Collective and Cooperative Group Behaviours: Biologically Inspired Experiments in Robotics

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Abstract

This paper describes the implementation of two biologically inspired collective behaviours on a group of Khepera miniature mobile robots. The first experiment is concerned with the gathering and clustering of randomly distributed small cylinders. In the second experiment the group of robots are expected to remove long sticks from holes, requiring a synchronous collaboration between two robots. The results are quantified, analysed and discussed, showing interesting (both positive and negative) aspects of this approach. Furthermore, we compare the results of both experiments with those reported by Deneubourg [1], [2] where similar behaviours are observed in ant colonies.

1. Introduction

In the last years we observe more and more collaborations between biologists and engineers [3]. For instance, common experiences, where biologically inspired control structures are implemented on real robots, allow biologists to understand how living organisms work, and engineers to develop new technologies that can deal with unsolved problems. This interaction between biologists and engineers is bringing new ideas to the traditional computational paradigms of robotics which typically involve several sequential and precise functional processes. First, sensing the environment, then detecting features, then constructing and modifying a world model, reasoning for the task and the world model in order to find some sequence of actions which might lead to success, then executing the action sequence one step at the time while updating the world model and replanning it if necessary at any stage. This is a very time consuming operation and requires a remarkable computational power and basic knowledge.

the “subsumption” architecture [4]. The control architecture, inspired from some biological aspects, consists of a small number of simple modules, each capable to sense some limited aspect of the environment and to control part or all of the robot effector systems to achieve some limited tasks. Also in the field of neural networks, the biological inspiration plays an important role in the design of control architectures. At the Microcomputing Laboratory of the Swiss Institute of Technology many efforts has been undertaken to design and realize robots and control structures, based on biological models and to implement autonomous agents.

Let us now talk about the actual state of the research in a particular mutual domain of the biology and of the engineering fields: collective behaviour. Ant colonies are able to collect objects (such as food or dead ants) and place them in particular places. All ants of a given colony place the food at the same place and the carcass in another place. In this way they can collect and store food or carry dead ants to a “cemetery”: if a large number of ant corpses or food particles are scattered outside a nest, they will pick them up, carry them for a while, and drop them. Within a short time we can observe that the corpses are being arranged into small clusters and, as time goes on, the number of clusters decreases and their size increases until eventually all the corpses will be in one or two large clusters. The emergence of these clusters has been studied with social insects by Deneubourg [1], who showed that a simple mechanism involving the modulation of the probability of dropping corpses as a function of the local density, was sufficient to generate the observed sequence of the clustering of corpses.

Gaussier and Zrehen [5] carried out an experiment with a group of Khepera robots implementing similar mechanisms with the same property: the probability of dropping corpses was a function of the local density. They mounted a hook behind the robot, which was therefore able, with an appropriate sequence of movements, to grasp and shift small cylindrical objects. Precise rules for the basic behaviours were defined: the perception of the objects and obstacles (Winner-Takes-All neuronal net) as well as dragging and placing objects were preprogrammed in such a way that the global probability of building a cluster was greater than that of destroying it. So, after a few minutes, the first clusters began to appear on the arena (see [5] for more details).

Beckers [6] made the same experiment with robots of approximatively 25 cm in diameter. The collective behaviour was analysed on the basis of the stigmergy principle, which signifies ‘incitement to work by the products of the work’. It consists in essentially the production of a certain behaviour in agents as a consequence of the effects produced in the environment by previous actions. The experiment was carried out using 1 to 5 robots in an arena where many pucks of 4 cm in diameter were scattered. The robots were equipped with a frontal surface to push the pucks. A microswitch was installed behind the surface to control the maximal number of pucks which can be pushed at the same time. The robot was able to shift two pucks, but when three pucks were detected by the microswitch, the robot stopped pushing and changed direction. Their results indicated that the optimal density of robots on the arena surface, in order to accomplish the given collective task in a minimal time lapse (relative to the number of robots), was three. According to the authors, the reasons for the presence of this optimum were attributed to the geometry of the clusters and to the constructive and destructive interferences among the agents.

behaviour of a colony of ants. They rammed some sticks close to the nest and they observed what occurred. After a few minutes, the ants tried to grasp the sticks in order to accumulate building material for their nest, but a single ant was not able to accomplish this task. A few minutes later, the colony solved the problem with a collaborative behaviour among two or more ants.

We can classify the above mentioned experiments into two categories, considering the different tasks involved:

- collective noncooperative behaviour, which does not necessarily need cooperation among the individuals to be solved, i.e., a greater number of agents can only accelerate the work to be accomplished;
- collective cooperative behaviour, which absolutely needs the collaboration of two or more individuals in order to be carried out, because of some physical constraints of a single agent.

This paper aims to describe two experiments on real robots, which can be classed into the two above mentioned categories. The discussion will also focus on the radical difference between the two tasks.

