Formation Control and Obstacle Avoidance in Swarm Robots

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Summary
This paper presents an approach for formation control and obstacle avoidance of a swarm robot (SR). Swarm robots are significant with their various tasks and range of applications, and also because they can identify and describe the challenges that need to be resolved in the real world. This work proposes a new formation control and an obstacle avoidance method for the dynamic region of swarm robot systems in order to prove SRs' ability to manage their formation by scaling and rotating while moving. Here, the Gradient Descent formula is adopted to update the range and the robot orientation vector of the SRs systems. Simulink MATLAB is also used to simulate the formation controller performance and the obstacle avoidance. The distributed formation control and the switching formation strategy for obstacle avoidance are illustrated in order to show the effectiveness of our proposed algorithm. We conclude that our method is easy to implement and achieve, not only the required distributed formation control and Obstacle Avoidance, but also to contribute to the usage in the tracking method.

Key words:
Autonomy; Intelligent Robots; Swarm Robots; Navigation

1. Introduction

Recently, swarm robotic research has extended from an intelligent concept of application into multi-robot systems that concentrate on the physical structure and the interactions among mobile robots individually, between each one, and with the environment [1]. The word “swarm” indicates a number of robots that locally interact on a common target. Swarm is common for describing all combined behaviors in spite of it bringing up associations linking their movements in space [2]. The brainpower of swarm is the technology to emerge interactions among large numbers of autonomous robots [3].
The structure of the next sections of this research is as follows: in the next sub-sections of the introduction, we describe the motivations and some background, then, SRs' formation, control and the connectivity are addressed. The second section defines swarm formation and the tracking problem, while the third section describes our objectives. In the fourth section, the methodology flows into two: distributed formation control, and the switching formation strategy for obstacle avoidance. We report the results of the numerical simulations based on the proposed algorithm. Finally, conclusions and discussions are inserted.

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1.1. Motivations

Several potential advantages related to the application for controlling swarm robots are the major motivation for SRs' research and implement it in the following missions:

A. SRs' provides the possibility to use the sensing capabilities for large numbers of groups, which means that an individual can find their region of interest speedily in order to decide whether to enter among them or quickly indicate when to leave [4].
B. SRs' support an advanced rank of robustness for mission failures compared to systems which rely on one robot as other robots can adopt work previously implemented by a lost or failed member of the SRs' [5] [6].
C. SRs' distributes workload for its members to attain more significant results such as carrying out tasks over wide spatial areas [7], manipulating the surroundings more professionally than one robot [8] or attacking from multiple directions simultaneously [9].
D. SRs' conduct several numbers of tasks simultaneously in cheaper and simpler robots than if more sophisticated robots are used to implement each task separately [7].

Since the SRs' also come with the benefits associated with common robotics, they support situational awareness in a potentially dangerous environment without allowing the human to face the hazard [8]. The drawbacks connected with SRs' systems should also be considered such as: SRs' communication is neither centralized nor decentralized, while the control schemes make it simple for individuals to control the SRs' systems. Another problem is the centralized SRs' systems, which adopt communication and the control scheme, do not range well with the rising number of robots and are also affected by the loss of a central leader[10]. Therefore, the clean central systems do not maintain a robust control of a large number of swarms through a single user operator. On the other hand, the decentralized SRs' system is unable to tune or manage data globally unless all the robots are associating with each other when no central control algorithm which can synthesize data among all members of SRs' exists. When decentralized SRs' systems are in use, it becomes hard to produce the global data used for facilitating globally the best control with a user operator. It is difficult to predict the accurate performance of SRs' systems with a human controller when the global performance has interactions among large number of locally interacting robots.

Although with the above drawbacks, the potential advantages are highly required following the wide application range in robotics areas, include chemical, nuclear, and organic attack detection[11], the wide application in battlefield surveillance [12], in pollution detection[13], and for search and rescue purposes [14].

