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Multi Robot System Dynamics and Path Tracking

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Abstract
The Leader detecting and following are one of the main challenges in designing a leader-follower multi-robot system, in addition to the challenge of achieving the formation between the robots, 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 light. In this paper, a multi-robot system in which the robots are following a spotlight is designed based on the behavior of the Artemia aggregations. Three models are designed: kinematic and two dynamic models. The kinematic model reveals the light attraction behavior of the Artemia aggregations. The dynamic model will be derived based on the newton equation of forces and its parameters are evaluated by two methods: first, a direct method based on the physical structure of the robot and, second, the Least Square Parameter Estimation method. Several experiments are implemented in order to check the success of the three proposed systems and compare their performance. The experiments are divided into three scenarios of simulation according to three paths: the straight line, circle, zigzag path. The V-Rep software has been used for the simulation and the results appeared the success of the proposed system and the high performance of tracking the spotlight and achieving the flock formation, especially the dynamic models.

KEYWORDS: Leader-Follower System, Flock Formation, Artemia Motion Behavior, Newton Equation, Parameters Estimation, The Least Square Method.

I. INTRODUCTION

The multi-robot system attracts 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 main challenge in designing such systems is how to control the motion of the group of robots. Most researchers are depending on the distributed control, where, each robot implements its feedback motion control law; depending on limited information about other robots within the group and other effects in the environment [3]. Further simplification of the robot's motion control may be achieved by following a leader, where, the group could be guided by this leader [4]. The main challenge in designing a leader follower system is the detection and recognition of the continually moving leader within several other robots. Some researchers are using a GPS to maintain the location of the leader the satellite signal may be lost [5]. Other uses a camera with a pattern detection, which gives a better following information than GPS, but the camera has a range limited and some other problems [6]. Other researchers use a beacon fitted on the robot, which is composed of two sensors those are the distance and IR sensors to calculate the position and the identity of each robot [7], this is a more complicated technique. As noticed, following a robot as a leader is a difficult task and required a complex technique for better performance.
In nature, there are aggregations of animals are capable of maintaining advanced collective motion behavior, So, these systems represent a source of inspiration to design a control strategy for multi-agent systems [8]. Especially, some kind of these aggregations follow an external stimulus as a leader such as the bee colony clustering in which the bees attract to the optimal temperature when no light exists [9]. Another model, the ant colony clustering which is attract to the pheromone [10]. Also, the groups of electric fish which are depending on a low electric field to communicate with other individuals [11].
One of the most important models is the light attraction model that is inspired by the aggregations of Artemia Salina. These creatures swim in random directions and only avoiding collide with other individuals. But, when a spotlight is appeared near the aggregation, these creatures move directly to the center of the spotlight. During its attraction to

the spotlight, the members reveals a flock formation, where, each member of Artemia will align its motion direction with others, keeping a certain distance between the neighbors and achieving the obstacle avoidance to avoid collision [12].

Although The collective motion of the individuals of these biosystem can be simply modeling by the kinematic model, but for a better performance a dynamic model should be derived. There are several methods to derive a dynamic model such as newton, Lagrangian and Kane method. In the newton method, two kinds of forces are effect on the motion of the robot, first the interaction forces with the neighbor robots and second are the influence of the external effects. The challenge of implementing this model is the evaluation of the system parameters that leads the robots to the best performance [13].

In this paper, a kinematic and two dynamic models of the multi robot system is derived based on the collective motion behavior of the Artemia aggregations. The dynamic model is based on the Newton equation and its parameters is evaluated by two methods: first, the parameters are calculated directly from the physical structure of the mobile robot, second, depending on a set of parameters that estimated by using the Least Square method. The three proposed systems are experimentally tested by using the V-rep simulator, in addition to the performance comparing of these systems while achieving formation and tracking the path of the spotlight.

