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Multi-Robot System Dynamics and Path Tracking

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Abstract

Leader detection and follow it are the main challenges in designing a leader-follower multi-robot system, in addition to the challenge of achieving the formation between the members while tracking the leader. The biological system is one of the main sources of inspiration for understanding and designing such multi-robot systems, especially, the aggregations that follow an external stimulus such as the population of Artemia. In this paper, a dynamic model of a multi-robot system following a spot of light, as a leader will design based on the collective motion behavior of the aggregations of Artemia. The kinematic model will derive based on observation of Artemia behavior under external stimuli, while the dynamic model will be derived based on the newton equation and its parameters will be evaluated by two methods: first one based on the physical structure of the mobile robot and the other based on Least Square Parameter Estimation method. Several experiments have been implemented in order to check the success of the proposed system, which are divided into four scenarios of simulation according to four trajectories, the straight line, circle, zigzag and compound path pattern. V-Rep software has been used for the simulation and results appeared the success of the proposed system and the high performance when robots are tracking the leader.

KEYWORDS

multi-robot system, self-organization, formation system, Artemia, leader follower system.

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1 | Introduction

The multi-robot system attract the attention of academics and corporate executives, since, the range of its application is wide and it is able to perform tasks that impossible to do by a single robot, such as outer space or underwater discovering, shop's goods transporting, escorting, harvesting, spraying and patrolling missions [1]. The advantage of this system over the single robot system is greater flexibility, robustness, and adaptability [2].

The major challenge in designing such systems is the motion planning of the robots, since the complexity of this control increase for the bigger group of robots. Therefore, most researchers are studying the motion planning of the robots from the perspective of distributed control, where each robot implements its feedback motion control law; depend on limited information about other robots within the group and other effects in the environment. However, the task of designing a separate motion algorithm for the members by which the total group can satisfy a desired coherent motion may be difficult [3, 4].

Many instances in nature have been observed, where the aggregations of animals are capable of maintaining advanced collective motion behavior in spite of that every animal in the group decides its motion commands, without an external decision-maker. So, these systems represent a source of inspiration to design a control strategy for multi-agent systems [5, 6]. Some kind of these aggregations follow a leader that may be one of the individual or maybe an external stimulus such as the two following examples: several models of multi-robot systems are inspired from the bee colony clustering in which the bees attract the optimal temperature when there is no light exist [7]. Another model, the ant colony clustering which is attract to the pheromone [8]. Also, the hunting model of the group of dolphins, where, they take a specific formation in order to surround and hunt any notice pray [9].

There is a model in which the members are attracted to the light, which can be inspired by studying the collective behavior of the aggregations of Artemia [10]. These individuals follow only a spot of light, while they will move with a formation, aligning with each other and avoid collisions. However, this model has not implemented for a model of a multi-robot system.

In this paper, kinematic and dynamic models of the multi-robot systems will be derived depending on the model of Artemia behavior. Newton equation will employ for driving the model of each robot. Two methods have been used to evaluate the parameters of the multi-robot model, in the first method, the parameters calculated from the physical properties of the mobile robot, while the other method by the Least Square Parameter Estimation method. The multi-robot system will experimentally tested by using a V-rep simulator, in addition to performance evaluation of the system's formation while tracking the spot of light.

2 | Background

Artemia Salina is a tiny creature, lives in the water. Its length is about 0.4 mm, it has one eye with a photo receiver used for obstacle avoidance, and it depends on a pair of antennae as fins as in figure 1. Several experiments on Artemia behaviour achieved in [11], it is observed that under uniform light the individuals are swimming independently from each other, within

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random directions and activating an obstacle avoidance to avoid a collision as in figure 2.a. When a spot of light has appeared, instead of the uniform light, some of the aggregation members redirect their swimming to the spot of light, thus attracting a preferential direction and perform a flocking behaviour as in figure 2.b. In addition, two sources of light have been used which placed on two opposite sides. First, when only the left light source is turned on, the individuals are direct to the left source, after that, the left source is turned off and the right light on, this led to, individuals of Artemia have changed their direction towards the right source as in figure 3.

Fig 1 artemia salania.

(a) Uniform of light. (b) Spot of light.

Fig 2 The behavior of Artemia.

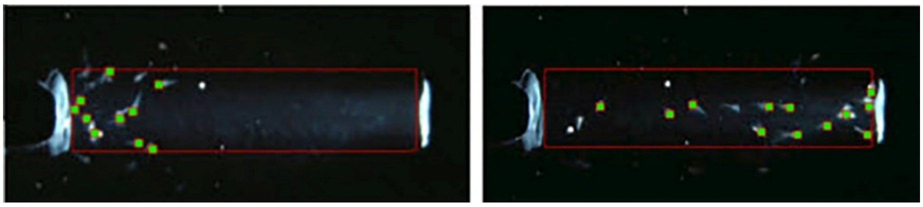

Fig 3 The following of artemia to a source of light.

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As noticed from the experiments of [12], the collective motion of Artemia can be controlled. The idea to perform that is to control the position of the spot of light, in which a wireless robot system has been used for this purpose, while the aggregation of Artemia has been tracking for the spot of light. The different sets of experiments performed on the aggregation of Artemia have confirmed the possibility of controlling the flock's motion under different trajectories such as linear, circular, zigzag as in figure 4.

3 | MODELING OF MULTI ROBOT SYSTEM

In this section, a kinematic and dynamic model of the system will derive. The parameters of the dynamic model will be evaluated by two methods: the first method based on the physical properties of the robot, while the other method by using the Least Square Parameters Estimation method, which depends on information captured from the motion of the aggregations of Artemia.

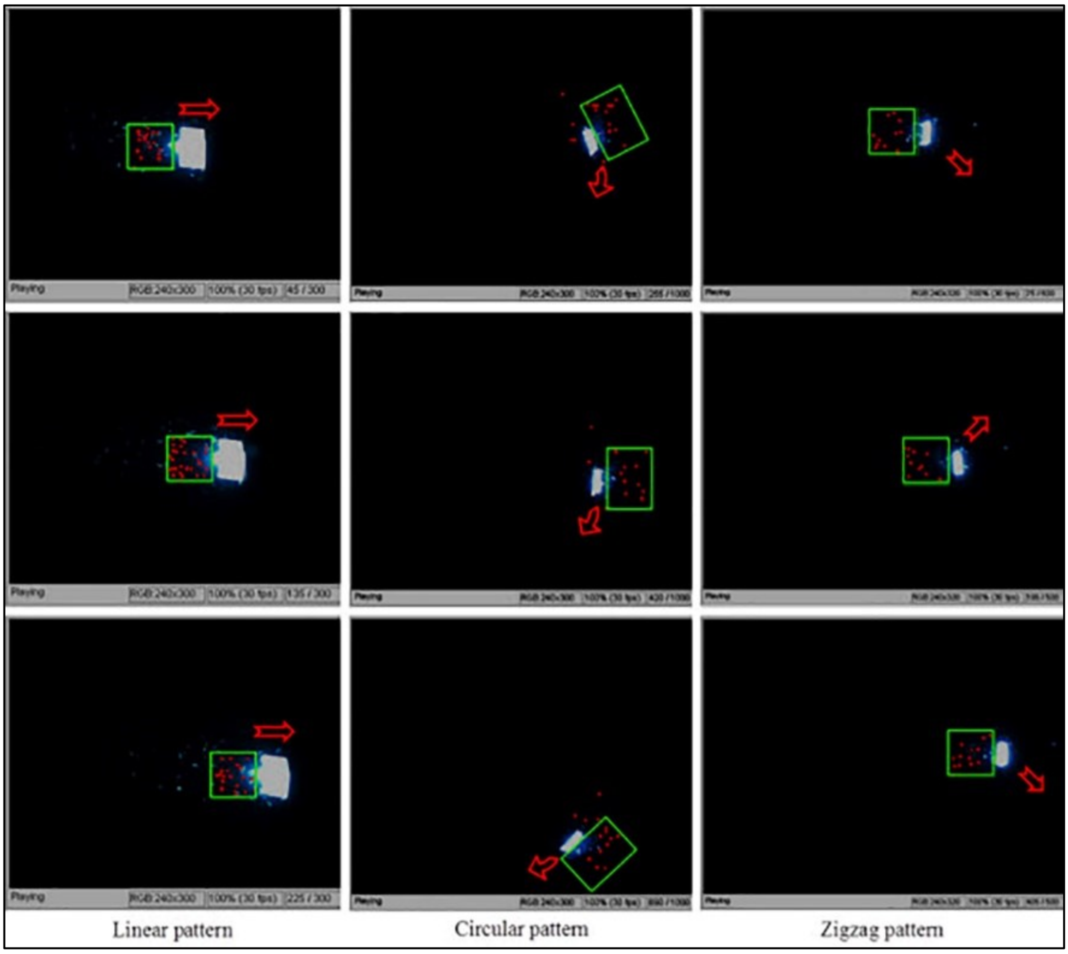

Fig 4 Motion control of population of Artemia [12].

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3.1 | The Kinematic Model of Multi-Robot System

The kinematic model of the robots is divided into two cases; the first case concerns the motion behavior of the group when the light is normally distributed within the robots-sensing zones, while the other case is about appearing spot of light in the robots-sensing zone.

When the light is normally distributed, each robot within the light zone will move in a random direction, there is no target point, and the robots are performing an obstacle avoidance task when there are two robots about to collide. The motion direction of each robot is described by the equation [13]:

$$\vec{d}_r(t+\tau) = -\sum_{j\neq i}^{n} \frac{\vec{r}_{ij}(t)}{\left|\vec{r}_{ij}(t)\right|} \quad (1)$$

Where, d_r is the new direction calculated at each time constant τ, $r_{ij} = (r_j - r_i)/|r_j - r_i|$ is a unit vector centered on the i^{th} member and in the direction of the neighbor j, n is the number of robots within the repulsion zone of the member i.

In the second case, modeling the group of robots moves in the presence of light spot, which robots change the direction of their motion towards the spot, since the maximum intensity of light be at the center of the spot, so, the robots tracking the center by the light sensor. If more than one robot sensing the light spot, these robots will interact with each other while attacking the light according to the zones of interaction. The robot zone is divided into three zones includes attraction, orientation, and repulsion zones as shown in figure 5.

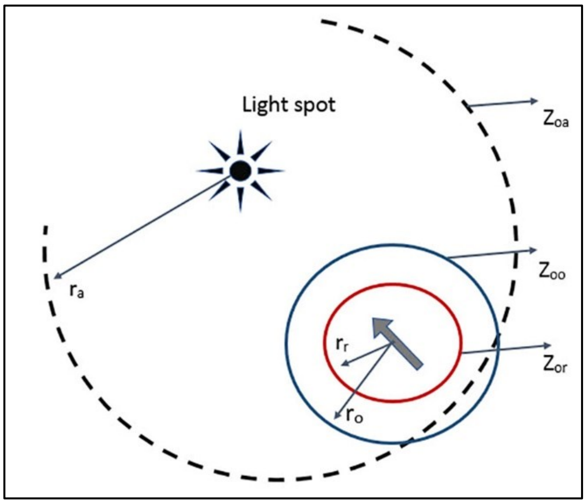

Fig 5 the three interaction zones of artemia.

