Discontinuity, Nonlinearity, and Complexity

https://lhscientificpublishing.com/Journals/DNC-Default.aspx

Path Planning of Multi-Robot System Based on Tracking of External Stimuli

Yousif Abdulwahab Kheerallah, Mofeed Turky Rashid, Abdulmuttalib Turky Rashid, Ali Fadhil Marhoon.

Electrical Engineering Department, University of Basrah, Basrah, Iraq

Submission info

Communicated by albert c.j. Luo
Received 24 january 2012
Accepted 25 february 2012
Available online 2 april 2012

Keywords

Multi-robot system
Leader follower system
Artemia aggregation
The dynamic model
The least square method
Obstacles avoidance
The virtual circle method

Abstract

In designing a leader-follower system, the main challenge is how to distinguish the leader among other moving robots. In this paper, a multi robot system will be designed in which the robots are attracting to a spotlight as their leader. This behavior is inspired from the collective motion of the Artemia aggregations. Two dynamical models will be designed based on the newton equation and its parameters can be estimated by two methods: first, depending on the physical feature of the robots, second, the using the least square estimation method. The performance of the proposed systems will be test by: tracking the spotlight path, achieving formation and avoiding obstacles depending on the virtual circle method. For this purpose, several experiment will be implemented, which may be divided into two scenarios: without and with obstacles. Each scenario has three type of experiments, depending on the spotlight path, such as the straight, circle and zigzag path experiment. These tests will be implemented within the V-REP simulator and the results of the tests show perfect behavior of the robots during the path tracking and the obstacles avoiding.

© 2012 l&h scientific publishing, llc. All rights reserved.

1 Introduction

The wide area of research is concerning the multi robot system, because of the wide range of applications that scale from the microrobots applications, such as the group of searching under the rubbles [1], to the large robots' applications such as the group of unmanned air vehicles for searching and rescuing [2]. The main challenge in the design of a multi-robot system is how to make a number of moving robots to interact with each other to construct a certain group formation. There are several methods have been proposed to design a control strategy for the motion of multi-robot systems such as virtual structure [3], graph theory [4], artificial potential approach [5] and leader-follower [6]. The leader follower method has widely used because the motion of the members can be controlled by controlling a single leader. But, the attracting to the leader is a difficult problem, since, each robot must detect continuously the identity and the location of the moving leader, between many moving robots, and then a synchronization must be achieved with the speed and the direction of the leader and with that of other moving members. [7].

In nature, there is an example of self-organizing behavior of individuals, which is the flock, it's a group of moving members which follow a specific group object and while that they reveal a collective motion behavior. Such as the flocks of birds [8], school of fish [9] and the collective behavior of dolphins [10]. Studying the behavior of these flocks is considered a source of inspiration in modulating a simple strategy for designing multi-agent systems.

There are aggregations of animals are following a leader, but, instead of following one of the individuals, the members are attracting to an external stimulus, such as light, heat and pheromone. For example, the aggregations of honey bee are attracted to the optimal temperature when there is no light in the environment [11]. Inspired from the groups of electric fish which live in the turbid waters where the communication by the vision is failed, so the individuals are depending on a weekly electric field to communicate with other individuals [12]. One of the most important models, the light attraction model that is inspired by the aggregations of Artemia salania [13]. These creatures attract a spotlight and the members reveal a collective motion behavior, where, each member of artemia will align its motion direction with the others, keeping a certain distance from the neighbors and achieving the obstacle avoidance to avoid a collision.

The accurate dynamic model is necessary for achieving high performance in many applications of robotics. In the case of multi-robot system, it's necessary for the interaction between the moving members [7], tracking a certain leader and regulating the affected forces on each robot [9]. There are several methods to design a dynamic model such as newton [14], lagrangian [15] and Kane method [16]. In the newton method, two kinds of forces are effect on the motion of the robot, first the interaction forces between with the neighbor robots and second are the influence of the external effects. Controlling these forces is dependent on a set of parameters that decided the real behavior of the members. Therefore, the challenge of evaluating the newton model is how to estimate the set of parameters that control the system according to the desired behavior. Usually, an optimal value of the parameters is identified by using one of the identification methods such as the least square method [17]. It is used if the features of the system are unknown and an optimal performance should be reached, its complex methods. So, when the features of a known system, like the multi-robot system, the parameters are simply and directly calculated, on the cost of losing the optimality in the performance of the robots [18].

The most important challenge of the system is the path planning of the robots in the presence of obstacles, where, the path planning must be combined with an obstacle avoidance algorithm. For this purpose, a switching control strategy is used, where, an obstacle avoidance algorithm is switched on when the flock is reaching the obstacles, that's results in losing the formation and the path tracking. After passing the obstacles, the path planning and the formation of the flock will be activated again by the robots [19]. For that, a simple and effective obstacle avoidance method should be implemented. Such as, the appearance variation method in which the appearance variation of the obstacle can be captured due to the variation in color and texture of the captured image. Also, it must be noticed that the variations are reduced when the camera is close to an obstacle [20]. Another method represented by the virtual circles of the visible vertices in which the robot will detect the presence of the obstacle if it's within its sensing zone, then the virtual circle for the visible vertices is calculated and considered as the new shape of the obstacle [21].

In this paper, the multi-robot system will be designed, in which the robots are following the spotlight as its leader. The model of the robots will be derived based on the dynamic model of the Artemia aggregations, where, the newton equation is used to derive this model. The parameters of the newton equation will be calculated by two methods: first, a direct method based on the physical features of the robot, second, the least square method by which an optimal set of parameters will be calculated. also, the obstacles avoidance algorithm will be implemented based on the virtual circle for the visible vertices of the obstacles. The multi-robot system will be implemented within the v-rep simulator environment, in which several experiments will be achieved to test the performance of the proposed system.

2 Methodology

In this part, the collective behavior of artemia individuals will be described in order to design a mathematical model to control the motion of the robot. This model is based on the influence of the light on the motion direction of artemia aggregations. Also, the dynamic model will be derived based on the newton equation, where, each robot is considered as a mass subjected to several forces that can be controlled by a set of parameters. The parameters will be estimated depending on: first, a direct method based on the physical features of the robots, second, the least square estimation method, where, an optimal set will be generated. Since these dynamic models didn't have the obstacles avoiding ability, so, the virtual circles of the visual vertices method will be used.

2.1 the kinematic model of artemia

Artemia is the creatures that attract the light, where, each, the member has three-zone of interactions which are the attraction, orientation, and the repulsion zone. When the light is within the attraction zone then the individual will follow it, so if the light is distributed normally on the area then motion direction will be random and only obstacle avoidance will be activated to avoid collision with those within the repulsion zone [22]. If a spotlight appears then only the individuals those sensing it within their attraction zone will follow the spot, which, the attraction behavior will be:

$$\vec{d}_a(t+\tau) = \vec{g}_i \tag{1}$$

Where, is a unit vector in the direction of the light. During the following of the light, orientation must be achieved when they come close to each other, within the orientation zone. Their directions will be aligned with each other and described by the mathematical model;

$$\vec{d}_o(t+\tau) = \sum_{j=1}^{n} \frac{\vec{v}_j(t)}{|\vec{v}_j(t)|} \tag{2}$$

Where, vj is the direction of moving of the jth neighbor.

At last, to avoid collision with that within a very close range, in the repulsion zone, obstacle avoidance will be activated. Each member will turn its motion direction in the opposite side as in equation,

$$\vec{d}_r(t+\tau) = -\sum_{j\neq i}^{n} \frac{\vec{r}_{ij}(t)}{|\vec{r}_{ij}(t)|} \tag{3}$$

2.2 the dynamic model of artemia

The mathematical model of the collective motion behavior of the aggregation of artemia based on newton equation is derived for each individual. There are two cases, the first one concerns the uniform light and the second is about the spotlight. In the first case, each individual moves in a random direction so we will concentrate on the second case at which the individuals attract the spotlight, as shown in Fig. 1, newton equation will be [17]:

$$m\frac{d\vec{v}_i}{dt} = a\vec{n}_i - \gamma\vec{v}_i + \sum_{i\neq j} a_{ij}\,\vec{f}_{ij} + \vec{g}_i. \tag{4}$$

Where, m is the mass of artemia, $\vec{v}i$ the velocity of the member, a is the locomotive force affected in the heading direction $\vec{n}i$, γ the resistivity coefficient. f_{ij} is the interaction force between the individuals, which could be a repulsion force to avoid collision with the closer individuals or an orientation force to align with other members within the formation.

$$\vec{f}_{ij} = -c\left[\left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-3} - \left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-2}\right] * \left(\frac{r_j(t-T_s) - r_i(t-T_s)}{d_{ij}(t-T_s)}\right) \quad (5)$$

Where, $\left(\frac{d_{ij}(t-Ts)}{rc}\right)^{-3}$ is the repulsion term, $\left(\frac{d_{ij}(t-Ts)}{rc}\right)^{-2}$ is the orientation term.

The interaction with those in the front position is stronger than that with those on the sides, this is decided by the direction sensitivity coefficient a_{ij} :

$$a_{ij} = 1 + d \cdot cos(\beta) \quad (6)$$

Where, d is a controlling parameter (d= (0,1)), β is the angle between the direction of the ith member and a unit vector from the ith to jth member.

The traction force to the light $\vec{g}_i$ is:

$$\vec{g}_i = c_g * Kv_i * Kr_i * (r_a(t) - r_i(t)) \quad (7)$$

Where, are the sensitivity and speed factors are the positions of light and individual. This is the dynamic model of artemia, which takes into account all the forces affected by each individual. It required the knowledge of parameters, which are difficult to identify.

2.3 the dynamic model of the multi robots

The dynamic model of the system is derived based on the dynamic model of artemia, Eq (4), which can be rewritten in the x, y direction as follows;

$$m\frac{d\vec{v}_{ix}}{dt} = a_x\left(\frac{r_{ix}(t) - r_{ix}(t-T_s)}{r}\right) - \gamma\vec{v}_{ix} + \sum_{i\neq j} a_{ij}\vec{f}_{ijx} + \vec{g}_{ix} \quad (8)$$

$$m\frac{d\vec{v}_{iy}}{dt} = a_y\left(\frac{r_{iy}(t) - r_{iy}(t-T_s)}{r}\right) - \gamma\vec{v}_{iy} + \sum_{i\neq j} a_{ij}\vec{f}_{ijy} + \vec{g}_{iy} \quad (9)$$

Where, $\vec{f}_{ijx}, \vec{f}_{ijy}$ are the interaction force between the individuals, which could be repulsion force to avoid collision with the closer individuals or orientation force to align with other members within the formation.

$$\vec{f}_{ijx} = -c\left[\left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-3} - \left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-2}\right] * \left(\frac{r_{jx}(t-T_s) - r_{ix}(t-T_s)}{d_{ij}(t-T_s)}\right) \quad (10)$$

$$\vec{f}_{ijy} = -c\left[\left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-3} - \left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-2}\right] * \left(\frac{r_{jy}(t-T_s) - r_{iy}(t-T_s)}{d_{ij}(t-T_s)}\right) \quad (11)$$

Here, dij the distance between the ith and jth individual, r_c is the optimum distance between individuals and c is the force constant.

