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Design and Experimental Validation of Dynamic Model of Multi Robot System

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Abstract: **In a multi-robot system, following the leader is a challenge since the robot must detect the leader first and then responding accordingly. So, in this paper, the motion control of a group of robots is achieved based on the dynamic model of the collective motion behavior of the aggregation of Artemia, a creature that follows a spotlight. Modeling the collective behavior of Artemia that follows the spotlight will be inspiring for modeling a collective of robots that achieves the same tasks. The model is based on the newton equation and its parameters will be calculated directly from the features of the multi-robot system. Several experiments will be implemented to check the behavior of the proposed system, which is divided into four experiments according to four trajectories, the straight line, circle, zigzag and complex path pattern. The V-rep software is used to derive and simulate the proposed design, also test its performance.**

Keywords—Multi-robot system, self-organization, formation system, Artemia, leader follower system.

I. Introduction

The multi robot system have advantage over single robot system that its more flexible, robustness and able to do tasks that cannot done by the single robot [1,2]. However, the formation control of such system considered as a challenge since each robot should notice the movement of the other robots within the aggregation to follow the group and avoid collision with the other. There are several methods to control the formation of the robots such a virtual structure [3], leader-follower [4], graph theory [5] and artificial potential approach [6]. The leader follower method has widely used because the members can be controlled by controlling the leader. However, attracting the leader is a difficult problem and the individuals should continuously update the information about the leader location.

The knowledge of the precise dynamic model is an important matter for wide applications of robotics. It is important for designing a controller with high performance, in case of the interactions with other members or with the environment [7], following the leader, the response to an unexpected obstacle or collision [8], or regulating the affected forces on each robot [9].

In the biological system, there are many groups of animals, which are called flocks such as the school of fish, flock of birds and the colony of the ant. These aggregations reveal the self-organization behavior, where, each individual within a certain distance from the neighbor will align itself with him or repulse with the closer members. The importance of studying these flocks is to inspire the simple interactions between the members, which can be efficiently implemented [10, 11]. Many models for multi-robot systems can be inspired from the biological flocks such as the colony of ants which follow the effect of pheromone while searching for food [12], other use the model of bees that attract the optimal temperature when there is no light [13] and some researchers used the model of Artemia which, is attract a spotlight [14].

There are several methods to design a dynamic model such as newton [15], Lagrangian [16] and Kane method [17]. 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 [18], the fuzzy-neural method [19]. However, 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 lost the optimality in the performance of the robots [20].

In this paper, the dynamic model of the multi-robot system will be derived based on the collective motion behavior of the aggregation of Artemia. The kinematic and the dynamic model of Artemia will be derived and the parameters of the dynamic model will be calculated depending on the features of the robots. V-rep simulator will be used to evaluate the models of the multi-robot and test the performance of the system's formation while tracking the spot of light.

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II. METHODOLOGY

Since, the proposed model of the multi-robot's system based on the dynamic model of Artemia, so, the kinematic, and the dynamic model of collective motion of Artemia will be derived, and then the parameters, for the proposed model, will be estimated from the features of the robots.

A. The kinematic model of Artemia

Artemia is the creatures that attract to 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 [23].If a spotlight is appeared then only the individuals those sensing it within their attraction zone will follow the spot, which, the attraction behaviour will be:

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

Where, $\vec{g}_i$ 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 the 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, v_j is the direction of moving of the j^{th} neighbour.

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 opposite side as in equation:

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

B. 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 case, first one concern the uniform light and the second is about a spotlight. In the first case, each individual move in random direction so we will concentrate on the second case at which the individuals attract the spotlight as in Fig. 1, Newton equation will be [20]:

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

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.

Where, $\vec{f}_{ij}$ 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.

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

where, $\left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-3}$ is the repulsion term , $\left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-2}$ 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}:

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

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:

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

Where, Kr_i , Kv_i are the sensitivity and the speed factors. $r_a(t), r_i(t)$ are the positions of light and individual. This is the dynamic model of Artemia, which take into account all the forces affected on each individual. It required the knowledge of parameters, which are difficult to identify.

C. Parameters evaluation

Evaluating the parameters is an important matter since these parameters are controlling the forces that affected the response of the robots. Before evaluating the parameters of the multi-robot system, the dynamic model of the system should be derived which is based on the dynamic model of Artemia.

$$m\frac{d\vec{v}_i}{dt} = a\vec{n}_i - \gamma\vec{v}_i + \sum_{i\neq j} a_{ij}\vec{f}_{ij} + \vec{g}_i \tag{8}$$

Which can be rewritten in the x, y direction as follows;

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

$$m\frac{d\vec{v}_{iy}}{dt} = a_y\left(\frac{r_{iy}(t)-r_{iy}(t-T_s)}{r}\right) - \gamma\vec{v}_{iy} + \sum_{i\neq j} a_{ij}\vec{f}_{ijy} + \vec{g}_{iy} \tag{10}$$

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.