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within the attraction zone, the robot changes its motion direction toward the light, the mathematical model of the robot in this zone is:

$$\vec{d}_a(t+\tau) = \vec{g}_i \tag{2}$$

Where g_i is a unit vector of the i^{th} member in the direction of the light spot.
During the following of the spotlight, they will move close to each other and alignment is achieved with those within the orientation zone, the direction of the robot will be aligned with the neighbor robots, and the mathematical model of this behavior is described by the equation:

$$\vec{d}_o(t+\tau) = -\sum_{j=1}^{n} \frac{\vec{v}_j(t)}{|\vec{v}_j(t)|} \tag{3}$$

Where v_j is the moving direction of the j^{th} neighbor.
At last, if the robots are about to collide, with those within the repulsion zone, then they will perform an obstacle avoidance, which can be described by the equation:

$$\vec{d}_r(t+\tau) = -\sum_{j\neq i}^{n} \frac{\vec{r}_{ij}(t)}{|\vec{r}_{ij}(t)|} \tag{4}$$

So, the motion direction of each robot will be updated each time constant τ as follow:

1- The first priority, if any individual exists in the repulsion zone then $d_r = d_r(t+\tau)$.
2- If no one in the repulsion zone, the orientation zone is checked and the direction will be: $d_r = d_o(t+\tau)$.
3- If no one in the surrounding area then: $d_r = d_a(t+\tau)$.

According to these rules, each robot will keep a fix distance from the source of light and a formation must be achieved between the robots while following the spotlight as in figure 6.

3.2 | The Dynamic Model of Multi-Robot System

Deriving a model of the robots is achieved by finding a formula for the x and y positions of each robot from the state space of the dynamic model of Artemia [14]. Following these positions will lead the robots to a collective behavior similar to that of the population of Artemia since the calculation process of the locations is depending on the same effects that

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influence on the collective motion behavior of Artemia. A dynamic model of Artemia can be rewritten according to the x, y direction:

$$m\frac{d\vec{v}_{ix}}{dt} = a_x\left(\frac{r_{ix}(t) - r_{ix}(t - T_s)}{r}\right) - \gamma\vec{v}_{ix} + \sum_{i\neq j} a_{ij}\,\vec{f}_{ijx} + \vec{g}_{ix} \qquad (5)$$

$$m\frac{d\vec{v}_{iy}}{dt} = a_y\left(\frac{r_{iy}(t) - r_{iy}(t - T_s)}{r}\right) - \gamma\vec{v}_{iy} + \sum_{i\neq j} a_{ij}\,\vec{f}_{ijy} + \vec{g}_{iy} \qquad (6)$$

Where, $\vec{f}_{ijx}, \vec{f}_{ijy}$ are the x and y interaction force between the robots, which could be repulsion force, or orientation force depending on the distance from the neighbors and according to the following equations:

$$\vec{f}_{ijx} = -c\left[\left(\frac{d_{ij}(t - T_s)}{r_c}\right)^{-3} - \left(\frac{d_{ij}(t - T_s)}{r_c}\right)^{-2}\right] * \left(\frac{r_{jx}(t - T_s) - r_{ix}(t - T_s)}{d_{ij}(t - T_s)}\right) \qquad (7)$$

$$\vec{f}_{ijy} = -c\left[\left(\frac{d_{ij}(t - T_s)}{r_c}\right)^{-3} - \left(\frac{d_{ij}(t - T_s)}{r_c}\right)^{-2}\right] * \left(\frac{r_{jy}(t - T_s) - r_{iy}(t - T_s)}{d_{ij}(t - T_s)}\right) \qquad (8)$$

where, d_{ij} is the distance between the ith and jth members, r_c is the optimum space between individuals and c is a constant.

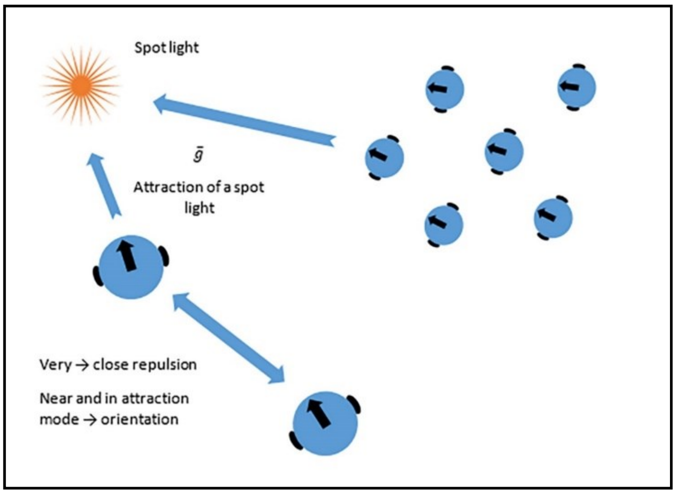

Fig 6 the robots attract to a lightspot [13].

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The following force toward the light $\vec{g}_{ix}, \vec{g}_{iy}$ are:

$$\vec{g}_{ix} = c_g * Kv_i * Kr_i \left(r_{ax}(t) - r_{ix}(t)\right) \tag{9}$$

$$\vec{g}_{iy} = c_g * Kv_i * Kr_i * \left(r_{ay}(t) - r_{iy}(t)\right) \tag{10}$$

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

$$v_i(t) = \dot{r}_i(t) = \frac{r_i(t) - r_i(t - T_s)}{T_s} \tag{11}$$

$$\dot{v}_i(t) = \ddot{r}_i(t) = \frac{\dot{r}_i(t) - \dot{r}_i(t - T_s)}{T_s} = \frac{r_i(t) - 2r_i(t - T_s) - r_i(t - 2T_s)}{{T_s}^2} \tag{12}$$

Now, newton equation will be:

$$\begin{aligned} m\ddot{r}_{ix}(t) = {} & a_x\left(r_{ix}(t) - r_{ix}(t - T_s)\right) - \gamma\,\dot{r}_{ix}(t) - \frac{\alpha_{ij} * c}{{r_c}^{-3}} \\ & * \sum_{i \neq j} (d_{ij})^{-4}\left(r_{jx}(t - T_s) - r_{ix}(t - T_s)\right) + \frac{\alpha_{ij} * c}{{r_c}^{-2}} * \sum_{i \neq j} (d_{ij})^{-3} \\ & * \left(r_{jx}(t - T_s) - r_{ix}(t - T_s)\right) + c_g * Kv_i * Kr_i \\ & * \left(r_{ax}(t) - r_{ix}(t)\right) \end{aligned} \tag{13}$$

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$$m\ddot{r}_{iy}(t) = a_y\left(r_{iy}(t) - r_{iy}(t - T_s)\right) - \gamma\dot{r}_{iy}(t) - \frac{\alpha_{ij} * c}{{r_c}^{-3}} * \sum_{i\neq j}\left(d_{ij}(t)\right)^{-4}\left(r_{jy}(t - T_s) - r_{iy}(t - T_s)\right)\frac{\alpha_{ij} * c}{{r_c}^{-2}} * \sum_{i\neq j}\left(d_{ij}(t)\right)^{-3} * \left(r_{jy}(t - T_s) - r_{iy}(t - T_s)\right) + c_g * Kv_i * Kr_i * \left(r_{ay}(t) - r_{iy}(t)\right) \tag{14}$$

Finally, the model of the robots is complete by rearranging Eq. (13), (14) as follows:

$$r_{ix}(t) = \alpha_{x1} * r_{ix}(k-1) + \alpha_{x2} * r_{ix}(k-2) - \alpha_{x3} * \sum_{i\neq j}\left(d_{ij}(k)\right)^{-4}\left(r_{jx}(k-1) - r_{ix}(k-1)\right) + \alpha_{x4} * \sum_{i\neq j}\left(d_{ij}(k)\right)^{-3}\left(r_{jx}(k-1) - r_{ix}(k-1)\right) + \alpha\_x5 * (r\_ax(k)) \tag{15}$$

$$r_{iy}(k) = \alpha_{y1}r_{iy}(k-1) + \alpha_{y2}r_{iy}(k-2) - \alpha_{y3} * \sum_{i\neq j}\left(d_{ij}(k)\right)^{-4}\left(r_{jy}(k-1) - r_{iy}(k-1)\right) + \alpha_{y4} * \sum_{i\neq j}\left(d_{ij}(k)\right)^{-3}\left(r_{jy}(k-1) - r_{iy}(k-1)\right) + \alpha_{y5}\left(r_{ay}(k)\right) \tag{16}$$

As notice from Eq. (15), (16) the robot will decide its next position, x and y position, depending on the several influences, which are the light, the interactions with the neighboring robots, and the previous location of the robot. The contribution of each one of these effects, in determining the value of the next position, depends on two factors. First is the distances between these influences and the robot. Second and the most important factor, the value of the parameter related with each term.

Since these parameters decide the behavior of the robot, so, an accurate set of parameters should be estimated to achieve the desired performance of the dynamic model. The parameters will be found by two methods, by using physical features of robots and by using the Least Square Parameter Estimation method.

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3.3 | Dynamic Model Parameters Evaluation by Physical Properties of Robot

This is a simple and direct method where a set of parameters will be calculated depending on the physical features of the robots. The parameters can be derived from Eq. (13), (14), (15), (16), and can be describe by the following equations:

$$\alpha_1 = \frac{2m - a}{[m - a + kvkr]} \tag{17}$$

$$\alpha_2 = \frac{m}{[m - a + kvkr]} \tag{18}$$

$$\alpha_3 = \frac{{r_c}^3}{[m - a + kvkr]} \tag{19}$$

$$\alpha_4 = \frac{{r_c}^2}{[m - a + kvkr]} \tag{20}$$

$$\alpha_5 = \frac{kvkr}{[m - a + kvkr]} \tag{21}$$

Where the x and y parameters are equal. m is the mass of the robot, a is the locomotive force, kvkr is the sensitivity of the robot to the light. , rc is the optimal distances between the robots and γ is the resistivity of the media which is equal to zero.
The multi robot's system is simulated by the V-rep simulator, from which the features of the system will be as in table (1).

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

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After replacing these features in the Eqs. (17) - (21), The parameters will be Accordingly as in table (2):

Table 2 The Dynamic parameters.

the parameters	The values
α1	0.44817
α2	0.44817
α3	0.17205
α4	0.20239
α5	0.10364

3.4 | 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, As in Figure 7.