II. METHODOLOGY

In this section, the kinematic and the dynamic model of the robots is derived based on the models of the light attraction that is inspired from the Artemia population. The parameters of the dynamic model are evaluated by two methods: the first method based on the physical properties of the robot, while the other method by using the Least Square Estimation method.

A. The Kinematic Model of the Robot in Presence of a Spotlight

The kinematic model of the robots can be derived Depending on the light attraction behavior of the Artemia aggregations. When the robot detects the spotlight then the robots changes its motion direction towards the detected spotlight and attract to the maximum light intensity, at the spot center. While attracting to the spotlight, if a robot is detected then an interaction is achieved according to the location of the detected robot within the interaction zones. The robot interaction zone divided into three zones includes attraction, orientation, and repulsion zone as shown in Fig. 1. [14,15]

The robot is able to detect the light that pass through its attraction zone and then changes its motion direction toward the light, as in equation below:

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

Where, $\vec{d}_a$ is the new direction calculated at each time constant τ, $\vec{g}_i$ is a unit vector of ith robot in the direction of the spotlight.

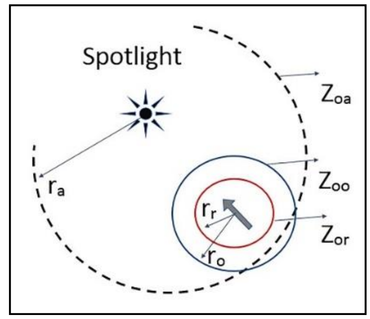


Fig.1: The three interaction zones, Zoa the attraction, Zoo the orientation and Zor the repulsion zone.

While, following the spotlight, the robot align its direction with those within the orientation zone, as follows:

$$\vec{d}_o(t+\tau)=\Sigma_{j=1}^{n}\frac{\vec{v}_i(t)}{\left|\vec{v}_i(t)\right|} \tag{2}$$

Where, $\vec{v}_i$ is the moving direction of the jth neighbor, n is the number of the detected robots.

If the robots are about to collide, with those within the repulsion zone, then they perform an obstacle avoidance behavior, which can be described by the equation:

$$\vec{d}_r(t+\tau)=-\Sigma_{j=1}^{n}\frac{\vec{r}_{ij}(t)}{\left|\vec{r}_{ij}(t)\right|} \tag{3}$$

Where, $\vec{r}_{ij}$ is a unit vector centered on the ith member and in the direction of the neighbor j.

So, the motion direction of each robot is 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 is: $d_r = d_o(t+\tau)$.

3) If no one within the sensing zones then: $d_r = d_a(t+\tau)$.

According to these rules, each robot keeps a fix distance from the spotlight and a formation is achieved between the robots while following the spotlight path, as in Fig. 2.

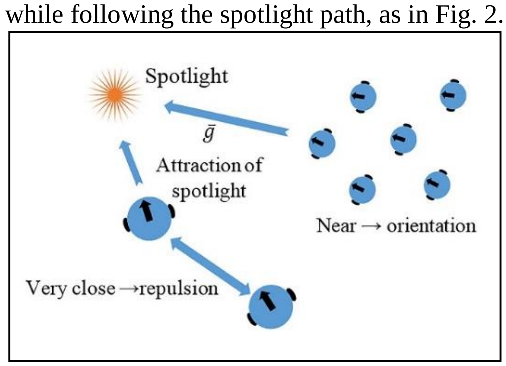


Fig.2: The robots attract to a lightspot

B. The Dynamic Model of Multi-Robot System

The dynamic model of the robots is achieved by implementing the dynamic model of Artemia to find the new x and y position that should be reached by the robot. Following these positions lead the robots to a collective behavior similar to that of Artemia [16].

the dynamic model of Artemia can be derived based on the newton equation as follows:

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

Where, m is the mass of artemia, $\vec{v}$ The velocity of the member, a is the locomotive force affected in the heading direction $\vec{n}_i$, γ the resistivity coefficient

The newton equation can be rewritten in the x, y direction as follows;

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

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

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:

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

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

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.

