

Emergence of Leadership in a Group of Autonomous Robots

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Abstract

For modern biology and ethology, the reason for the emergence of leaders-followers patterns in groups of living organisms, is the need of social coordination. In this paper we attempt to examine factors contributing to the emergence of leadership, trying to understand the relation between leader role and behavioral capabilities. In order to achieve this goal, we use a simulation technique where a group of foraging robots has to choose between two identical food zones. Thus, robots must coordinate in some way in order to select the same food zone and collectively gathering food. Behavioral and quantitative analysis indicate that a form of leadership emerges and the emergence of leadership relates with high level of fitness. Moreover, we show that more skilled individuals in a group tend to assume a leadership role, in agreement with literature.

Index Terms: Leadership, Evolutionary Robotics, Flocking

1. Introduction

Many animal species, including humans, live in groups [1]. The advantages of living in groups have been extensively explored in ethology and robotics, and they are related to (a) protection from predators [2], (b) feeding efficiency [3], (c) competition with other groups of conspecifics [4], and (d) possibility of information sharing [5].

Living in groups poses a fundamental problem of social coordination. Researches in robotics and agent-based modeling have usually focused on homogeneous groups, in which social coordination emerges from local rules followed in the same way by all individuals [6,7].

Anyway, in real animals, especially in mammals and virtually always in primates, whenever there are groups, there is a leadership / followership pattern emergence. Evolutionary biologists use the term leadership for behaviors that influence the type, timing and duration of group activity [8] and generally argue that the reason for the emergence of leadership / followership patterns is the need to coordinate [9]. It has been proposed, for example, [10] that personality differences may represent a prerequisite for the emergence of leadership, where individuals more prone to environmental exploration tend to assume the role of leaders.

Game-theoretical analysis has shown how, in some situations, leadership is almost inevitable. In a simple two-player “coordination game”, a pair of individuals has to reach two simple goals: one individual must stay near the partner for protection, and the other needs to seek resources such as food patches and waterholes. In this situation, any trait (physical or behavioral) that increases the likelihood of one individual moving first will make him more likely to emerge as the leader, and the other player is left with no option but to follow.

Furthermore, if this trait difference between players is stable (i.e. if the first individual is always hungry first) then leadership-follower patterns will be stable over time [11]. Therefore, it seems that individuals are more likely to emerge as leaders if they have a particular physiological or behavioral trait increasing their propensity to act first to solve coordination problems. In the human case, social environment may have increased the conditions for the emergence of sophisticated leadership / followership patterns [12].

Biological and ethological experiments are often difficult to be performed in laboratory and it is hard to get experimental evidences of theories about leadership and grouping emergence using experimental animal or human subjects.

In this work we propose an alternative and original approach based on a collective robotics experimental setup. We have simulated a group of artificially evolving robots (kepera-like) situated in an environment where they must coordinate in order to forage. We conceived the evolutionary process in order to maintain genetic (and behavioral) diversity within the groups, so to reproduce conditions which can lead to leadership emergence according to the literature previously provided. We tried to answer to some fundamental questions, such as: Does leadership arise in a group of genetically *heterogeneous* robots? Who is the leader? What are characteristics and skills of leaders?

The originality of our approach comes from the implementation of an evolutionary robotics model in order to study decision making in a social group. These kind of simulations are been performed, in the past, but with a merely agent-based approach (e.g. [13]).

2. Experimental Setup

2.1. The Task

A group of four simulated robots live in an environment consisting of a 110cm x 110cm squared arena surrounded by walls. When a robot bumps against environment’s wall or against another robot, it bounces back in the neighborhood of the contact point, with a new random direction.

The food source is located in two target areas placed in a fixed position of the environment. Each robot is made of a circular chassis with a radius of 11 cm and it is equipped with two motors controlling the movements of two wheels, respectively (Fig. 1). Moreover, the robot is geared with two sensors which “smell” the relative position of the food zone in respect to the position of the robot body, as illustrated in Fig.2. According to the position of the food zone with respect to a fixed sector of the robot, smell sensors will be activated with a two digits binary code.

Each robot is characterized by a color of the body: green, blue, light blue and yellow and it is equipped with a linear retina system in order to see the position and the color of the other

group members. The linear retina is made of five RGB photoreceptors that manage a portion of the robot field of view.