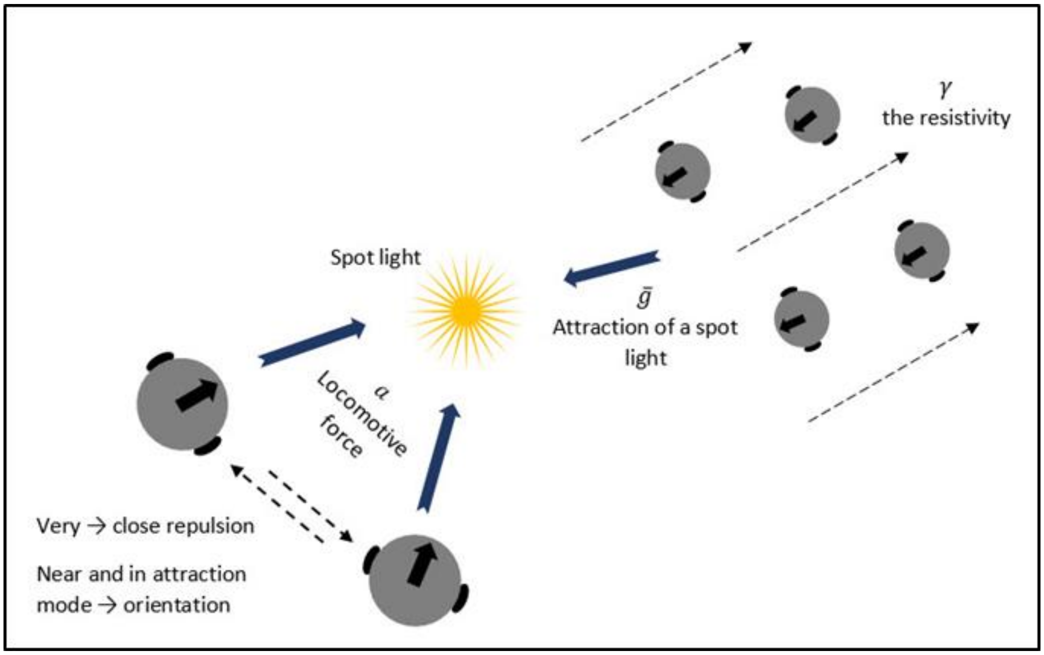

Fig.1. Show the forces affected on each artemia.

The attraction forces to the light $\vec{g}ix$,$\vec{g}iy$ are ,

$$\vec{g}_{ix} = c_g * Kv_i * Kr_i \left(r_{ax}(t) - r_{ix}(t) \right) \tag{12}$$

$$\vec{g}_{iy} = c_g * Kv_i * Kr_i * \left(r_{ay}(t) - r_{iy}(t) \right) \tag{13}$$

After writing newton model, the state apace of the system can be derived as follows:

$$v_i(t) = \dot{r}_i(t) = \frac{\left(r_i(t) - r_i(t - T_s)\right)}{T_s} \tag{14}$$

$$v_i(t) = \dot{r}_i(t) = \frac{\dot{r}_i(t) - \dot{r}_i(t - T_s)}{T_s} = \frac{r_i(t) - 2.r_i(t - T_s) - r_i(t - 2.T_s)}{{T_s}^2} \tag{15}$$

After replacing each term, newton equation will be:

$$\begin{gathered} m\ddot{r}_{ix}(t) = a_x \left(r_{ix}(t) - r_{ix}(t - Ts)\right) - \gamma r_{ix}(t) - \\ \frac{(\alpha_{ij} * c)}{{r_c}^{-3}} \sum_{i \neq J}^{n} {d_{ij}}^{-4} \left(r_{jx}(t - T_s) - r_{ix}(t - T_s)\right) + \\ \frac{(\alpha_{ij} * c)}{{r_c}^{-2}} \sum_{i \neq J}^{n} {d_{ij}}^{-3} \left(r_{jx}(t - T_s) - r_{ix}(t - T_s)\right) + \\ c_g . K_{vi} . K_{ri}(r_{ax}(t) - r_{ix}(t)) \end{gathered} \tag{16}$$

$$m\ddot{r}_{iy}(t) = a_y\left(r_{iy}(t) - r_{iy}(t - Ts)\right) - \gamma r_{iy}(t) - \frac{(\alpha_{ij} * c)}{r_c^{-3}} \sum_{i \neq J}^{n} d_{ij}^{-4}\left(r_{jy}(t - T_s) - r_{iy}(t - T_s)\right) + \frac{(\alpha_{ij} * c)}{r_c^{-2}} \sum_{i \neq J}^{n} d_{ij}^{-3}\left(r_{jy}(t - T_s) - r_{iy}(t - T_s)\right) + c_g.K_{vi}.K_{ri}\left(r_{ay}(t) - r_{iy}(t)\right) \tag{17}$$

$$r_{ix}(k) = \alpha_{x1}\, r_{ix}(k-1) + \alpha_{x2}\, r_{ix}(k-2) - \alpha_{x3}.\sum_{i \neq J}^{n} d_{ij}^{-4}\,(r_{jx}(k-1) - r_{ix}(k-1)) + \alpha_{x4}.\sum_{i \neq J}^{n}.d_{ij}^{-3}\,(r_{jx}(k-1) - r_{ix}(k-1)) + \alpha_{x5} r_{ax}(k) \tag{18}$$

$$r_{iy}(k) = \alpha_{y1}\, r_{i.y}(k-1) + \alpha_{y2}\, r_{i.y}(k-2) - \alpha_{y3}.\sum_{i \neq J}^{n}.d_{ij}^{-4}\,(r_{jx}(k-1) - r_{ix}(k-1)) + \alpha_{y4}.\sum_{i \neq J}^{n}.d_{ij}^{-3}\,(r_{jy}(k-1) - r_{iy}(k-1)) + \alpha_{y5}.r_{a.y}(k) \tag{19}$$

Where, Eqs (18, 19) represent the dynamic model of the robot that decided the next position, to be attracted by the robot, depending on the parameters values and location of the light and the neighboring robots.

2.4 the parameters identification

Since the parameters are controlling the forces that affected the response of the robots, so, the accurate set of parameters should be identified. Here, two methods of parameter identification are proposed: the direct method that depends on the physical properties of the robot, and the least square estimation method, where, an optimal set of parameters will be found.

According to Eqs (16-19) the parameters will be calculated depending on the properties of the robots which are (m) the mass of the robot, (a) the locomotive force, (kv*kr) the sensitivity to the light, (rc) the optimal distances between the robots and (γ) the resistivity. So, the parameters will be equal to:

$$\alpha_1 = \frac{2m - a}{m - a + k_v k_r} \tag{20}$$

$$\alpha_2 = \frac{m}{m - a + k_v k_r} \tag{21}$$

$$\alpha_3 = \frac{{r_c}^3}{m - a + k_v k_r} \quad (22)$$

$$\alpha_4 = \frac{{r_c}^2}{m - a + k_v k_r} \quad (23)$$

$$\alpha_5 = \frac{k_v k_r}{m - a + k_v k_r} \quad (24)$$

The multi robot's system is simulated by the v-rep simulator, from which, the features of the robots will be as in table (1). After replacing these features in the Eqs (20, 21, 22, 23 and 24). The parameters will be accordingly as in table (2):

Table 1 the physical features of the system.

The features	Values
M	1.6 kg
A	-1.6
Kv * kr	0.37
Rc	0.85 m

Table 2 parameters calculated depending on the physical properties of the robots [17].

	X-parameters	Y-parameters
α1	0. 44817	0. 44817
α2	0. 44817	0. 44817
α3	0.17205	0. 17205
α4	0. 20239	0. 20239
α5	0. 10364	0. 10364

2.5 the least square parameter estimation method

In universe, there are some system has unknown physical features, or it is difficult to evaluate physical features. Therefore, the concept of using least square parameter estimation can be represented by comparing the measured and the calculated values that concern the output of the system and then the error will be used in an algorithm to modify the values of the parameters.

So, before implementing the modification algorithm, the output values will be compared as follows [23]:

$$\tilde{z}(k) = z(k) - \hat{z}(k) \quad (25)$$

Where, $\tilde{z}(k)$ is the error vector that will used in the algorithm:

$$\tilde{z}(k) = H(k) \cdot \theta - V(k) \quad (26)$$

Here $\tilde{z}(k), H(k)$ *and* $V(k)$ are vectors of measured output values, observed input values and measured error values. θ is the parameters vector

$$\hat{z}(k) = H(k) \cdot \hat{\theta} \tag{27}$$

Where, z῀(k), $\hat{\theta}$ are the output of the identified model and its parameters vector.
The optimal values of the parameters will minimize the error vector, so, the minimum cost j[θ῀(k)] is equal to a weighted sum of the square value of error:

$$J[\tilde{\theta}] = \tilde{z}'(k) \cdot W(k) \cdot \tilde{z}(k) \tag{28}$$

$$J[\tilde{\theta}(k)] = w(k) \cdot \tilde{z}^2(k) + w(k-1) \cdot \tilde{z}^2(k-1) + \cdots + w(k-L) \cdot \tilde{z}^2(k-L) \tag{29}$$

At last, the algorithm of the parameter's correction is applied:

$$\tilde{\theta}(k+1) = \tilde{\theta}(k) + K^*(k+1) \cdot [Z(k+1) - h'(k+1) \cdot \tilde{\theta}(k)] \tag{30}$$

$$K^*(k+1) = P(k)h(k+1)[h'(k+1)P(k)h(k+1) + 1/W(k+1)]^{(-1)} \tag{31}$$

$$P(k+1) = [1 - K^*(k+1)h'(k+1)]p(k) \tag{32}$$

Where, $K^*(k)$ is a gain matrix.
Finally, the optimal set of parameters is estimated as in table (3).