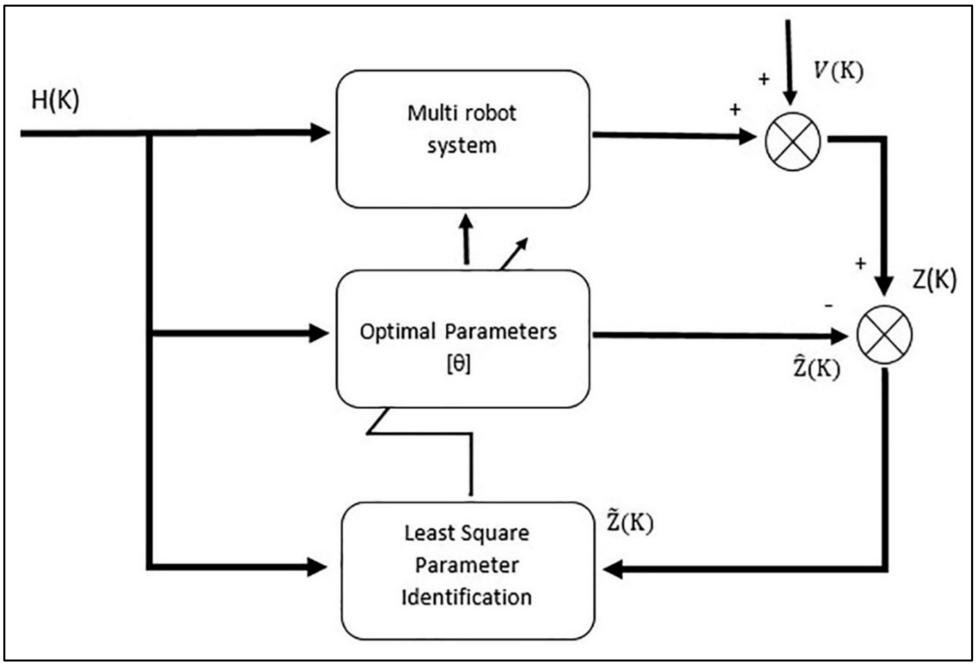

Fig 7 Least Square Parameter Estimation method [12].

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

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$$\tilde{z}(k) = z(k) - \hat{z}(k) \tag{22}$$

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

$$z(k) = H(K)\,\theta + V(K) \tag{23}$$

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

$$\hat{z}(k) = H(K)\,\hat{\theta}(k) \tag{24}$$

Where, $\hat{z}(k), \hat{\theta}(k)$ 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 $J\left[\hat{\theta}(k)\right]$ is equal to a weighted sum of the square value of error vector:

$$J\left[\hat{\theta}(k)\right] = \tilde{Z}'(k)W(k)\tilde{Z}(k) \tag{25}$$

$$J\left[\hat{\theta}(k)\right] = w(k)\tilde{z}^2(k) + w(k-1)\tilde{z}^2(k-1) + \cdots + w(k-L)\tilde{z}^2(k-L) \tag{26}$$

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

$$\hat{\theta}(k+1) = \hat{\theta}(k) + K^*(k+1)\left[Z(k+1) - h'(k+1)\hat{\theta}(k)\right] \tag{27}$$

$$K^*(k+1) = P(k)h(k+1)[h'(k+1)P(k)h(k+1) + \frac{1}{W(k+1)}]^{-1} \tag{28}$$

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$$P(k+1) = [1 - K^{*}(k+1)h'(k+1)]p(k) \qquad (29)$$

Where, $K^{*}(k)$ is a gain matrix.
The sequence of these process is:

$$p(k) \Rightarrow K^{*}(k+1) \Rightarrow \hat{\theta}(k+1) \Rightarrow P(k+1)$$

To implement the Least Square Parameter Estimation method, the motion information about the collective motion behavior of Artemia should be captured and applied to the identification system. This information is about the input, which is the location of the light and the output represented by the average position of the flock, which is captured and extracted by using a video recorder and manipulated by image processing [14]. The data is collected while following the spot of light that moves within a certain trajectory such as straight line, circle, and zigzag pattern as in figure 8. In addition to a compound path trajectory, figures 9 and 10, which is added the complexity of any possible path.

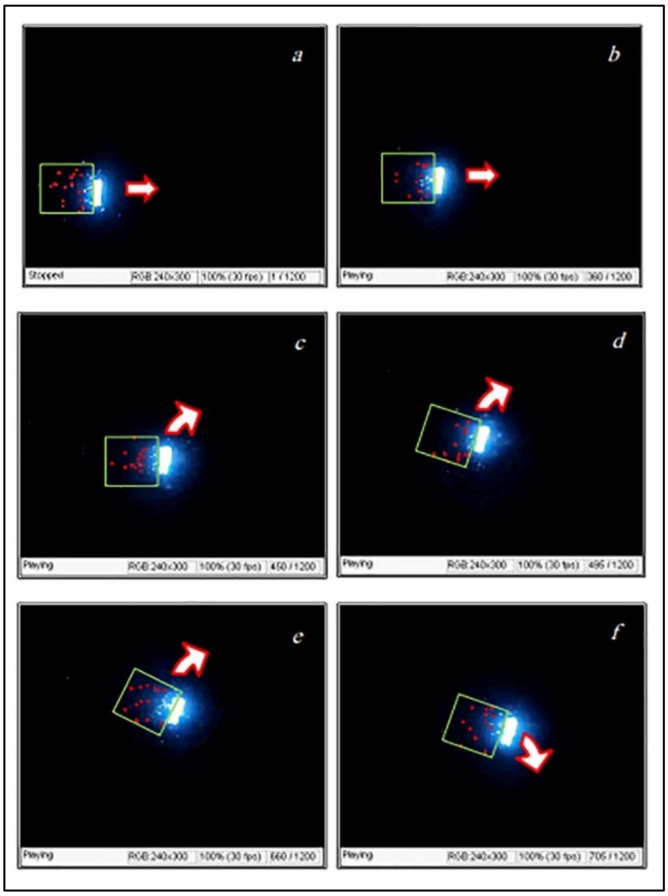

Fig 8 The collective motion behaver of artemia while following a spotlight moves within straight, circular and zigzag path.

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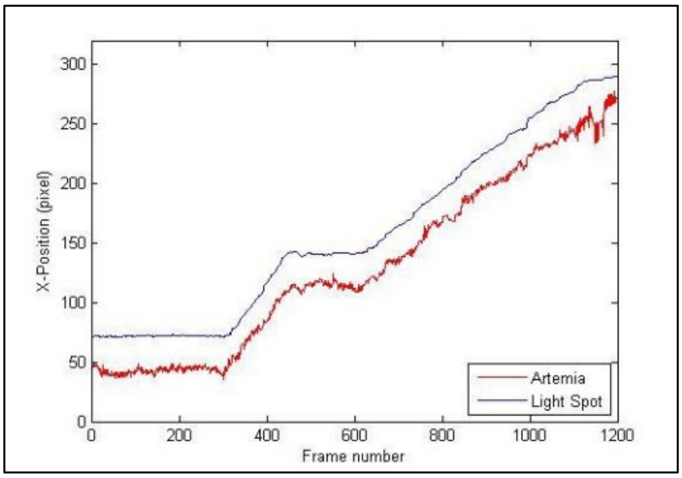

Fig 9 The average x-positions of tacking artemia to the spot of light [14].

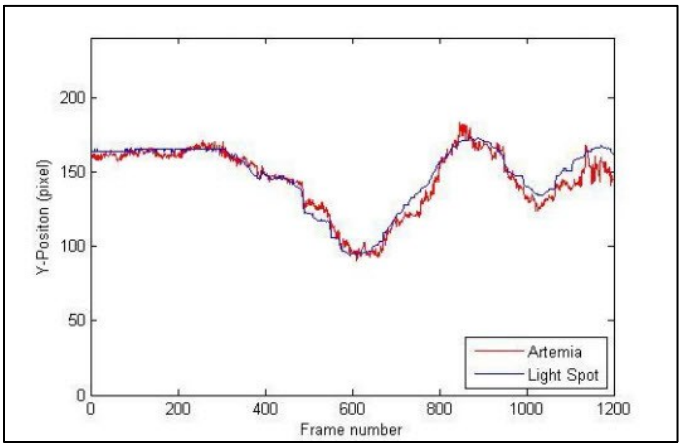

Fig 10 The average y-positions of tacking artemia to the spot of light [14].

Finally, the optimal set of parameters is estimated as in table (3).

Table 3 Parameters estimated by Least Square Parameter method [14].

	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 Eq. (15), (16), an optimal performance will be achieved.

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3.5 | Modeling of the Mobile Robot

The robot is a differential-drive mobile robot with a center represented by the coordinates (xo, yo). as in figure 11, the reference direction is the line from the right to the left wheel passing through the center. The motion direction (θ) is the angle between reference direction and the x-axis, its result from the difference in speed between the left and right wheel as in figure 12.

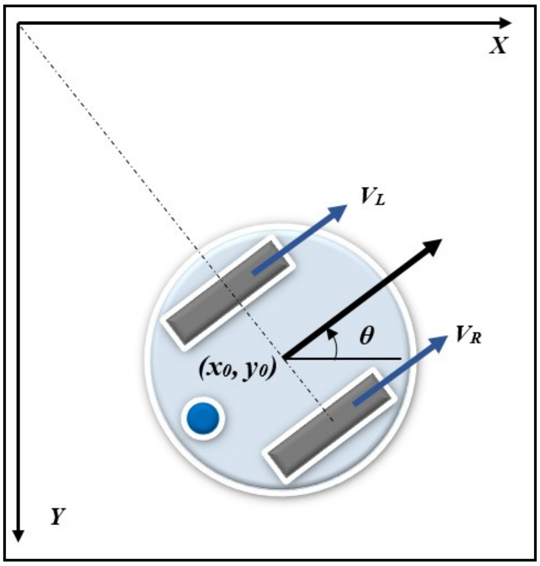

Fig 11 The kinematics of the mobile robot [13].

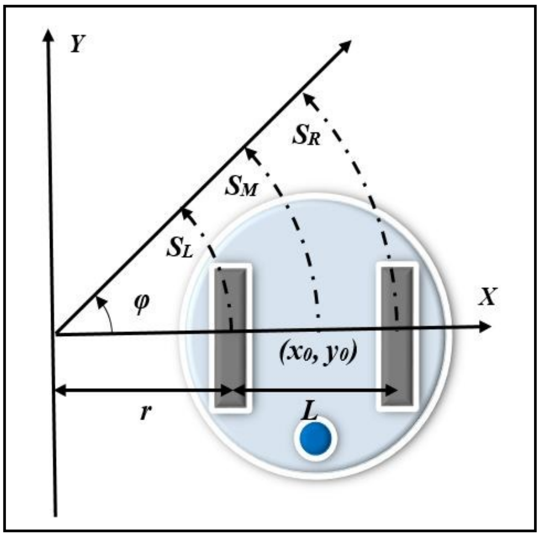

Fig 12 Mobile robot during steering process [13].

