i^j(p_i) = -k_{i3}^j \frac{(p_i - p_{j\,m2})}{\|p_i - p_{j\,m2}\|} - k_{iv}^j(v_i - v_{j\,m2})$$

end

end

In this algorithm, $k_{i1}^j, k_{i2}^j, k_{i3}^j, (p_i - q_j), (v_i - v_j)$ and d_i^j are the positive gain factors, the relative position vector, the relative velocity vector and the distance between robot i and node j.

C. Target reaching control algorithm

Firstly, one robot, which has the closest distance to the target $d_l^t = \|p_l - p_t\| = \min\left\{ \|p_i - p_t\|, i = 1,...N \right\}$, is selected as the leader in order to control the motion of the formation. The target reaching controller, which is designed based on the relative position between the leader and the target, has to

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guarantee that the formation's motion is maintained in the stable direction to the target. This control law is designed as follows:

$$f_l^t(p_l) = F_l^t(p_l)n_l^t - k_{l2}^t(p_l - p_\beta) - k_{lv}^t(v_l - v_t). \qquad (10)$$

This equation shows that the first component $F_l^t(p_l)n_l^t$ is used to control the target tracking with the value of the attractive force $F_l^t(p_l)$ and the unit vector $n_l^t = (p_l - p_t)/\|p_l - p_t\|$. The attractive force $F_l^t(p_l)$ is computed as follows:

$$F_l^t(p_l) = \begin{cases} -\dfrac{k_{l1}^t}{r^\tau}\|p_l - p_t\|, & if\ d_l^t < r^\tau \\ -k_{l1}^t, & otherwise. \end{cases} \qquad (11)$$

Here, k_{l1}^t and r^τ are the positive factor and the radius to reach the target, respectively. The second component $-k_{lv}^t(v_l - v_t)$ is added as a damping term. The remaining component $-k_{l2}^t(p_l - p_\beta)$ works as the orientation controller in order to maintain the formation's motion in the stable direction towards the target. In other words, this controller guarantees that $\lim_{t\to\infty}(p_l(t) - p_\beta(t)) = 0$ or $\lim_{t\to\infty}(\alpha(t)) = 0$. Here, k_{l2}^t and $(p_l - p_\beta)$ are a positive constant and the relative position vector between the leader and the desired leader position $p_\beta = (x_\beta, y_\beta)^T$. This desired position is depended on the rotation direction of the desired orientation angle β_d. Assume that the positive desired orientation angle rotates clockwise, and opposite.

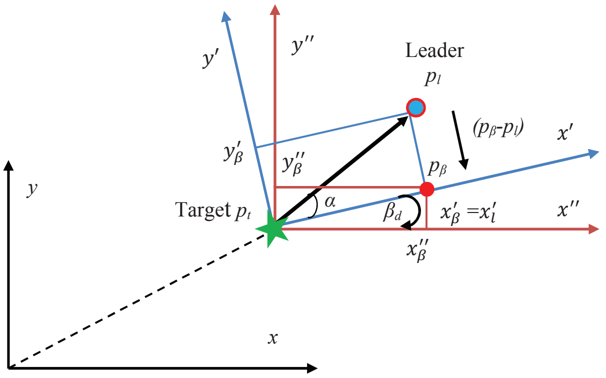

Fig.4 The desired leader position in case the positive desired angle.

Consider the case that the desired orientation angle is positive. We build the coordinate system $x'y'$ based on this positive desired orientation angle β_d as depicted in Fig.4. The desired coordinates on the coordinate system $x'y'$, at which the leader has to reach in order to guarantee that the movement direction towards the target is stable, is determined as $(x'_\beta, y'_\beta)^T = (x'_l,\ 0)^T$. On the coordinate system xy, the coordinates of this desired leader position are determined as follows:

$$\begin{pmatrix} x_\beta \\ y_\beta \end{pmatrix} = \begin{pmatrix} x_t \\ y_t \end{pmatrix} + x'_l \begin{pmatrix} \cos\beta_d \\ \sin\beta_d \end{pmatrix}. \qquad (12)$$

On the other hand, from Fig.4 the coordinates of the leader is determined similar to equation (3) as follows:

$$\begin{pmatrix} x_l \\ y_l \end{pmatrix} = \begin{pmatrix} x_t \\ y_t \end{pmatrix} + \begin{pmatrix} \cos\beta_d & -\sin\beta_d \\ \sin\beta_d & \cos\beta_d \end{pmatrix} \begin{pmatrix} x'_l \\ y'_l \end{pmatrix}. \qquad (13)$$