1.2. Formation control and connectivity

SRs' success often depends on the ability to produce and maintain suitable formation. For instance, the loss in the rear guard may cause the whole group to be annihilated, surrounding an enemy as a target can achieve a fast victory, and the swarms in the scattered formation have better ability for surviving serious attacks than when formed in a compact type [9]. Therefore, it is important to ensure the appropriate formation which can be created by SR systems into the real-world domain.

Various patterns of robot distribution can be used to achieve the desired formations by SRs'. Equilateral triangle models are the most selected in terms of the number of robots that are required to cover large areas. Such patterns should be used if the target is supporting models of a limited number of robots. Fig. 1, shows a graphical summary of the formation models with their used methods to create them.

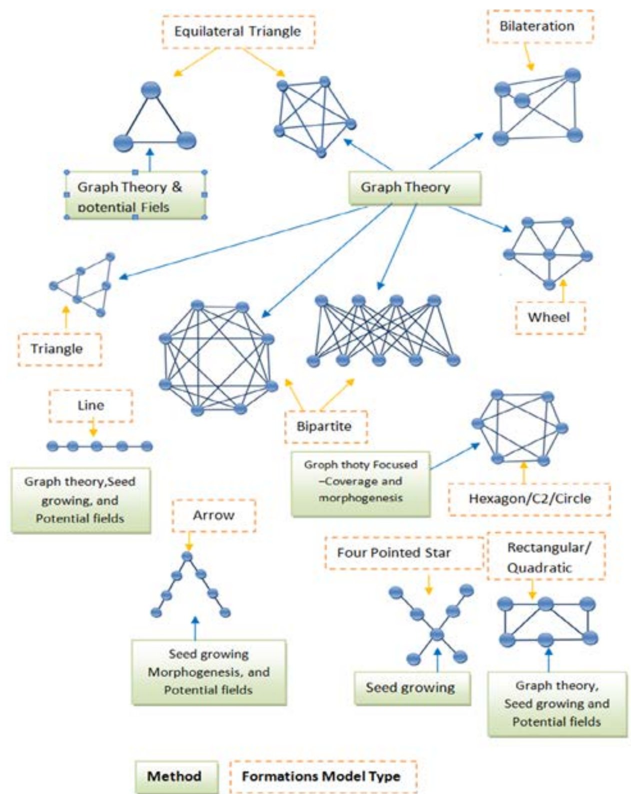

Fig. 1. Different distribution models in swarm robots to achieve various formation shapes.

Alternative models that have been produced based on graph theory are also included such as; bilateration, bipartite, the wheel, the straight line and the rectangle [4][15]. Graph theory is just an option to generate the SR formations, but there are other models such as; lines, stars, arrows, and rectangles, which can also grow from a seed robot by a rules set [16]. Based on what is called “morphogen gradients” , different shapes such as circular, N-shaped, R-shaped, ring, and lobed formations can be created [17]. Voronoi categories also used to produce other formations and have been used to shape polygons, ellipses, segments, and uniform distributions.

1.3. Classification of the Mobile Robot Navigation Algorithms

The navigation’s main aim is to extract an optimal or suboptimal trajectory of a particular start point to a target point with the capability of obstacle avoidance. Essentially, the navigation of a mobile robot has been implemented by either Deterministic algorithm or Nondeterministic algorithm (Stochastic). Recently, the combination of both algorithm forms called Evolutionary algorithm has been used to solve the navigation problem of the mobile robot. Generally, Fig. 2 shows the classification of Deterministic, Nondeterministic (Stochastic), as well as Evolutionary algorithms, which are applicable to the navigation of mobile robots in the literature review [18].