Table 3 parameters estimated by least square parameter method [17].

	X-parameters	**Y-parameters**
α1	0.42012452	0.338294409
α2	0.444365296	0.335011807
α3	1.000153359	1.000032658
α4	0.999982971	0.999997093
α5	0.114045668	0.324450437

By applying this set to the parameters to dynamic model of the multi robot system Eqs (18, 19), an optimal performance will be achieved.

2.6 the virtual circles algorithm of obstacles avoidance

This section shows and illustrates the method of avoiding the obstacles with vertices, it's based on drawing a virtual circle round the obstacles, where, these virtual circles will represent the new shape of the obstacles [20]. The circle will be created, only, to the obstacles that are detected by the sensors of the robot, so, the hidden vertices will not be within the created circle, then the robot will be searching for the shortest path towards its target and moving tangent with the virtual circles of the obstacles.

The algorithm to construct the virtual circles around the obstacles can be described by the following steps:
Step 1: several information should be known which is the robot location, velocity, and direction (pr, vr, θR); also, the target location pt.
Step 2: read the sensor information about the visible vertices of the detected obstacles (ob1, ob2, …. Obn),

where, n represent the number of the detected obstacles, as shown in Fig. 2.
Step3: the calculation of the virtual circle of each detected obstacle. Is implemented as bellow:

$$distance = \begin{array}{c} \\ v1 \\ v2 \\ vk \end{array}\!\!\begin{array}{c} \begin{array}{ccc} v1 & v2 & vk \end{array} \\ \begin{bmatrix} 0 & d(1,2) & d(1,k) \\ d(2,1) & 0 & d(2,k) \\ d(k,1) & d(k,2) & 0 \end{bmatrix} \end{array} \quad (33)$$

1. Suppose the visible vertices, that can be detected by the sensors of the robot, of a certain obstacle are ob1(v1, v2 ,.., vk), as shown in Fig. 3.
2. Apply the distance matrix of the vertices, which include the distances between each vertex with the others, as in equation below;
3. From the distance matrix, the diameter of the circle ci is computed which is equal to the largest distance. Then the virtual circle will be drawn with a center located in the midpoint of the vertices that have the largest distance, as shown in fig. 3.

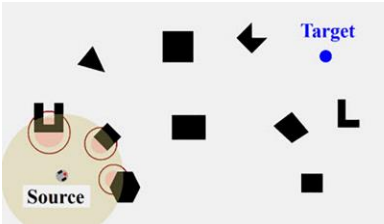

Fig.2. the detected obstacles by the sensing zone of the robot [20].

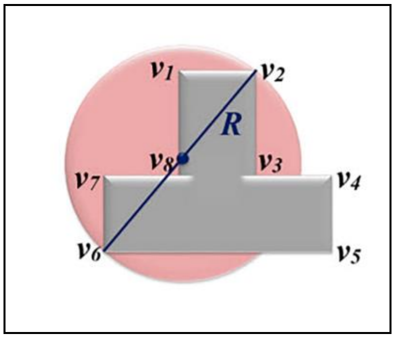

Fig.3. the visible vertices of the detected obstacle [20].

4. Check if the created circle ci includes all the vertices of the obstacle, starting from i=1 to k, compare the circle radius with the distance dvi between the circle center and the vertex vi, if the distance dvi is larger than the radius, then an expansion will be applied to circle ci that its radius will become equal to this distance of vertex vi. The diameter of the new circle ci+1 is drawn from the vertex vi passing through the center of ci to the far side of the circle ci, as shown in Fig. 4. The complete virtual circle of the obstacle will become as shown in Fig. 5.
Step 4: choose the shortest path to your target position and move according to the tangent line with the new circular shape of the obstacle, as shown in Fig. 6.
Step5: after computing the shortest tangent paths, then the robot will pass the first obstacle and the steps from 2 to 5 are repeated again, until reaching the target point, as shown in Fig.7 shows the complete path.

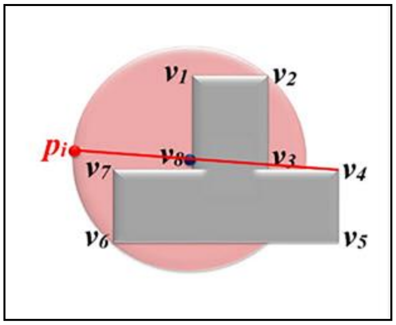

Fig.4. the radius of the new virtual circle [21].

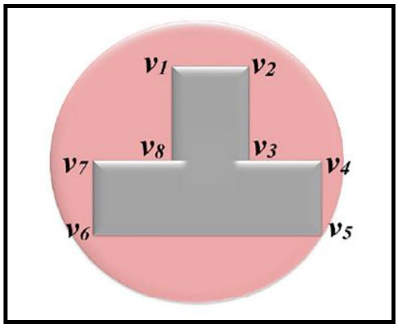

Fig.5. the complete virtual circle of the obsticle [21].

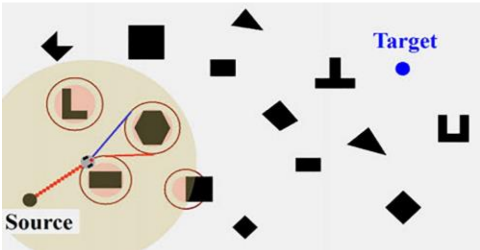

Fig.6. the shortest tangent path of the obstacle virtual circle [21].

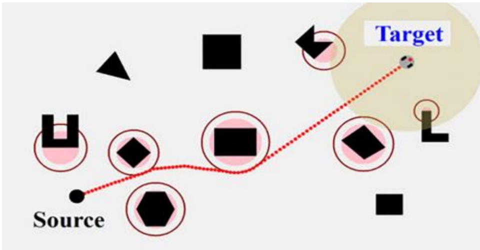

Fig.7. the virtual circular shapes of the obstacles [21].

3 Simulation and results

In a v-rep software within an environment of (10 m * 10 m), a spherical differential drive mobile robot is used to implement some experiments that simulate the proposed design of the multi-robot system. Each robot body has a diameter of (27 cm) and a mass of (1.031 kg), and has two active cylindrical wheels, right and left, and one passive spherical back wheel. The cylindrical wheels have a diameter of (12.35 cm), a thickness of (3.08 cm), a mass of (0.29 kg), and each one is driven by a motor with maximum torque (2.5 n.m). The spher-

ical wheel has a radius of (6.7 cm) and mass (0.37 kg).
Several experiments are implemented in order to check the performance of the flock according to the two proposed dynamic models, where, these experiments may be divided into two scenarios: the first one concerns the path planning of the robots while following the spotlight, the second scenario concern the obstacles avoidance. In each scenario, the robots should keep a fixed distance from the movable spotlight, have the same speed of the spotlight and moving within a certain formation. To ensure that the robots will follow the spotlight within any path, several patterns of the spotlight paths have been chosen such as straight line, circle and zigzag path pattern.

3.1 the path planning depending on the spotlight trajectory

In this scenario, the ability of the robots to follow the trajectories of the spotlight and forming an organized flock that moves at a speed similar to that of the spotlight will be tested. Also, the error of the flock path planning will be calculated, within the three paths of the spotlight, to show the model of better performance.

3.1.1 straight line trajectory

In the first experiment, the robots are tracking fixed direction trajectory, so, the tasks of the robots are concentrated on the attraction to the light, flock formation and synchronize its speed with that of the spotlight. As in fig. 8, 9 that shows the performance of the proposed systems according to the parameters of the physical structure of the robot's and the parameters of the least square parameter estimation method, respectively. Also, the error of the average x and y positions of the flock with respect to the spotlight locations.

3.1.2 circle line trajectory

This path has a more challenge, where, the spotlight motion direction is changing continuously, so, each robot should synchronize its speed and direction with that of the spotlight. This is another difficulty that is added to the synchronization that must be achieved between the moving robots, where, the robots are achieving orientation and repulsion behavior while following the circular path. Fig.10, 11, shows the response of the model with the parameters of the physical structure and the optimal parameters, respectively. In addition to the error of the x and y average positions of the flock with respect to the spotlight locations.

3.1.3 Zigzag line trajectory

This test requires a high steering system, since, the spotlight is changing its motion direction in the opposite way, so, the whole flock should change its direction and turn in the opposite direction as quickly to catch up with the spotlight. Fig. 12, 13 show the response according to the two sets parameters, the physical and the optimal set respectively. Also, the error of the x and y average position of the flock with respect to the spotlight.

3.2 The path planning with obstacles avoidance

The second scenario shows the ability of the robots to avoid the obstacles during the spotlight path tracking, and reshape the flock again after passing the obstacles. The flock will follow the same spotlight trajectories, the straight, the circle and the zigzag path.

3.2.1 the straight path

This is the simpler path because the motion direction is fixed, so, each robot will separate from the flock and passing the obstacles, also, the collision with other robots must be avoided while passing the obstacles. After that, the flock will be reconstructed again and the path planning is continuing, as shown in Figs. 14, 15 which represent the response of the system with the physical and the optimal parameters, respectively.

3.2.2 the circle path

This test adds the challenge of following the continuously changing motion direction of the spotlight, so, the robots should separation from the flock and reconstruct it again, after passing the obstacles, while tracking the more complicated path. as shown in Figs. 16, 17 show the behavior of the flock according to the two proposed models, the evaluated and the optimal respectively.

3.2.3 the zigzag path

The challenges of this path are the most difficult, where, because the light is changing its motion direction in opposite way, so, the robots should: first, passing the obstacles, second, change its direction and turn to the opposite side to catch up with the moving spotlight. All this task must be achieved before being out of the spotlight attraction zone, as shown from the performance of the evaluated and the optimal systems, as shown in Figs. 18, 19.

