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Artemia swarm dynamics and path tracking

Mofeed Turky Rashid · Mattia Frasca · Abduladhem Abdulkareem Ali · Ramzy Salim Ali · Luigi Fortuna · Maria Gabriella Xibilia

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Abstract *Artemia* larvae may show swarming organization under the presence of a light spot, while being insensitive to several other external stimuli. In this paper, the dynamics of the *Artemia* population in response to this kind of stimuli has been exploited to design a robot moving inside the water and able to lead the direction of the group. The robot therefore implements external leadership, by driving the *Artemia* population along a set of desired trajectories. Experimental results and simulations based on a model of *Artemia* motion confirmed the suitability of the approach.

Keywords Robotics · Collective dynamics · *Artemia* swarming · External leadership

M.T. Rashid · A.A. Ali · R.S. Ali
Electrical Engineering Department, University of Basrah, Basrah, Iraq

M.T. Rashid
e-mail: mofid76@yahoo.com

M. Frasca (✉) · L. Fortuna
Dipartimento di Ingegneria Elettrica Elettronica e Informatica, Universitá degli Studi di Catania, Catania, Italy
e-mail: mfrasca@diees.unict.it

M.G. Xibilia
DiSIA, Facoltà di Ingegneria, Università degli Studi di Messina, Messina, Italy

1 Introduction

Groups of animals exhibiting forms of collective behaviors like fish schooling, herding, migrations and bird flocking have been both an intense subject of study, focusing on their modeling and their self-organizing capabilities [1, 2], and a constant source of inspiration for engineered systems, and, in particular, for the design of distributed control strategies [3, 4]. Being leadership and decision-making processes crucial aspects of animal coordination, the research has also focused on these issues. It has been demonstrated for instance that, in animal groups, a small proportion of few informed individuals possessing the knowledge about the objectives to be pursued (like the position of a food source or the direction of a migration path) is sufficient to lead the group [5].

Recently, the interest has been directed to external leadership and, more generally, to the interactions between robots and groups of animals [6–12]. To do this, robots must possess specific characteristics, depending on the animals with which they have to interact. According to the definition given in [6], external leadership can be considered as the action of a natural or artificial agent able to induce a collective response on the animal group. Examples of external leaders have been reported in [7–10]. Other forms of interactions between animals and robots have been considered in [11], where decision-making in a mixed group of cockroaches and autonomous robots has been shown to lead to shared shelter selection,

Fig. 1 A photograph of an *Artemia nauplius*

or in [12] where a mobile robot interacting with a group of chicks is introduced with the aim of deriving and testing ethological behavioral models of vertebrates.

In the case of fish, external leadership plays an important role, being a strategy for guaranteeing the safety of the population in case of disasters. Having in mind applications considering hundreds of small robotic units, external leadership can be viewed as a control strategy for a system based on small animals instead of microrobots. A single leader, for instance, can allow to move in an easy way the units (of microscopic size) of a distributed control system. Since the design and the production of microrobots at a microscale is a non-trivial and expensive task, such framework could permit to develop low-cost experimental setups and to evaluate the potential applications of external leadership with different animals in the fields of environmental monitoring, transport, exploration, and ethology studies.

In this paper, we investigate external leadership in a population of *Artemia Salina* by a robotic agent. *Artemia* are crustaceans smaller than insects in size and mass. In particular, hatched *Artemia* (also called *nauplii*), used in this work, have a length typically less than 0.4 mm, only one eye, containing a photoreceptor, and a pair of antennae used as fins for swimming [13–15]. A photograph of an *Artemia* nauplius is shown in Fig. 1.

The dynamics of a population of *Artemia* has been studied in [16], where it has been observed that *Artemia* motion depends on light, while they are not influenced by other external stimuli such as electromagnetic field, DC voltage or thermal gradients. In particular, their collective motion has been observed in presence of light spot and their behavior has been modeled as a system of self-propelled particles. Starting from the results reported in [16], in this work we investigate how to implement swarm path tracking in an *Artemia* population by implementing a robotic agent acting as an external leader.

The rest of the paper is organized as follows. In Sect. 2 some characteristics of the dynamics of *Artemia* populations, and in particular in response to external fields, are discussed. Section 3 introduces the features of the robot used as external leader for *Artemia* populations. Section 4 shows the results obtained. Section 5 concludes the paper.