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} :

$$a_{ij} = 1 + d * \cos(\beta) \tag{9}$$

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

$$\vec{g}_{ix} = K_{ri} * K_{vi} * (r_{ax}(t) - r_{ix}(t)) \tag{10}$$

$$\vec{g}_{iy} = K_{ri} * K_{vi} * (r_{ay}(t) - r_{iy}(t)) \tag{11}$$

Where, $K_{ri} * K_{vi}$ is the sensitivity and the speed factors. $r_a(t), r_i(t)$ are the positions of light and individual.

After writing newton model, the equation that describe the motion behavior of each Artemia individual can be derived as follows:

$$v_i(t) = \dot{r}(t) = \frac{r_i(t) - r_i(t-T_s)}{T_s} \tag{12}$$

$$\dot{v}_i(t) = \ddot{r}_i(t) = \frac{r_i(t) - 2r_i(t-T_S) - r_i(t-2T_S)}{T_s^{\,2}} \tag{13}$$

Now, newton equation is:

$$m\ddot{r}_{ix}(t) = a_x(r_{ix}(t) - r_{ix}(t-T_s)) - \gamma\dot{r}_{ix}(t) - \frac{a_{ij} * c}{r_c^{-3}} * \Sigma_{i\neq j}(d_{ij}(t))^{-4}(r_{jx}(t-T) - r_{ix}(t-T_s)) + \frac{a_{ij} * c}{r_c^{-3}} * \Sigma_{i\neq j}(d_{ij}(t))^{-3}(r_{jx}(t-T) - r_{ix}(t-T_s)) + K_{ri} * K_{vi} * (r_{ax}(t) - r_{ix}(t)) \tag{14}$$

$$m\ddot{r}_{iy}(t) = a_y(r_{iy}(t) - r_{iy}(t-T_s)) - \gamma\dot{r}_{iy}(t) - \frac{a_{ij} * c}{r_c^{-3}} * \Sigma_{i\neq j}(d_{ij}(t))^{-4}(r_{jy}(t-T) - r_{iy}(t-T_s)) + \frac{a_{ij} * c}{r_c^{-3}} * \Sigma_{i\neq j}(d_{ij}(t))^{-3}(r_{jy}(t-T) - r_{iy}(t-T_s)) + K_{ri} * K_{vi} * (r_{ay}(t) - r_{iy}(t)) \tag{15}$$

Finally, the model of the robots is complete by rearranging equations (14, 15) as follows:

$$r_{ix}(t) = \alpha_{x1}r_{ix}(k-1) + \alpha_{x2}r_{ix}(k-2) - \alpha_{x3} * \Sigma_{i\neq j}(d_{ij}(t))^{-4}(r_{jx}(k-1) - r_{ix}(k-1)) + \alpha_{x4} * \Sigma_{i\neq j}(d_{ij}(t))^{-3}(r_{jx}(k-1) - r_{ix}(k-1)) + \alpha_{x5} * (r_{ax}(k)) \tag{16}$$

$$r_{iy}(t) = \alpha_{y1}r_{iy}(k-1) + \alpha_{y2}r_{iy}(k-2) - \alpha_{y3} * \Sigma_{i\neq j}(d_{ij}(t))^{-4}(r_{jy}(k-1) - r_{iy}(k-1)) + \alpha_{y4} * \Sigma_{i\neq j}(d_{ij}(t))^{-3}(r_{jy}(k-1) - r_{iy}(k-1)) + \alpha_{y5} * (r_{ay}(k)) \tag{17}$$

As notice from equations (16, 17) the robot decides its next position, x and y position, depending on the same influences that effect on the Artemia individual, which are: the spotlight location, 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 are found by two methods, by using physical features of robots and by using the Least Square Parameter Estimation method.

