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Self-Organization of Multi-Robot System Based on External Stimuli

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Abstract *In modern robotic field, many challenges have been appeared, especially in case of a multi-robot system that used to achieve tasks. The challenges are due to the complexity of the multi-robot system, which make the modeling of such system more difficult. The groups of animals in real world are an inspiration for modeling of a multi-individual system such as aggregation of Artemia. Therefore, in this paper, the multi-robot control system based on external stimuli such as light has been proposed, in which the feature of tracking Artemia to the light has been employed for this purpose. The mathematical model of the proposed design is derived and then Simulated by V-rep software. Several experiments are implemented in order to evaluate the proposed design, which is divided into two scenarios. The first scenario includes simulation of the system in situation of attraction of robot to fixed light spot, while the second scenario is the simulation of the system in the situation of the robots tracking of the movable light spot and formed different patterns like a straight-line, circular, and zigzag patterns. The results of experiments appeared that the mobile robot attraction to high-intensity light, in addition, the multi-robot system can be controlled by external stimuli. Finally, the performance of the proposed system has been analyzed.*

Index Terms**—multi-robot system, self-organization, formation system, Artemia, leader follower system.**

I. INTRODUCTION

Recently, the multi-robot systems strongly attracted the attention of researchers and the employment of this system has been increased in many application such as intelligent security systems: [1], Coverage and Mapping [2], Surveillance [3], humanitarian demining [4], Searching and Tracking People [5, 6] and health care [7]. Multi-robot systems are numbers of robots with interactions between them and they appear a self-organization behavior, while some types of these systems follow a leader. These systems are more complex than a single robot system because of the several interactions between the units, so these systems known as a Complex System. Design and modeling of such systems can be extracted by observation of the behavioral of the biological systems in the real world. Biological systems have many aggregations of animals, these groups are called the flocks such as flocks of birds, school of fish and ant colony. These flocks showed the self-organization phenomenon, in which each member keep a distance, align itself and avoid collision with the others. Studying these flocks is important because of the simple interactions between the individuals which can be easily and efficiently implemented [15, 16, 17, 18].

There are many models of multi-robot that inspired from biological system such as the model in [8]. In which the collective behaviors of fish schools is achieved by making the acceleration force depend on the distance and the direction of the two interacted members. So, if they are close then the acceleration force will be decrease, else if they are far away then it will be increase. Another model based on the bee’s thermal response [9], they are act normally in presence of a light, but when its dark then the bees will follow the temperature gradient until they reach the high degree. They do that by comparing the temperature between two points and follow the higher. When, the coordination of the ant colony by the indirect communication through pheromones [10], is done while the searching for food, which have a certain number of pheromones. After finding the food, the ants start to cluster it in a group, where they put it in positions with higher pheromones density. The probability of creating a new cluster depends on the pheromone's density in the other groups, where the ants prefer to put in the current groups and stop creating a new cluster when the density of other aggregation is high.

Some of multi-robot systems are attracting to the leader with self-organization while searching for stimuli such as food. Today, the design of a system with a leader attracts many researchers since the whole group can be controlled by controlling the leader. However, attracting the leader is a difficult problem and the follower should update their information about the leader location continuously to continue the attraction. For this purpose, some researchers use a GPS to maintain the location of the leader but the satellite signal may be lost. Other uses a camera, which gives a better following information than GPS, but the camera has a range limited and some other problem. Both GPS and camera have a problem of how to recognize the leader between the flock. A marker on the leader is used as a solution for this matter [13]. 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 within the range. The beacon is rotate continuously and the distance sensor detect the presence of the neighbors while the IR communicate with the detected units. The information collected by the IR sensor is used later to detect the identity and the location of the robots [21]. Others present a vision-based system to find and attract the position of the others. The basic part of the system is a pattern detector, simple camera, and a small computer to handle a program. The basic part of the program is an algorithm that will process the detected patterns. The algorithm is able to process many images per second while following a lot of units and with a very high accuracy. So, the positions can be estimated from the parameters of the camera and using the hardware processor [20]. Some researchers proposed a model for the multi-robot system based on collective motion behavior of Artemia aggregation, which is the motion direction of Artemia aggregation tracking to the path motion of light spot [11, 19, 22].

In this paper, a multi-robot system will be designed and mathematical model for this system will be derived based on self-organization behavior of Artemia aggregation. The flock formation of a multi-robot system will be achieved in case of a spot of light appears in the robot light attraction zone. In addition, multi-robot motion control will be performed to track the motion of light spot. The V-rep robotic simulator will be used to test multi-robot system and evaluate the performance of system formation and tracking to the dynamic light spot.

II. MODELING OF MULTI-ROBOT SYSTEM

From the experiments that simulated the motion behavior of Artemia [18], it has been noticed that without external stimuli (i.e. light), the individuals will move in random directions. When a uniform light is appeared, they also move in random directions and avoid collision with each other. If a spot of light appeared in the zone of Artemia sensing, they will move directly to the spot of light and reveal a form of the uniform flock. The flock members will be attracted to the intensity of the light until reaching a specific high intensity, so, they will follow the light if its location is changed.

During the following of the group of Artemia to the light spot, the individuals interact with each other in order to avoid collisions between each other and continuing to the direction of the light spot [14]. It has been noticed that in the school of Artemia, the individuals keep a certain distance between each other during tracking the light spot which gradually decreases until the individuals become close to each other and exceed the allowable value among individuals then the repulsion will be achieved. So, for each individual, there are zones of interaction, which are the repulsion, orientation and attraction zones. In the attraction zone, Artemia senses light spot, so it changes the motion direction to light spot, while in orientation zone, the individuals are trying to move in parallel direction between each other towards the light spot, finally at repulsion zone, the individuals will achieve obstacle avoidance between each other as shown in Fig. 1.

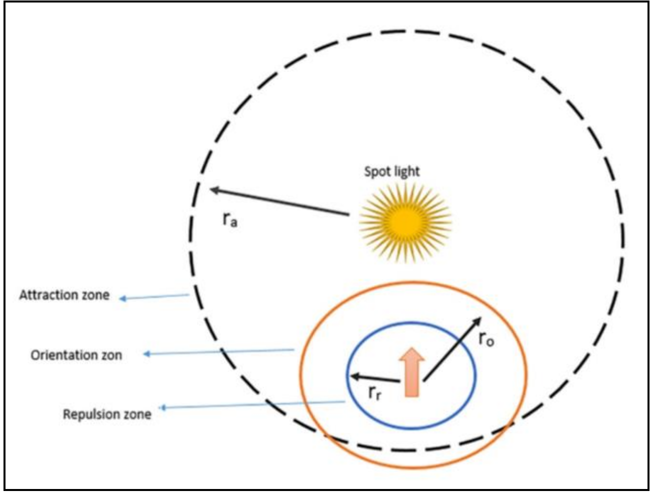

Fig. 1 The three zones of mobile robot during attraction to the light spot.

A. Kinematic model of a differential-drive robot

The schematic diagram of a differential drive mobile robot is shown in Fig. 2. The reference coordinate of the robot is (x_o, y_o) at the center of the body. The horizontal line from the left wheel to the right wheel passing through the reference coordinate indicates the reference direction. The orientation of robot can be evaluated based on the angle between the reference direction and x- axis (θ) which represents the motion direction of robot resulted from the difference between Left and Right wheel velocities (V_L, V_R) [12] as shown in Fig. 3. Therefore, the mathematical model that describes the robot motion is

$$S_L = r * \Phi \tag{1}$$

$$S_R = (r + L) * \Phi \tag{2}$$

$$S_M = (r + L/2) * \Phi \tag{3}$$

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

The kinematics equations of the mobile robot is:

$$X_c(t) = X_o + \frac{L(V_R + V_L)}{2(V_R - V_L)}\left[\cos\left(\frac{(V_R + V_L)t}{L} + \Phi\right) - \cos\Phi\right] \tag{4}$$

$$Y_c(t) = Y_o + \frac{L(V_R + V_L)}{2(V_R - V_L)}\left[\sin\left(\frac{(V_R + V_L)t}{L} + \Phi\right) - \sin\Phi\right] \tag{5}$$

Where $L(V_R+V_L)/2(V_R-V_L)$ is the radius for the steering path, X_c and Y_c are the new coordination of the robot's center.