The mathematical model can be described as follow [15]:

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$$S_L = r * \Phi \tag{30}$$

$$S_R = (r + L) * \Phi \tag{31}$$

$$S_M = (r + L/2) * \Phi \tag{32}$$

Where, SR ,SL is the displacement of the left and the right wheel, SM is the displacement of the center. r is the distance between the center of the turning path and the inner wheel. L is the space between the left and right wheel, Φ is the turning angle.

The kinematics equations of the robot will be:

$$X_c(t) = X_o + \frac{L(V_R + V_L)}{2(V_R - V_L)}\left[\cos\left(\frac{(V_R + V_L)t}{L} + \Phi\right) - \cos\Phi\right] \tag{33}$$

$$Y_c(t) = Y_o + \frac{L(V_R + V_L)}{2(V_R - V_L)}\left[\sin\left(\frac{(V_R + V_L)t}{L} + \Phi\right) - \sin\Phi\right] \tag{34}$$

Where, $L(V_R+V_L)/2(V_R-V_L)$ is the turning arc radius, Xc and Yc are the location of the new center.

For a small robot, the model can be approximated as:

$$X_c(t) = X_o + S \cdot \cos\Phi \tag{35}$$

$$Y_c(t) = Y_o + S \cdot \sin\Phi \tag{36}$$

where $S = (S_L + S_R)$.

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4 | Simulation and Results

The V-rep simulator has been used to simulate the proposed system. Within an environment of (10m*10m), a differential drive mobile robot is used to implement several experiments to check the performance of the proposed design of the leader-follower multi-robot system. The robot has a spherical body with a diameter of 27 cm, a mass of 1.031 kg, and two active cylindrical wheels (left and right) and a passive spherical back wheel. The diameter of the cylindrical wheels is 12.35 cm, the thickness of 3.08 cm, and a mass of 0.29 kg, each wheel is driven by a motor with a maximum torque of 2.5 N.m. The radius of the spherical wheel is 6.7 cm and a mass of 0.37 kg.

Three scenarios of simulation will be achieved in order to test the performance of attracting the multi-robot to the movable light spot. the first scenario is about the performance according to the kinematic model of the system, The second scenario concerns implanting the dynamic model using the physical features of the robot to calculate parameters and, finally, the dynamic model with optimal parameters that calculated by Least Square Parameter Estimation method will be tested. In these experiments, each robot must keep a certain distance from the other robots and from the movable spot of light. also, the robots aggregation move with the same speed as the spot of light. Therefore, within each type of test, several patterns concern the motion of the light that has been chosen such as straight line, circle, and zigzag pattern.

In the first scenario, the robots tracking a spot of light while moving in a fixed direction trajectory. So, the formation between the robots will be checked where fix distance must be kept between the robots by performing orientation with the neighbor robots and repulsion to avoid a crash. Figure 13 shows the behavior of the robots according to the kinematic model. The dynamic model performance has been shown in figure.14 which in this case the system parameters based on the physical structure of the robots system, and figure 15 shows the performance of dynamic model which the parameters evaluated by Least Square Parameter Estimation. In addition, the average x and y position of the robots and of the light spot with respect to the time by which the performance of attracting to the light spot can be observed.

In the second scenario, the circular trajectory has been used. In this trajectory, the direction of the light change continuously, so, each robot should synchronize its motion direction with the light spot, also a synchronization must be achieved with the surrounding robots to maintain the formation of the flock. Therefore, they perform orientation and repulsion while changing their direction. Figures 16, 17, 18 show the response according to the kinematic model, the dynamic model based on physical structure of robots and by optimal estimation method, respectively, also the average x and y position, of the robots according to the light spot.

The final scenario, which zigzag trajectory has been used. It is a more challenging test, where, the light changes the direction of its movement in the opposite way, so, the synchronization process with the motion of the light and with the others will be harder. The responses of the kinematic and dynamic models are shown in figures 19, 20, 21. In addition to average x and y positions for the multi-robot system.

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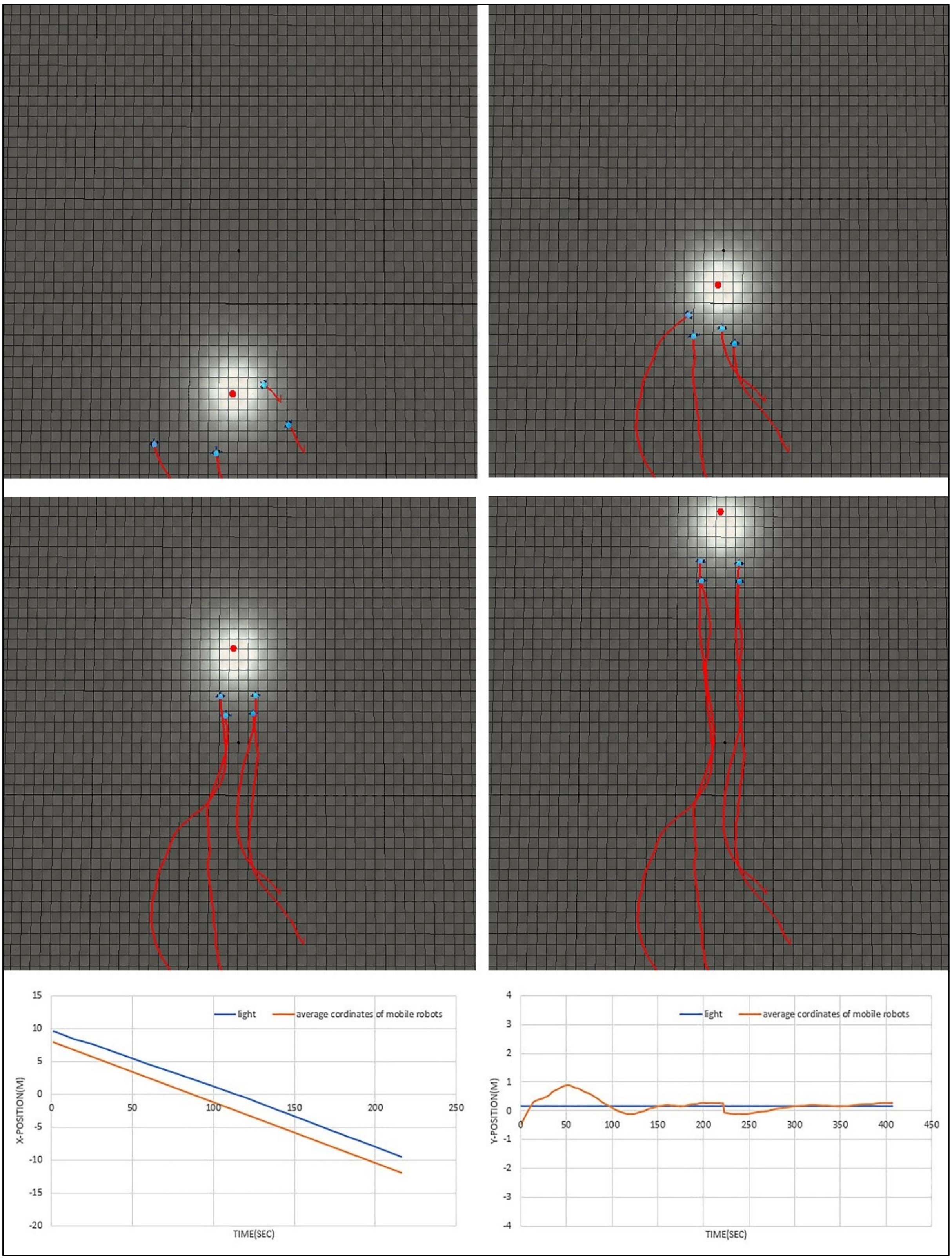

Fig 13 The straight-line pattern according to the kinematic model.

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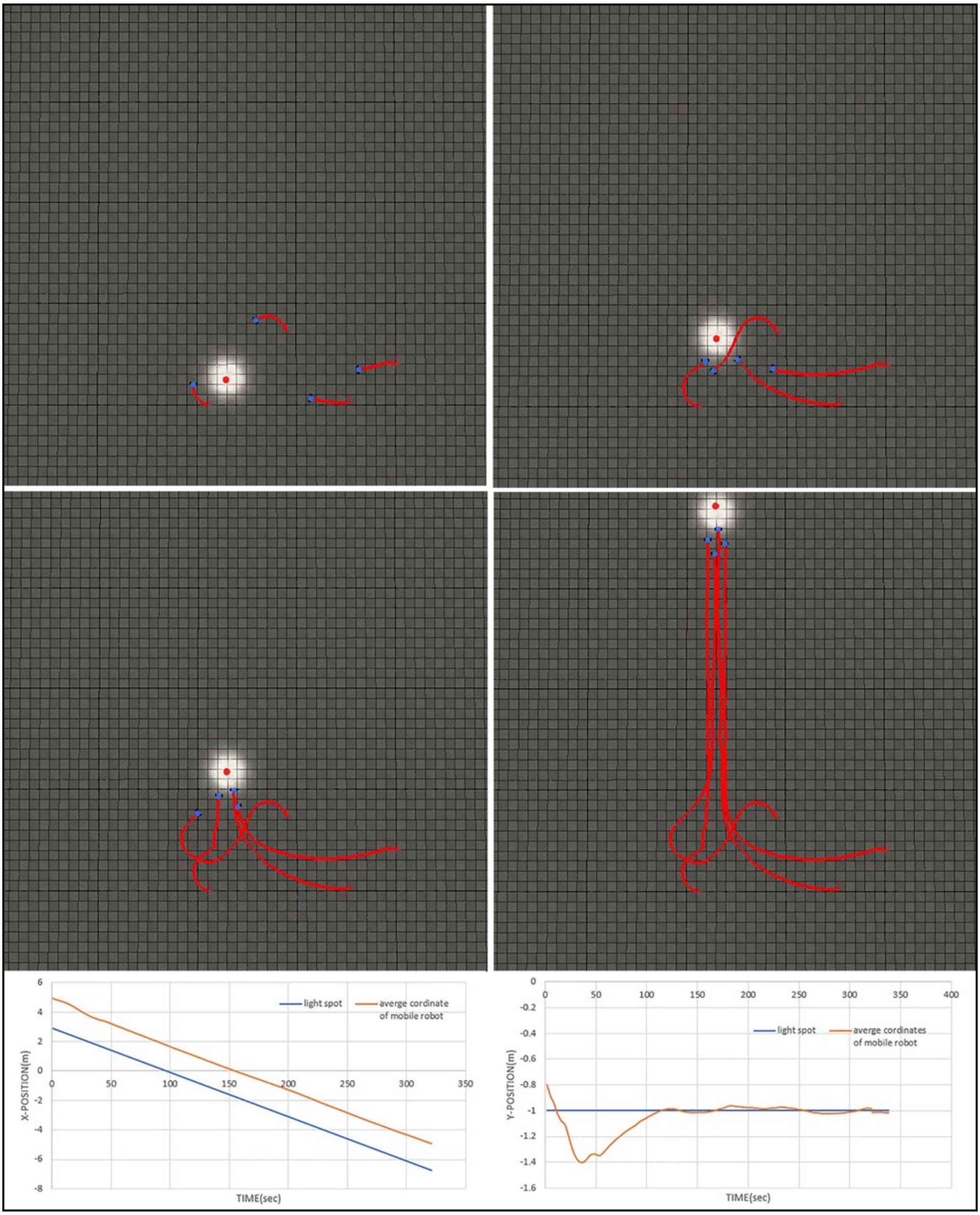

Fig 14 The straight-line pattern according to the dynamic model (parameters evaluated by physical structure of robots).