C. Dynamic Model Parameters Evaluation by Physical Properties of Robot

This is a simple and direct method where a set of parameters is calculated depending on the physical features of the robots. The parameters can be derived from equations (14, 15, 16, 17), and can be describe by the following equations:

$$\alpha_{x1} = \alpha_{y1} = \frac{2m - a}{m - a + K_r K_v} \quad (18)$$

$$\alpha_{x2} = \alpha_{y2} = \frac{m}{m - a + K_r K_v} \quad (19)$$

$$\alpha_{x3} = \alpha_{y3} = \frac{{r_c}^3}{m - a + K_r K_v} \quad (20)$$

$$\alpha_{x4} = \alpha_{y4} = \frac{{r_c}^2}{m - a + K_r K_v} \quad (21)$$

$$\alpha_{x5} = \alpha_{y5} = \frac{K_r K_v}{m - a + K_r K_v} \quad (22)$$

Where, m is the mass of the robot, a is the locomotive force, $K_{ri} * K_{vi}$ is the sensitivity of the robot to the light, r_c is the optimal distances between the robots. These are the parameters of equation (16, 17) which decide the behavior of the robots, the x, y parameters are equal.

The multi robot's system is simulated by the V-rep simulator, from which the features of the system are as in Table (1). After replacing these features in the equations (18, 19, 20, 21, 22), The parameters are Accordingly as in Table (2):

TABLE 1

The physical features of the robots.

The Features	Values
m	1.6 kg
a	-1.6
kv * kr	0.37
rc	0.85 m

TABLE 2

The calculated set of parameters.

The parameters	The Values
α1	0.44817
α2	0.44817
α3	0.17205
α4	0.20239
α5	0.10364

D. The Least Square Parameter Estimation Method

The least square method can be used to generate an estimated set of parameters that will lead the system to a best performance. To implement this method, the collective motion information of Artemia while tracking a compound path of the spotlight should be captured and adding to the identification system. This information is about the input which is the location of the light and the output which is represented by the average position of the flock, as in Fig. 3. This information is added to the identification system, where, the light location, H(k), will be added to the system as input and the output of the system, Z(k), is calculated depending on a random set of parameters and then compared with the average position of the real flock. the error is inserted to the least square algorithm to modify the values of the parameters, Fig. 4. The procedure is repeated again until reaching the optimal parameters, Table 3, at which the error will be zero [17].