For a small robot application, the mathematical model of the robot can be approximated as [12]:

$$X_c(t) = X_o + S \cdot \cos\Phi \tag{6}$$

$$Y_c(t) = Y_o + S \cdot \sin\Phi \tag{7}$$

where $S = (S_L + S_R)$

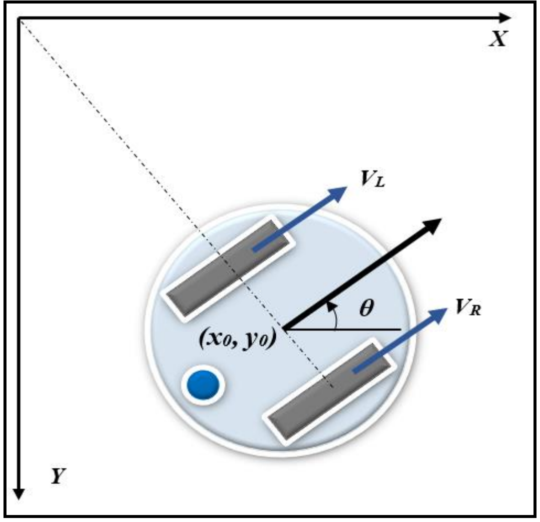

Fig. 2. The kinematics of the mobile robot.

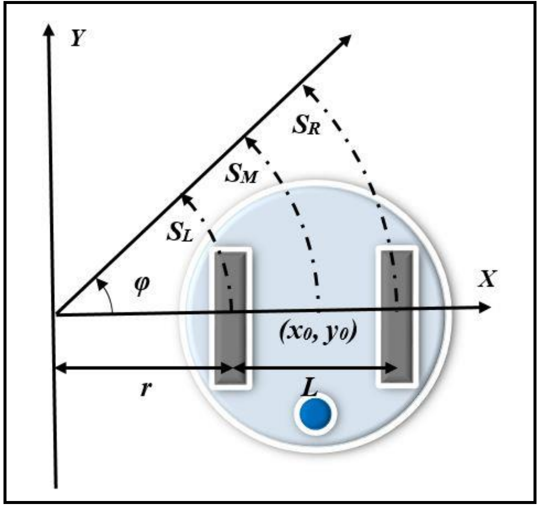

Fig. 3 Mobile robot during steering process.

B. Kinematic model of multi-robot in presence of light spot

The kinematic model of the group of robots in the presence of light is divided into two cases; the first case includes modeling the motion behavior of the group of robots when the light is normally distributed in the robot-sensing zone, while another case, the spot of light is appearing in the robot-sensing zone.

In the case of normally distributed of light, the robots in the light zone move in random direction since the light intensity is equilibrium, so there is no target point, and the robots are achieving only obstacle avoidance task when two robots or more are located inside the repulsion zone as shown in Fig. 4. The motion direction of the robot can be described by the following equation [20]

$$\vec{d}_r(t+\tau) = -\sum_{j\neq i}^{n} \frac{\vec{r}_{ij}(t)}{\left|\vec{r}_{ij}(t)\right|} \tag{8}$$

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

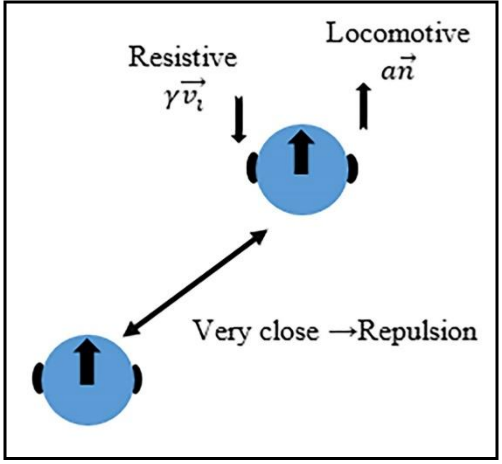

Fig. 4 The robots in case of uniform light.

In the case of modeling the group of robots moves in the light spot zone, the robots change motion direction to the center of the light spot since the intensity of light will be the maximum value at the center of the light spot and the robots tracking the maximum intensity by the light sensor. If more than one robot sensing the light spot at the same time, these robots will be tracking the light spot at the same time. In order to achieve high-performance tracking to the light spot, the robot zone must be divided into three zones includes attraction, orientation, and repulsion zones as shown in Fig. 5.

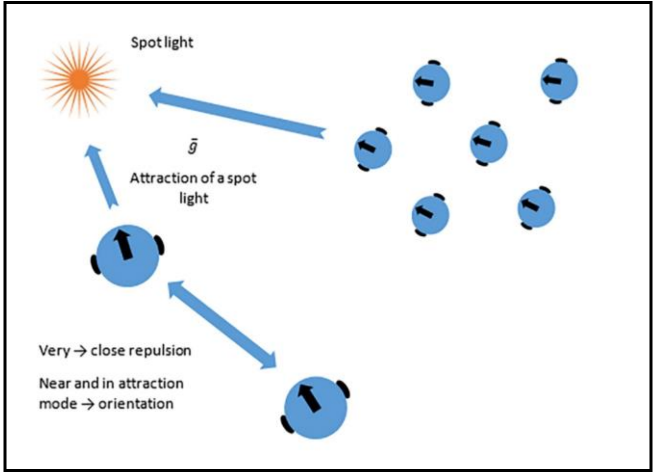

Fig. 5 The interactions of the robots during attraction to the light spot.

At the attraction zone, the robot change motion direction toward the light spot, so the mathematical model of the robot in this zone is

$$\vec{d}_a(t+\tau) = \vec{g}_i \tag{9}$$

Where g_i is a unit vector of the ith member in the direction of the spot of light.

During the robots tracking the light spot, they will be in close with each other and they enter the orientation zone, so the orientation task must be achieved by the robots, in which, the direction of each robot will be aligned with the neighbor robots, and the mathematical model of the motion behavior is described by the following equation

$$\vec{d}_o(t+\tau) = -\sum_{j=1}^{n} \frac{\vec{v}_j(t)}{\left|\vec{v}_j(t)\right|} \tag{10}$$

Where v_j is the moving direction of the jth neighbor.

Finally, if the robots continued to come closer together during tracking to light spot and enter to the repulsion zone, the robots may collide by each other, so to solve this problem; obstacle avoidance must be performed in this zone, which describes by the mathematical equation

$$\vec{d}_r(t+\tau) = -\sum_{j\neq i}^{n} \frac{\vec{r}_{ij}(t)}{\left|\vec{r}_{ij}(t)\right|} \tag{11}$$

The direction of each member will be updated each time constant τ according to the following manner:

1- If any individual exist in the repulsion zone then $d_r = d_r(t+\tau)$
2- if there are no one in the repulsion then the orientation zone is checked and the new direction will be $d_r = d_o(t+\tau)$
3- if no one near the robot then it will just attract the spot light $d_r = d_a(t+\tau)$

Each robot will follow the high light intensity until reaching the highest intensity, and then it will stop. If the light spot move then the position of the maximum light intensity will change and accordingly the robot direct to a new position.

C. Mobile robot path planning

When a robot detects the light it will change its direction and direct move toward the high density light until reaching a specific intensity of light then it stops. So the motion direction of the mobile robot related to the gradient of light intensity. Controlling the motion direction of the mobile robot is achieved by control the left wheel and right wheel velocity, so the left wheel and right wheel velocities are related to the pattern of the light gradient. The light sensor has been used to sensing the light while the direction of the light gradient is evaluated by using two sensors in the mobile robot as shown in Fig. 6.

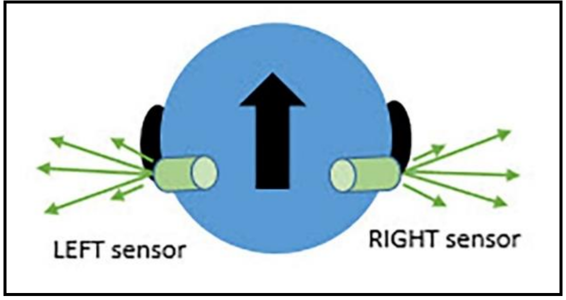

Fig. 6 The light sensors of the mobile robot.

The light sensors are measuring light, which converted into a voltages value. These values will be varied between the left sensor and right sensor depending on the light intensity. So, the robot will change direction toward the sensor has larger value until the instantaneous values of the left sensor and the right sensor are equal (see Fig. 7).