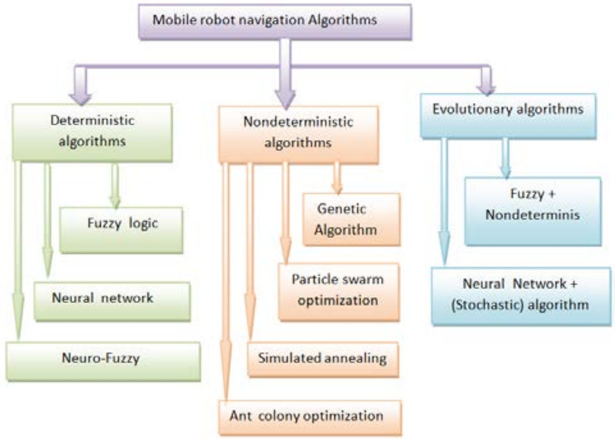

Fig. 2. General classification of Mobile Robot Algorithm

2. Swarm Formation and Tracking Problem

Let us consider a swarm robot system includes N autonomous agents, each individual agent is represented by Cartesian coordinates as $x_i^{\bullet}$ and $y_i^{\bullet}$, they move with velocity v_i and θ_i as a steering angle that is labeled as $A_1, \ldots. A_N$. Initially, we will assume that the agent A_i has a distribution as shown in Fig 3.

Therefore, the agent motion equations can be described by:

$$x_i^{\bullet} = v_i \cos(\theta_i) \quad (1)$$

$$y_i^{\bullet} = v_i \sin(\theta_i) \quad (2)$$

$$\theta_i^{\bullet} = \omega_i \quad (3)$$

where ω_i is the angular speed of the agent A_i. While the Computations of robot trajectories can be regarded as in Fig. 3.

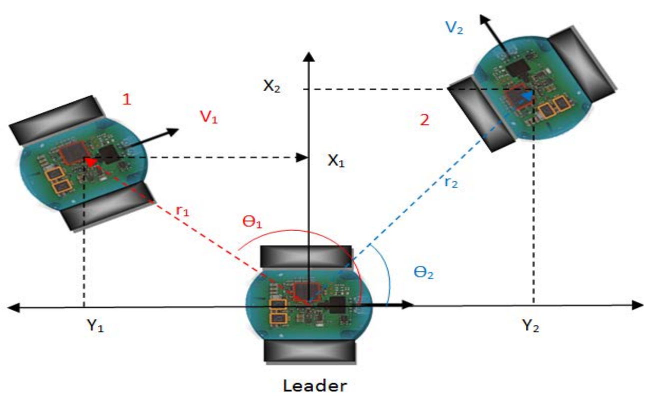

Fig. 3. Computation of robot trajectories

As can be noticed in the above figure, the Cartesian coordinates x_i, y_i and the steering angle θ_i for each agent A_i as well as the velocity vector is considered in all the stages of the proposed formation algorithm according to the number of robots and the adopted model as well as their relative respect to the Leader robot.

3. Research objectives

A. To solve the problem of maintaining the formation control with a given extended escorting mission presented above.
B. To address the issue of the potential obstacles and the detection to offer the control algorithm that can overcome this problem.
C. To modify the current modelling for the swarm robotics towards better performance.
D. To keep the swarm tracking going throughout the implementation of real-time localization algorithm
E. To achieve fast tracking and accurate formation of the performance by addressing all the system scale environment and adopting a new proposed model in such a way that each robot is both capable of identifying its real-time location within the swarm formation and the potential obstacles.

Due to a limitation in physical resources, this work will be done solely in simulation and graphical animation. As such, the identification of the formation threat level of any object in the simulation will be determined by communication techniques (as will be explained while discussing the implementation of the algorithm used). proposed solution will be tested against an alternate algorithm based on more commonly used methods of navigation in robotics. This work will also deal with wheeled robots only; which means that the solution will only be tested in two dimensions rather than three though extending the solution into the third dimension will be relatively trivial.