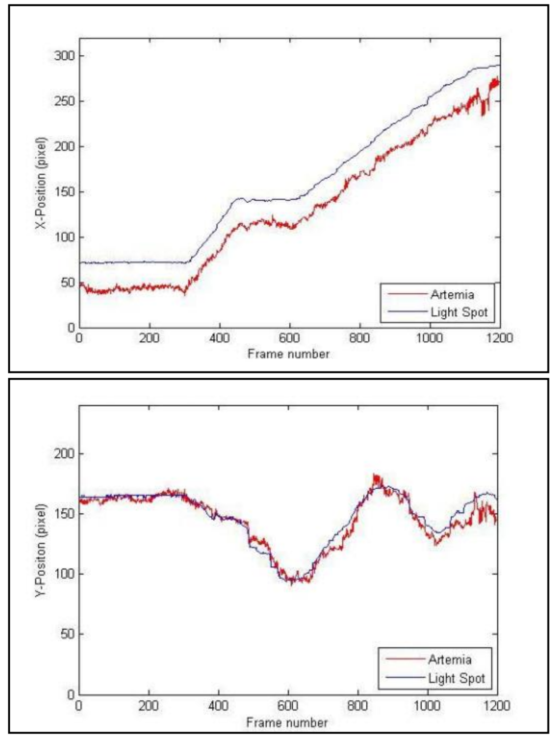


Fig.3: The performance of the robots

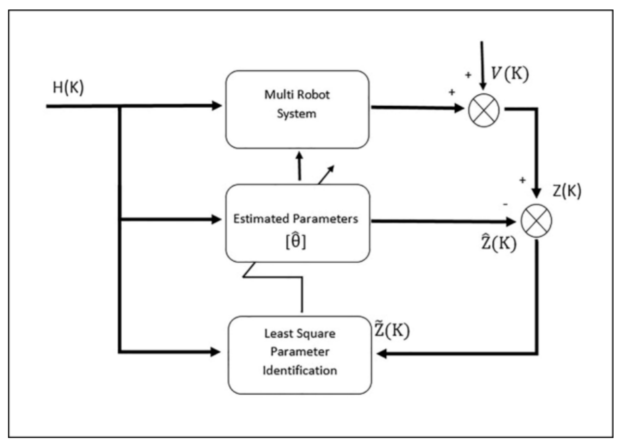


Fig. 4: The Least Square identification system

TABLE 3

The Parameters of the Least Square method

The Parameters	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

III. SIMULATION AND RESULTS

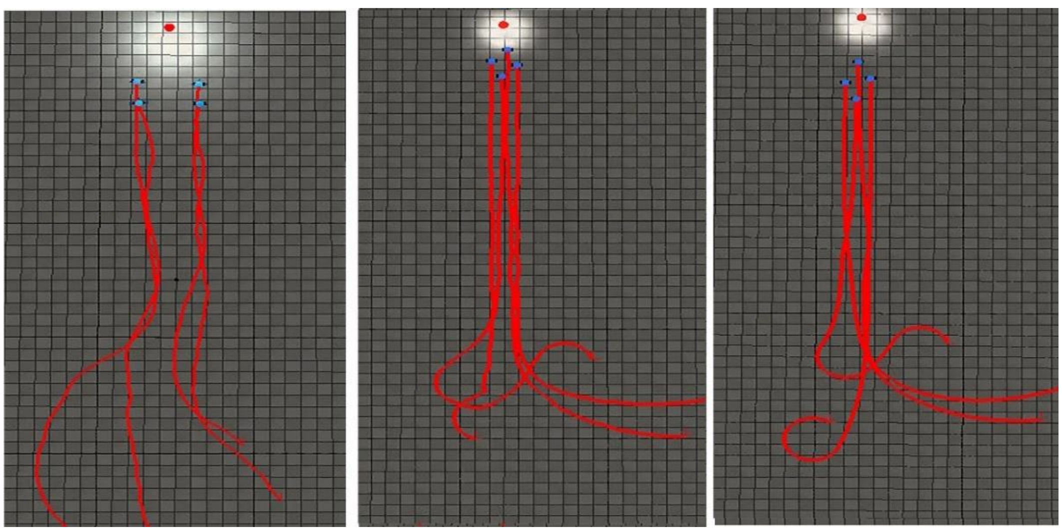
Within the V-rep simulator, an environment of (20m*20m), a differential drive mobile robot is used to implement several experiments to check the performance of the proposed systems. The robot has a spherical body with a diameter of 27 cm, a mass of 1.031 kg, and two active cylindrical wheels (left and 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.

Three scenarios of simulations will be achieved in order to test the systems performance. The first scenario is tracking the straight path of the spotlight, the second scenario concerns circle path and the final of the zigzag path. Each scenario will be implemented by the three proposed systems. In these simulations, each robot must keep a certain distance from the other robots and from the movable spotlight. Also, the robots moves with the same speed as the spotlight.

In the first simulation, tracking the straight path, the tasks of the robots are concentrated on the flock formation and synchronize its speed with that of the spotlight. Fig. 5 show the performance of the three proposed systems. Fig. 6 shows the x and y error comparison of the three systems while following the straight path of the light.

The circular path has more challenges, the light motion direction is changing continuously, so, each robot should synchronize its speed and direction with that of the spotlight, in addition to the synchronization between the robots and the flock formation. Fig. 7 show the response of the three systems. Fig. 8 show x and y error of the circular path tracking.

The zigzag test requires high steering system, since, the spotlight is changing its motion direction to the opposite way, so, the whole flock should change its direction and turn to the opposite way as quickly to catch up with the spotlight, in addition to the formation keeping. Fig. 9 show the response according to the three systems. Fig. 10 shows the error of tracking the zigzag path.