The procedure is described by the following pseudo

```
//Mobile robot tracking to light spot
LV is the light intensity value of left sensor
RV is the light intensity value of right sensor
RT = LV – RV
Loop
   Until |RT| <= error value
      If RT > 0
         Robot steering to left
      Else
         Robot steering to right
      End
      Update LV and RV
      While LV or RV >= threshold value
         Robot is stop
           End
Robot move forward direction to the light spot
```

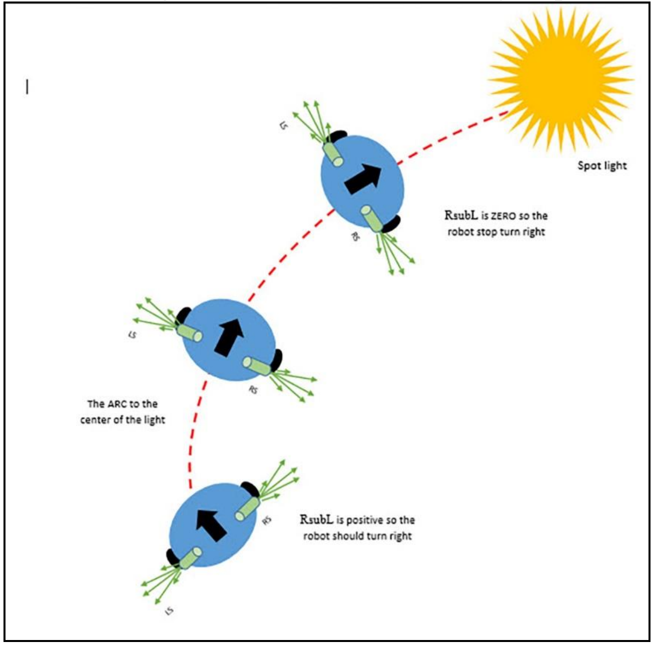

Fig. 7 The mobile robot tracking to the light spot.

III THE SIMULATION OF MULTI-ROBOT SYSTEM

Within a (35m*25m) environment, a differential drives mobile robot with a circular body is used to achieve several experiments in order to simulate the proposed approaches of the multi-robot system. The diameter of the robot body is 27 cm and the mass of the body is 1.031 kg, it has two active left and right wheels and one passive back wheel which the two wheels are cylindrical shape with a dimension of diameter is 12.35cm, and the thickness is 3.08cm while the mass of wheel is 0.29kg, each active wheel has driven by a motor with maximum torque is 2.5 N.m. The back wheel is spherical with radius is 6.7 cm and mass is 0.37 kg. In order to track the light by the robot, two light sensors are fixed to the front of the body in the right and left sides. While to interaction the robots with each other, three proximity laser sensors are used, which are fixed in the mid, left side, and right side of the robot body. The proximity sensors are used to maintain the fixed distance between robots inside the light tracking zone. The laser sensing is a cone with a range of less than 0.6 m and an angle of 40˚ for the side, and 20˚ for the front sensor.

The simulation of the system includes two groups of experiments. The first group for a fixed light spot while the second group for a dynamic light spot.

A. Attraction of Robot to Fixed Light Spot

In the first group of experiments, there are several scenarios of experiments will be achieved in order to test the performance of attracting the robot to the light spot which the robots will be tested in case of light spot appear in the region of robot sensing.

1) Single light spot

Robot attraction to the fixed light spot has been tested, which the frames of Fig. 8 describe the path planning of a robot. A case of a light spot outside the sensing region of the robot, the robot moves to random target, while in case of appearing the light spot in sensing region of the robot, the robot will change the motion direction toward the light spot.

In Fig. 9, multi-robot attraction to the fixed light spot has been tested, in which four robots are used for this experiment, from observation of the simulation, we can see each robot change its direction to the light spot when it is inside the attraction zone, in addition, the robots form flock and achieved obstacle avoidance between each other.

2) Two light spots

In Fig. 10, two light spot has been used for this experiment, which these light spots working sequentially. The mobile robot attraction to the first light spot which is turned on, at the moment of turning off first light spot and turning on the second light spot, the mobile robot instantly change its motion direction toward the second light spot. In Fig. 11, multi-robots have been used in order to test the performance of attraction to light spot with more than one robot.

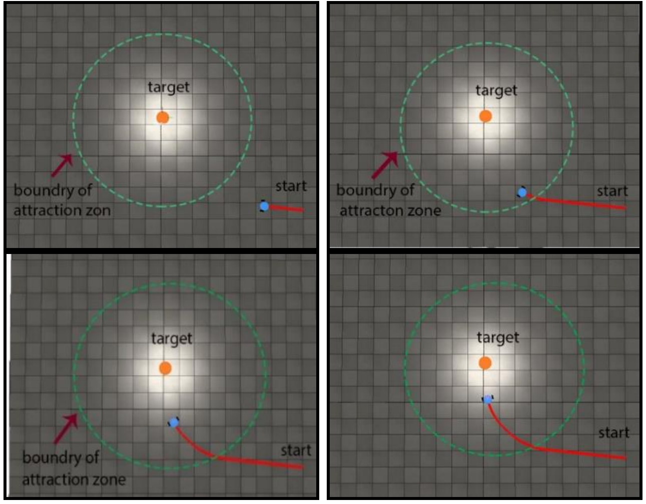

Fig. 8 Attraction robot to the light spot.

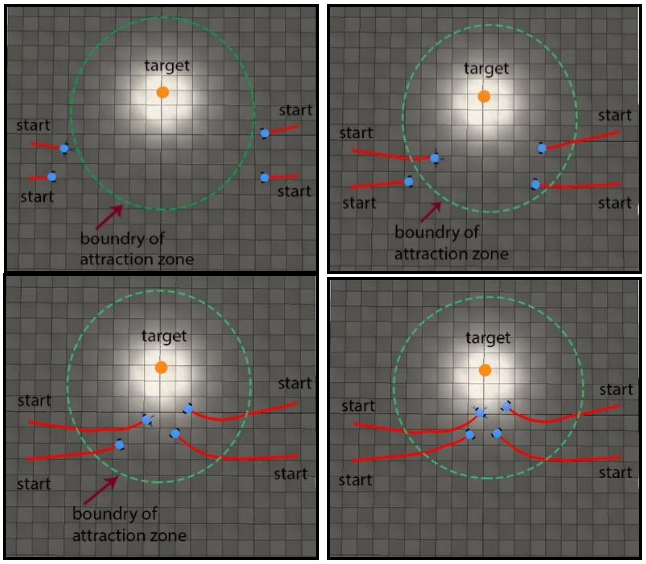

Fig. 9 Multi robot attraction to the light spot

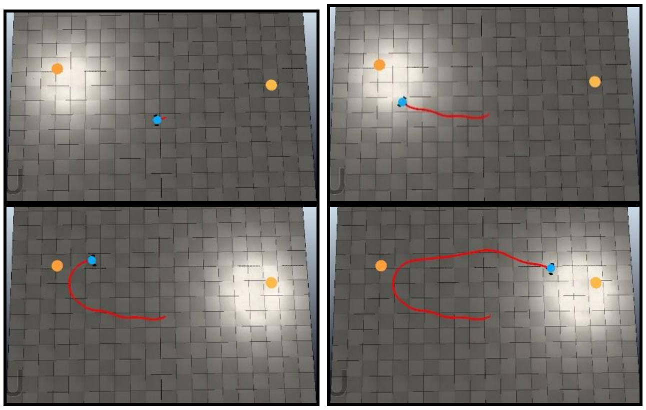

Fig. 10 The simulation of system by using of two light spots.