By equating (14), we obtain x'_l as follows:

$$x'_l = (x_l - x_t)\cos\beta_d + (y_l - y_t)\sin\beta_d\,. \qquad (14)$$

In case the desired angle is negative, we will find x'_l as follows:

$$x'_l = (x_l - x_t)\cos\beta_d - (y_l - y_t)\sin\beta_d\,. \qquad (15)$$

D. Obstacle-avoiding control algorithm

Similar to the equation (9), the obstacle-avoiding control algorithm for robot i ($i=1,2,..,N$) is also designed as follows:

$$f_i^o(p_i) = \sum_{o=1, o\neq k}^{M}\left(F_i^{op}(p_i) + F_i^{or}(p_i) + k_{iv}^o c_i^o(v_i - v_o)\right). \qquad (16)$$

In this equation, $(v_i - v_o)$, and $k_{iv}{}^o$ are the relative velocity between the robot i^{th} and the obstacle *(o),* and the positive constant, respectively. The scalar $c_i{}^k$ is defined as:

$$c_i^o = \begin{cases} 1 & if\ d_i^o \le r^\beta \\ 0 & otherwise. \end{cases} \qquad (17)$$

Here $d_k^o = \|p_k - p_o\|$ and $r^\beta > 0$ are the Euclidean distance and an obstacle detecting range, respectively. The force field $F_i^{op}(p_i)$ is used to repel the robot away from the detected obstacle ($c_i^o = 1$). Hence, this vector field is given as follows:

$$F_i^{op}(p_i) = c_i^o\left(\left(\frac{1}{d_i^o} - \frac{1}{r^\beta}\right)\frac{k_{i1}^o}{(d_i^o)^2} - k_{i2}^o\left(d_i^o - r^\beta\right)\right)\mathrm{n}_i^o\,. \qquad (18)$$

In this equation, k_{i1}^o, k_{i2}^o, $n_i^o = (p_i - p_o)/\|p_i - p_o\|$ are the positive factors, and the unit vector from the obstacle to the robot. The rotational force field $F_i^{or}(p_i)$ is added to combine with the repulsive force field to drive the robot to quickly escape the obstacle. This rotational force is built as follows:

$$F_i^{or}(p_i) = w_i^o n_i^{or}\,. \qquad (19)$$

Here, the unit vector n_i^{or} is described as follows:

$$n_i^{or} = \begin{pmatrix} \dfrac{(\mathrm{y}_i - \mathrm{y}_o)}{d_i^o} & \dfrac{-(\mathrm{x}_i - \mathrm{x}_o)}{d_i^o} \end{pmatrix}^T. \qquad (20)$$

The element w_i^o is used to control robot to quickly escape the obstacle, but its velocity does not overcome the limited velocity.

Finally, the control law for each robot i ($i=1,2,..,N$) is given as follows:

$$u_i = \begin{cases} f_i^k(p_i) + f_i^j(p_i) + f_i^o(p_i), & if\ i\ is\ not\ leader \\ f_i^t(p_i) + f_i^o(p_i), & if\ i\ is\ leader. \end{cases} \qquad (21)$$

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V. SIMULATION RESULTS

In this section, we give the simulation results in order to verify the function of the above presented control algorithms. The target is assumed stationary. The general parameters for simulations are listed in the table I.

TABLE I
PARAMETER VALUES

Parameter	Definition	Value
d	Desired distance between robots	60
λ	Positive constant	0.5
N	Number of robots	9
r^{β}	Obstacle detecting range	25
r^{τ}	Target reaching radius	25
k_{i1}^{t}, k_{i2}^{t}	Factors for approach to target	9, 0.6
k_{i1}^{k}, k_{i2}^{k}	Positive factors for fast repulsion	80, 12
k_{i1}^{o}, k_{i2}^{o}	Constants for fast obstacle avoidance	90, 15
k_{i1}^{j}, k_{i2}^{j}, k_{i3}^{j}	Positive constants	3, 4, 9
k_{iv}^{j}, k_{iv}^{t}, k_{iv}^{k},	Damping factors	1.4

Firstly, we test the algorithms to generate the collinear desired formation (5), (6), and the algorithm to drive the robots towards the collinear desired formation. The results of the simulations in Fig.5 show that the collinear desired formation can easily be created with the different formation angles δ_d. Robots, which have the random initial positions, have achieved the optimal positions in this desired formation while reaching the target.