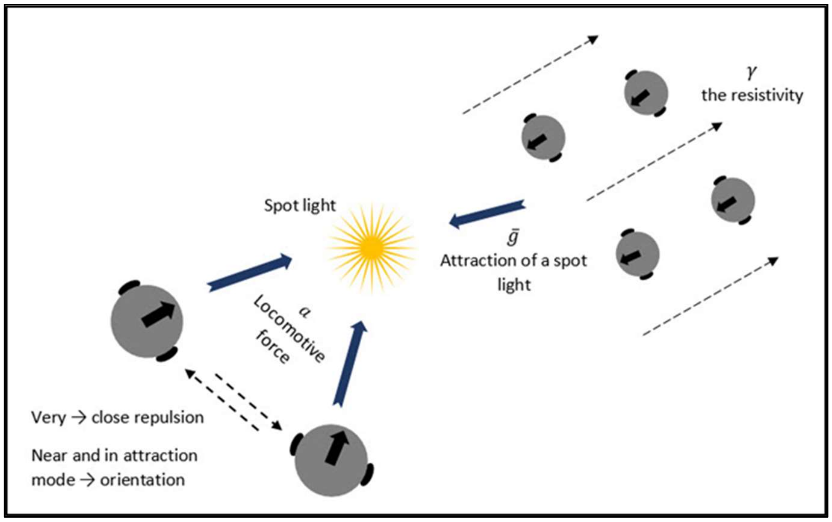

Fig. 1. Show the forces affected on each robot.

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

$$\vec{f}_{ijy} = -c\left[\left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-3} - \left(\frac{d_{ij}(t-T_s)}{r_c}\right)^{-2}\right] * \left(\frac{r_{jy}(t-T_s)-r_{iy}(t-T_s)}{d_{ij}(t-T_s)}\right) \quad (12)$$

Here, d_{ij} the distance between the ith and jth individual, r_c is the optimum distance between individuals and c is the force constant.
The attraction force to the light $\vec{g}_{ix}, \vec{g}_{iy}$ are given by:

$$\vec{g}_{ix} = c_g * Kv_i * Kr_i\,(\,r_{ax}(t) - r_{ix}(t)\,) \quad (13)$$

$$\vec{g}_{iy} = c_g * Kv_i * Kr_i * (\,r_{ay}(t) - r_{iy}(t)\,) \quad (14)$$

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

$$v_i\,(t) = \dot{r}_i\,(t) = \frac{r_i(t)-r_i(t-T_s)}{T_s} \quad (15)$$

$$\dot{v}_i\,(t) = \ddot{r}_i\,(t) = \frac{\dot{r}_i(t)-\dot{r}_i(t-T_s)}{T_s} = \frac{r_i(t)-2r_i(t-T_s)-r_i(t-2T_s)}{{T_s}^2} \quad (16)$$

After replacing each term, newton equation will be:

$$m\ddot{r}_{ix}\,(t) = a_x\left(r_{ix}(t) - r_{ix}(t-T_s)\right) - \gamma\,\dot{r}_{ix}\,(t) - \frac{\alpha_{ij}*c}{r_c^{-3}}\sum_{i\neq j}(d_{ij})^{-4}\left(r_{jx}(t-T_s) - r_{ix}(t-T_s)\right) + \frac{\alpha_{ij}*c}{r_c^{-2}}\sum_{i\neq j}(d_{ij})^{-3} * \left(r_{jx}(t-T_s) - r_{ix}(t-T_s)\right) + c_g * Kv_i * Kr_i * (\,r_{ax}(t) - r_{ix}(t)\,) \quad (17)$$

$$m\ddot{r}_{iy}\,(t) = a_y\left(r_{iy}(t) - r_{iy}(t-T_s)\right) - \gamma\dot{r}_{iy}\,(t) - \frac{\alpha_{ij}*c}{r_c^{-3}} * \sum_{i\neq j}\left(d_{ij}(t)\right)^{-4}\left(r_{jy}(t-T_s) - r_{iy}(t-T_s)\right) + \frac{\alpha_{ij}*c}{r_c^{-2}} * \sum_{i\neq j}\left(d_{ij}(t)\right)^{-3}\left(r_{jy}(t-T_s) - r_{iy}(t-T_s)\right) + c_g * Kv_i * Kr_i * (\,r_{ay}(t) - r_{iy}(t)\,) \quad (18)$$