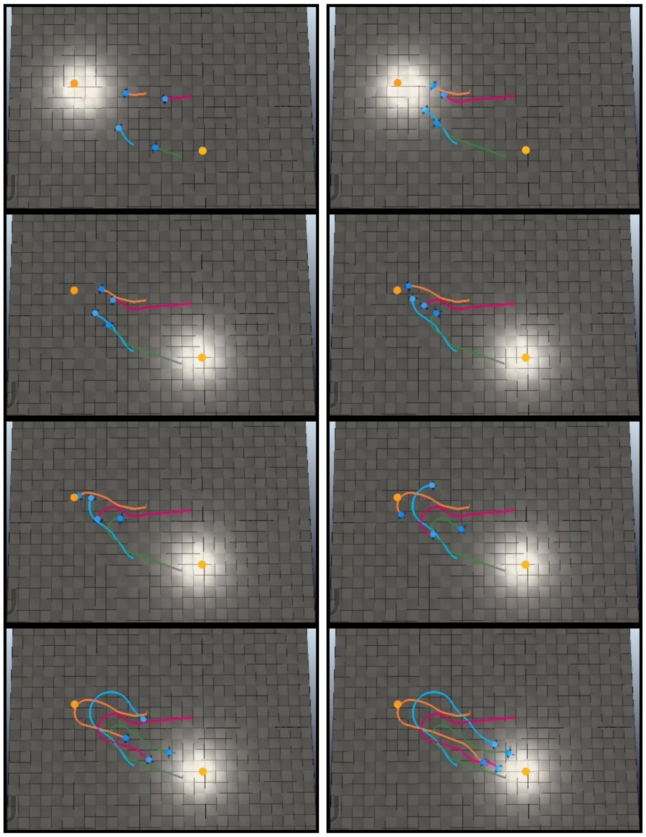

Fig. 11 The simulation of multi-robots system by using to light spots.

B. The tracking mobile robot to the movable light spot

Several experiments are implemented in order to test the performance of tracking mobile robot to movable light spot. The simulation of tracking mobile robot to the movable light spot shows that the mobile robot trying to keep a fixed distance from the movable light spot and move by the same velocity of the light spot. In order to test the performance of tracking to movable light spot, several patterns of light spot motion have been used such as the pattern of straight-line motion, circular motion pattern, and zigzag motion pattern.

Fig. 12 shows the results of mobile robot tracking to movable light spot that performed straight-line pattern, in addition to x-plot and y-plot with respect to time, which can observe the performance of tracking to light spot. In Fig. 13, multi-robots are used, in which all mobile robots are tracking the movable light spot, in addition, it achieved formation process by self-organization based on orientation process to form a flock, while at the case of the individuals are entered to the repulsion zone, obstacle avoidance will be performed.

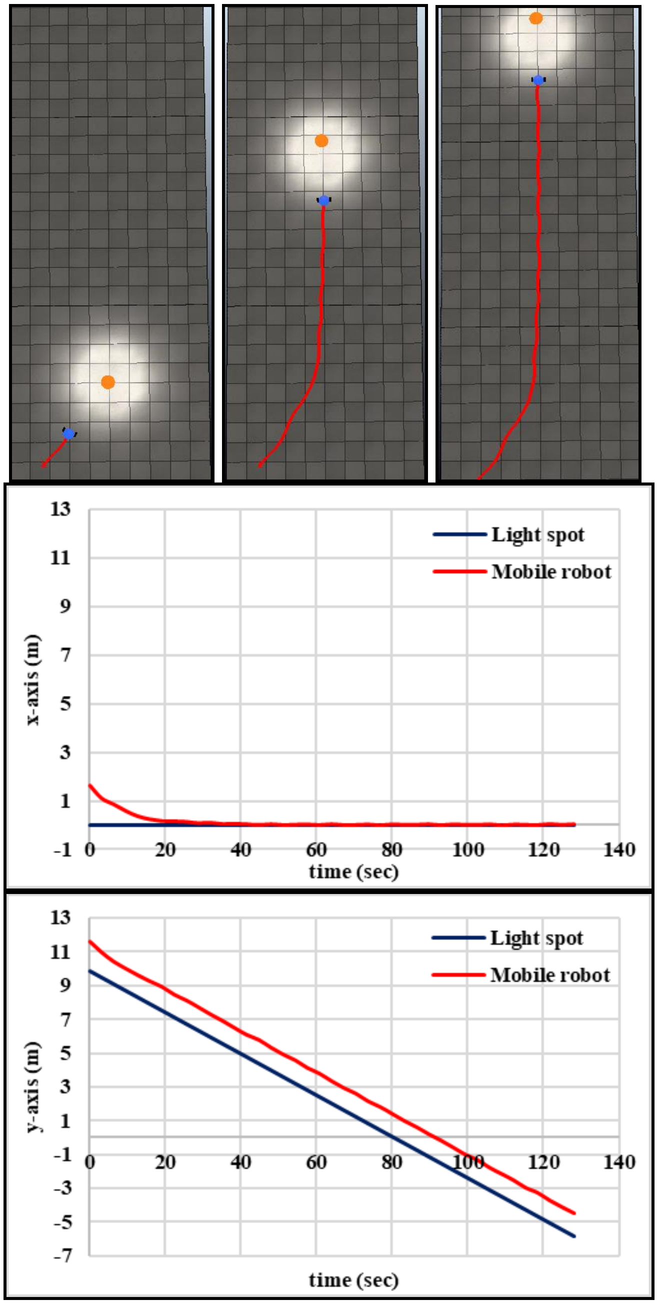

Fig. 12 Tracking the mobile robot to movable light spot in case of the straight-line pattern.

In order to test the performance of tracking mobile robot to movable light spot, the circular pattern has been achieved by movable light spot in which the mobile robot must change the motion direction instantaneously during tracking the movable light spot. Fig. 14 shows only one mobile robot tracking the movable light spot, which the mobile robot must achieving high-performance of synchronization of motion direction with the motion direction of the movable light spot.

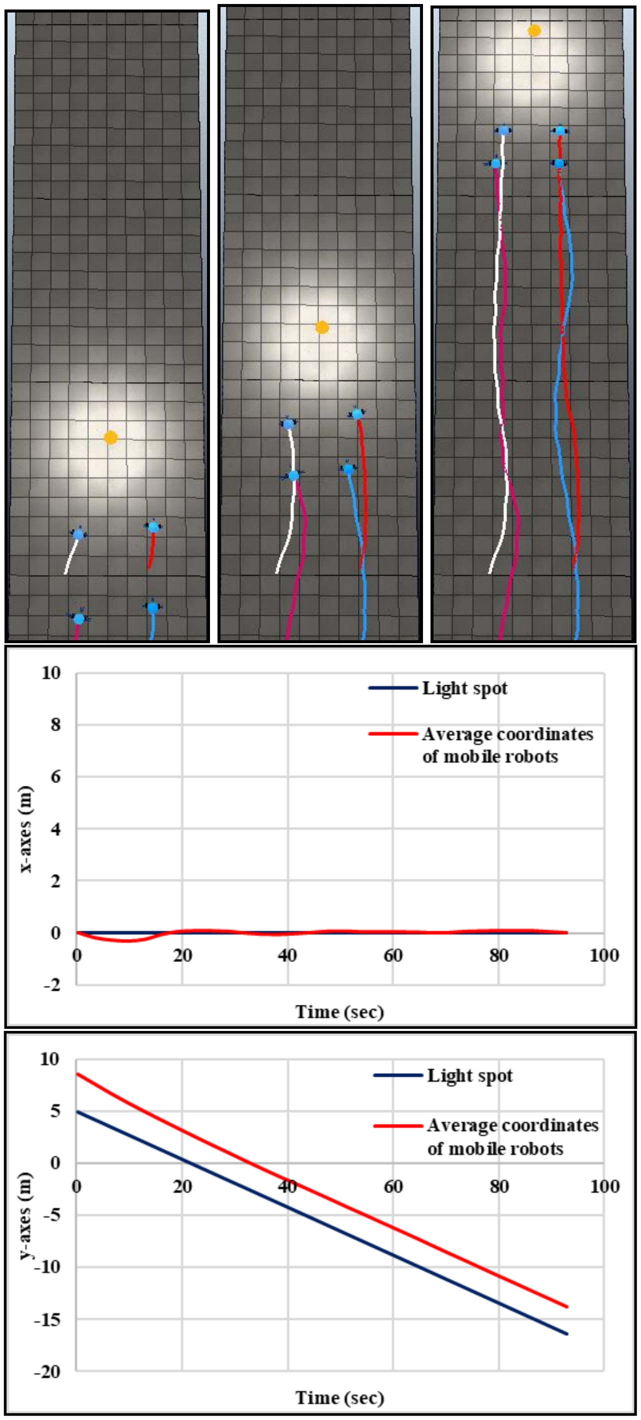

Fig. 13 Tracking the multi-robots to movable light spot in case of the straight-line pattern.