2 Effects of exogenous stimuli on *Artemia* swarm dynamics

The study of *Artemia* populations can be carried out with simple and low-cost experiments. In a series of experiments discussed in [16] it has been proven that, while under uniform light *Artemia* swim independently from each other, taking random directions and avoiding other individuals, when a spot of light is used, *Artemia* direct towards light, thus following a preferential direction and exhibiting a flocking behavior. A further series of experiments have analyzed the effects of other external influences (i.e., DC currents, electromagnetic fields and acoustic signals). The results of these experiments show that *Artemia* are insensitive to any of these external influences.

Based on this experimental characterization and on the principles of collective behavior in animals, a mathematical model of *Artemia* motion under a light spot has been derived. The model relies on three different zones, accounting for orientation, attraction and repulsion between individuals and between individuals and the light spot, and is described in Sect. 4.

These results suggest that light can be used to drive *Artemia* swarms along some desired trajectories. In this paper, this is achieved by a microrobot driving a light source inside the water. The experimental setup used in this paper is described below.

A population of *Artemia* hatched in a tank filled with salt water is considered. A controlled number of individuals is then transferred with a medicine dropper into a second tank placed in a dark environment, where their motion can be monitored and controlled. The dark environment is needed in order to eliminate the effects of environmental light and to have a black background which increases the contrast of movies and pictures. To the aim of monitoring, a digital camera with a 3× optical zoom and 10 megapixels resolution is used. The camera is mounted at a distance of 10 cm above the tank as shown in Fig. 2. Image processing techniques are then used to extract the *Artemia* trajectories, as well as important information on *Artemia* motion from the recordings.

3 The robotic external leader

In this section the structure of the robot used as external leader in an Artemia swarm is described. A robot with the structure shown in Fig. 3 has been designed. The robot consists of a wheeled structure moving outside the tank which drives, through a magnet, a light source placed inside the tank.

The underwater part of the robot consists of three iron ball wheels which are moved by applying a magnetic field source from outside of the tank as is schematically shown in Fig. 3. By making this part of the robot passive, its dimensions can be reduced compared to the case in which it had to be equipped with mechanisms for actuating its motion. An underwater robot, large with respect to the *Artemia* size, could in fact heavily affect *Artemia* motion by generating for instance flow waves. This part of the robot is equipped with an autonomous circuitry to generate a light spot source, made of a LED and a 12 V battery. The size of this part of the robot is 5 cm × 5 cm × 1.5 cm (width, length, height).

The wheeled structure moving outside the tank consists of a differential drive robot. The size of this part of the robot is 7 cm × 7 cm × 11 cm (width, length, height). The two active wheels of the robot are actuated by two independent servo motors modified for continuous rotation. In particular, we used ZS-F135 sub-micro servo motors with the following specifications: speed 0.16 s/60° at 4.8 V; torque 1.2 kg cm at 4.8 V; weight 8 g, size 22.8 mm × 11.6 mm × 22.6 mm. The robot is powered by three 1.5 V batteries. The robot is equipped with a microcontroller AVR Atmega162, which receives control signals from a PC and generates the two PWM signals needed to control the servo motors. The communication between PC and robot is implemented through a ZigBee wireless protocol with XBee ZigBee/Mesh RF modules.

The top of the wheeled part of the robot contains three magnetic iron sticks as shown in Fig. 4 which describes both the robot and the control circuitry used. Each one of these magnetics attracts one of the iron balls of the underwater part of the robot, so that the motion of the wheeled part is reproduced by that of the underwater part. In this way, two advantages can be obtained: the dimensions of the underwater mechanical part of the robot are reduced in order to minimize the influence of its motion on that of *Artemia* and simple control techniques, based on differential drive, can be used to control the trajectory of the robot.