$$r_{ix}(k) = \alpha_{x1}r_{ix}(k-1) + \alpha_{x2}r_{ix}(k-2) - \alpha_{x3} * \sum_{i\neq j}\left(d_{ij}(k)\right)^{-4}\left(r_{jx}(k-1) - r_{ix}(k-1)\right) + \alpha_{x4} * \sum_{i\neq j}\left(d_{ij}(k)\right)^{-3}\left(r_{jx}(k-1) - r_{ix}(k-1)\right) + \alpha_{x5} * (\,rax\,(k)) \quad (19)$$

$$r_{iy}(k) = \alpha_{y1}r_{iy}(k-1) + \alpha_{y2}r_{iy}(k-2) - \alpha_{y3}\sum_{i\neq j}\left(d_{ij}(k)\right)^{-4}\left(r_{jy}(k-1)r_{iy}(k-1)\right) + \alpha_{y4}\sum_{i\neq j}\left(d_{ij}(k)\right)^{-3}\left(r_{jy}(k-1) - r_{iy}(k-1)\right) + \alpha_{y5}(\,r_{ay}(k)\,) \quad (20)$$

Where, equations (27, 28) represent the dynamic model of the robot that decided the next position, to be attracted by the robot, depending on the values of the parameters and the location of the light and the neighboring robots. According to equations (17-20) 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, (r_c) the optimal distances between the robots and (γ) the resistivity. So, the parameters will be equal to:

$$\alpha_1 = \frac{2m-a}{[m-a+kvkr]} \quad (21)$$

$$\alpha_2 = \frac{m}{[m-a+kvkr]} \quad (22)$$

$$\alpha_3 = \frac{{r_c}^3}{[m-a+kvkr]} \quad (23)$$

$$\alpha_4 = \frac{{r_c}^2}{[m-a+kvkr]} \quad (24)$$

$$\alpha_5 = \frac{kvkr}{[m-a+kvkr]} \quad (25)$$

The resistivity of air will be neglected. So, to find these parameters a V-rep simulator will be used at which the features of the system will be M= 1.6 kg, A=-1.6, kv*kr=0.37, and r_c=0.85 m. The parameters will be calculated according to equations (21-25) which are, α_1=0.44817, α_2=0.44817, α_3=0.17205, α_4=0.20239, α_5=0.10364.

D. Kinematic model of a differential-drive robot

The diagram of the robot is shown in Fig. 1, it's a differential-drive mobile robot at which (x_o, y_o) represent the reference coordinate at the center of the robot. The line from the right to left wheel passing through the reference point represent the reference direction. The motion direction of the robot (θ) is evaluated by the angle between the x-axis and the reference direction and it has resulted from the difference between the right and left wheel velocity (V_R, V_L) as in Fig. 2. The model of the robot that describe its motion is [23]:

$$S_L = r * \Phi \tag{26}$$

$$S_R = (r + L) * \Phi \tag{27}$$

$$S_M = (r + L/2) * \Phi \tag{28}$$

Where, S_R ,S_L is the displacement of the right and left wheel, S_M is the robot center displacement. r is the distance from the center of the turning path to the inner wheel. L is the distance between the left and right wheel, Φ is the turning angle.

The kinematics equations of the robot will be:

$$X_c(t) = X_o + \frac{L(V_R+V_L)}{2(V_R-V_L)}\left[cos\left(\frac{(V_R+V_L)t}{L} + \Phi\right) - cos\,\Phi\right] \tag{29}$$

$$Y_c(t) = Y_o + \frac{L(V_R+V_L)}{2(V_R-V_L)}\left[sin\left(\frac{(V_R+V_L)t}{L} + \Phi\right) - sin\,\Phi\right] \tag{30}$$

Where, $L(V_R+V_L)/2(V_R-V_L)$ is the radius of the turning arc, X_c and Y_c are the new position of the robot's center.

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

$$X_c(t) = X_o + S \cdot cos\,\Phi \tag{31}$$

$$Y_c(t) = Y_o + S \cdot sin\,\Phi \tag{32}$$

where, $S = (S_L + S_R)$.

III. 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 multi-robot system. Each robot body has a dimeter 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 dimeter of (12.35 cm), thickness of (3.08 cm), mass of (0.29 kg) and each one is driven by a motor with maximum torque of (2.5 N.m). The spherical wheel has a radius of (6.7 cm) and mass of (0.37 kg).