In Fig. 15, the system is complicating by increasing number of a mobile robot to four, in this case, the challenge of the system is all mobile robot must synchronize its motion direction with the direction of the movable light spot. In addition, they must achieve synchronization between each other in case of all mobile robot entered into the attraction zone and performing orientation in case of being close together which achieved formation process. Also, in the case of the mobile robots being close with each other that means entered in the repulsion zone, so the obstacle avoidance must be performed.

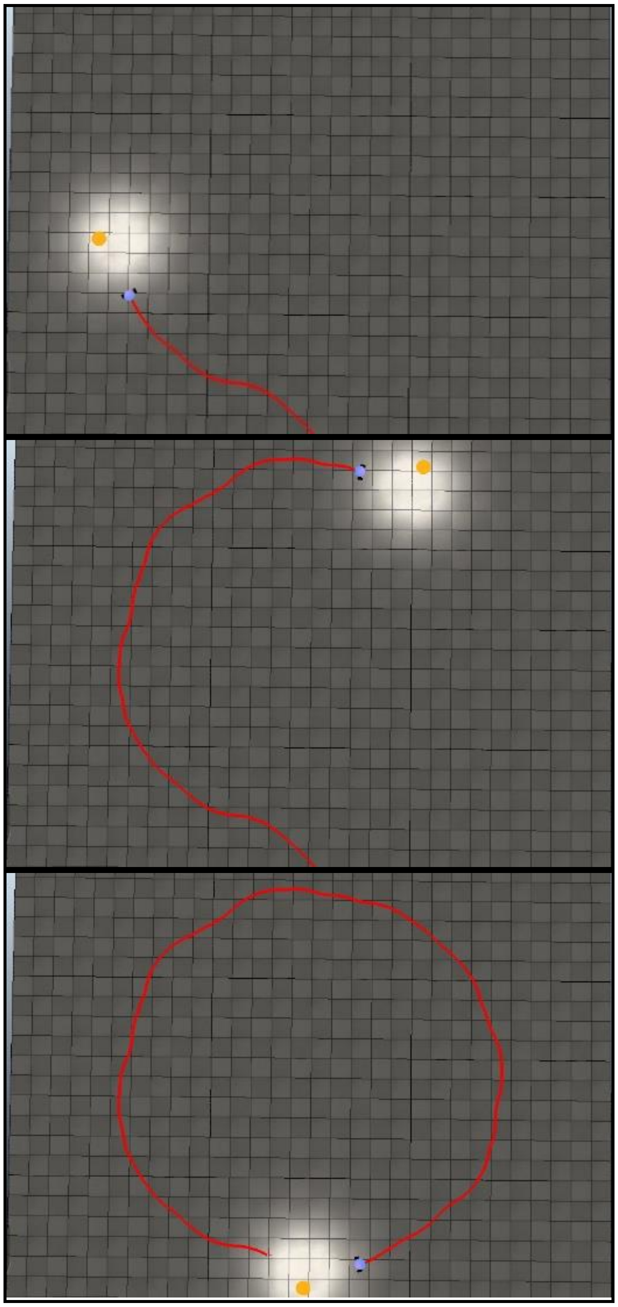

Fig. 14 Tracking the mobile robot to movable light spot in case of the circular pattern.

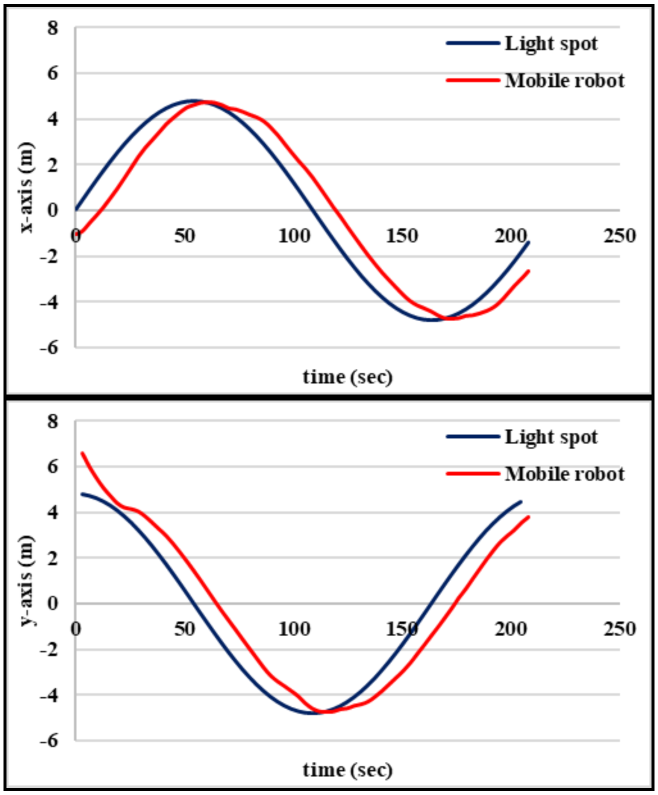

Fig. 14 Continued.

Several experiments have been achieved in order to test the performance of robots maneuver during the robot tracking the movable light spot, which this challenge needs for high-performance steering system of the mobile robot. In Fig. 16, only one mobile robot has been used to tracking the movable light spot, while the zigzag pattern is selected because of the direction of the path in this pattern change in the opposite way. Fig. 17 shows multi-robot tracking the movable light spot, as mentioned this case includes many challenges and the maneuver that achieve by these robots more complex due to achieving synchronization to the movable light spot direction by achieving attraction to the light, and performed formation by orientation process, in addition, to achieving the obstacle avoidance in case of entered the more than one robot to repulsion zone.

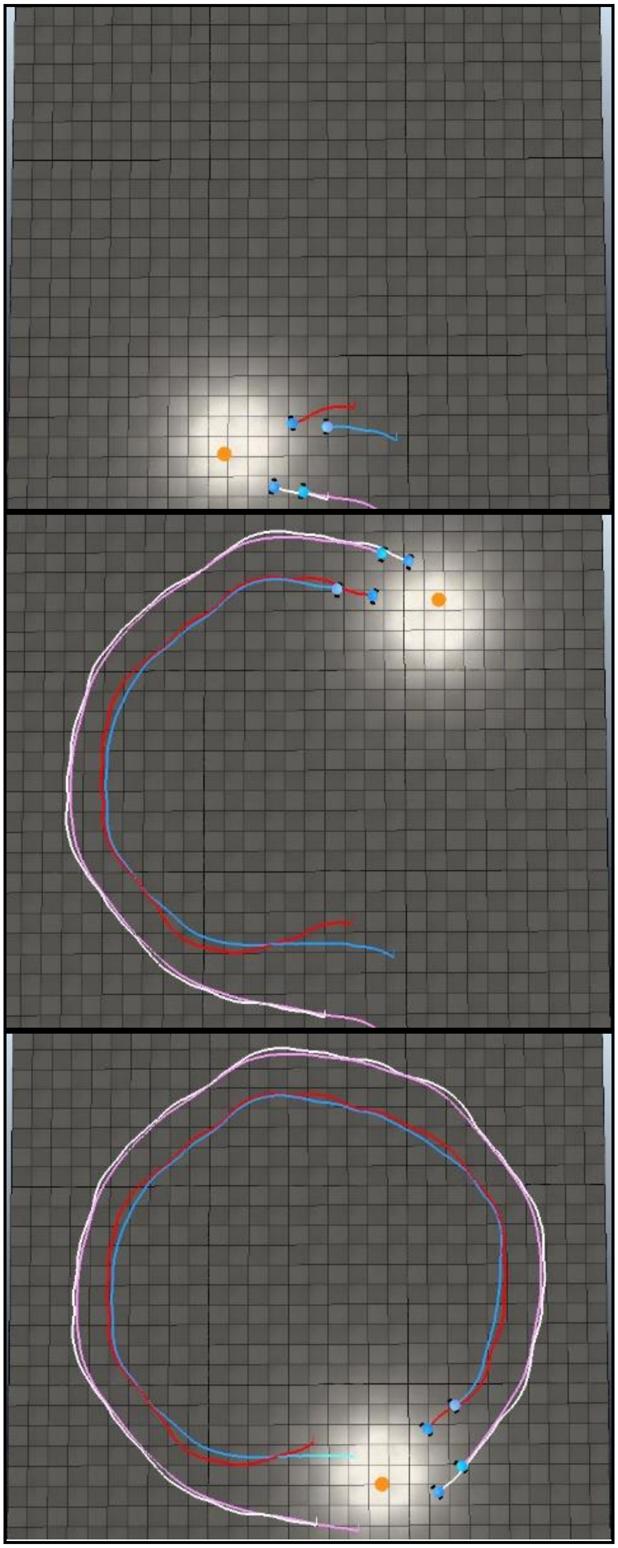

Fig. 15 Tracking the multi-robots to movable light spot in case of the circular pattern.