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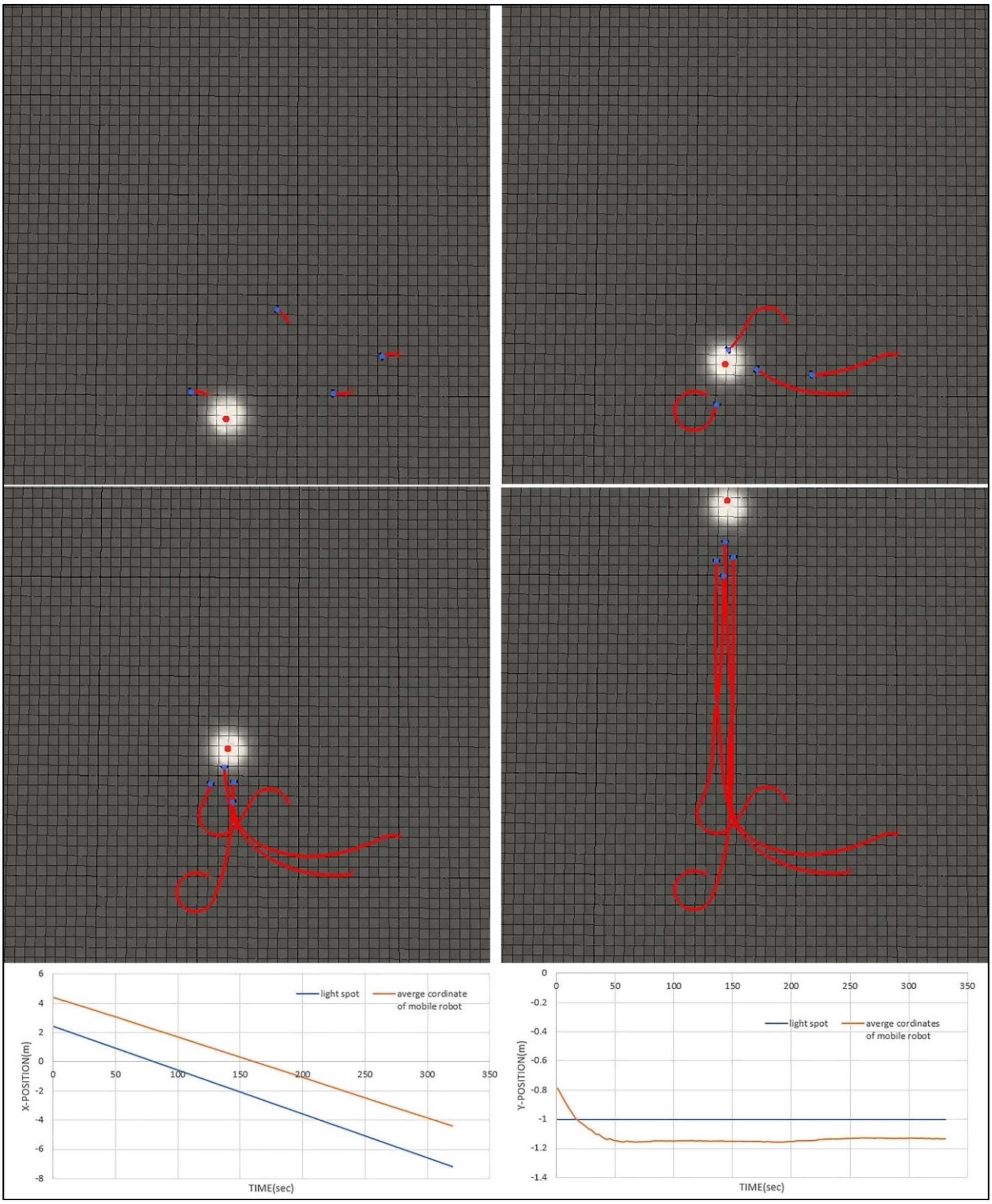

Fig 15 The straight-line pattern according to the dynamic model (parameters evaluated by Least Parameter Estimation method).

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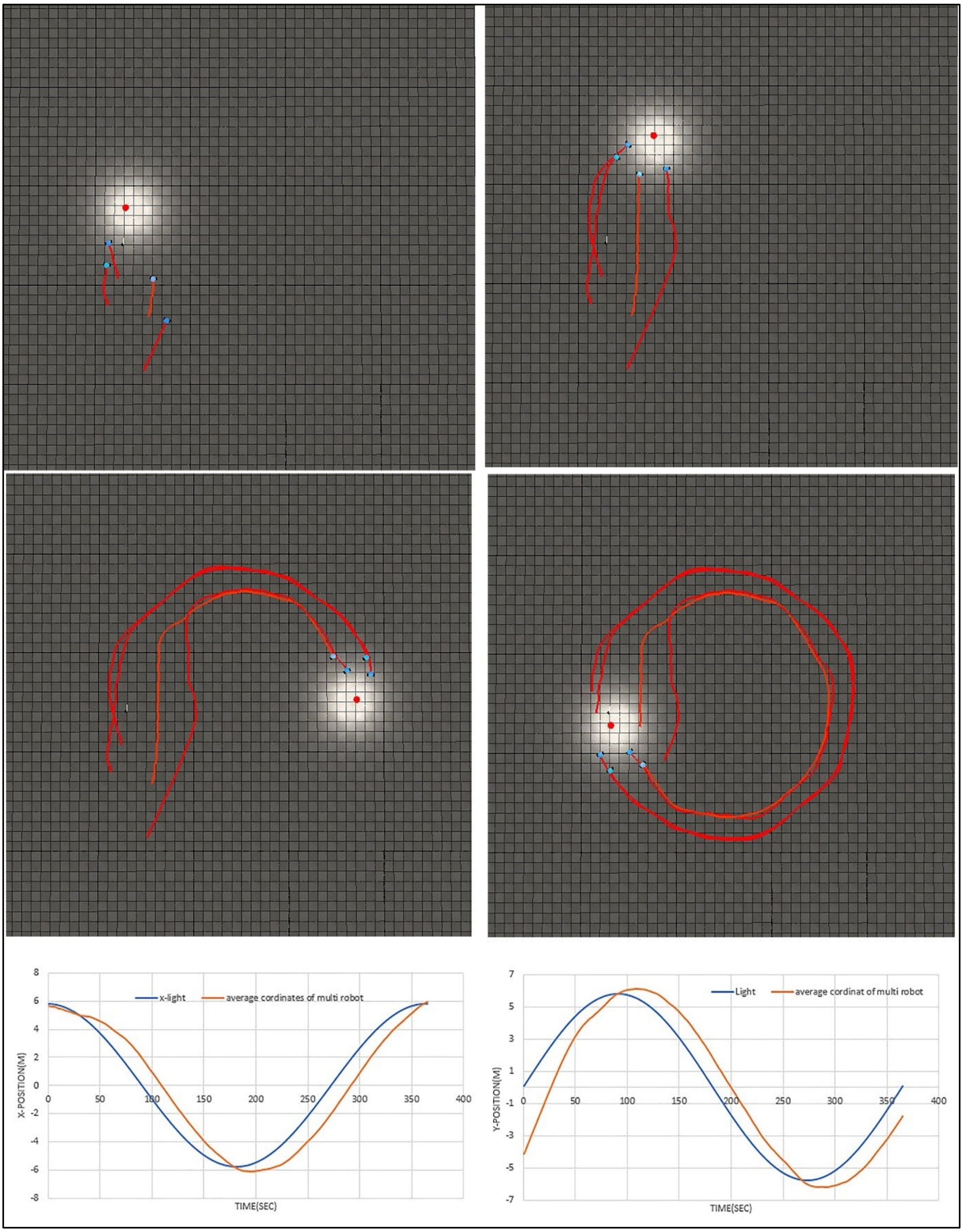

Fig 16 The circle line pattern according to the kinematic model.