(a) (b) (c)

Fig. 5: The Straight- path pattern according to, (a) the kinematic model, (b) the dynamic model with the directly calculated parameters and (c) with the optimal parameters.

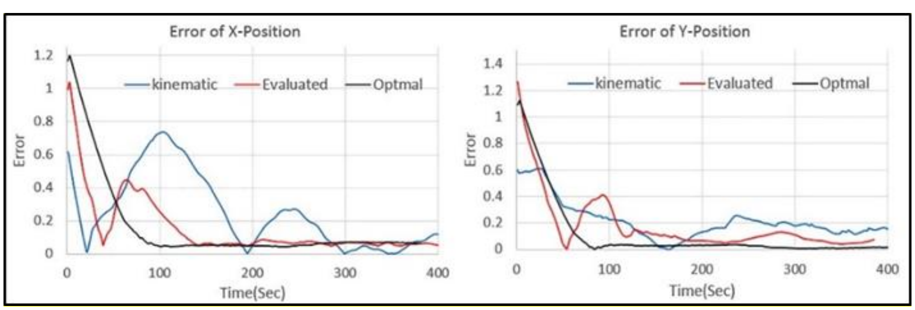
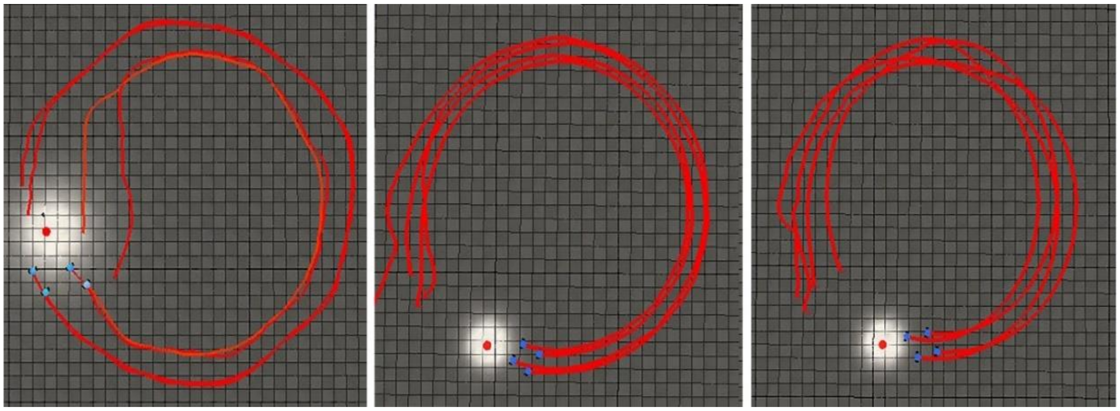


Fig. 6: The x and y path tracking error of Straight- path pattern



(a) (b) (c)

Fig. 7: The circle-path pattern according to (a) the kinematic model, (b) the dynamic model with the directly calculated parameters and (c) with the optimal parameters.