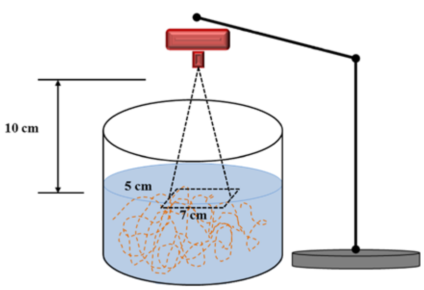

Fig. 2 Setup used for recording the trajectories of *Artemia*

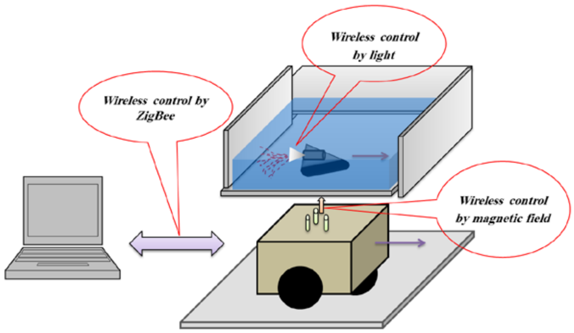

Fig. 3 Structure of the robot used as external leader in an *Artemia* population

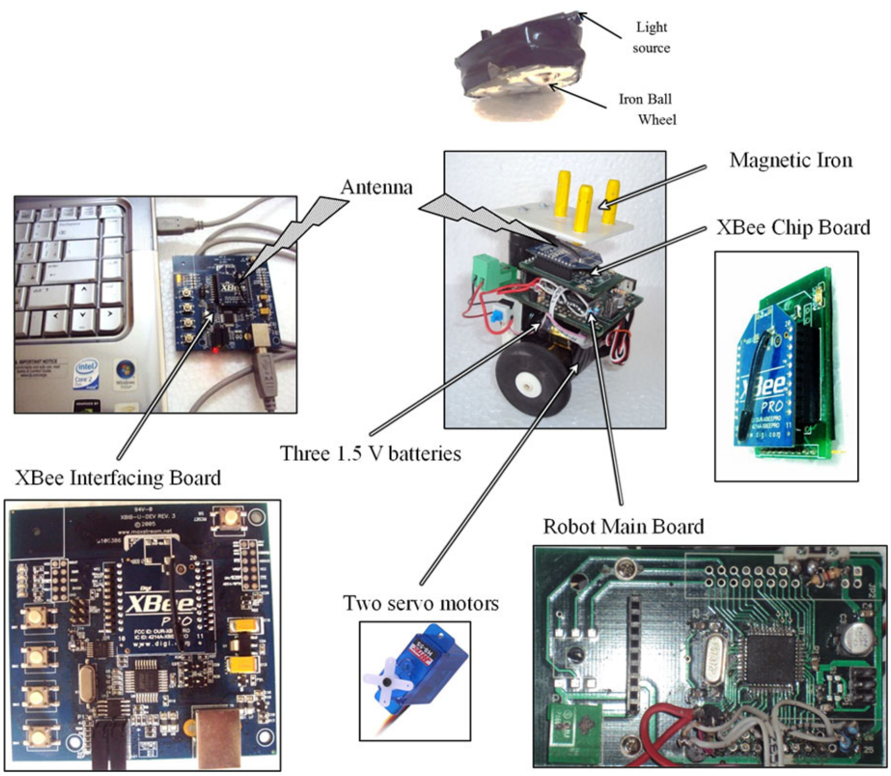

Fig. 4 A photograph of the robot and of the control circuitry

Let X and Y indicate the coordinates of a global reference frame, x_m and y_m, those of a reference system placed in the center of the robot P, R the radius wheel, L the distance of the wheel from P, (x_0, y_0) the coordinates of P in the global reference frame and θ the robot orientation in this reference frame, as shown in Fig. 5. Using these notations, the equations to derive the control signals v_R and v_L (i.e., the linear velocities of the left and right wheel, respectively) are reported in the following. For a differential drive robot, it holds:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{1}$$

where $\dot{x}$ and $\dot{y}$ denote the velocity of the robot in the direction of X and Y axes, respectively, $\dot{\theta} = \omega$ the angular velocity and v the linear velocity of the robot in the head direction. Hence, the robot motion is controlled by v and ω which are function of time t. These parameters are linked to v_R and v_L by:

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2L} & \frac{1}{2L} \end{bmatrix} \begin{bmatrix} v_L \\ v_R \end{bmatrix} \tag{2}$$