2. Materials and Methods

Khepera is a miniature mobile robot developed to perform "desktop" experiments [7]. Its main characteristic is a diameter of 55 mm. It also has other very interesting possibilities, such as an important processing power (32 bits processor at 16 MHz), autonomy, precise odometry, light and proximity sensors, grasping possibilities, and many other additional features that can be added on a extension bus. In its basic configuration Khepera is equipped with 8 infrared (IR) sensors, 6 on the front and 2 behind its cylindrical structure. On the front these sensors are distributed with a gap of about 14 mm. The wheels are controlled by two DC motors with an incremental encoder (12 pulses per mm of advancement of the robot), and can move in both directions. The simple geometrical shape and the motor layout allow Khepera to negotiate any kind of obstacle or corner. Each robot is extended with a gripper module, which can grasp and carry objects with a maximum diameter of 50 mm (see fig. 2a). A robot of this size is not only optimal for the test of basic features in an individual behaviour, but is also a very interesting platform with which to perform experiments in collective robotics: 20 robots can easily work on $2\,\mathrm{m}^2$, which approximately represents an area of $10 \times 20\,\mathrm{m}$ for a bigger robot (being for instance 50 cm in diameter).

Our two experiments on collective behaviour use 1 to 5 Kheperas. In both cases, the number of robots involved has been gradually increased and the performance measured and compared. The objects manipulated by the robot in the first experiment have a cylindrical form, with a diameter of 16 mm and a height of 25 mm. In the second experiment, we use longer cylinders (150 mm) with the same diameter as before; they stretch out 50 mm from the ground (see fig. 6b). Both experiments are carried out in a square arena of $80 \times 80\,\mathrm{cm}$. The initial scattering of the objects is arbitrarily predefined. Our experiments are repeated and quantified 3 times and each experiment takes approximately 30 minutes.

It is worth emphasising that in both experiments the robots operate completely autonomously and independently; all sensors, motors and controls are on-board,

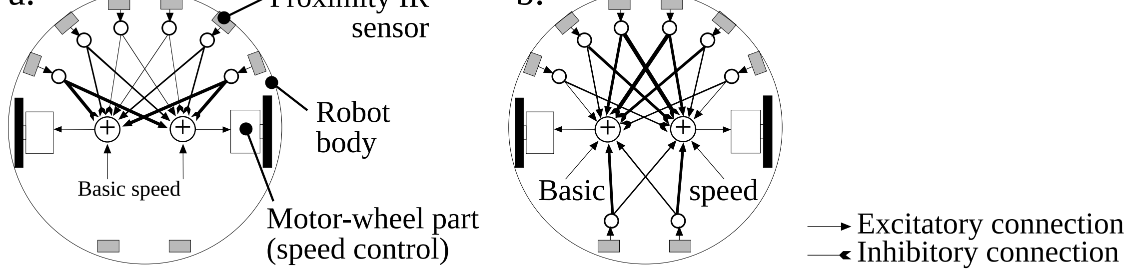


Figure 1. a) Neural connection to implement the search behaviour. These kinds of connections are inspired from the Braitenberg vehicle 3c [6]. The IR proximity sensors have an activation proportional to the proximity of an obstacle. The thickness of the connection represents the value of the weight of the connection. b) Neural connection that implements obstacle avoidance.

and there is not explicit communication (IR or radio link) with other robots or with the experimenters. The only possible interactions among robots are the reciprocal avoidance of collisions and an indirect form of messages, which arise from the modifications of the environment (i.e., for instance the cluster geometry).

2.1. First Experiment

In this first experiment, the task performed is object clustering. The object searching behaviour is based on a Braitenberg vehicle as described in figure 1a. The real object recognition is made when the front proximity sensors exceed a given activity threshold (in most cases this activity corresponds to a distance between the robot and the object of about 20 mm): the recognition algorithm differentiates between the proximity values of the two central and two lateral sensors. Two cases can occur: if all the four sensors are very active, this indicates to Khepera that there is a large obstacle in front of it and has to avoid it, independently from its structure (wall, another robot, or an array of objects); in this case the control algorithm commutes his behaviour to obstacle avoidance (implemented as described in figure 1b) and stays in this mode until none of the proximity sensors notice any obstacle. On the other hand, if the two lateral proximity sensors are not saturated, it indicates to Khepera that there is a small object in front of it; if Khepera is not carrying an object, it moves slightly backwards and grasps the object with the gripper; if Khepera is carrying an object, it moves further backwards and drops the carried object close to the new object found; then, in both cases, it turns about 180 degrees and begins a new search. With the control algorithm mentioned above, the typical form of a cluster will be more or less an array of objects.

2.2. Second Experiment

In the second experiment the task is completely different. The robot group has to remove long cylinders from holes in the ground. This is only possible if two robots collaborate together at the right moment (see fig. 6c). The individual behaviour is exactly the same as in the first experiment. However, due to the different global task, the robots do not need to transport the objects but only remove them from the ground. For this reason we have added a timeout to the grasping behaviour, to give a maximal time lapse for removing the stick, in case that an other robot does not collaborate.