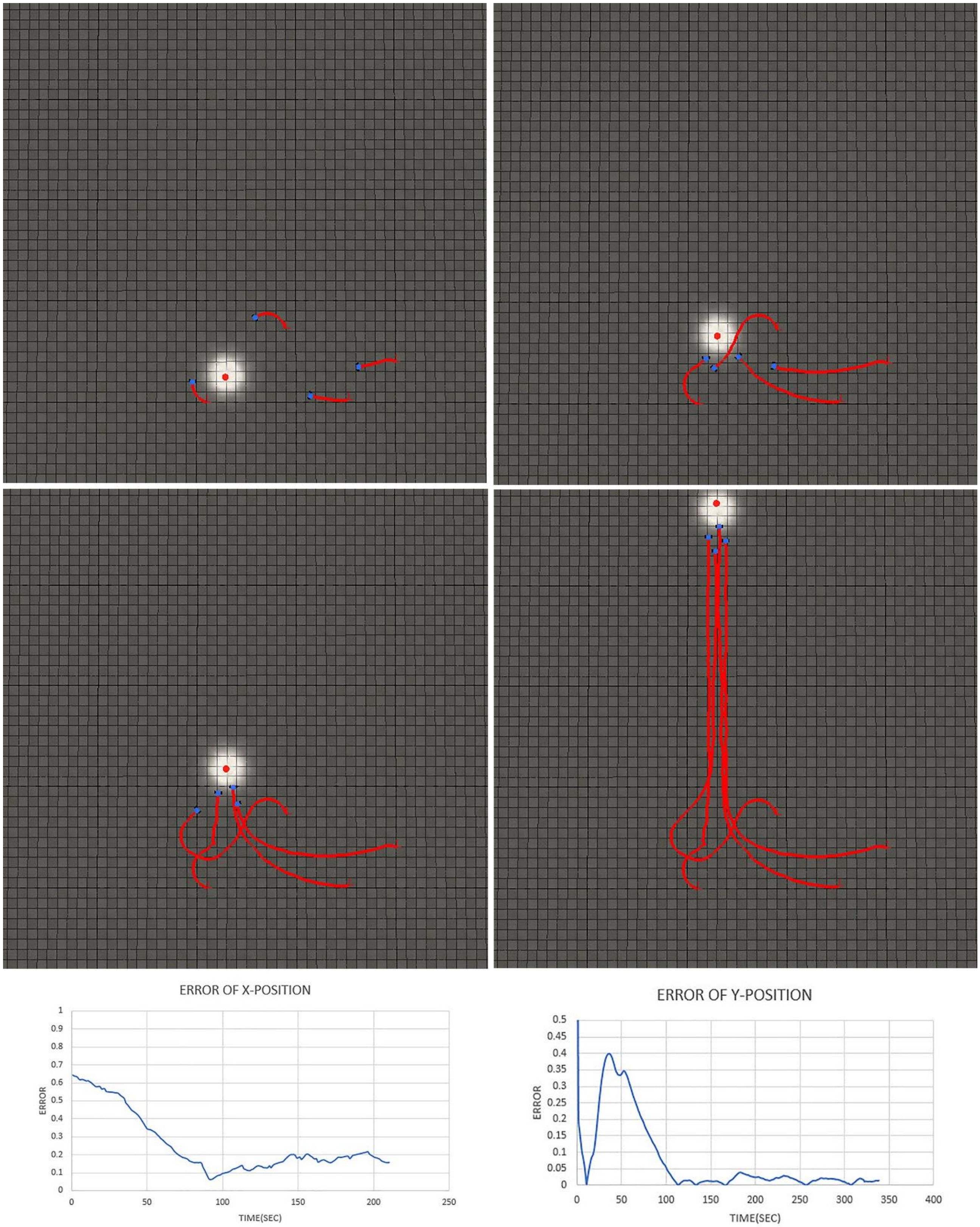

Fig.8. Straight-line pattern according to the dynamic model (parameters evaluated by the physical structure of the robot)

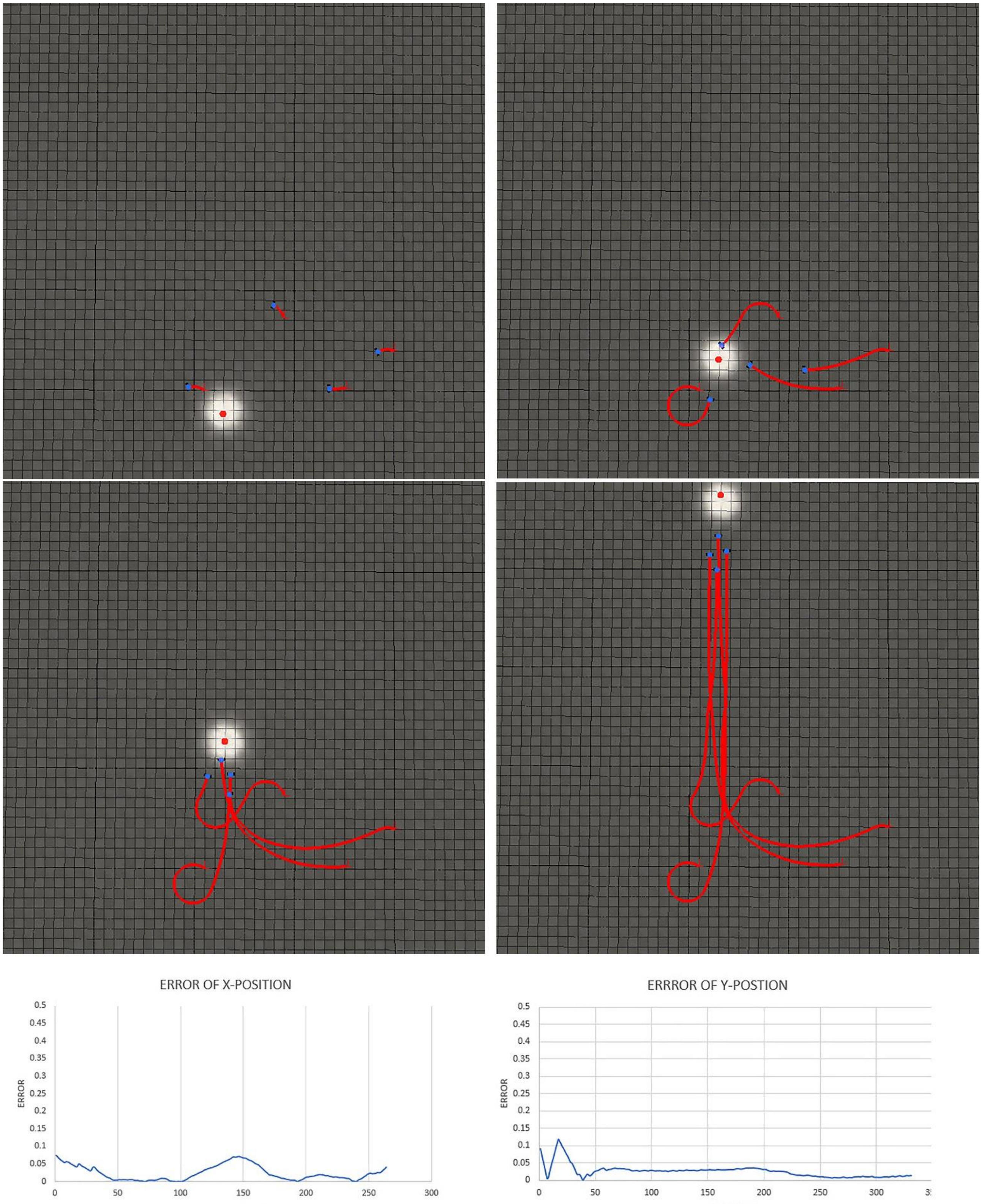

Fig.9. The straight-line pattern according to the dynamic model (parameters evaluated by the least parameter estimation method).

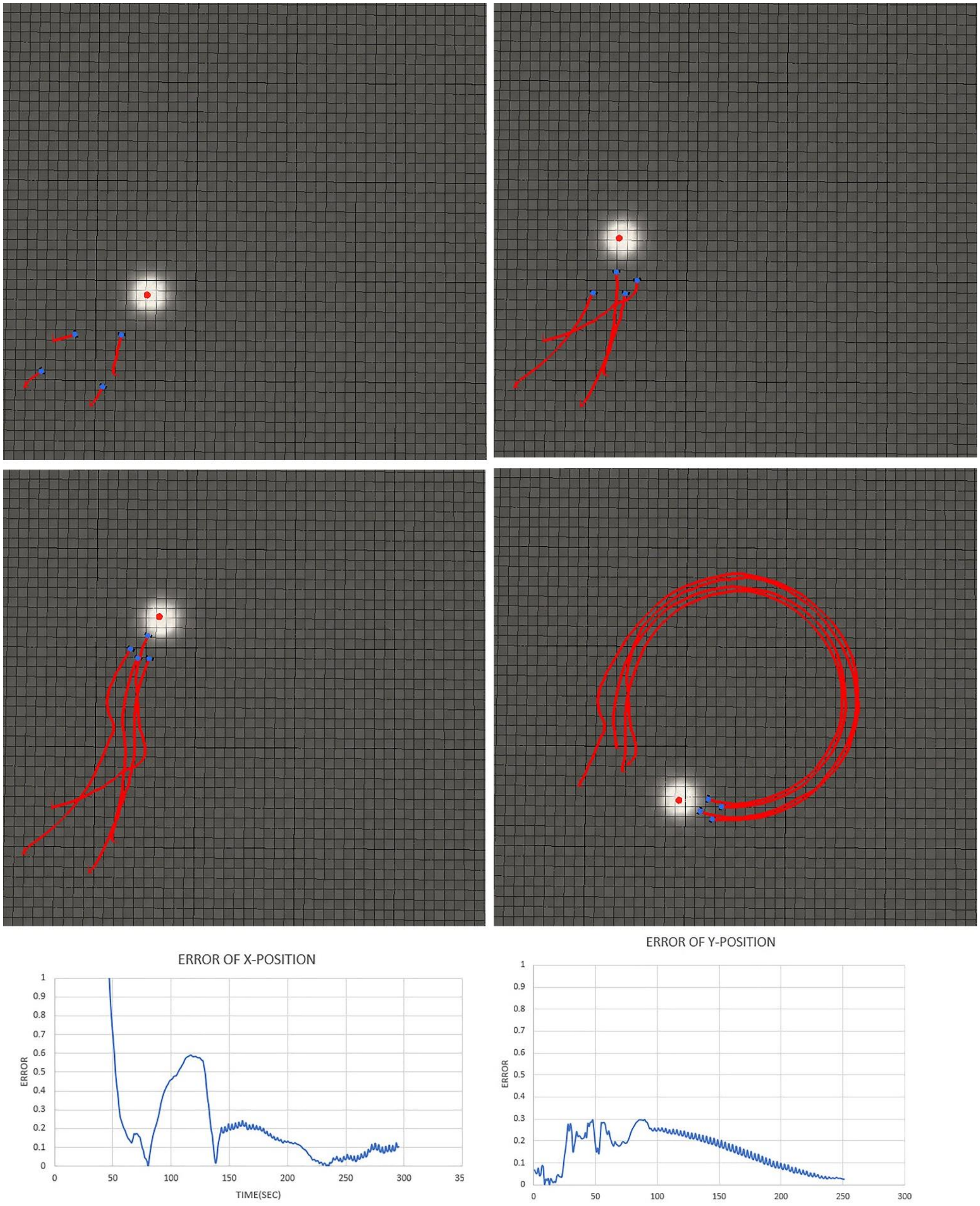

Fig.10. The circular pattern according to the dynamic model (parameters evaluated by the physical structure of the robot).