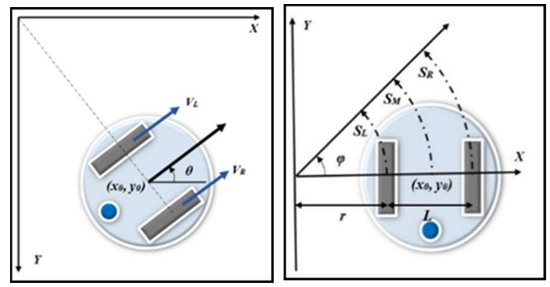

Fig. 2. The kinematics of the mobile robot [18].

Several experiments are implemented in order to check the performance of following multi-robot to a movable light spot. In these experiments, the robots should keep a certain fixed distance from the movable spot light and have the same speed of the spotlight. So, several patterns concern the motion of the light have been chosen such as straight line, circle, zigzag and complex motion pattern.

A. Straight line trajectory

In the first experiment, the robots attracting a spotlight that move in a straight line. The attraction of the robots to the spotlight is achieved from interactions between them is tested here. Each robot should keep a fix distance from the spotlight and from the others by performing orientation with those within a certain distance and repulsion with closer one. Fig. 3, represent the behavior of the robots, which the performance of tracking the light can be observed.

B. Circle line trajectory

A circular path in which the direction of motion is changed continuously, so, each robot should synchronize its movement direction with respect to the spotlight; also, the synchronization is achieved between the robots in order to keep the formation of the flock. So, when they came close to each other they perform orientation to achieve the group formation. In addition, the obstacle avoidance between them is achieved to avoid collision when they are so close. Fig. 4, concern the response of the system.

C. Zigzag line trajectory

A more challenging test is the zigzag pattern in which the robots should attract the light that change its movement direction in opposite way so the robots should synchronize their motion with each other while changing their direction to attract the light. They also achieve formation by orientation process and avoid collision with those within repulsion zone as in Fig. 5.

D. Complex trajectory

Finally, a hybrid test that contains the three previous patterns together, where the robots should move in a straight line then in a circle and finally in a zigzag pattern. Therefore, the robots will follow any path if they succeed in this test as in Fig. 6.

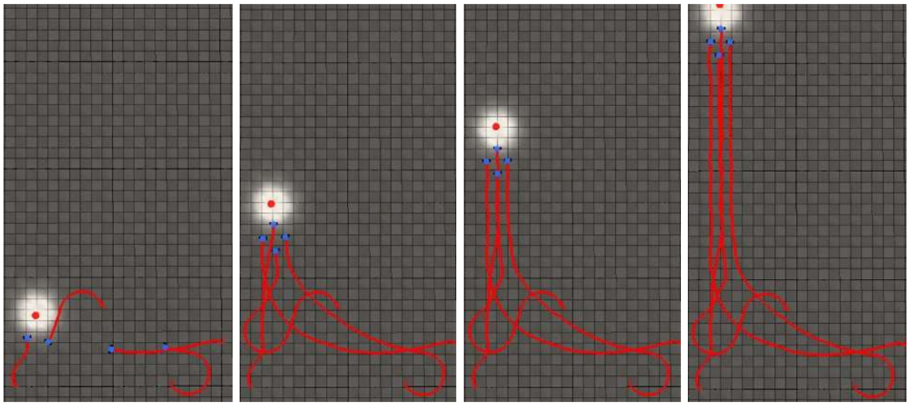

Fig. 3. The attraction of the robots to a spotlight moving in a straight line.

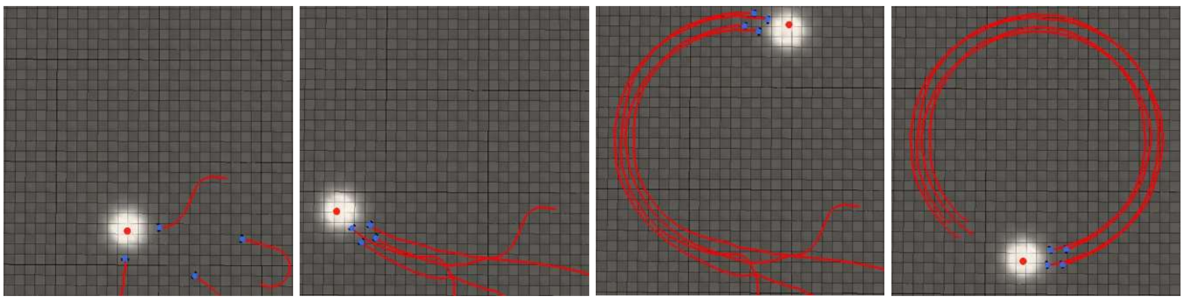

Fig. 4. The attraction of the robots to a spotlight moving within a circle pattern.