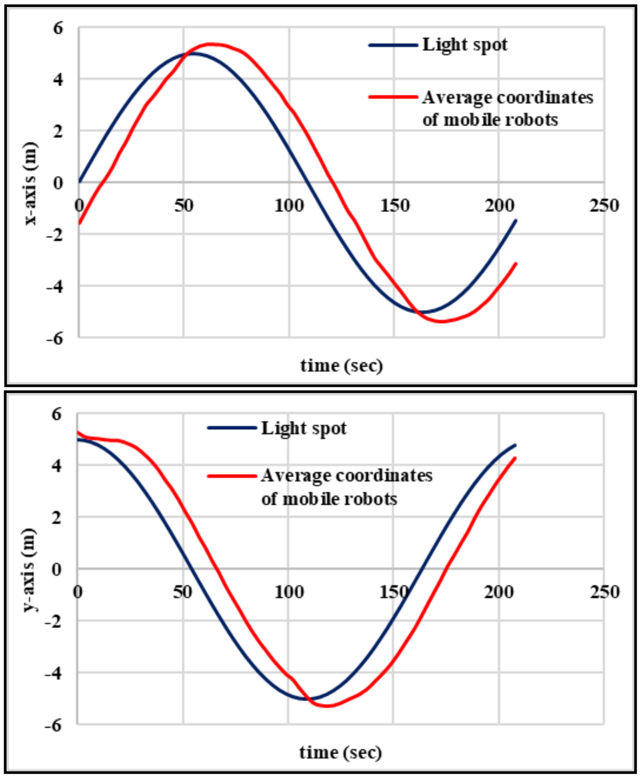

Fig. 15 Continued.

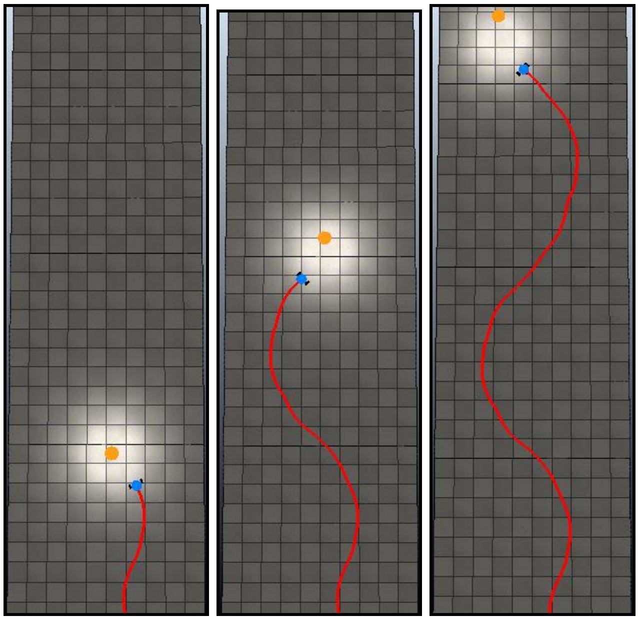

Fig. 16 Tracking the mobile robot to movable light spot in case of the zigzag pattern.

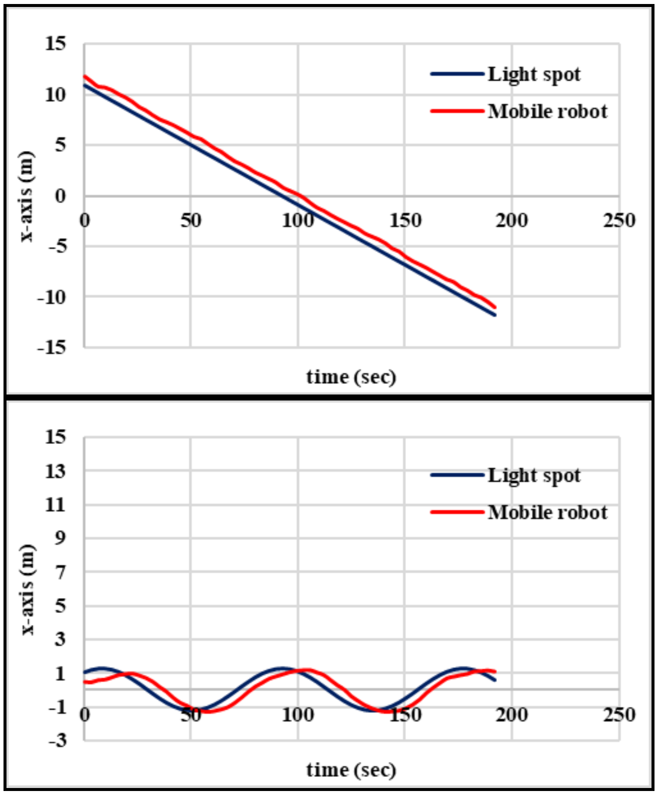

Fig. 16 Continued.

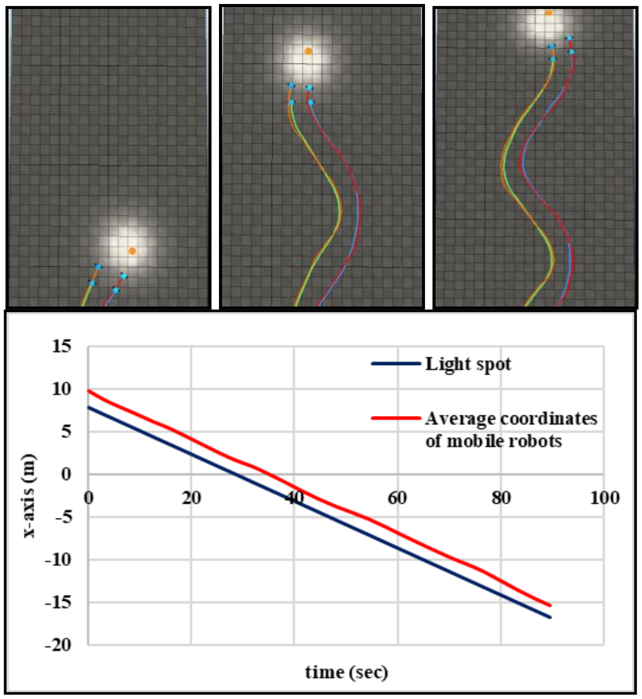

Fig. 17 Tracking the multi-robots to movable light spot in case of the zigzag pattern.

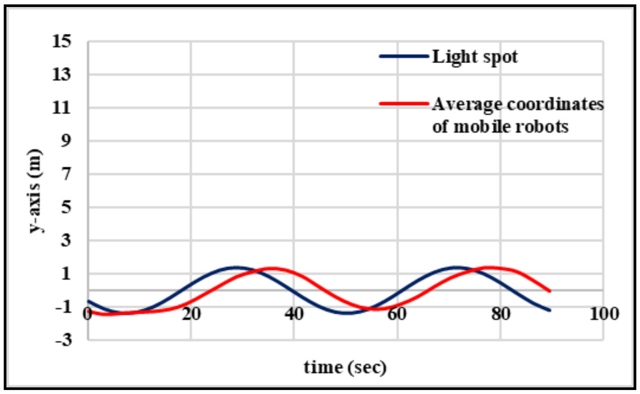

Fig. 17 Continued.

Fig. 17 and Fig. 18 shown single robot coordinates error and multi-robot coordinates error respectively during tracking movable light spot in case of the straight line pattern, which the error in case of the single robot is less than the case of multi-robot because the robot trying to perform formation process and obstacle avoidance during attraction to the light spot.