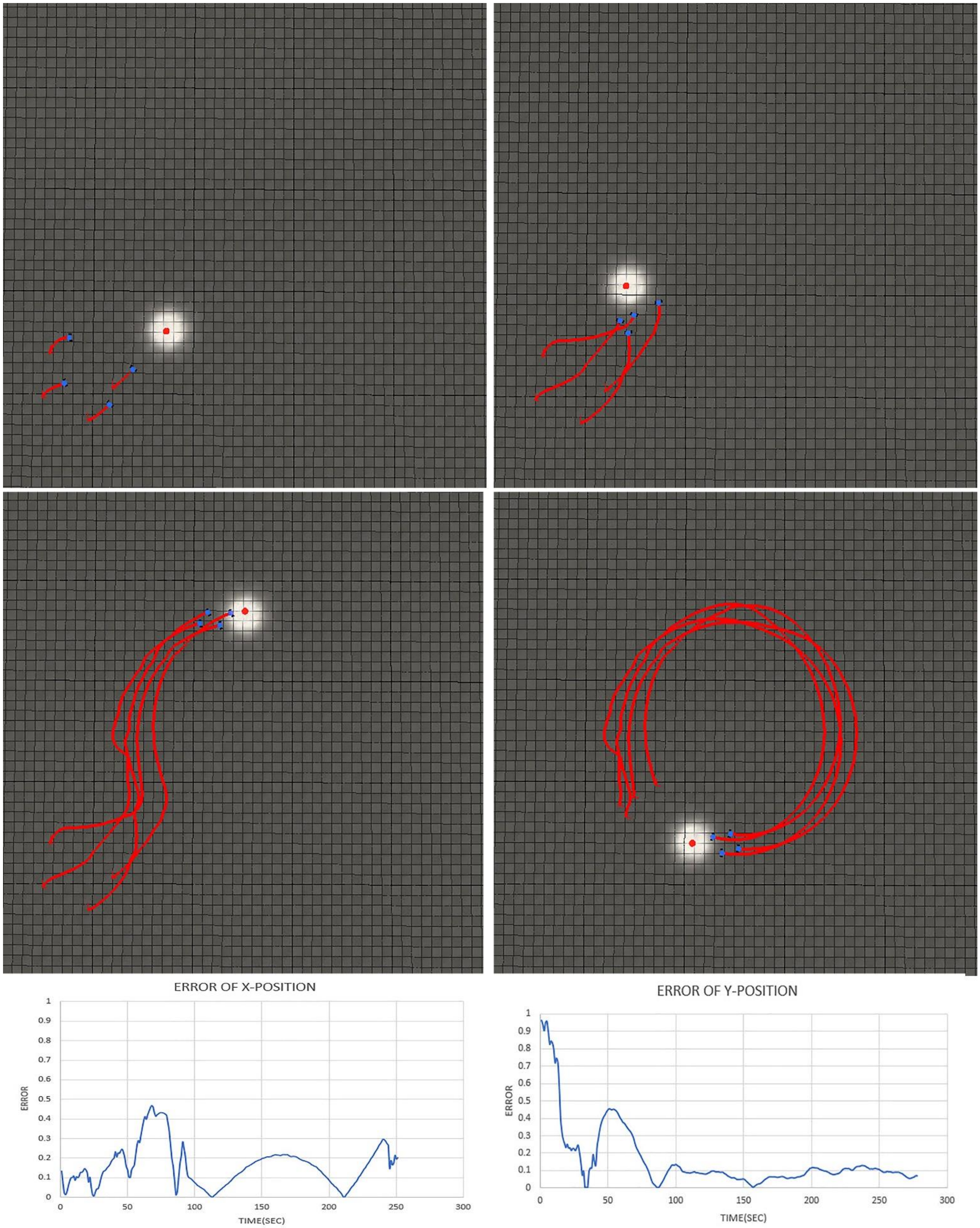

Fig.11. The circular pattern according to the dynamic model (parameters evaluated by the least parameter estimation method).

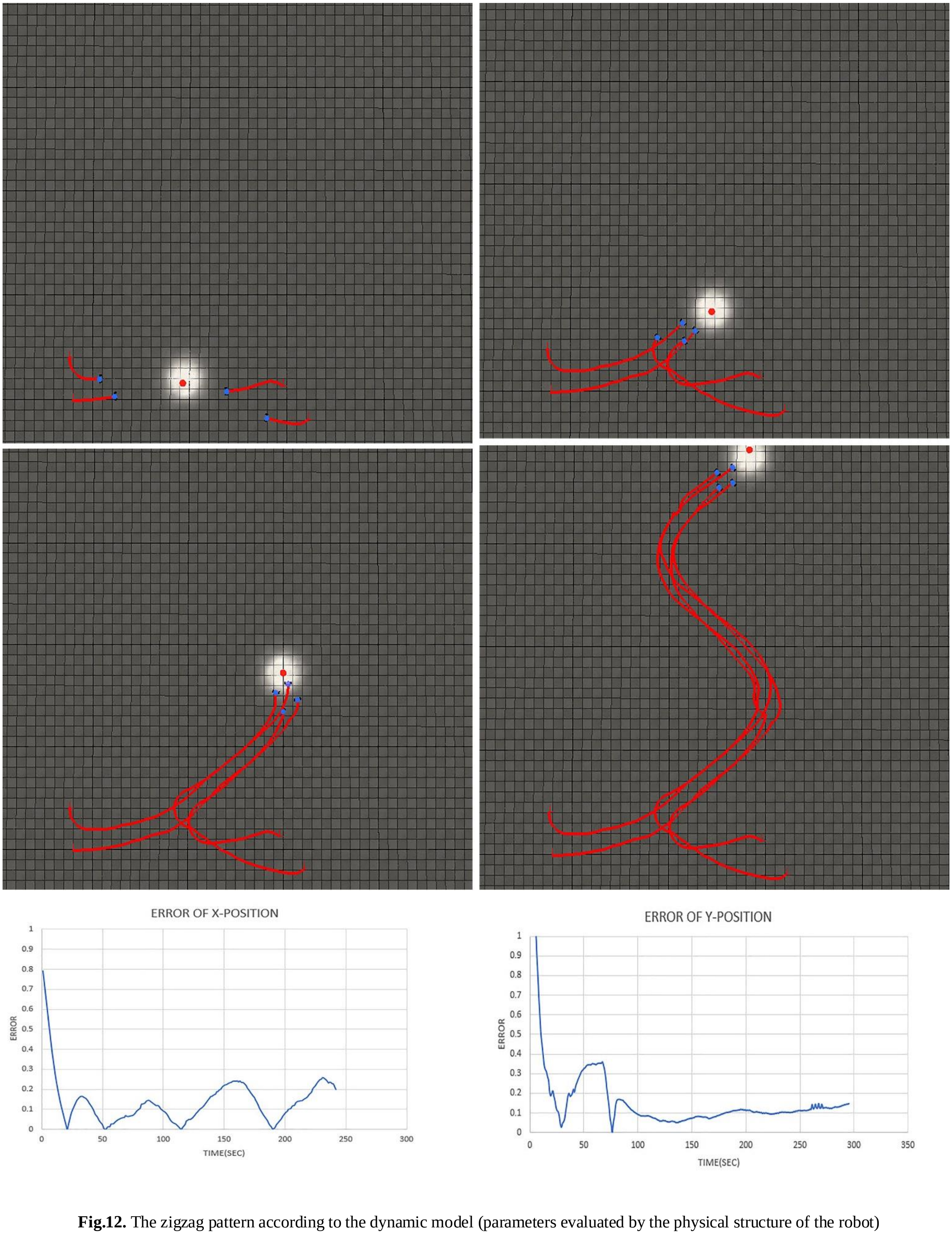

Fig.12. The zigzag pattern according to the dynamic model (parameters evaluated by the physical structure of the robot)