The initial position of any mobile robot can be denoted by (x, y, Θ). According to the formula of coordinate transformation, the mathematical equations of the orientation/posture error coordinates that denoted by $(x_e, y_e, \Theta_e)^T$ in the local coordinates of the mobile robot. Thus:

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_d - x_c \\ y_d - y_c \\ \theta_d - \theta_c \end{bmatrix} \quad (4)$$

Where $[x_d - x_c, x_d - x_c, x_d - x_c]^T$ denote the difference/error vector of desired and actual

Position of the current moment during mobile robot movement. According to [19], the location error differential equations can be written as:

Vector (v, w). Therefore, as time goes longer, the co

$$\begin{bmatrix} \dot{x_e} \\ \dot{y_e} \\ \dot{\theta_e} \end{bmatrix} = \begin{bmatrix} y_e w - v + v_r \cos\theta_e \\ -x_e w + v_r \sin\theta_e \\ w_r - w \end{bmatrix} \quad (5)$$

Which represents the tracking trajectory equation of the mobile robot over the time, and in which the aim is to find the motion control ntrol criteria allows the mobile robot to track the required trajectory to achieve the target position, thus:

$$\lim_{n\to\infty} \| (x_e, y_e, \Theta_e)^T \| = 0 \quad (6)$$

4. Methodology

This work proposes a formation controller, and a trajectory tracking algorithm for the SRs' to manage a dynamic region. The major challenge results from the difficulties to maintain accurate SRs' formation with the trajectory tracking by indicating the variations in the individual robot locations or constraint relationships. This work assumes the swarm members as a differential wheeled mobile robot. Therefore, for a 2-wheeled differential driven mobile robot with coordinating x, y and heading angle θ [20], the nonholonomic constraints can be written as:

$$x^{\bullet} \sin\theta - y^{\bullet} \cos\theta = 0 \quad (7)$$

$$x^{\bullet} = V_x$$

$$y^{\bullet} = V_y$$

$$\tan\theta = \frac{V_y}{V_x}$$

$$\omega = \dot{\theta} \quad (8)$$

$$V = \sqrt{V_x^{\,2} + V_y^{\,2}} \quad (9)$$

Where Vx and Vy, denote the robot's velocity in directions x and y respectively. V and ω, denote the robot's linear and angular velocity respectively.

4.1. Distributed Formation Control

The literature formation control methods require particular roles or orders for the robots within the dynamic formation, which is not the case for our proposed method in the formation process. It is still that SR have the ability to coordinate with their neighbors and the swarm Leader to construct a formation and manage their formation throughout their orientation and displacement. The communication network is maintained by the Leader robot and the formation shape can be achieved by selecting a suitable objective function. The proposed system is scalable in such a way that any individual may move away from the formation or avoid an obstacle without affecting the formation structure. The Lyapunov theory is adopted to test the stability of the overall SR system.

MATLAB simulation results are offered to describe the performances of the proposed SR formation system.

Initially, six agents would be assigned in the proposed method, which can be described under the formation process At the beginning, the robots are distributed randomly over the dynamic area, and then, the Leader is selected according to the shortest distance with respect to the target. The other members of the swarm are adjusted and moved to distribute toward their location according to their shortest distance for each position in the swarm formation as can be seen in Fig. 4.

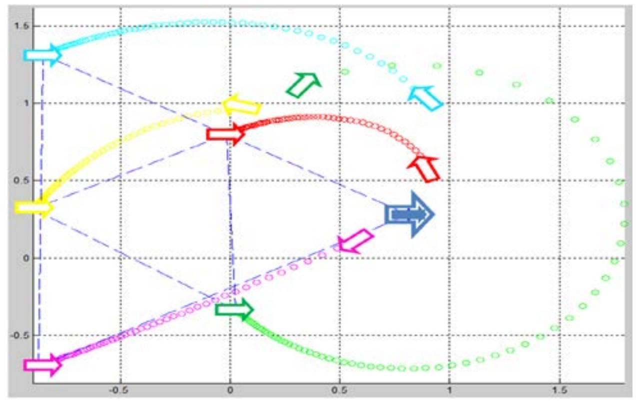

Fig. 4. Formation process for the proposed algorithm

The procedure adopted in this work to implement the formation learning process in a SRs' is the Gradient Descent as a training algorithm to update the new locations of the individuals in the SRs'. To demonstrate the formation control algorithm on the formation of Fig. 3, the following steps were performed as follows:

A. Initializing a random distribution for the SRs'.
B. Determining the Leader of the swarm according to the shortest distance to the target.
C. Sorting the followers in descending order and specifying the vector of the distances and angles among the followers as given by (10)