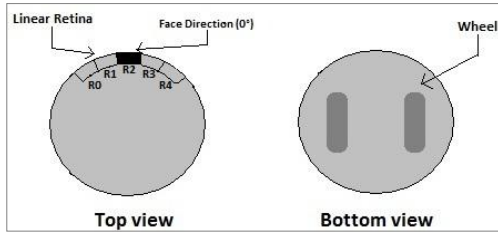


Figure 1: Schematisation of top and bottom view of the robot chassis.

The field of view (FOV) of each robot is 90 degrees wide, and represents the extent of the observable world that the robot can see at any moment. The FOV ranges from -45 degrees to +45 degrees with respect to the direction of movement (0°). In this way, each photoreceptor manages a 18 degree wide portion of the FOV, the first one is associated to a range of [-45°, -27°] respect to the face direction, the second one to [-27°, -9°], and so on.

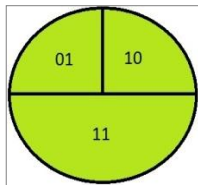


Figure 2: Representation of the activation patterns of the robot smell system.

Each photoreceptor consists of 3 colour sensitive components, respectively Red, Green, and Blue. When an object (such as a robot) is located in the front of a photoreceptor, within its vision angle, the sensor is activated to the corresponding RGB value for that object. The maximum vision distance of receptors is the environment size. The setup is illustrated in Fig. 3.

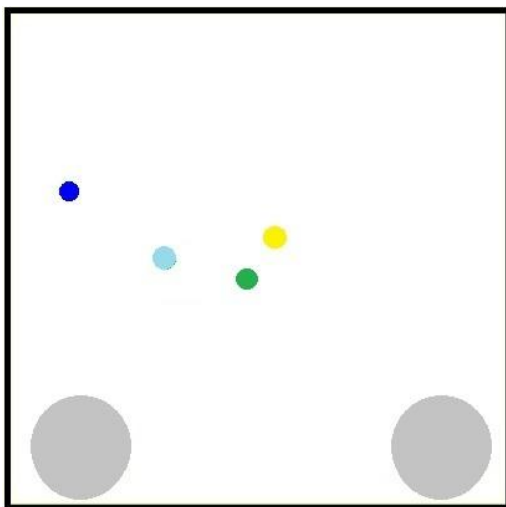


Figure 3: The environment and the robots.

2.2. Neural Controller

The control system (Fig. 4) of each robot consists of a feed-forward neural network with 18 input neurons, 2 hidden, and 2 output neurons. Each layer of neurons is connected to the next layer with a pattern of synaptic weights representing the strength of the connections. The input layer contains 15 neurons encoding the activation state of the corresponding photoreceptors RGB components, 2 neurons that receive smell signals and 1 neuron that receives output from ground sensor. The output layer is made of 2 neurons which control the speed of two motors, respectively.

2.3. Artificial evolution

The evolutionary process for the robots is based on a ranking type genetic algorithms (e.g. [14]). Each individual is represented by a genotype that encodes the sequence of synaptic weights and biases of a neural network controller. Each parameter is encoded with 8 bits. In order to provide robots with different behaviours, each of the four robots belongs to a different population of 100 individuals. Thus, the evolution starts with 4 populations of completely “naive” robots (i.e. with randomly generated genomes) with no skills about how to move and identify the food sources.

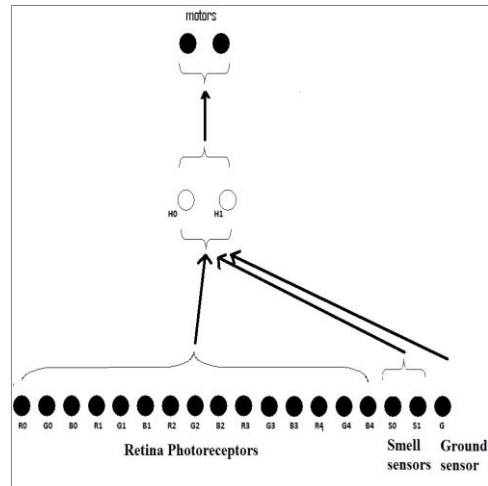


Figure 4: Neural network architecture.