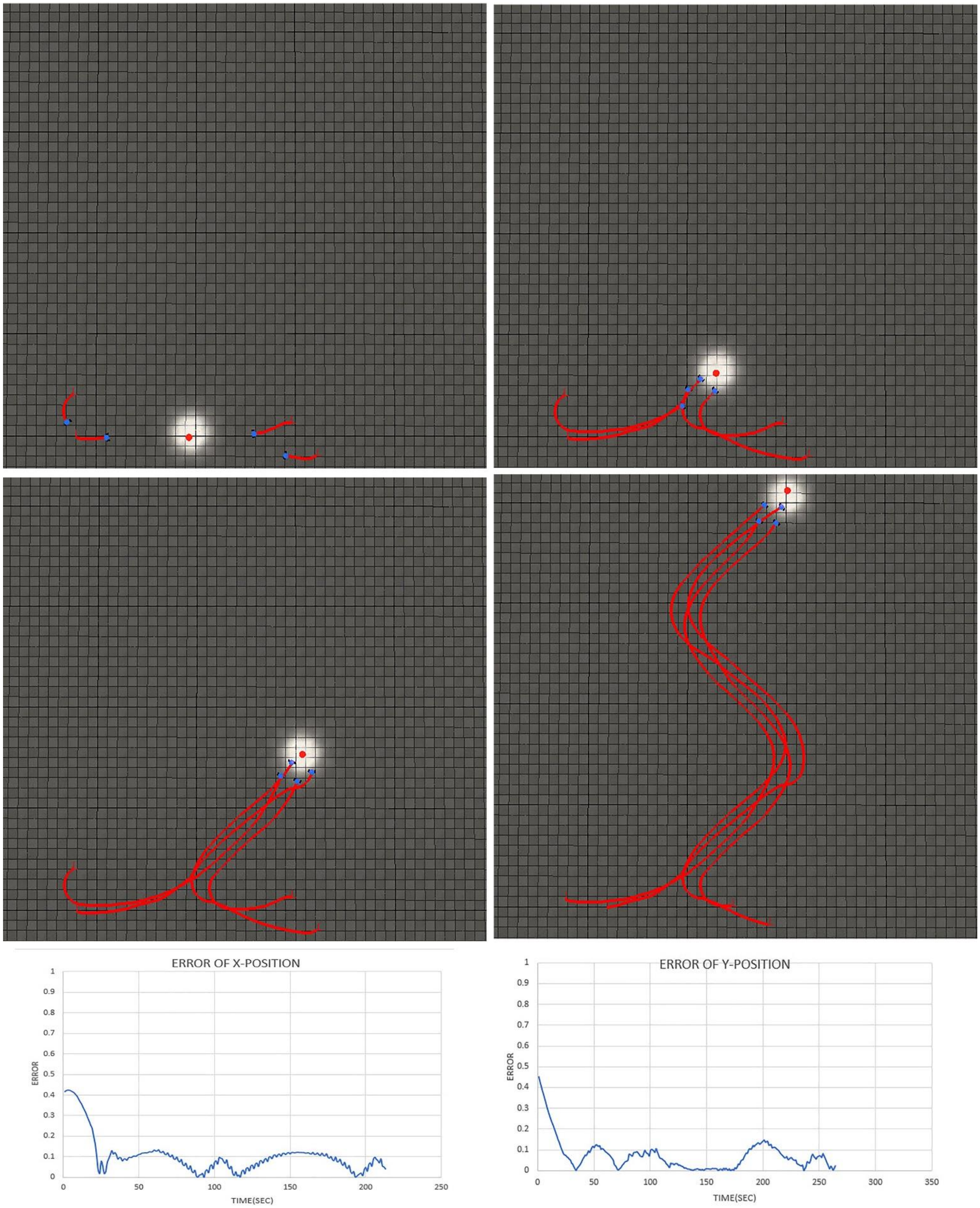

Fig.13. The zigzag pattern according to the dynamic model (parameters evaluated by the least parameter estimation method)

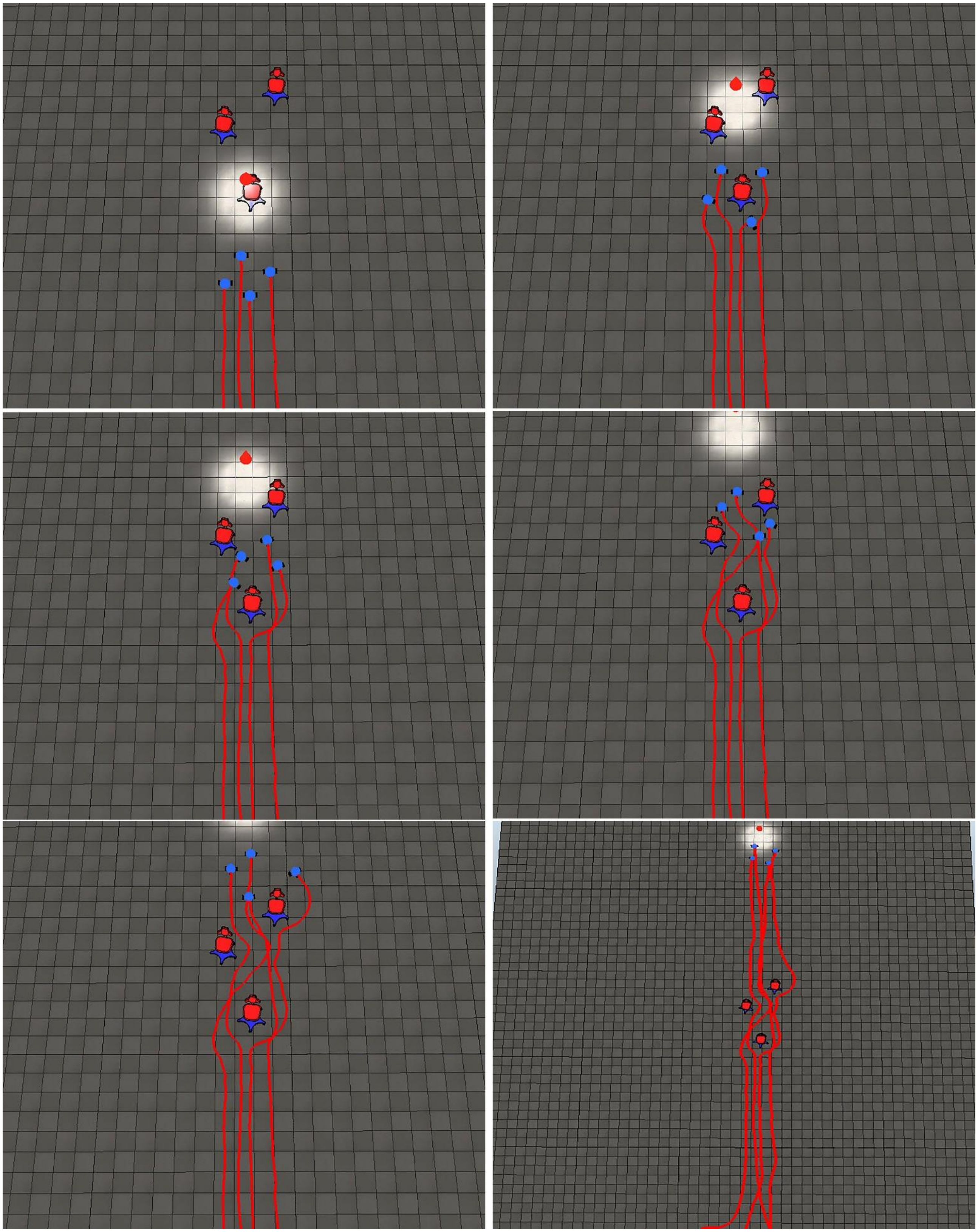

Fig.14. Straight-line pattern with obstacles avoidance according to the dynamic model (parameters evaluated by the physical structure of the robot)

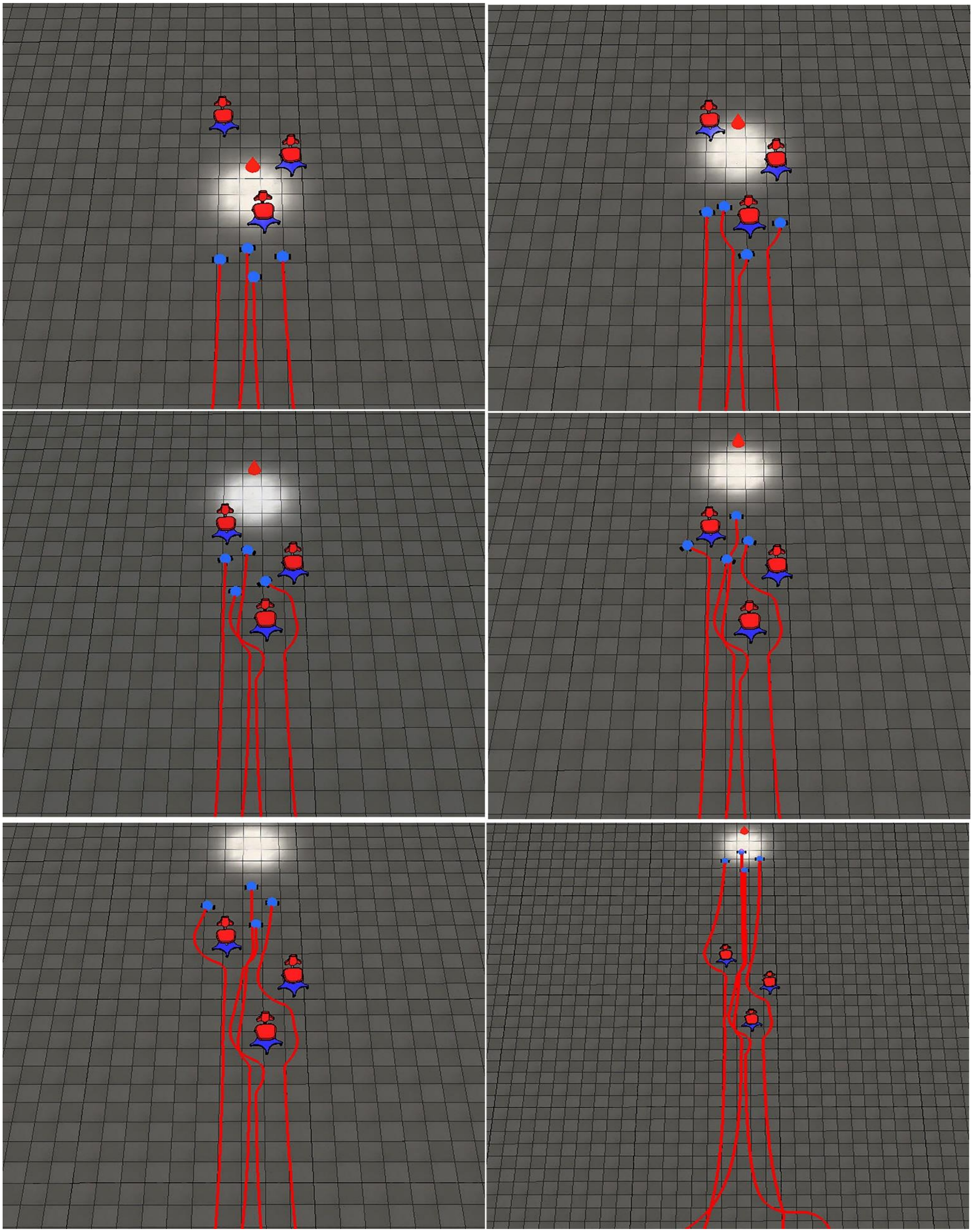

Fig.15. The straight-line pattern with obstacles according to the dynamic model (parameters evaluated by the least parameter estimation method).