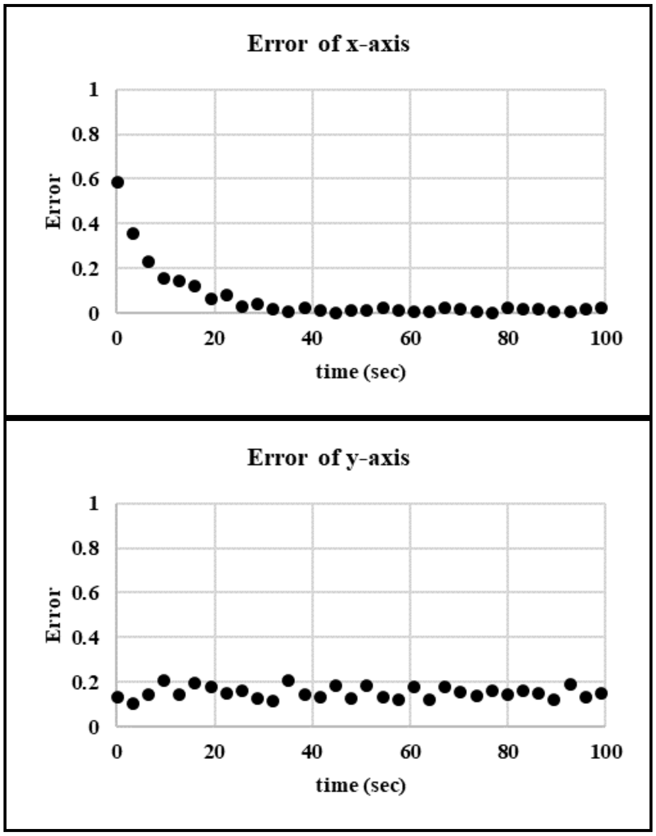

Fig. 18 The mobile robot cordinates error during tracking to movable light spot at case of stright line pattern.

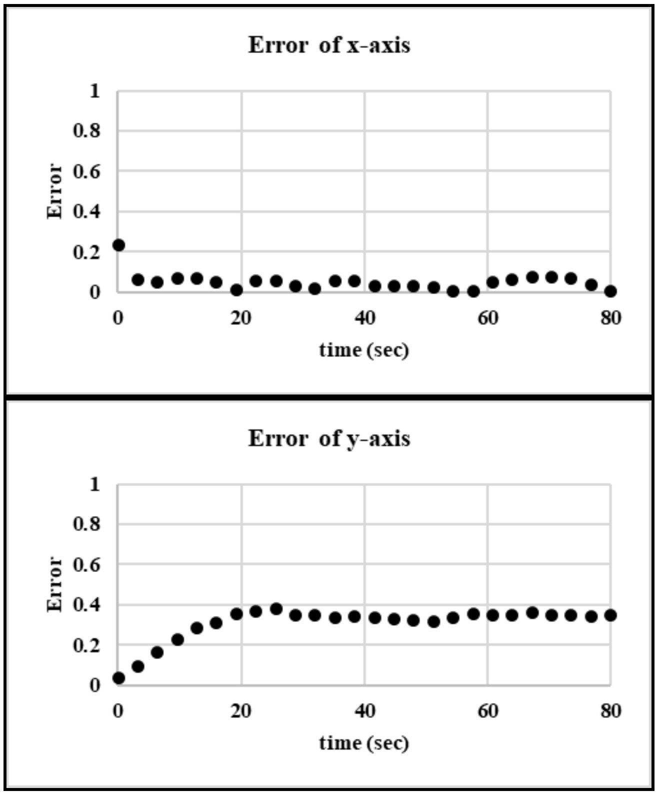

Fig. 19 The multi-robots cordinates error during tracking to movable light spot at case of stright line pattern.

Fig. 19 and Fig. 20 shown single robot coordinates error and multi-robot coordinates error respectively during tracking movable light spot in case of the circular pattern, which the error in this case more than the error in case of the straight-line pattern because the circular path is more complex than straight line, so the robot may be lost the tracking to the movable light spot, in this case, the robot must update its direction each time.

Fig. 21 and Fig. 22 shown single robot coordinates error and multi-robot coordinates error respectively during tracking movable light spot in case of the zigzag pattern, in this case the performance of tracking is less the two previous cases due to the complexity of the zigzag path more, which the robots must update the direction instantaneously, in addition, to change the direction of mobile robot in order to track the movable light spot.

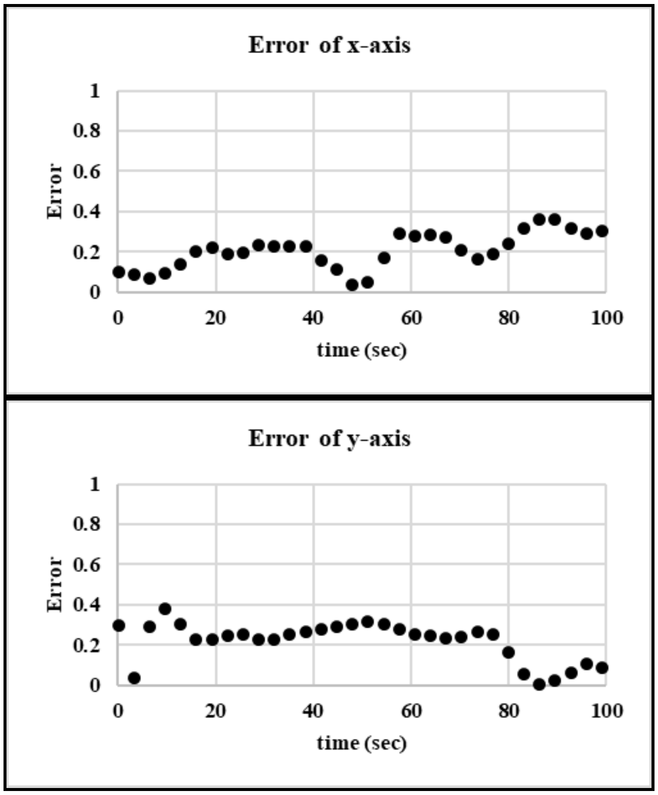

Fig. 20 The mobile robot cordinates error during tracking to movable light spot at case of circular pattern.

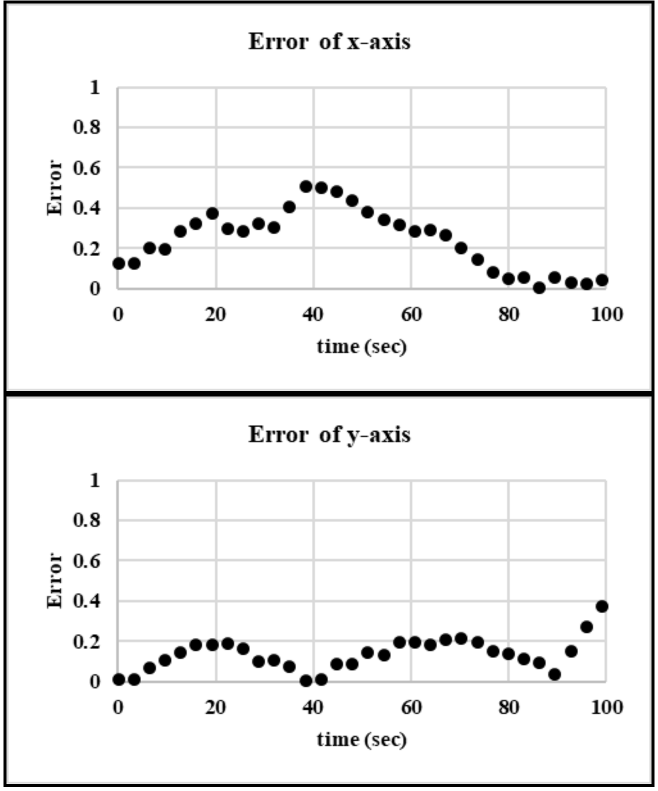

Fig.21 The multi-robot cordinates error during tracking to movable light spot at case of circular pattern.