Genotypes are randomly selected within each population: for each generation, individuals of each population is numbered by an index (0-99) and a sequence of indexes is chosen (i.e 3-4-5-4) from the four populations in order to extract the genotype that will control the robots. The first genotype (3), from the first population, controls the green robot, the second genotype, from the second population (4) controls the blue robot and so on. For 100 trials, a new different sequence of individuals is compared in the environment, and robots fitness is calculated at the end of life. If the same individual is extracted in more trials, in different sequences, (i.e 4-6-7-2 for a trial and 3-6-3-1 for another trial), the fitness score of that individual will be averaged over all trials. The same index sequence never will be extracted twice. The extraction of sequences is depicted in Fig. 5.

Each robot is rewarded with +1.0 at a given time step in which the entire group stays in the same food zone. Life time consists of 3000 cycles of neural network activation. At the end of 100 trials (end of one generation), each individual (neural controller) is separately ranked according to

the fitness score. The 20 higher-ranked individuals are selected from the list of genotypes for each population. Each best individual generates 5 offspring individuals which inherit its genotype. The first offspring individual preserves entirely the genotype of the father (elitism) while the other four ones receive a random mutation with a probability of 2%. The total number of new individuals 20(bests) x 5(off) x 4(pop), will populate the next generation. Since, each population evolves separately: this mechanism fosters the genetic differentiation between the four robots and allows the robots to evolve distinctly their behavioral skills.

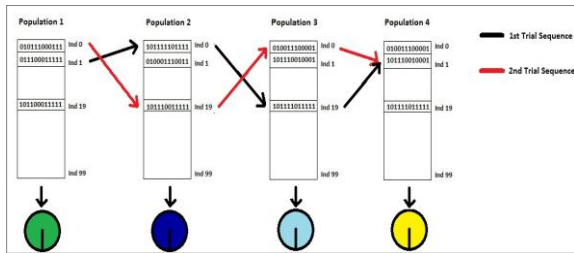


Figure 5: Schematization example of index sequence selection.

3. Results

By evolving the control systems robots for 10 replications with different initial populations and for a total of 300 generations, we observe the emergence of a grouping behavior. For a better understanding of the behavioral observations, we performed some detailed analysis. For each replication (seed) we calculated the average fitness over the last 20 generations, plotted in Fig.6. The variation between seeds suggests that in some replications there could be a stronger grouping and following pattern with respect to others

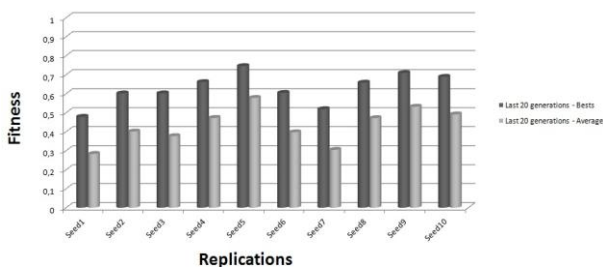


Figure 6: Schematization example of index sequence selecting.

This variation is also confirmed by running tests where we measured which robot in a group, is the closest to the group “center of mass”. For each generation, 4 tests are performed by stopping one robot of the group in a fixed position of the environment. Then, the average distance between the fixed individual and the other robots is calculated. In this way, we obtained 4 curves that show the distance of each robot from the group “center of mass” (and example is the plot in Fig. 7). We can observe that the yellow robot has the minimum average distance from the “center of mass”, especially in the

last generations. It means that it is always near the centre of the group and the other robots surround or follow it. This fact suggests the emergence of a leader/followers pattern, where the yellow robot is the leader.

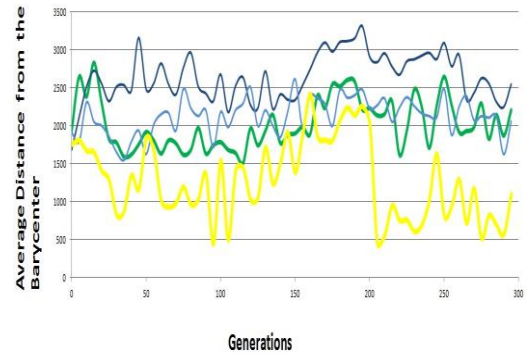


Figure 7: Evolution of distance from group centre of mass over generations. Replication n.9.