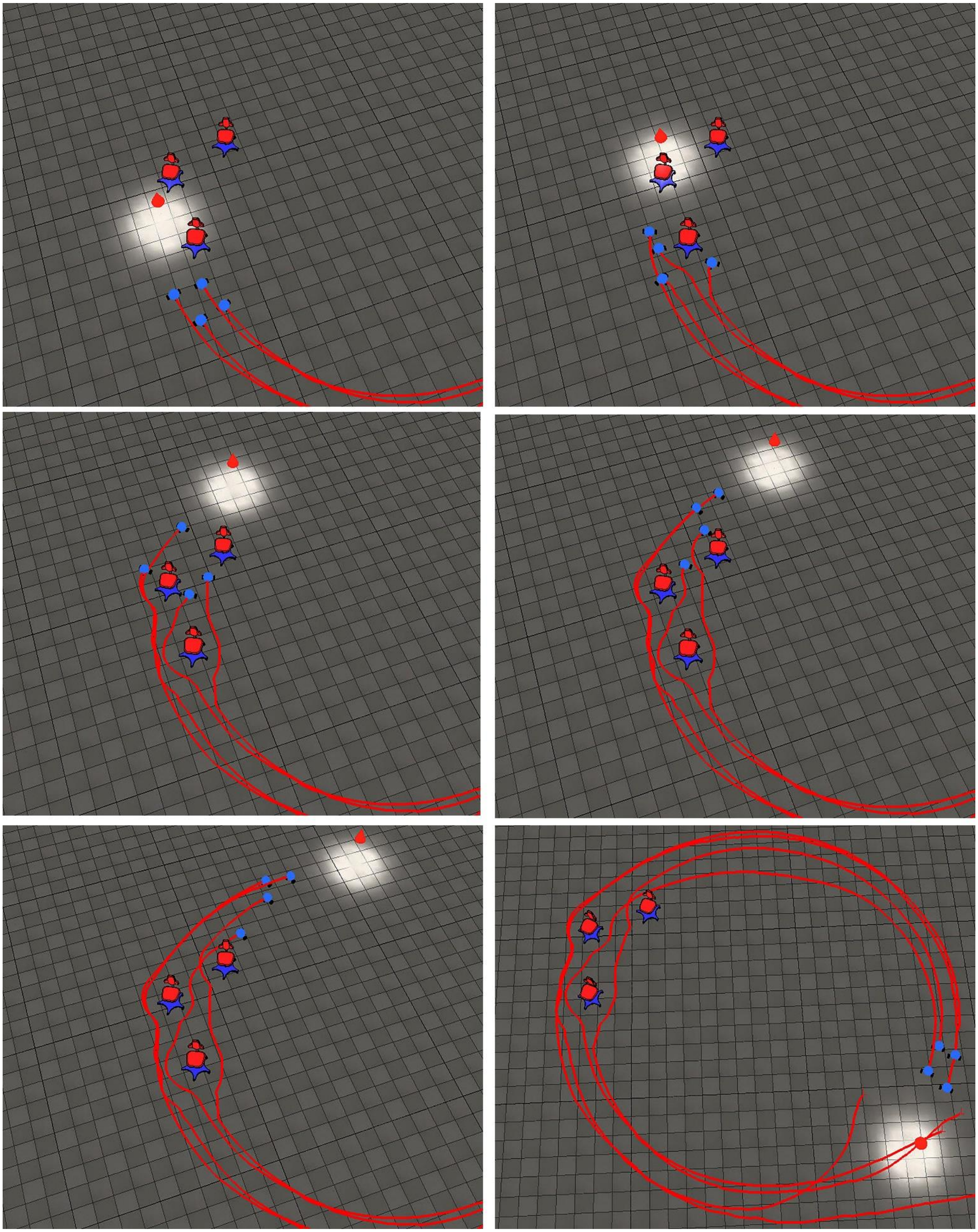

Fig.16. The circular pattern with obstacles according to the dynamic model (parameters evaluated by the physical structure of the robot).

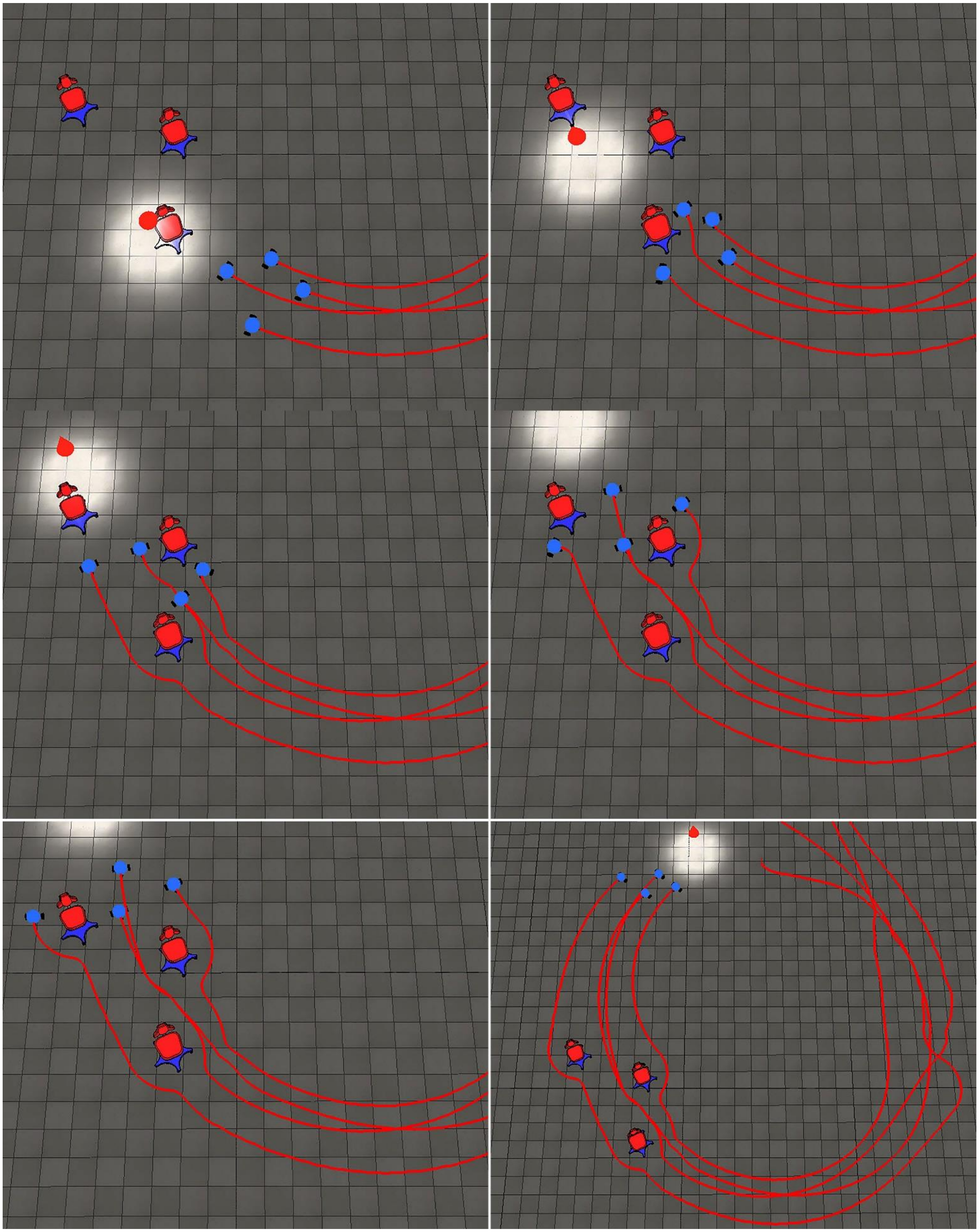

Fig.17. the circular pattern with obstacles according to the dynamic model (parameters evaluated by the least parameter estimation method).

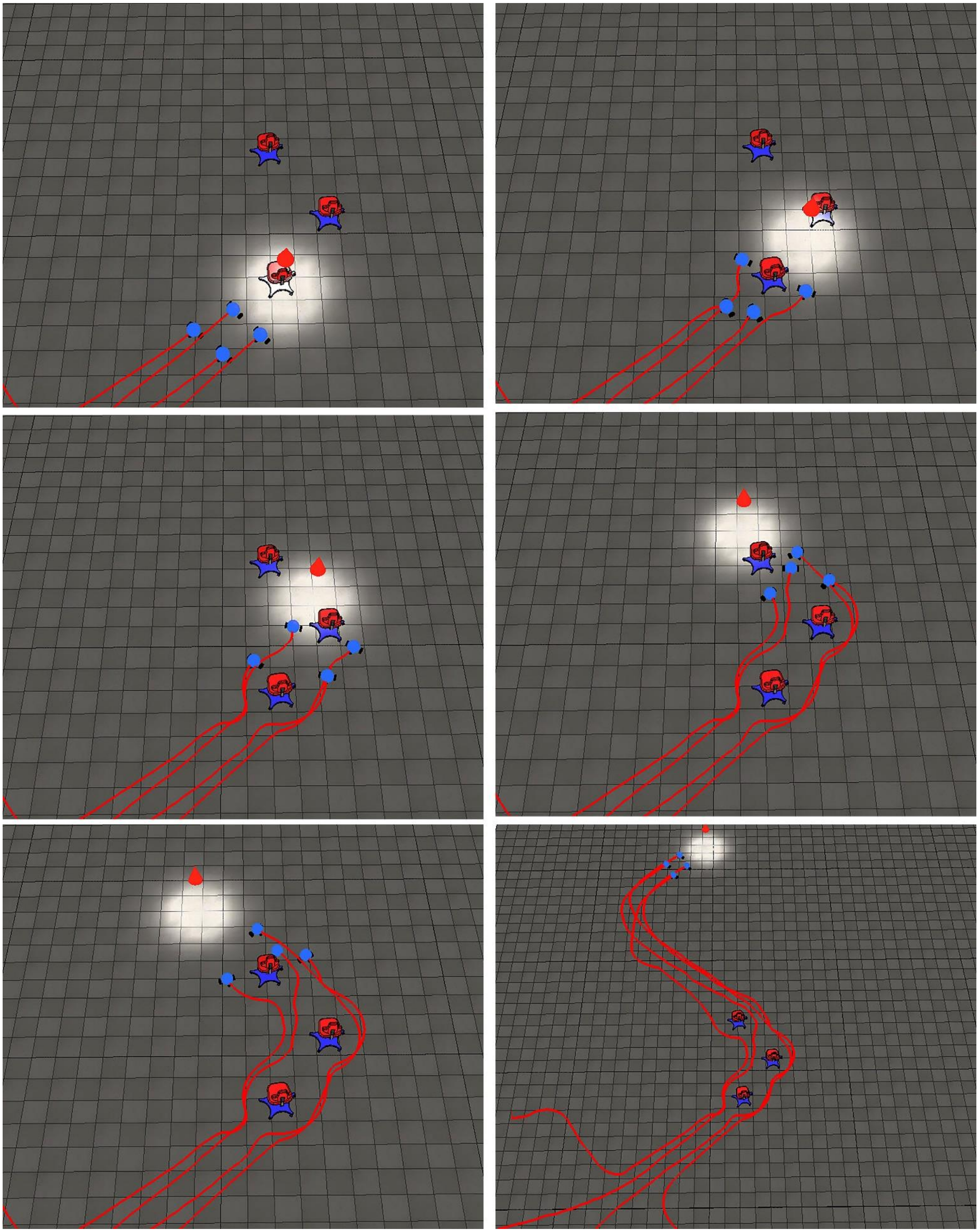

Fig.18. the zigzag pattern with obstacles according to the dynamic model (parameters evaluated by the physical structure of the robot)