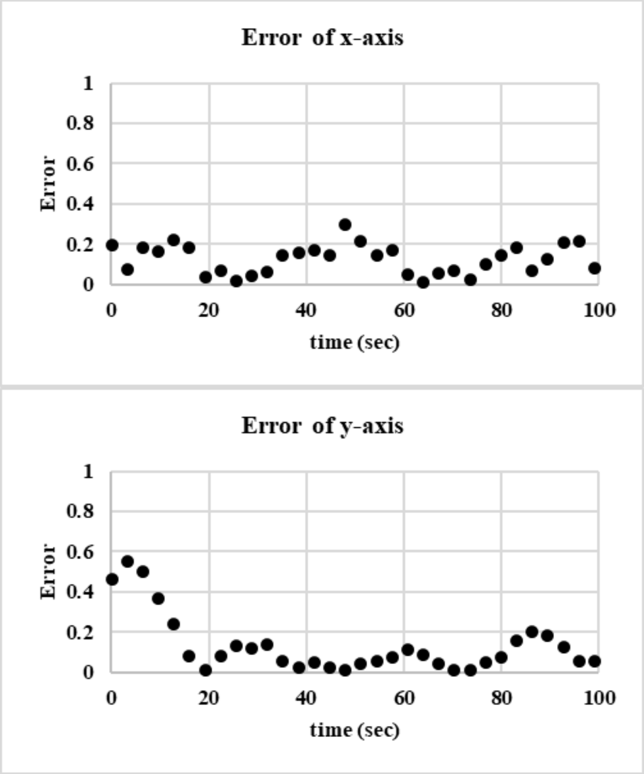

Fig. 22 The mobile robot cordinates error during tracking to movable light spot at case of zigzag pattern.

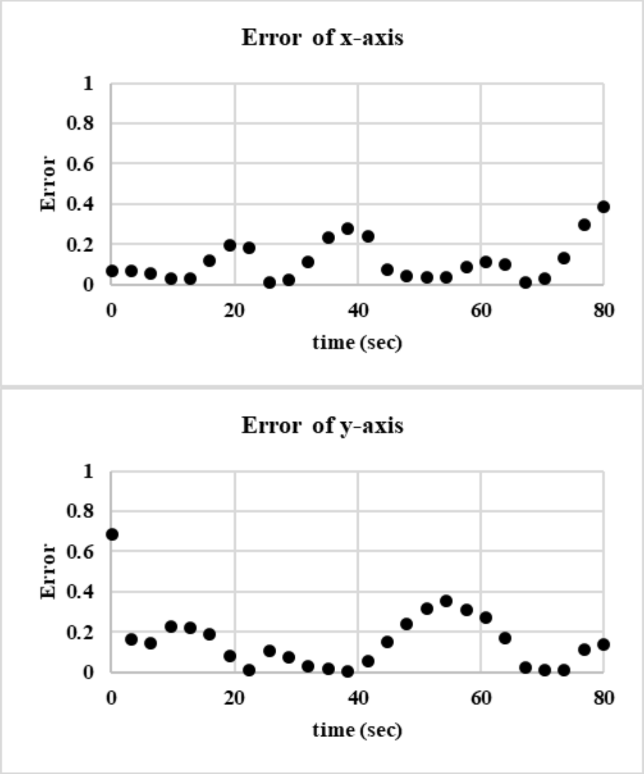

Fig. 23 The multi-robot cordinates error during tracking to movable light spot at case of zigzag pattern.

IV CONCLUSION

In this paper, the multi-robot system controlled by external stimuli has been proposed. The Artemia model has been used for modeling this system in which the group of Artemia is tracking to the light spot. Several experiments have been implemented in order to test the performance of the proposed model by using V-rep software. The simulation of the model is divided into two scenarios, in the first one, the system tested in presence of a fixed spot of light, while in the second, the system tested in presence of a moving light spot. From the results of the simulation, we have approved that the robots are attracting to the light spot and change its motion direction when entered to the attraction zone. In addition, the results of moving light spot proved that the multi robots can be controlled by external stimuli such as light with several moving patterns (straight line, circular and zigzag) used for achieving this proving and to evaluate the performance of tracking to the moving light spot.

REFERENCE

[1] Yi-Lin L., Kuo-Lan S., “Multi-robot-based intelligent security system”, Artif. Life Robot., Vol. 16, pp. 137–141, 2011.

[2] L. Matignon, O. Simonin, “Multi-Robot Simultaneous Coverage and Mapping of Complex Scene - Comparison of Different Strategies”, Robotics Track, Jul 2018, Stockholm, Sweden. pp.559-567.

[3] Marino A., Parker L. E., Antonelli G., Caccavale F., “A decentralized architecture for multi-robot systems based on the null-space-behavioral control with application to multi-robot border patrolling”, J. Intell. Robot. Syst., Vol.71, pp. 423–444, 2013.

[4] Khamis A., ElGindy A., “Minefield mapping using cooperative multirobot systems”, Journal of Robotics, 2012.

[5] Alex Goldhoorn, Anaís Garrell, René Alquézar, Alberto Sanfeliu, “Searching and Tracking People with Cooperative Mobile Robots”, Vol. 42, Issue 4, pp. 739–759, 2018.

[6] Shkurti F., Xu A., Meghjani M., Gamboa Higuera J. C., Girdhar Y., Giguere P., Dudek G., et al., “Multi-domain monitoring of marine environments using a heterogeneous robot team”, Intell. Robots Syst. (IROS), pp.1747–1753, 2012.

[7] Shiomi M., Kamei K., Kondo T., Miyashita T., Hagita N., “Robotic service coordination for elderly people and caregivers with ubiquitous network robot platform”, In: IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO), 2013.

[8] A. Filella, F. Nadal, C. Sire, E. Kanso, and C. Eloy, “Model of collective fish behavior with hydrodynamic interactions”, Vol. 120, Iss. 19, 11 May 2018.

[9] Kevin M. Schultz, Kevin M. Passino, and Thomas D. Seeley, “Mechanism of flight guidance in honeybee swarms: subtle guides or streakier bees”, The Company of Biologists, 2008.

[10] Musad A. Haque, Amir R. Rahmani, and Magnus B. Egersted, “Biologically inspired confinement of multi-robot systems”, Int. J. Bio-Inspired Computation, Vol. 3, No. 4, (2011).

[11] Yael Katza, Kolbjørn Tunstrøma, Christos C. Ioannoua, Cristián Huepeb, and Iain D. Couzina, “Inferring the structure and dynamics of interactions in schooling fish”, Proc Natl Acad Sci USA. 2011 Nov 15, Jul 27-2011.

[12] Serge Kernbach, Ronald Thenius, Olga Kernbach, Thomas Schmick, “Re-embodiment of Honeybee Aggregation Behavior in an Artificial Micro-Robotic System”, Adaptive behavior in biological systems and autonomous artificial systems, Vol. 17, Issue 3, pp. 237-259, 2009.

[13] Yasushi Kambayashi , Yasuhiro Tsujimura, Hidemi Yamachi, Munehiro Takimoto, Hisashi Yamamoto, “Inferring the structure and dynamics of interactions in schooling fish”, 2nd International Conference on System Sciences/ Hawaii, 2011.

[14] Abdulmuttalib T. Rashid, “Leader Follower Tracking with Obstacle Avoidance using Circular Paths Algorithm”, Basrah Journal for Engineering Science, 2016.

[15] Tomáš Krajník, Matías Nitsche, Jan FaiglPetr VaněkMartin SaskaLibor Přeučil, Tom Duckett, Marta Mejail, “A Practical Multirobot Localization System”, Journal of

Intelligent & Robotic Systems, Vol. 76, Issue 3–4, pp 539–562, 2014.

[16] Mofeed Turky Rashid, “Design Model for Wireless Multi-Mobile Robot System Based on Modeling of Collective Motion of Artemia Population”, Electrical Eng. Depart./Univ. of Basrah, 2011.

[17] L. Fortuna, M. Frasca, M.G. Xibilia, A. A. Ali, M. T. Rashid, “Motion control of a population of Artemias”, Iraq J. Electrical and Electronic Engineering, Vol. 6, No. 1, 2010.

[18] Mofeed Turky Rashid, Mattia Frasca, Abduladhem Abdulkareem Ali, Ramzy Salim Ali, Luigi Fortuna, “Artemia swarm dynamics and path tracking”, springer June 2012, Volume 68, issue 4, pp 555–563, 2010.

[19] O. A. Hasan, Abdulmuttalib T. Rashid and R. S. Ali, “Centralized approach for multi-node localization and identification”, Iraq J. Electrical and Electronic Engineering, Vol. 12, No. 2, pp. 178-187, 2016.

[20] A. E. Parr, “A contribution to the theoretical analysis of the schooling behaviour of fishes”, Occasional Papers of the Bingham Oceanographic Collection1, pp.1-32, 1927.

[21] C. Wong, H. Wang, S. Li, and C. Cheng, “Fuzzy controller designed by GA for two-wheeled mobile robots”, International Journal of Fuzz Systems, vol. 9, no. 1, 2007.