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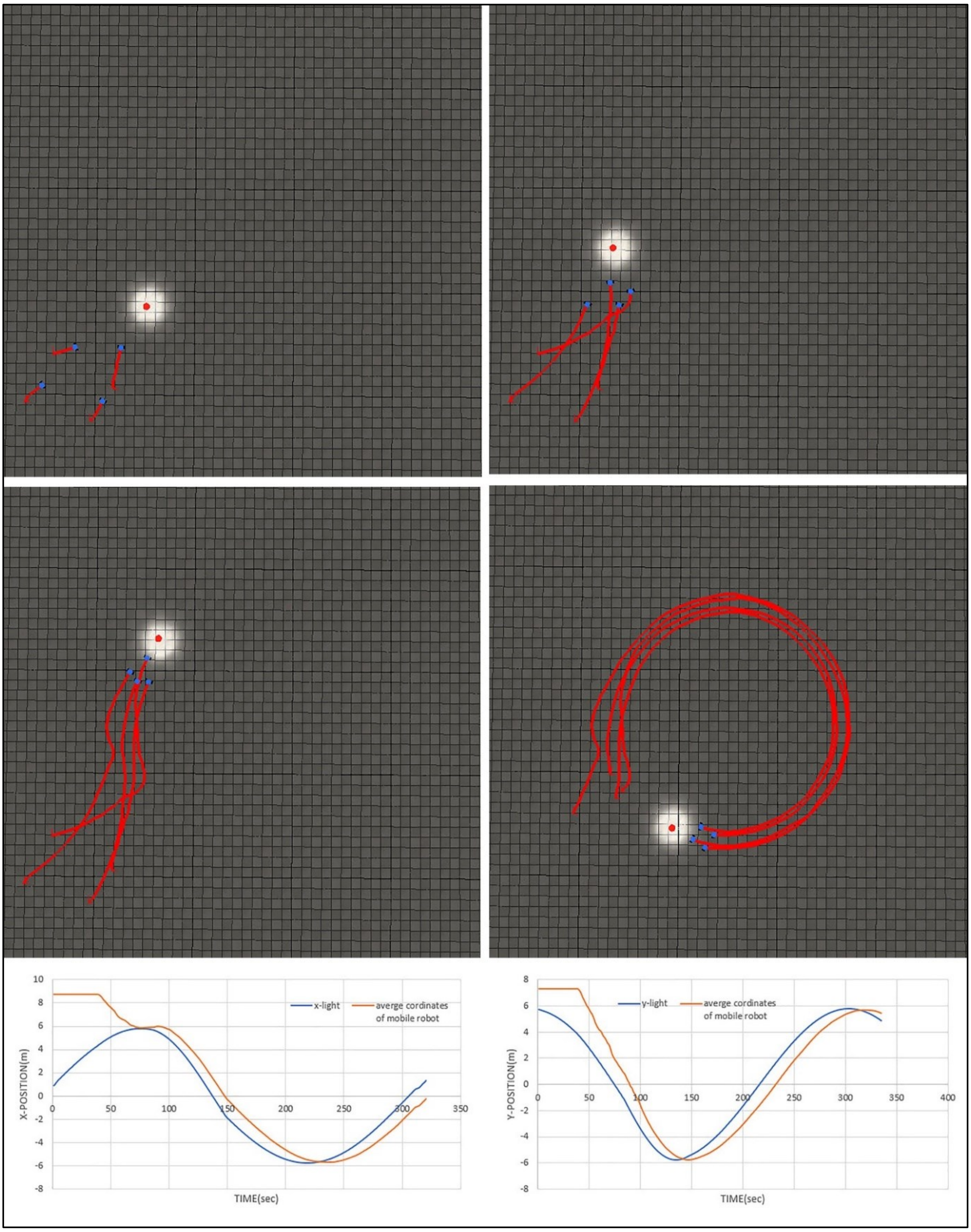

Fig 17 The circular pattern according to the dynamic model (parameters evaluated by physical structure of robots).

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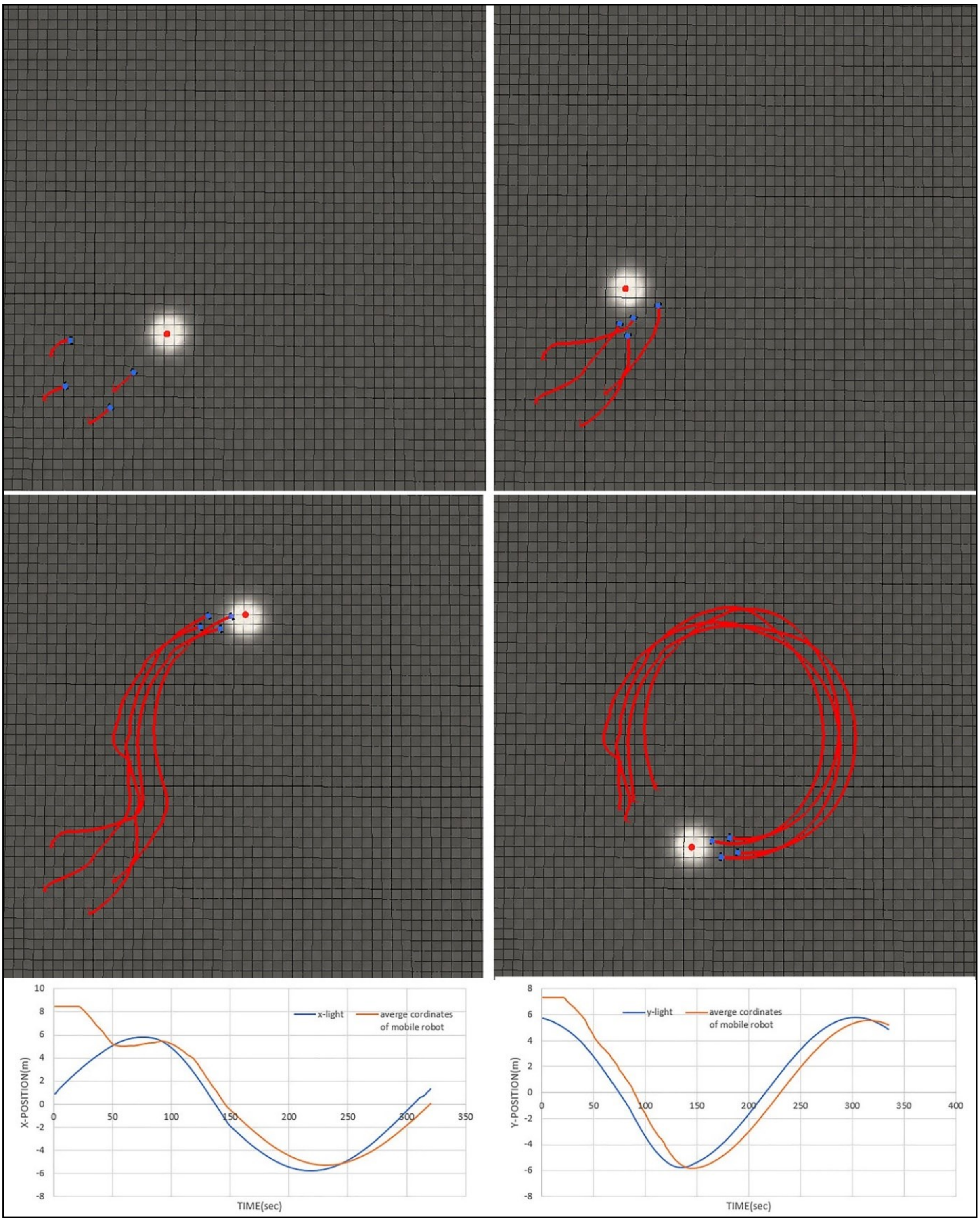

Fig 18 The circular pattern according to the dynamic model (parameters evaluated by Least Parameter Estimation method).

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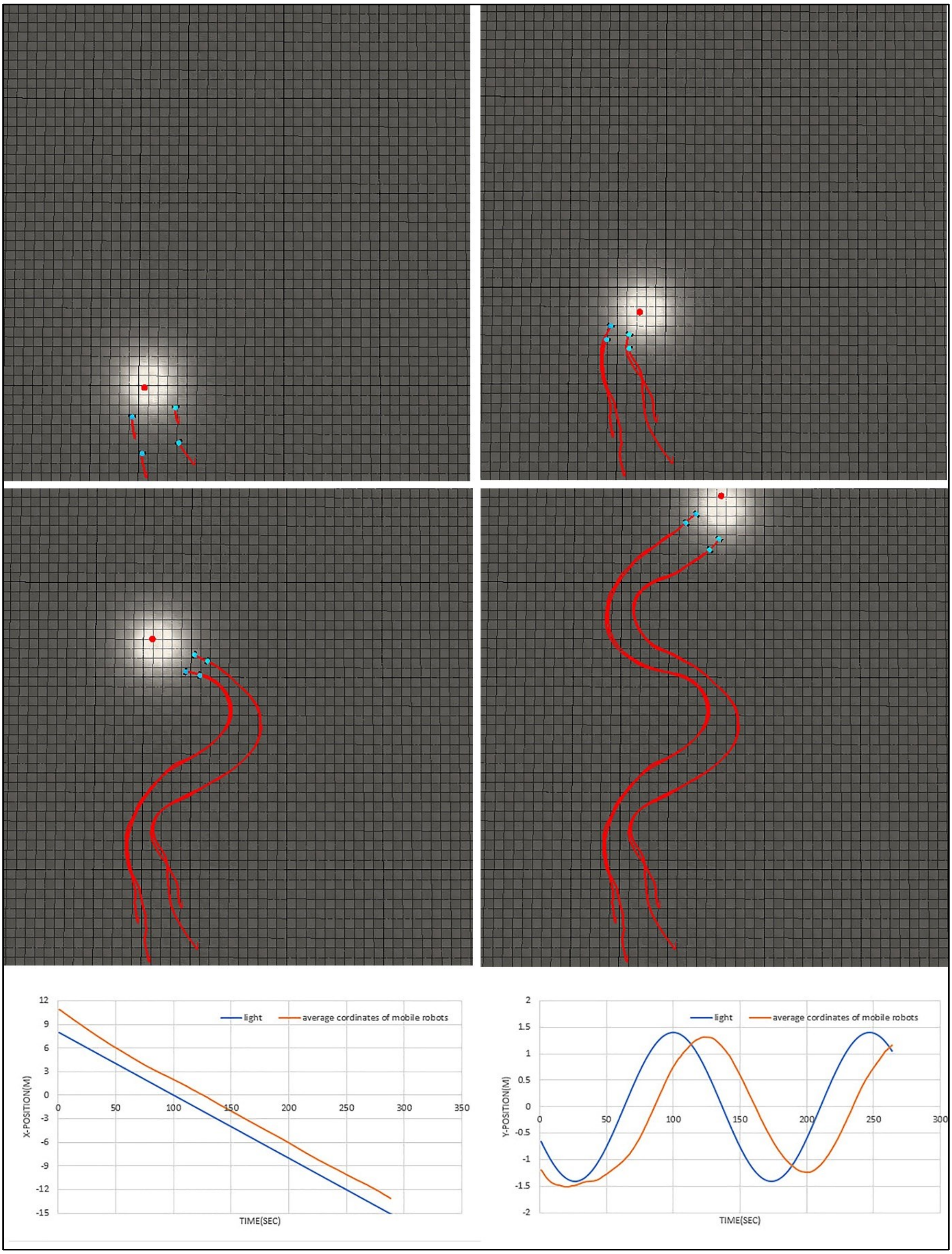

Fig 19 The zigzag line pattern according to the kinematic model.