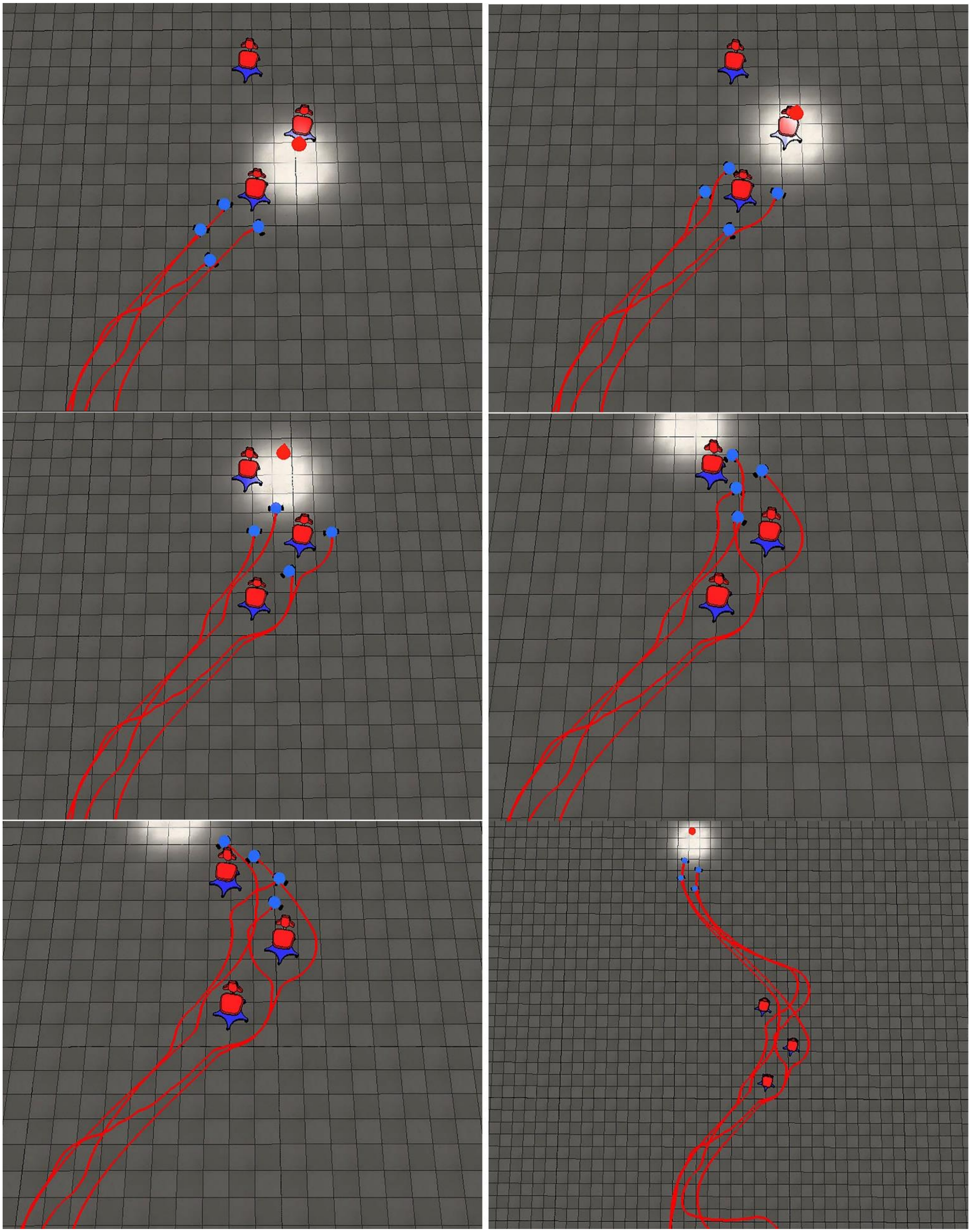

Fig.19. the zigzag pattern with obstacles according to the dynamic model (parameters evaluated by the least parameter estimation method).

4. Conclusion

In this paper, two multi-robot system have been designed, in which, the robots are attracting to the spotlight as their leader. The dynamic model of the system is inspired by the collective motion of the Artemia aggregations and it's based on the newton equation. the parameters of the dynamic models are derived based on: first, the physical features of the robot, second, the least square method. several experiments are implemented to test the path planning and the obstacles avoidance of the proposed systems. Form the results of the experiments, the robots show a perfect collective behavior during the path planning of the spotlight and the obstacles avoidance. Guiding the robots by the spotlight is a simple task because the light is distributed in a large area and can be detected easily by the robots, especially in the case of obstacle avoidance when the robots are delay while passing the obstacles, and being far from the leader. Also, detecting and tracking the light is a simple matter and doesn’t require complex techniques.

References

1. D.pescovitz,“robotbugs:handy,noticky,”popularscience,published8may2004,accessed1aug.2011.http://www.popsci.com/scitech/article/2004-05/robot-bugs-handy-not-icky.
2. R. W. Beard, t. W. Mclain, d. B. Nelson, d. Kingston and d. Johanson,“decentralized cooperative aerial surveillance using fixed-wing miniatureuavs,”proceedings of the ieee, vol. 94, no. 7, pp. 1306-1324, 2006
3. R. Sharma, r.w. Beard, c.n. Taylor, and s. Quebe, “graph based observability analysis of bearing-only cooperative localization”, ieee transactions on robotics, vol. 28, issue 2, 2012, pp. 522–529.
4. A. Abbaspour, s. A. Moosavian, and k. Alipour, “formation control and obstacle avoidance of cooperative wheeled mobile robots”, international journal of robotics and automation, vol. 30, issue 5, 2015, pp. 418–428.
5. X. Yang, j. Chen, and s. X. Yang, “dynamic bioinspired neural network for multi-robot formation control in unknown environments”, international journal of robotics and automation, vol. 30, issue 3, 2015, pp. 256–266.
6. Dongbing gu, zongyao wang “leader–follower flocking: algorithms and experiments” ieee transactions on control systems technology (volume: 17 , issue: 5 , sept. 2009).
7. Dianwei qian, andyafei xi “leader–follower formation maneuvers for multi-robot systems via derivative and integral terminal sliding mode” appl. Sci. 2018, 8(7), 1045.
8. P. Chen, j. Wan, a. Poo, and s. Ge, “formation and zoning control of multi-robot systems”, int. Journal of robotics and automation, vol. 26, issue1, 2011, pp. 35–48 (2016)
9. Audrey filella,1 fran¸cois nadal,2 cl´ement sire,3 eva kanso,4 and christophe eloy1, ∗ “model of collective fish behavior with hydrodynamic interactions” physical review letters 120(19) , 2018.
10. Musad a. Haque*, amir r. Rahmani and magnus b. Egerstedt "biologically inspired confinement of multi-robot systems"int. J. Bio-inspired computation, vol. 3, no. 4, 2011.
11. Kevin m. Schultz1,*, kevin m. Passino1 and thomas d. Seeley2 “the mechanism of flight guidance in honeybee swarms: subtle guides or streaker bees?” Journal of experimental biology, doi: 10.1242/jeb.018994.
12. Wei wang1, jindong liu2, guangming xie1, li wen3 and jianwei zhang4” a bio-inspired electrocommunication system for small underwater robots” bioinspiration & biomimetics, volume 12, number 3 2017.
13. Mofeed turky rashid · mattia frasca · abduladhem abdulkareem ali · ramzy salim ali · luigi fortuna · maria gabriella xibilia “artemia swarm dynamics and path tracking” springer, vol. 68, issue 4, pp. 555-563, june 2012.
14. S. Haddadin, a. De luca, and a. Albu-schäffer, “robot collisions: a survey on detection, isolation, and identification”, ieee transactions on robotics, vol. 33, no. 6, dec 2017, pp. 1292–1312.
15. Xiao li, hanxu sun, linjing liao, jingzhou song, “simulation and comparison research of lagrange and kane dynamics modeling for the 4-dof modular industrial robot”, international conference on advanced design and manufacturing engineering, 2015.
16. Rached dhaouadi and ahmad abu hatab, “dynamic modelling of differential-drive mobile robots using lagrange and newton-euler methodologies”, dhaouadi and hatab, adv robot autom, vol. 2, no. 2, 2013.
17. Mofeed turky rashid, mattia frasca, abduladhem abdulkareem ali, ramzy salim ali, luigi fortuna, maria gabriella xibilia, “nonlinear model identification for artemia population motion”, springer, nonlinear dynamics, vol. 69, no. 4, 2012, pp. 2237–2243.
18. Donald d. Dudenhoeffer michael p. Jones “a formation behavior for large-scale micro-robot force deployment” ieee xplore conference: simulation conference proceedings, volume: 1. 2000.
19. Kuppan chetty rm1,a, singaperumal m2,b and nagarajan t3,c “ behavior based multi robot formations with active obstacle avoidance based on switching control strategy” advanced materials research vols. 433-440 (2012) pp 6630-6635.
20. G.c.h.e. De croon, e. De weerdt, c. De wagter, and b.d.w. Remes “ the appearance variation cue for obstacle avoidance” ieee international conference on robotics and biomimetics, doi:10.1109/robio.2010.5723570, 2010.

21. Zahraa y. Ibrahim , abdulmuttalib t. Rashid , ali f. Marhoon “path planning with polygonal obstacles avoidance based on the virtual circles of the visible vertices” proc. Of the 2nd int. Sci. Conf. (1-2/march/2017).
22. Yousif abdulwahab kheerallah ali fadhil marhoon mofeed turky rashid abdulmuttalib turky rashid “self-organization of multi-robot system based on external stimuli” iraqi journal of electrical and electronic engineering volume 15, no.2 – 2019
23. Mofeed turky rashid · mattia frasca · abduladhem abdulkareem ali · ramzy salim ali · luigi fortuna · maria gabriella xibilia “artemia swarm dynamics and path tracking” springer, vol. 68, issue 4, pp. 555-563, june 2012.