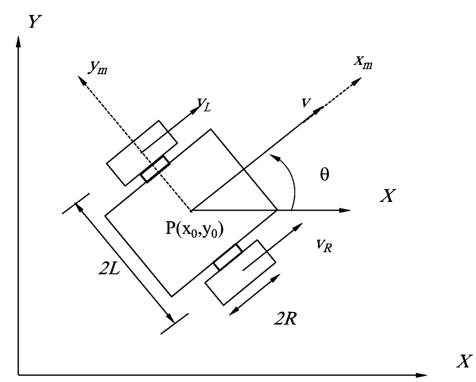

Fig. 5 Reference frames used for the wheeled part of the robot

From (1) and (2), the relationship between the trajectory parameters expressed in terms of $\dot{x}$, $\dot{y}$ and $\dot{\theta}$ and the control signals v_L and v_R can be derived:

$$\begin{bmatrix} v_L \\ v_R \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & L \\ -\cos\theta & -\sin\theta & L \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{3}$$

Equation (3) is used to derive the reference control signals for the wheel motors for several test trajectories (linear, circular and zigzag pattern) used in our experiments.

4 *Artemia* path tracking

In this section the robotic external leader described above is used to control *Artemia* motion in order to follow a predetermined trajectory. In particular, a set of different trajectories has been considered and both simulations and experiments have been used to confirm the suitability of the approach.

4.1 Simulation results

At first, the model derived in [16] has been used to simulate the motion control of a population of *Artemia*. The model is based on self-propelled particles (representing *Artemia*) which interact with rules depending on the relative distance between individuals and between individuals and the external source. It allows to account for the behavior of *Artemia* population either in the case of motion under an uniform light (where *Artemia* perform only individual avoidance) or in the presence of a light spot.

For each individual, three zones (repulsion, orientation, and attraction zones) are defined. In the repulsion zone, each individual i performs obstacle avoidance with the other individuals j lying in the same zone. Concerning the attraction zone, when a light spot is in the attraction zone of individual i, the individual points its motion direction towards the light spot. In the orientation zone, each individual i changes its motion direction according to the direction of the other individuals j lying in that zone. The position $\mathbf{r}_i$ of each individual of the population is computed as follows:

$$\mathbf{r}_i(t+\tau) = \mathbf{r}_i(t) + \tau \mathbf{v}_i \tag{4}$$

where τ is the sampling time (fixed as $\tau = 0.04$ s, since the frame rate of the recordings is 25 frames per second) and $\mathbf{v}_i$ is the velocity of each individual. This is assumed to have a modulus with a uniform distribution around the mean value of 0.36 cm/s as measured during our experiments. The direction of the velocity of each individual is computed taking into account the following rules.

Artemia perform obstacle avoidance inside their repulsion zone, and in this case they do not perform any other behavior (orientation or attraction) since repulsion is considered the most important behavior when two individuals are very close. Therefore, when an agent has individuals in the repulsion zone, the direction of its velocity is updated according to

$$\frac{\mathbf{v}_i}{|\mathbf{v}_i|} = -\sum_{i \neq j}^{n_r} \frac{\mathbf{r}_i(t) - \mathbf{r}_j(t)}{|\mathbf{r}_i(t) - \mathbf{r}_j(t)|} \tag{5}$$

where n_r is the total number of individuals in the repulsion zone of individual i.

Individuals sense (and are attracted by it) the presence of the spot of light only in the attraction zone. In this condition, they may also perform orientation, if other individuals are in their orientation zone. Therefore, we distinguish two cases: (1) update due only to the presence of the light spot in the attraction zone:

$$\frac{\mathbf{v}_i}{|\mathbf{v}_i|} = \frac{\mathbf{g}}{|\mathbf{g}|} \tag{6}$$

where $\mathbf{g}(t)$ is the position of the light spot; and (2) update due the presence of individuals in the orientation zone and to the light spot in the attraction zone:

$$\frac{\mathbf{v}_i}{|\mathbf{v}_i|} = \frac{\mathbf{g}(t)}{|\mathbf{g}(t)|} + \sum_{j=1}^{n_o} \frac{\mathbf{v}_j}{|\mathbf{v}_j|} \tag{7}$$

where n_o is the total number of individuals in the orientation zone of individual i.