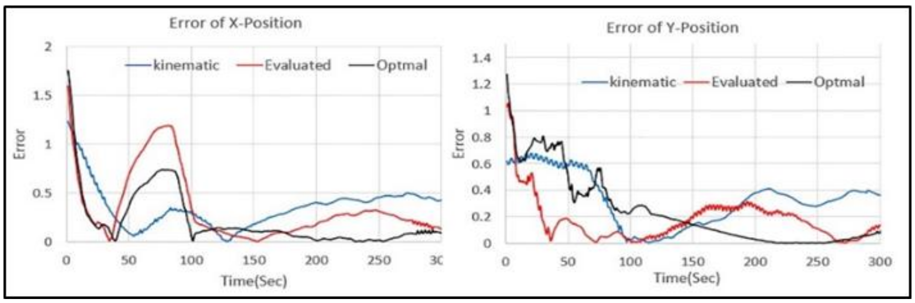
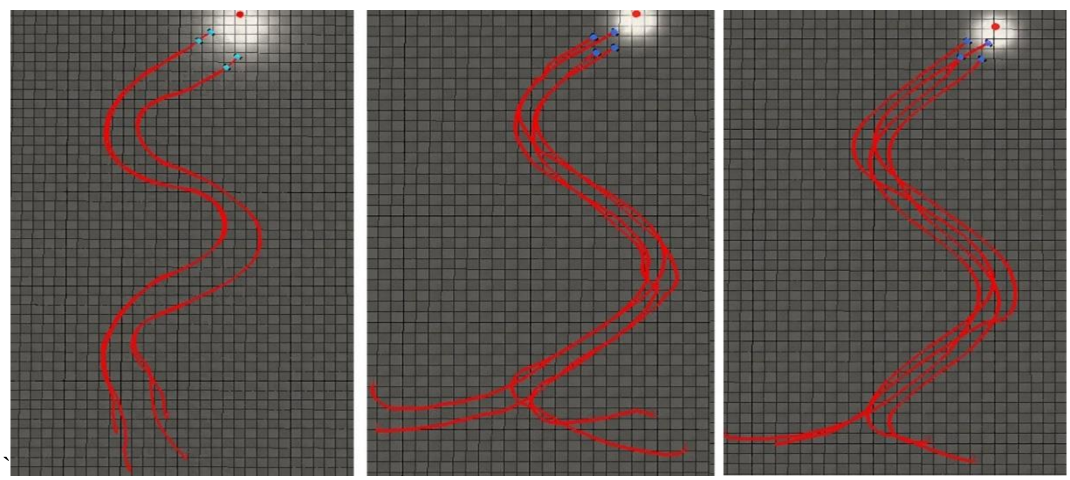


Fig. 8: The x and y path tracking error of circle- path pattern



(a) (b) (c)

Fig. 9: The zigzag- path pattern according to (a) the kinematic model, (b) the dynamic model with the directly calculated parameters and (c) with the optimal parameters.

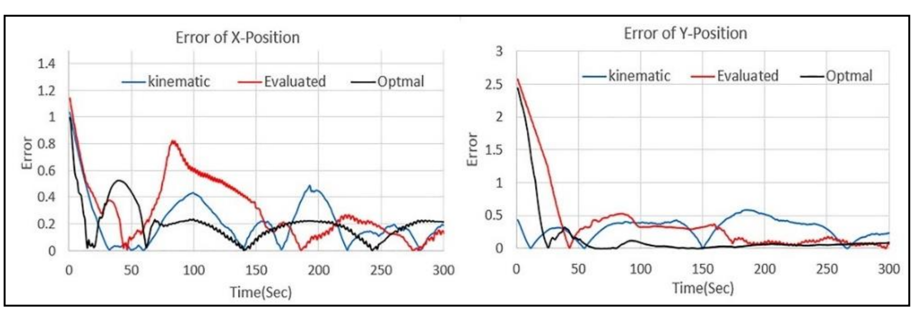


Fig. 10: The x and y path tracking error of zigzag- path pattern.

IV. Conclusion

In this paper, a multi-robot system guided by external stimuli has been proposed, where, the robots are following a spotlight as a leader. The model of Artemia is used to derive the kinematic and the dynamic models for this system. Several simulation have been implemented to check the performance of the three proposed systems. The simulation is divided into three scenarios: the straight path, the circle and the zigzag path scenario. According to the results of these simulation, it has been approved that the robots have a perfect performance in tracking the spotlight path, achieving the formation, and keeping it when the robots are turning, and the flock constructing speed. The most important matter, since the light is distributed on a large area, so, it can be easily detected and followed by the robots. It can be noticed from the error comparison that the performance of the system with the dynamic model is much better than that of the kinematic model, however, the best performance is achieved by the dynamic model with the least square parameters.

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