For robot 1
$[x_{o1}, y_{o1}] = pol2cart\ (deg2rad(150), 1)$
For robot 2
$[x_{o2}, y_{o2}] = pol2cart\ (deg2rad(-150), 1)$
For robot 3
$[x_{o3}, y_{o3}] = pol2cart\ (deg2rad(150), 2)$
For robot 4
$[x_{o4}, y_{o4}] = pol2cart\ (deg2rad(-150), 2)$
For robot 5
$[x_{o5}, y_{o5}] =$
$pol2cart\ (deg2rad(180), 2\cos(deg2rad(30)))$
(10)

D. The range error vector of the formation can be given by (11)

$$RangEr_i = [1;1;2;2;1.7321] - \eta_i \qquad (11)$$

Where η_i is the range vector.

E. The Gradient Descent formula was adopted to update the range vector, and we suppose that f(η_i) = η_i and ∇f(η_i) = $RangEr_i$. The method starts at the point η_0 and continues until the stopping criterion is fulfilled, then, it moves from η_i to η_{i+1} in the training direction = -$RangEr_i$. Thus, the gradient descent method iterates can be given by (12)

$$\eta_{i+1} = \eta_i + (\alpha.[RangEr_i]) \qquad (12)$$

Where α is the training rate, $RangEr_i$ is the error vector of the robot ranges with respect to the leader.

F. The same formula is applied to the angle vector of the formation; therefore, the angle error vector can be given

$$\mathrm{ThetEr}_i = [2.618;\mathrm{deg2rad}(210);2.618;\mathrm{deg2rad}(210);\mathrm{pi}] - \theta_i \qquad (13)$$

While the Gradient Descent formula for the angle vector can be represented by (14):

$$\theta_{i+1} = \theta_i + (a.[ThetEr_i]) \qquad (14)$$

G. The Cartesian coordinates vector of the followers can be given by (12):

$$[x_i, y_i] = pol2cart(\theta_i, \eta_i) \qquad (15)$$

Figure 5 shows the process of forming a swarm in a triangular shape by 6-robots including the Leader, which is the first one and is thought to have the shortest distance with respect to the tracked target; therefore, in this case we assumed that the target is far to the right hand side of the swarm.

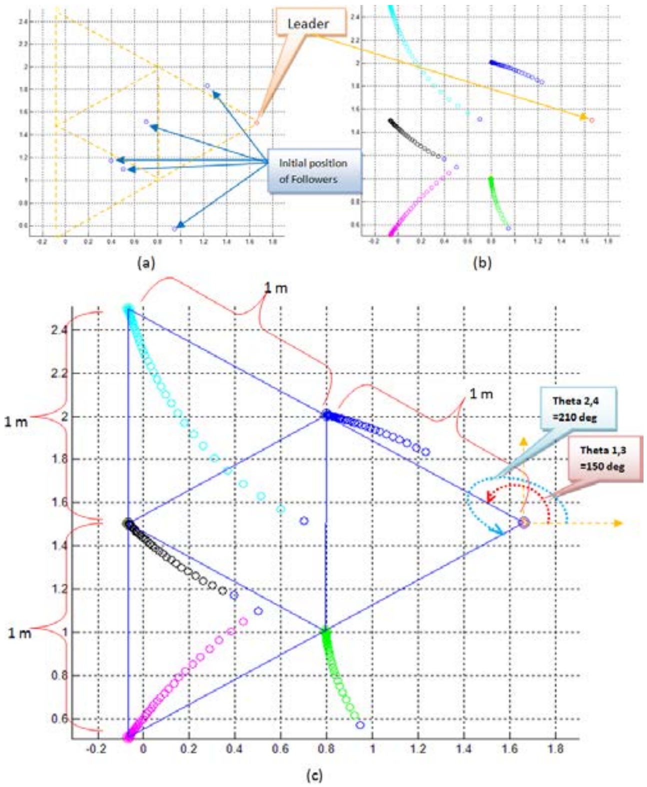

Fig. 5. The process of forming a triangular shape by 6-robots

4.2. Switching Formation Strategy for Obstacle Avoidance

In SRs', to avoid obstacles, apply the formation strategy for switching obstacle avoidance. Depending on the control method of the geometric obstacle avoidance, the Leader implements a safe trajectory and guides the followers to cross that obstacle. Therefore, for switching to a new formation, the followers switch to new required distances and bear angles according to the Leader robot's commands.