In [16] the case of a static light source has been considered. In order to validate both the model performance and the *Artemia* behavior, in this paper the position of the external light source is considered as time-dependent, i.e., $\mathbf{g} = \mathbf{g}(t)$ in (6). Three different trajectories (linear, circular and zigzag pattern) have been simulated. The choice of the velocity of the light source has been made in accordance with the previous experimental results on *Artemia* motion and will be discussed in more detail below.

Figure 6 shows four frames extracted from the results of simulation for each of the three different trajectories tested. As it can be observed, the model behavior demonstrates the possibility to induce *Artemia* to follow a given trajectory by controlling that of the light source. This is also shown in the experiments described in the next subsection.

4.2 Experimental results

The experiments designed to verify the capability of *Artemia* population to follow predetermined trajectories consist of four steps:

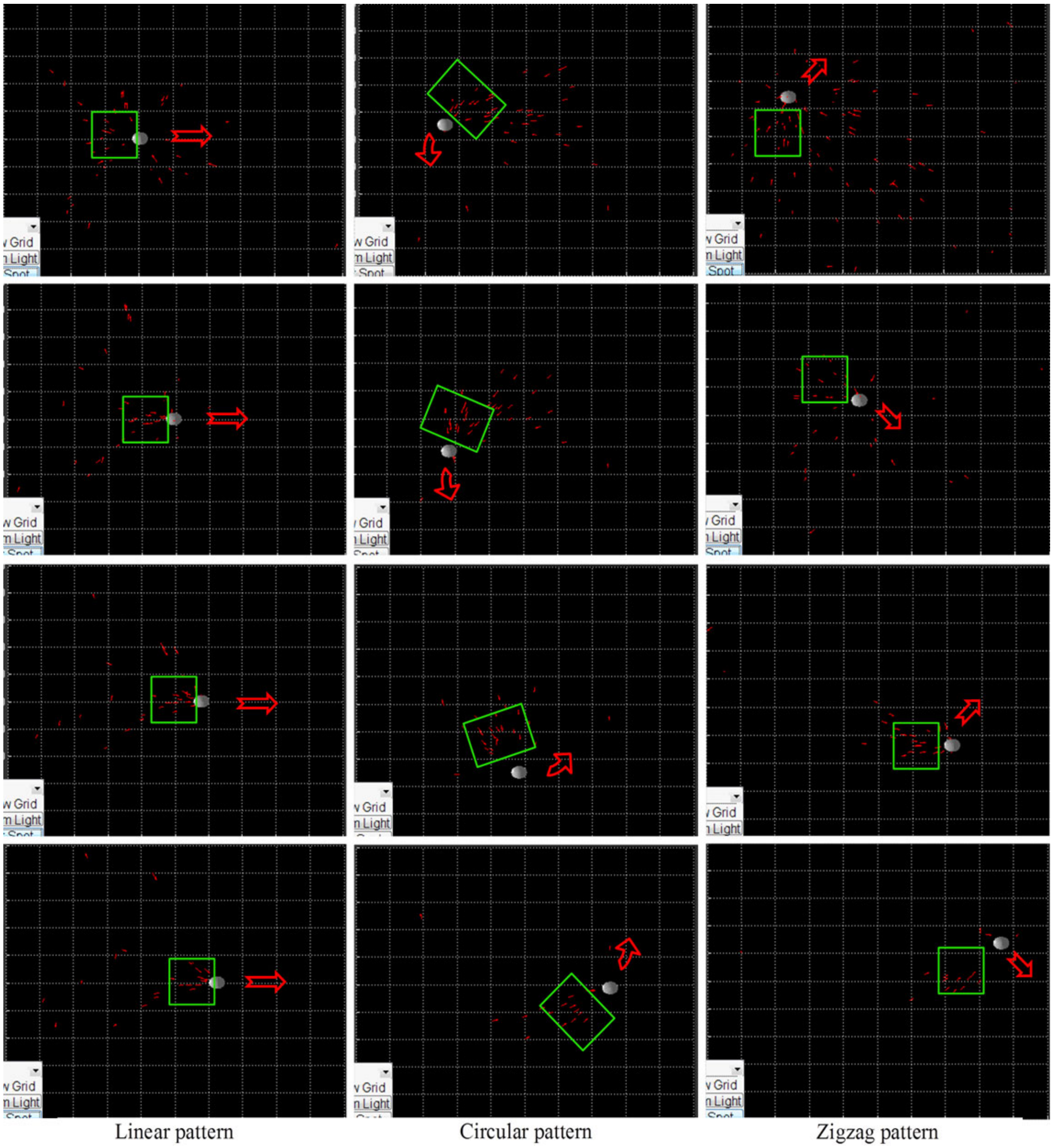

Fig. 6 Simulation results of *Artemia* motion following different trajectories of the robotic agent. The *light position* corresponds to the *white circle*. The *rectangular box* is used to highlight the *Artemia* following the light spot

1. Hatching of *Artemia* population under uniform light and transferring of a controlled number of individuals in the tank in a dark environment;
2. Driving the robot along a predetermined trajectory through ZigBee;
3. Recording the *Artemia* population motion;
4. Image processing of frames extracted from the videos.

Image processing is based on a object detection algorithm extracting the position and the number of individuals which are within a given distance (1 cm) from the light source. The video, taken at a frame rate of 30 frames per second, is split into a sequence of images and each image is then analyzed. In particular, images have been converted into binary images and processed by using a morphology algorithm [17, 18]

Table 1 The range of robot speed that *Artemia* are able to follow

Linear trajectory	
Robot speed	0.08–0.32 cm/s
Circular trajectory	
Robot speed	0.08–0.2 cm/s
Zigzag trajectory	
Robot speed	0.08–0.25 cm/s

aimed at removing noise and spurious objects and at labeling of individuals. This algorithm applies a structuring element to the input image to individuate each *Artemia* against the noisy background. The position of each *Artemia* is then calculated as the center of mass of the objects individuated by the morphology algorithm. For the purpose of our analysis and taking into account the characteristics of the experiment, it can be assumed that the motion of *Artemia* is essentially in