It is also interesting to measure the “quality” of the leadership within a group. This measure is obtained by a Leadership Measure (LM) calculated for each replication (Fig. 8). The LM is obtained by calculating the difference between the minimum distance from the group “centre of mass” (Leader) and the average distance of the other 3 individuals (Followers). High differences imply a good extent of a clear leader/followers relationship. Comparing Fig.6 and Fig.8 we can notice that in a replication where there is a high LM, it is also present an high level of fitness. This fact indicates that leadership is a successful strategy in these simulations.

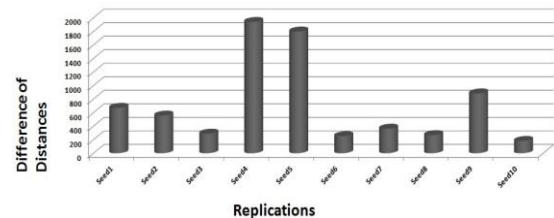


Figure 8: Leadership Measure.

Moreover the second important information emerges when we ran another test in which the fitness of the group and of the individuals is calculated. This test fitness is calculated by testing in the environment only the 4 best individuals for each generation (sampled with a step of 5 generations). Thus, a group fitness and individual fitnesses of each robot are calculated for each generation. The individual fitness, in this test, is taken by summing the times in which a given individual is located in the food zone, independently of the behavior of other robots. It should be noted that this is a virtual fitness, since it is not employed in evolution and it is only used in testing, so to understand the skill of each individual. We hypothesize that those fitnesses should be different, as the robots belong to different populations and play different roles in the group. By plotting individual fitness values for replication n.9, for example, (Fig.9), it is possible to

observe how the skills of each group member evolve throughout generations. In this case, after an initial phase (of about 30 generations), where the robots have almost the same individual abilities, the yellow robot consistently reaches better performances. This data prove, in a preliminary way, that whenever there is a strong presence of leadership in one replication, the most skilled individual (i.e. the fastest in approaching the food zone, the one that shows a better exploratory behavior) tend to be the leader of the group. This relation has been also observed in replication 4 and 5, that also show a consistent level of leadership (see figure 8) .

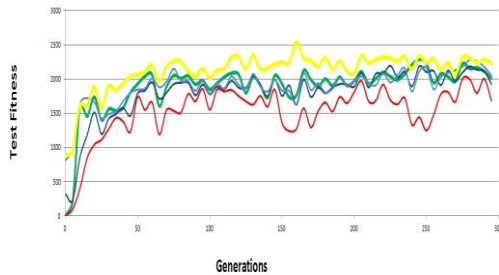


Figure 9: Evolution of abilities in reaching the food zone over generations. The group fitness is represented in red. Replication n.9.

The mechanisms underpinning the emergence of leadership are essentially based on the decision making process within the group. As we can see in figure 8, the yellow robot is the one that shows the best performance within the group. That is, it is the robot that reaches the food zone before the others, and this is true throughout all the evolutionary time. It should be noted that the better performance of the yellow robot, for example, depends entirely on the initial conditions of the population genotypes. In other replications of the same experiment, we observed different populations, i.e. different colours, as emergent leaders of the group.

The fact that the best robot is also the leader can be explained by the fact that it can reach the food zone faster and more frequently during the different tests. Therefore, during the evolutionary process the other robots of the group can use the best robot within the food zone as a landmark, which helps them to reach and remain within the same area and gain fitness. Thanks to this process, which facilitates the decision of the group towards one of the two areas, the best robot is elected as the leader of the group.

4. Conclusions

Although preliminary, these results show that in a group of robots, with variable distribution of skills (due to different genetic characters), leadership is often observed. In particular, the result of our simulation suggests that the stronger the leadership and the higher the level of the group coordination, the higher the overall fitness of the group. Interestingly, we observed that the robot which emerges as leader is also the best in reaching the food zone and foraging on it. This fact suggests similarities on what is reported in biological literature.

However, more analysis is needed to better understand the process that leads to the emergence of those types of social behaviors and many other questions can be addressed with this

kind of simulation, such as, what happens when robots are clones: do leadership/followership patterns emerge? What happens in a condition where the leader is not the individual with the best behavior? How does selective pressure on individual robots favor or inhibit the emergence of leadership? What happens when populations are not segregated and genotypes can mix and compete?

We believe that these kind of questions could be investigated in the future by following and extending the approach preliminarily presented here.

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