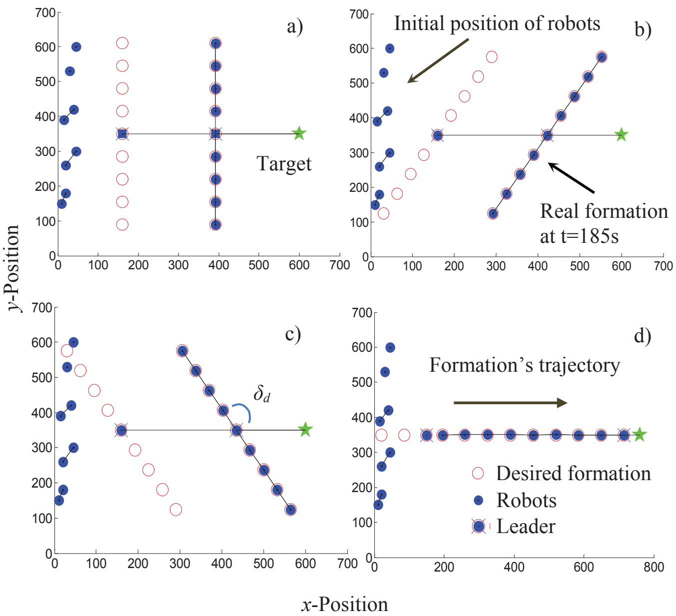

Fig.5 Simulations for the angle δ_d change of the collinear desired formation and the desired formation follower of robots in order to reach the target. Plots a), b), c), d) depict the formation's motion with angle $\delta_d=\pi/2$, $\delta_d=\pi/3$, $\delta_d=2\pi/3$, $\delta_d=0$, respectively.

Secondly, the stability of the swarm following the desired collinear formation in an invariable direction towards the target under the influence of the dynamic environment is tested. For this simulation, the target's position, the formation angle, and the desired orientation angle are chosen as $p_t=(700,350)^T$, $\delta_d=\pi/2$, and $\beta_d=0$, respectively. Obstacles o_1, o_2 and the initial position of the robots are depicted in Fig.6 and Fig.8.

Case1: The permutation between member robots in collinear formation while avoiding obstacles. The simulation results in Fig.6 and Fig.7a show that the collinear formation of robots, which follows a desired formation, is maintained during flight towards the target without collisions. At time t=0s, one robot is chosen as the leader of the swarm, and then it is saved in order to drive its formation to the target in the stable motion direction α, see Fig.7a. At time t=87s, the formation of a swarm is made based on the desired structure, and it is kept until the squares robot detects the obstacle o_1. While avoiding obstacle o_1, the virtual node, which the square robot has owned, became a free node, and it attracted the triangle robot to become the active node. After escaping the obstacle, the square robot quickly reached the remaining free node of the desired formation, see Fig.6. Similarly, at time t=230s, the rhombus robot is permuted with other robots in the swarm. In this simulation case, the obstacles of the environment can permute the position of the member robots in the formation, but they do not influence on the formation angle δ_d and the motion direction α of the swarm.

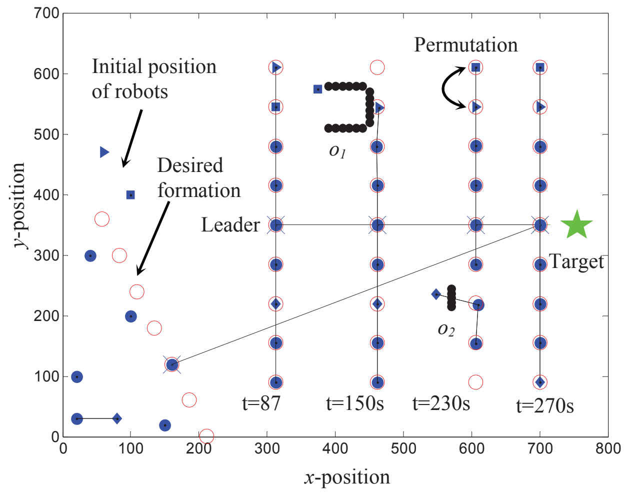

Fig.6 Simulate the influence of the environment on the collinear formation of robots during reaching towards the target. The red circles, blue shapes, and black shapes are the desired formation, robots, and the obstacles, respectively.