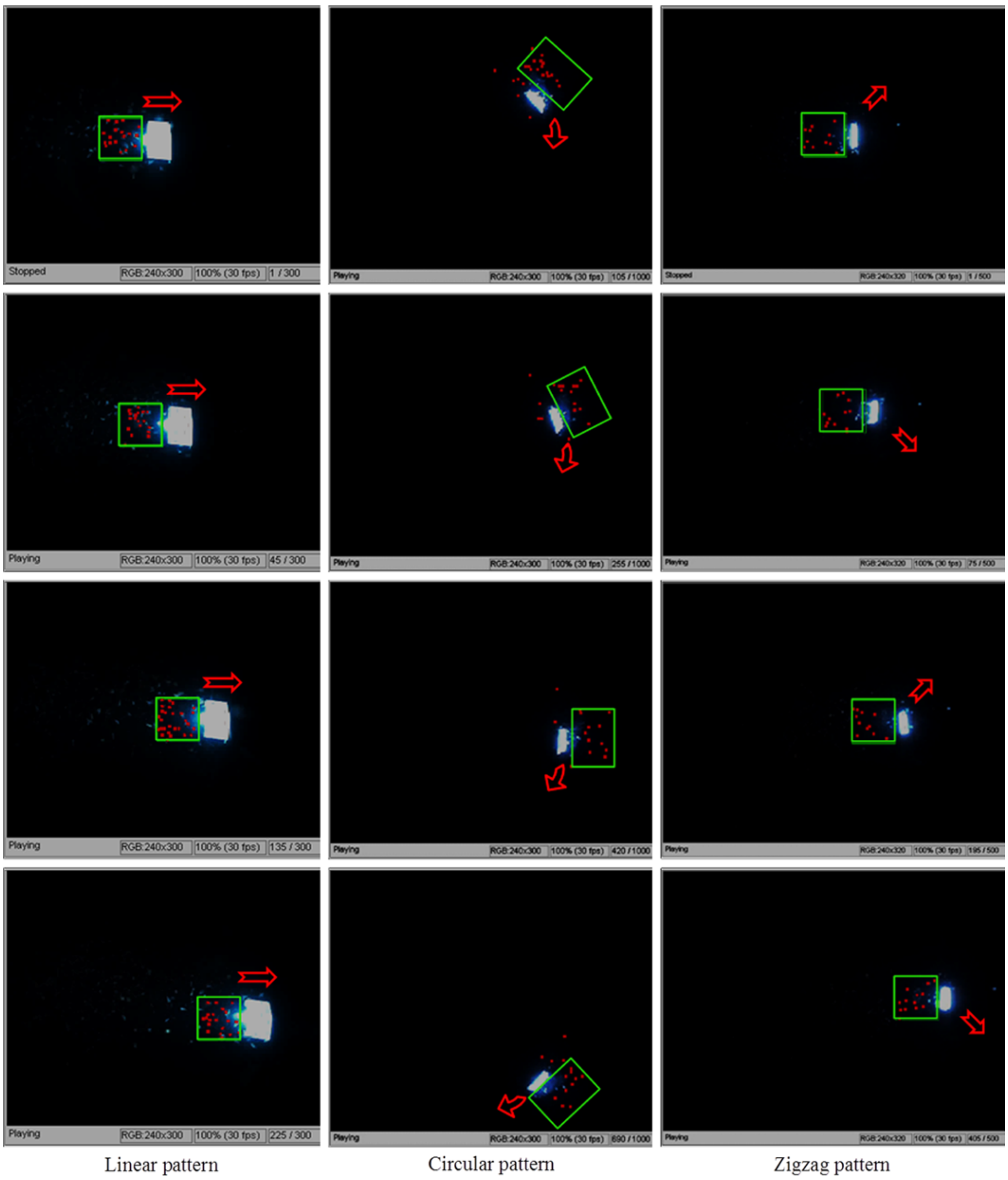

Fig. 7 Experimental results of *Artemia* motion following different trajectories of the robot. The *light position* corresponds to the *white circle*. The *rectangular box* is used to highlight the *Artemia* following the light spot