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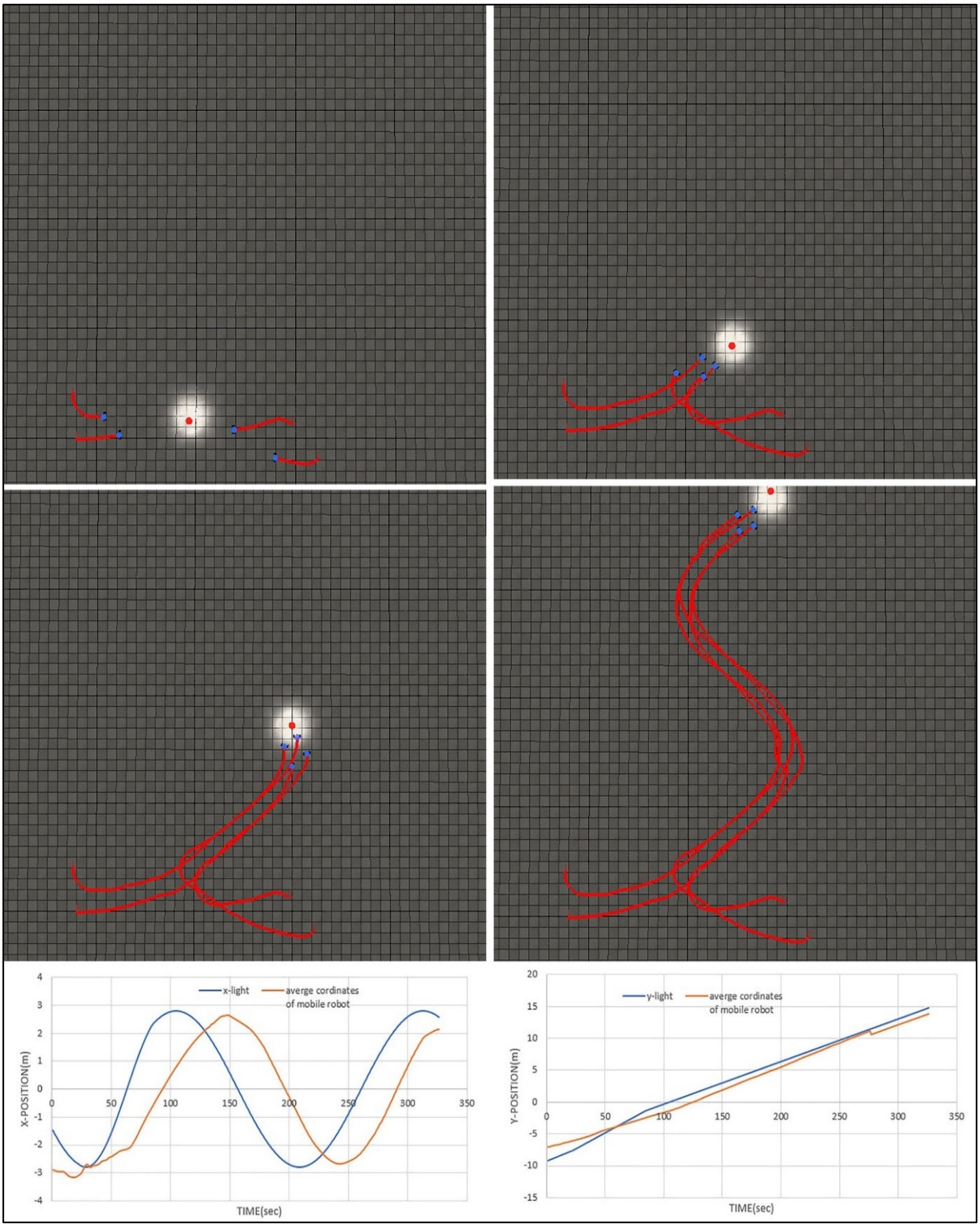

Fig 20 The zigzag pattern according to the dynamic model (parameters evaluated by physical structure of robots).

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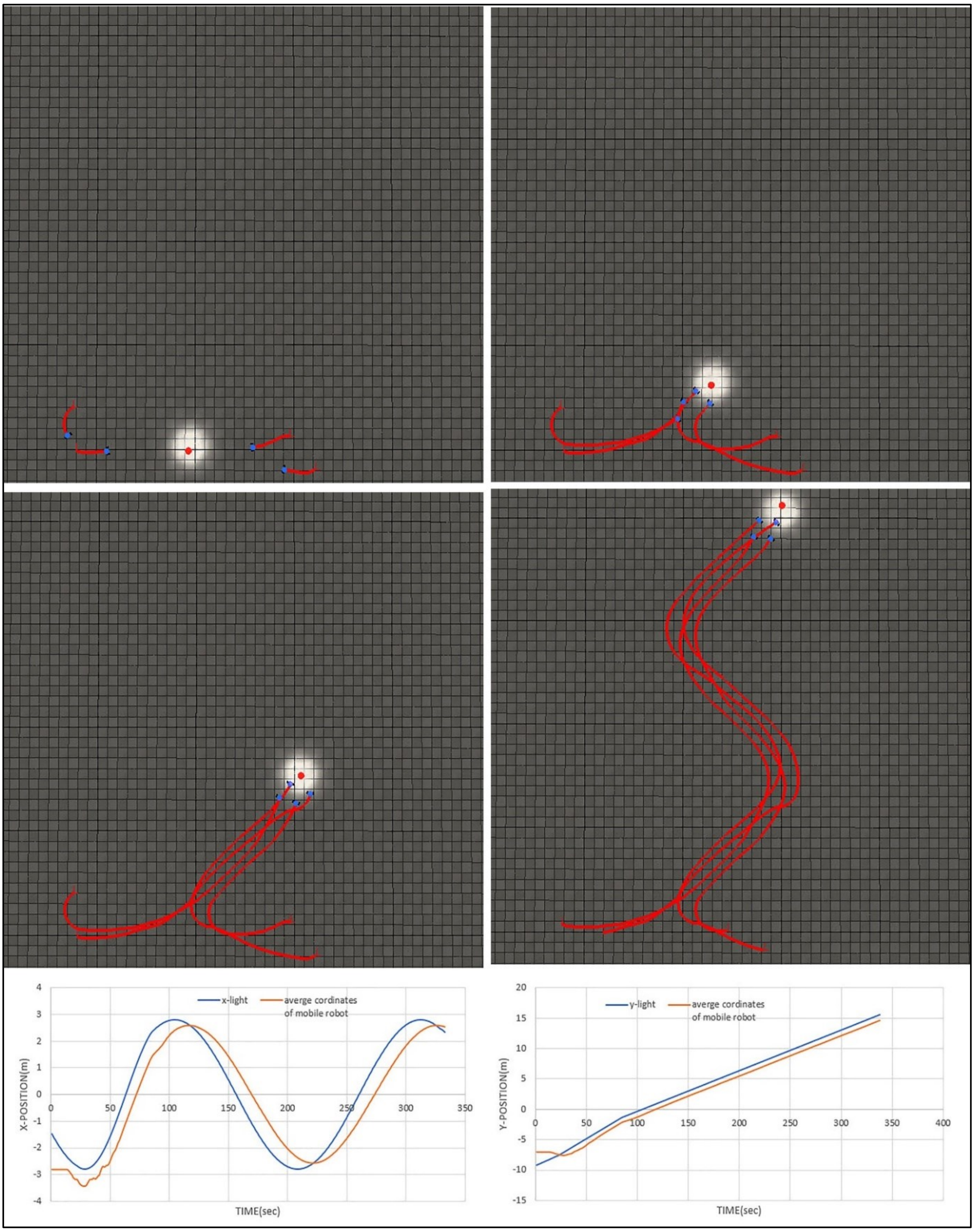

Fig 21 The zigzag pattern according to the dynamic model (parameters evaluated by Least Parameter Estimation method).

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In order, to compare the performance of the three proposed models, an error plot with respect to time will be shown, in which, the difference between positions of the light and that of the average positions of the robots while following the source of light.

Figure 22 shows the response of the three multi-robot models while following the straight line pattern of the spotlight. It can be noticed that the error of the kinematic model is larger than that of the dynamic model, however, the performance of the system with optimal parameters is the best, and have the minimum error.

Figure 23 describes the behavior of the three models while moving in the circular line trajectory, where, the error in this situation is more than that of the straight-line pattern because the robots must keep their formation while changing their direction continuously, to attract the spot of light. So, the robots may lose their tracking to the movable spot of light. In this case, the robot must update its direction each time.

Figure 24 shows the case of the zigzag path and it may be the most difficult task, where the robots must change their direction of motion to the opposite side while achieving formation and attracting to the spot of light.

5 | CONCULUSION

In this paper, a multi-robot system controlled by external stimuli has been proposed. The model of Artemia is used to derive a kinematic and dynamic model for this system, in which the population of Artemia is following a light spot. Several experiments have been implemented to check the performance of the three proposed models by using V-rep simulator. The simulation of the models is divided into three types of experiments, in the first type, the three proposed systems are following a spot of light moving in a straight-line path, while in the second, the spotlight move in a circular path and finally a zigzag path is implemented. According to the results of the position error, it has been approved that the robots are tracking the moving light spot, in which the performance of the dynamic model in case of optimal parameters is better than the dynamic model with parameters depending on the physical structure of robots.

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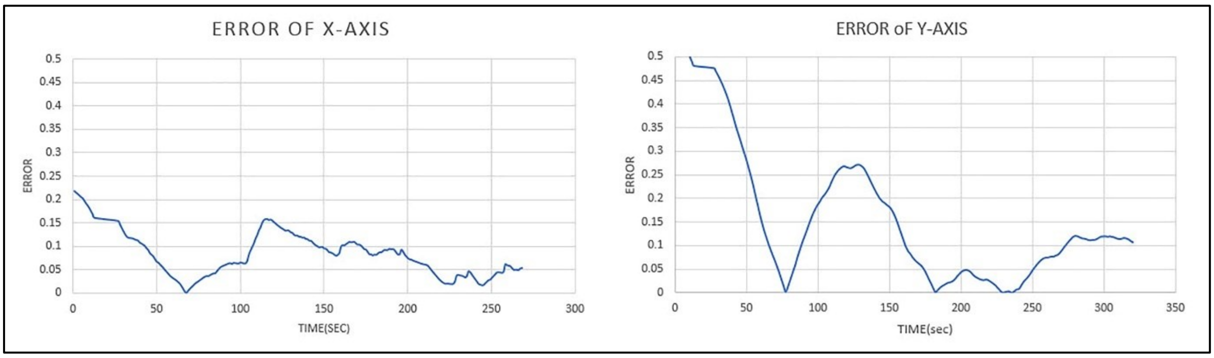