4.2.1. Leader Robot Trajectory

Based on the environment, multiple robots may cross obstacles or avoid them. According to the results mentioned, the leader robot plans its waypoint. To calculate the trajectory to cross the obstacles, the Leader plans a safe path for its motion based on the control method of the geometric obstacle avoidance as seen in Fig 6.

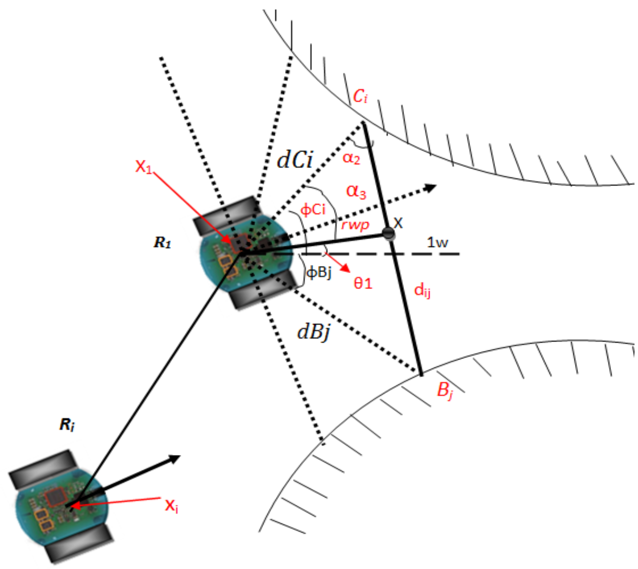

Fig. 6. Leader Robot plans the way through the control method of geometric obstacle avoidance

The dashed lines represent the measured range. C_i and Bj denote the intersection points of the calculated range line with the obstacle surfaces, where (i and j =1,2,3,…n) that are numbered in clockwise with respect to x toward the surfaces of other obstacle. Ci and Bj are assigned to calculate the next moving step for a robot. The lengths of the distances X_1-Ci and X_1-Bj are d_{Ci} and d_{Bj}, respectively. ϕ_{Ci} and ϕ_{Bj} represent the angles from the x-axis to the calculated range line, respectively. The angle parameter α1 can be defined and calculated as:

$$\alpha_1 = |\phi_{Ci}| + |\phi_{Bj}|$$

d_{ij} is the length of the connection line Ci- Bj given as (16). Let us define a variable d_m which stores the minimum value of $d_{ij}/2$ and equals to infinity, initially. For each sample, the robots check the existence of obstacles and find d_{ij}. Then, comparing $d_{ij}/2$ by d_m,

If $d_{ij}/2 < d_m$, then $d_m = d_{ij}/2$.

$$d_{ij} = \sqrt{d_{Ci}^2 + d_{Bj}^2 - 2d_{Ci}d_{Bj}cos\alpha_1} \quad (16)$$

The angle α_2 can be found as in (17):

$$\alpha_2 = \cos^{-1}\left(\frac{d_{Ci} - d_{Bj}cos\alpha_1}{d_{ij}}\right) \quad (17)$$

Let the central point which divides the Ci- Bj be the Leader robot required path point (X_{1w}). $(X_{1w}$-$X)$ distance is given by:

$$r_{wp} = \sqrt{d_{Ci}^2 + \frac{1}{2}d_{ij}^{\ 2} - 2d_{Ci}d_j cos\alpha_2} \quad (18)$$

The angle α_3 can be found by (19):

$$\alpha_3 = \cos^{-1}\left(\frac{d_{Ci} - \frac{1}{2}d_{ij}cos\alpha_2}{r_{wp}}\right) \quad (19)$$