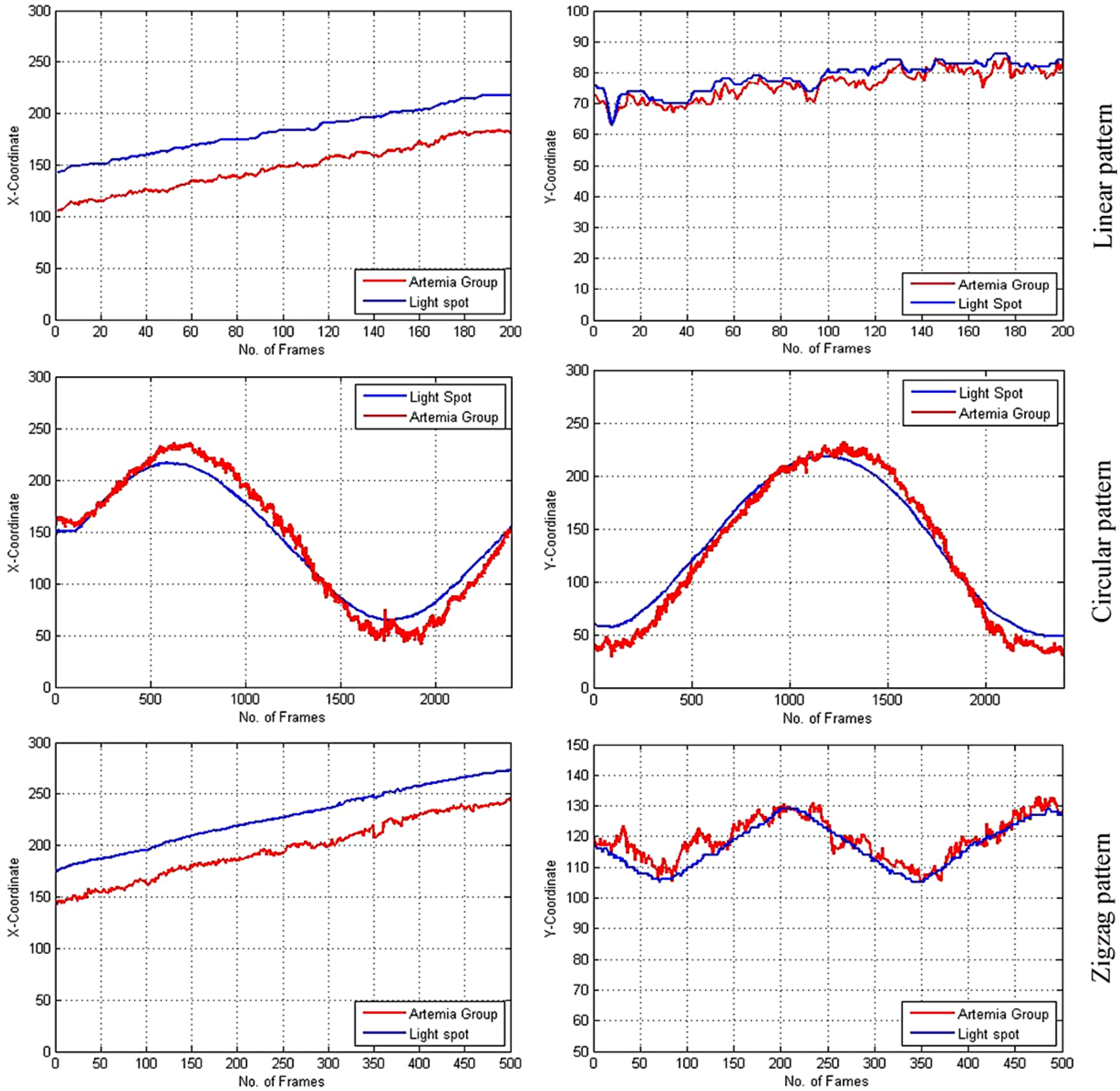

Fig. 8 Experimental results: comparison between the trajectory of *Artemia* and that of the robot

a plane. At each time instant, in order to define the group of *Artemia* following the light spot, the algorithm identifies the individuals at a distance less than 1 cm by the light spot. These *Artemia* follow the robot motion, as it has been also observed by calculating their direction of movements from consecutive frames of the recording. If we indicate with $\mathbf{x}_i$ the position of the ith *Artemia* in the group following the light spot and with N the number of individuals in the group, the group center of mass, calculated as $\mathbf{x}_c = \frac{1}{N}\sum \mathbf{x}_i$, has been then considered to trace the *Artemia* trajectory.

Experiments have been performed by using different trajectories at different robot speeds. The robot speed has been selected taking into account the typical velocities of *Artemia* nauplii. During their life, in fact, *Artemia* gradually grow additional limbs along the elongating trunk, their body length increases from about 0.4 to 4 mm, and the mean swimming speed increases from 0.18 to 0.99 cm/s [13, 14], while *Artemia* nauplii (larvae) reach typical speeds of 0.36 cm/s. The range of robot speeds that *Artemia* are able to follow has been tested by gradually increasing it in a set of ad hoc experiments and monitoring *Artemia* behavior. It has been found that this range depends on the trajectory used as shown in Table 1.