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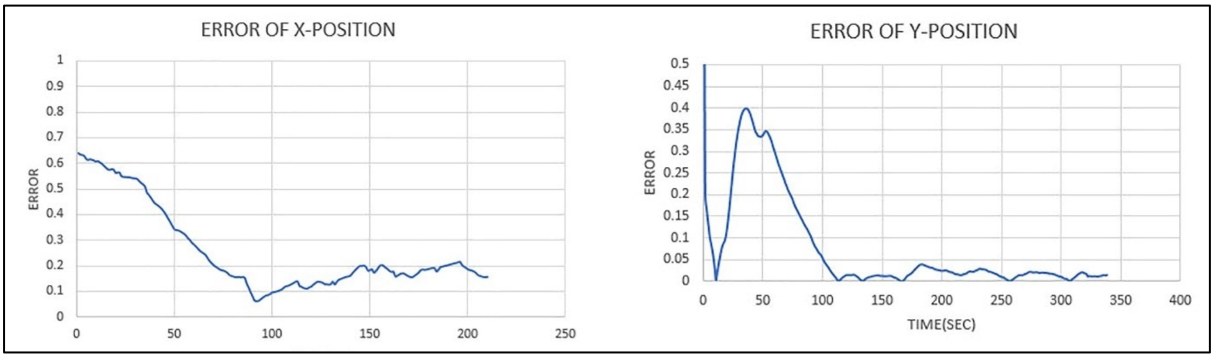
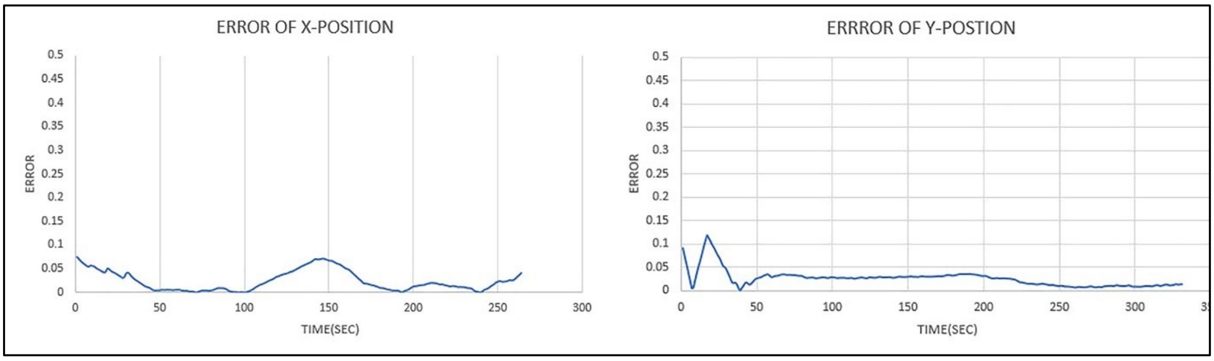


(b)



(c)

Fig 22 The X and Y positions errors while following a straight line of (a) kinematic model(b)dynamic model with physical parameters(c) dynamic model with optimal parameters. .

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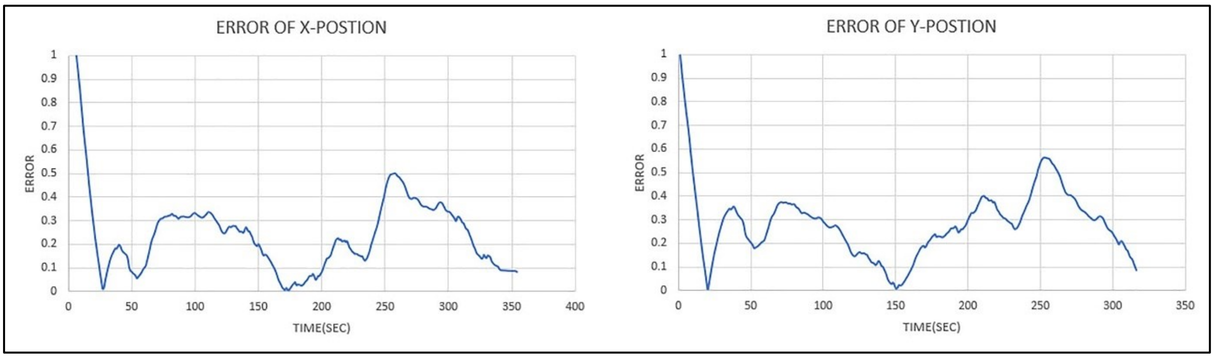

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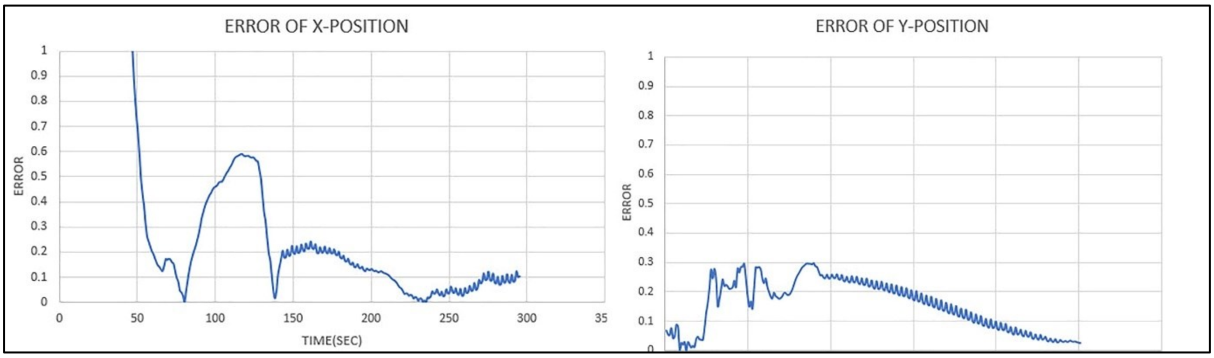

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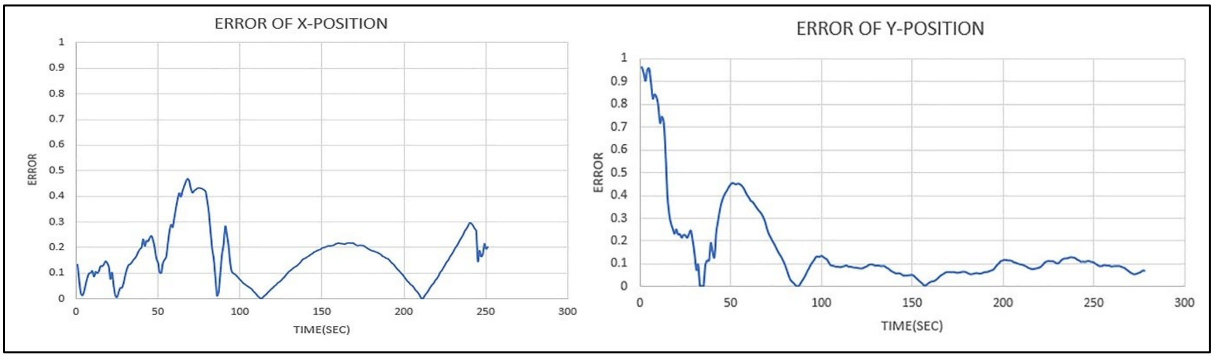

(c)

Fig 23 The X and Y positions errors while following a circular path of (a) kinematic model(b)dynamic model with physical parameters(c) dynamic model with optimal parameters. .

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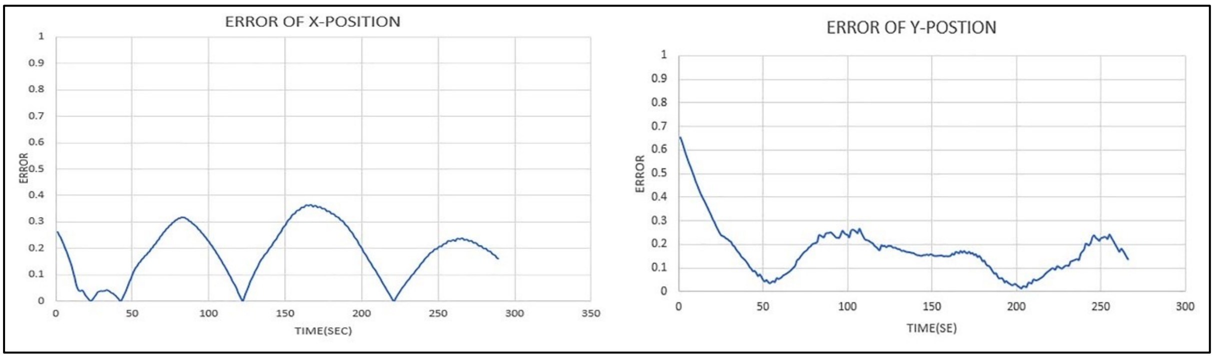
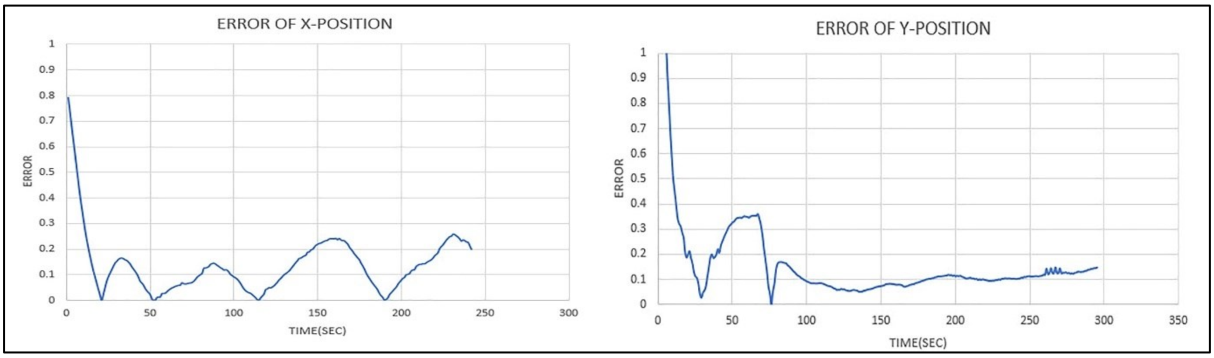


(a)



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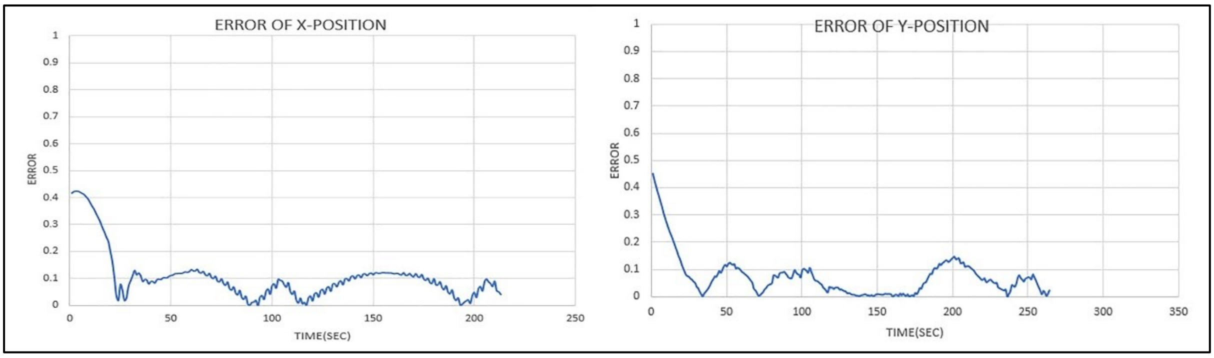

(c)

Fig 24 The X and Y positions errors while following a zigzag path of (a) kinematic model(b)dynamic model with physical parameters(c) dynamic model with optimal parameters.

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CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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