While the bearing angle φ_1 in the next step can be found by (20):

$$\theta_1 = \Phi_{Ci} - \alpha_3 \quad (20)$$

By using the variables above, the required path points by the Leader robot to cross the obstacles can be represented by (21):

$$\begin{bmatrix} x_1 \\ y_1 \\ \theta_1 \end{bmatrix}_{(t+1)} = \begin{bmatrix} x_1(t) + r_{wp}\cos(\Phi_{Ci} - \alpha_3) \\ y_1(t) + r_{wp}\sin(\Phi_{Ci} - \alpha_3) \\ \Phi_{Ci} - \alpha_3 \end{bmatrix} \quad (21)$$

4.2.2.The required path points for Follower Robots

When the Leader begins to sense obstacles and starts to cross their path, the follower robots are commanded to switch to Line formation [16][28][22]. Fig. describes the trajectories of five follower robots guided by a Leader; one crossing by avoiding obstacles. Before crossing the obstacles, the five follower robots with the Leader move in a triangular formation.

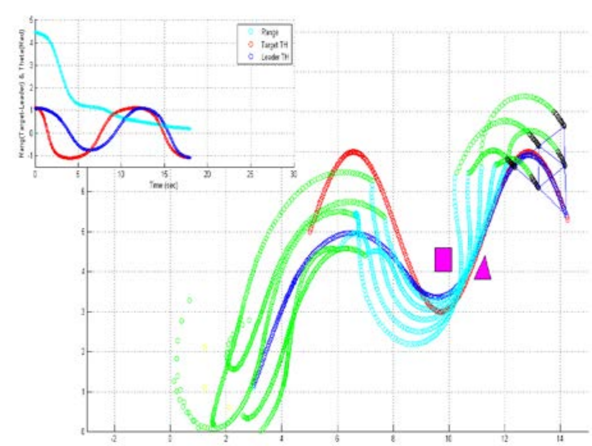

Fig. 7. Trajectories of five followers guided by a Leader one crossing with avoiding obstacles.

The green color circles represent robots (Followers), which follow the blue colour circle that represents the Leader. The Leader in contrast, tracks the target, which appears in the red color circle. The target, in this case, moves into the sinusoidal path and passes between the two obstacles; therefore, the SRs change their formation into line in this area when following the Leader, and then return to a triangular formation after passing the obstacle area.

Three curves are also displayed through the simulation time of the formation process (Fig. 7), and these curves show the real-time variation of the range between the target and Leader, target orientation angle, and Leader orientation angle respectively. Eventually, the robots

(Leader and followers) orientation and their final location is determined based on the orientation and location of the target at the catching time or the mission end. The black color trace shows the residual movement that required from the followers to maintain the formation shape.

As another case to clarify the application of the algorithm, Fig. 7 shows a specific trajectory during posture error curves tracked with keep maintaining the formation and obstacles avoidance by the developed Gradient Descent control method with a three mobile robot. In order to more clearly evaluate the effect of different tracking trajectory on the proposed control algorithm, Three mobile robots are set in this case to form triangle formation and also switched to line formation when crossing the obstacles, The follower appears in green colour robots and start with random initial positions and postures the target (red robot) manipulate with a trajectory:

$$y = 4 * \frac{sin(x)}{0.95 * x} \qquad for\ all\ x \in (0 \geq x \leq 5\,pi)$$

5. Conclusion

This paper proposed a formation control and obstacle avoidance method for a dynamic region for swarm robotic systems. The method proves that the SRs have the ability to manage their formation by scaling and rotating while moving. The Gradient Descent formula was adopted to update the range and the robot orientation vector of the SR systems. MATLAB based simulation was presented to demonstrate the formation controller performance. In this work, the distributed formation control and the switching formation strategy for obstacle avoidance have been illustrated in order to show the effectiveness of our proposed algorithm. It was determined that the proposed algorithm is easy to implement and can achieve not only the required distributed formation control, but also can contribute when used in the tracking method.

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