Some frames of an experiment are shown in Fig. 7. The experiment refers to the following set of trajectory parameters: linear trajectory with robot speed equal to $v = 0.3$ cm/s, circular trajectory with $v = 0.15$ cm/s and zigzag pattern with $v = 0.18$ cm/s. In Fig. 8 a comparison between the light spot position and the position of the center of mass of the *Artemia* group following the light spot is shown for each trajectory. A good agreement between the two paths can be observed, demonstrating how *Artemia* can be controlled to follow different motion patterns.

5 Conclusions

In this paper, controlling the motion direction of swarms of microorganisms (and, in particular, *Artemia* populations) along desired trajectories is achieved by exploiting external leadership by a robotic agent, which in turn exploits the specific sensitivity of *Artemia* to external stimuli (in this case, to light sources). The robot is wireless-controlled by a PC, and it induces motion of a light source, placed inside the tank, magnetically coupled to the wheeled structure of the robot. This procedure has been designed in order to avoid the generation, inside water, of flow waves which can perturbate *Artemia* swarming dynamics and which can be generated by a underwater self-propelled robot. The proposed system has the further advantage of minimizing the size of the underwater part and of the cost of the whole system. The idea of external leadership can be extended to other populations of microorganisms and animals by selecting the appropriate stimuli with the aim of exploiting the peculiarities of the selected animal in the context of the application envisaged.

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