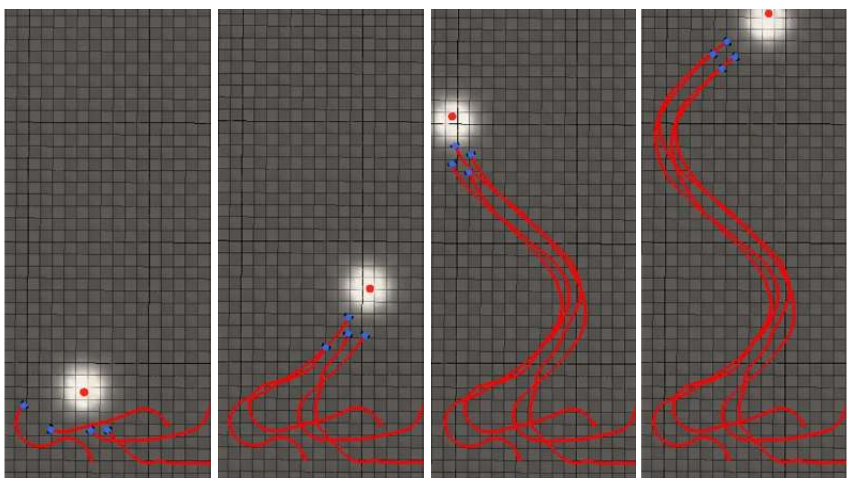

Fig. 5. The attraction of the robots to a spotlight moving within a zigzag pattern.

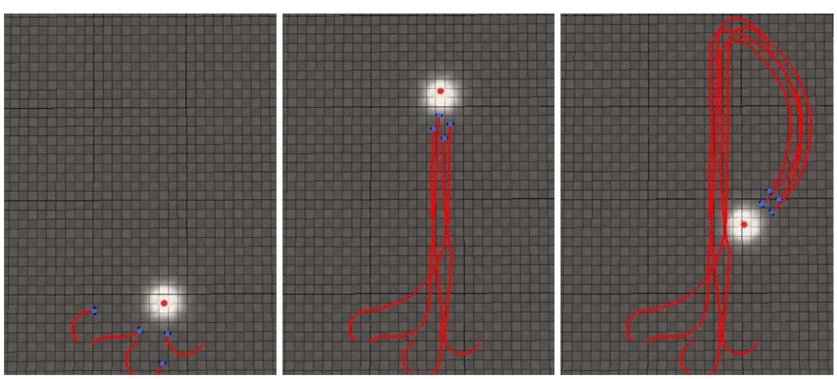

Fig. 6. The attraction of the robots to a spotlight moving within a complex path.

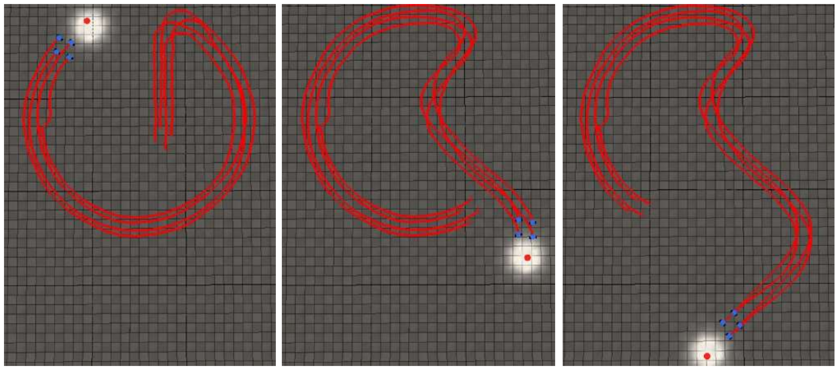

Fig. 6: continue.

IV. CONCLUSION

In this paper, the kinematic and dynamic model of the leader-follower multi-robot system has been derived. The spotlight is used as a leader for multi-robots. The constant parameters of the dynamic system have been calculated based on the physical features of the multi-robot system. In addition, several experiments have been achieved to test the validation of the proposed model. These experiments divided into four scenarios, which are a straight line, circular, zigzag, and complex path trajectories. The results of our experiments proved the validation and good performance in the case of performing leader-follower in addition to group formation missions.

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