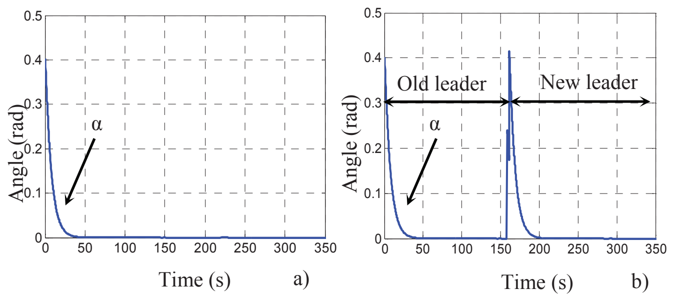

Fig.7 Simulate the stability of the motion direction $\alpha=((p_l-p_t),(p_\beta-p_t))$ to the target of the collinear formation when the environment changes, plot a) and the leader is permuted, plot b).

Case 2: The leader change influences the organization of the formation during movement towards the target. Fig.8 shows that, at time t=0, the square robot is chosen as the leader and it also saved to lead the swarm to the target. Using the orientation controller (12), this leader quickly achieved the desired direction β_d =0 to the target (t=50s to t=150s), see Fig.7b. The formation's organization is changed when the square leader (old leader) is trapped in the U-shape obstacle at time t=160s. In this situation, the square leader lost the leader role. It became a free robot and automatically found a way to escape this obstacle and continued to track its formation. The triangle robot, which is a free robot and closest to the target, is used as a new leader in order to continue to lead the swarm towards the target. Fig.7b shows the new leader has quickly led its formation in the desired direction before reaching the target.

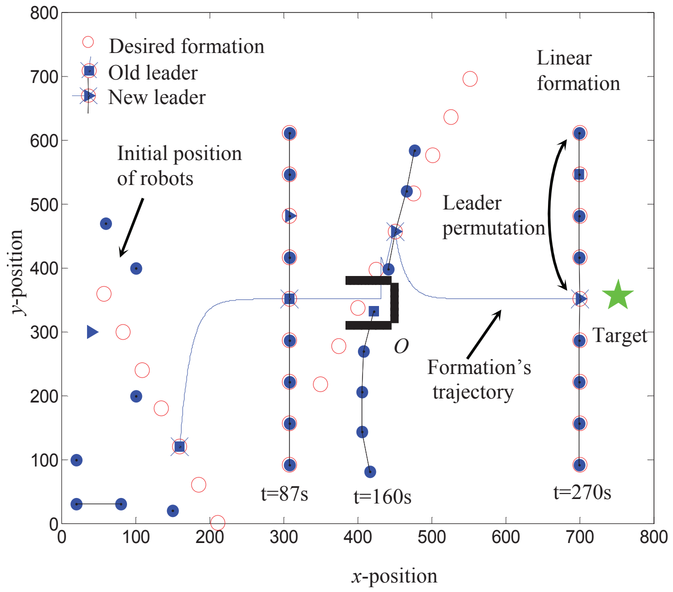

Fig.8 Simulate the leader permutation of a collinear formation while moving towards the target in a dynamic environment. The red circles, blue shapes, and black shapes are the desired formation, robots, and the obstacles, respectively.

VI. CONCLUSION

In this paper, we have proposed a novel approach to formation control of autonomous robots following a desired collinear formation to reach a stationary target. The desired formation with the different formation angles is built based on the relative position between the target and the leader of the swarm. The trajectory of member robots is driven by the artificial force fields from the virtual attractive nodes of the desired formation. The mission of the leader is to lead the formation towards the target in a desired direction. Furthermore, the repulsive force fields between robots are used to guarantee that there are no collisions in the swarm during movement. Moreover, in order to avoid obstacles of the environment, the repulsive and rotating force fields are also added. The results of the simulations have shown that using the proposed control algorithms the member robots have quickly achieved the optimal positions in the desired formation. In some cases, such as obstacle avoidance, the position of some robots in formation can be permuted, but the structure and the motion direction of the formation are kept. The development and application of this proposed approach for formation control of the autonomous robots in noisy environment with the moving target will be our next research directions in the future.

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