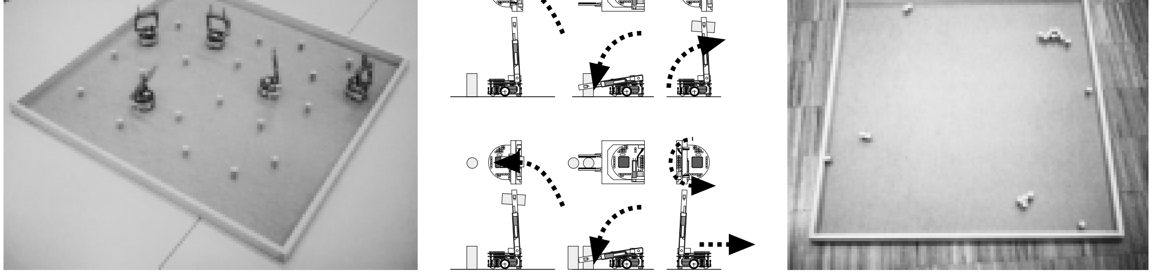

a) b) c)

Figure 2. a) Setup for the first experiment. b) Behaviour of the robots. c) Environment after 30 minutes.

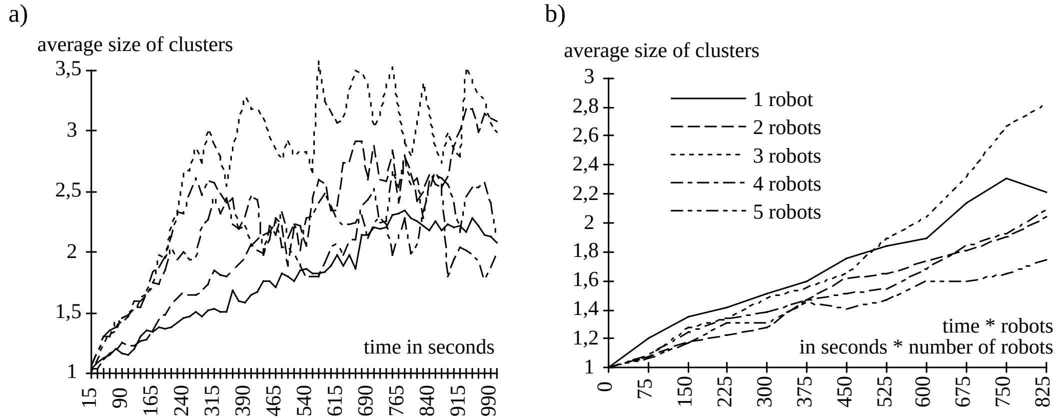


Figure 3. a) Absolute performance of the robot groups. b) Relative performance of the robot groups.

3. Results and Discussion

3.1. First Experiment

Figure 2 shows the setup employed for the first experiment and one of the resulting environments after 30 minutes.

In figure 3, the performances of the robot groups are presented. The number of robots involved in the experiment varies from 1 to 5. It is necessary to outline two skills of the absolute performance (i.e. versus time, fig. 3a): first, the cluster building process can be speeded up by increasing the number of robots on the arena; second, after a rapid rise in the first phase of the experiment (almost 10 minutes), the performance indexes reach a saturated zone, i.e. the mean size of clusters does not grow any more. This means that the “cluster system” presents a dynamical equilibrium point. Figure 3b gives indications on the relative performance (i.e. versus time * robots) of the robot colony: 30 minutes of work using a single robot have to be compared with 15 minutes of work using two robots, with 10 minutes of work using three robots, and so on. Notice that the performances of all groups of robots with two or more agents are worse than the performance of the single robot. The only exception is represented by the performance of the three robots shown on the right part of the graphic. However, we are convinced that this result is a fortuitous case and we do not consider the group of three robots as a density optimum in order to solve the given task. Observing carefully the

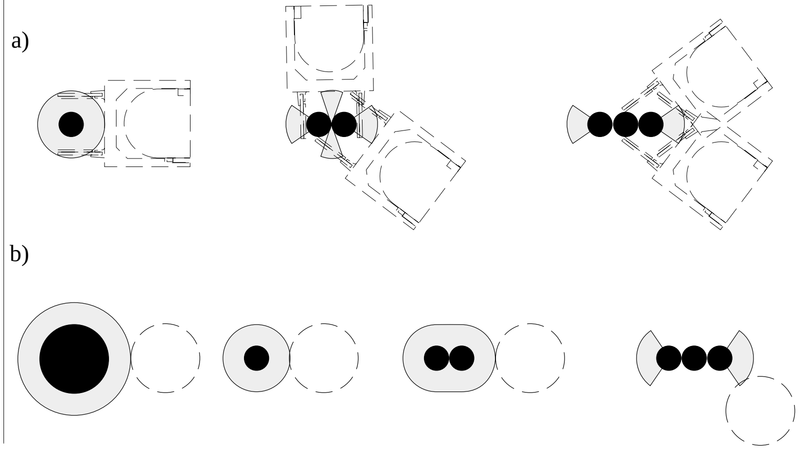


Figure 4. Geometrical representation of access areas for Khepera in order to destroy (a) a cluster of one object, a clusters of two objects and a clusters of three objects. b) Access areas for Khepera in order to build a group of one object from nothing (wrong detection of another robot), to build a group of two objects from one object, a group of three objects from a group of two and a group of four objects from a group of three.

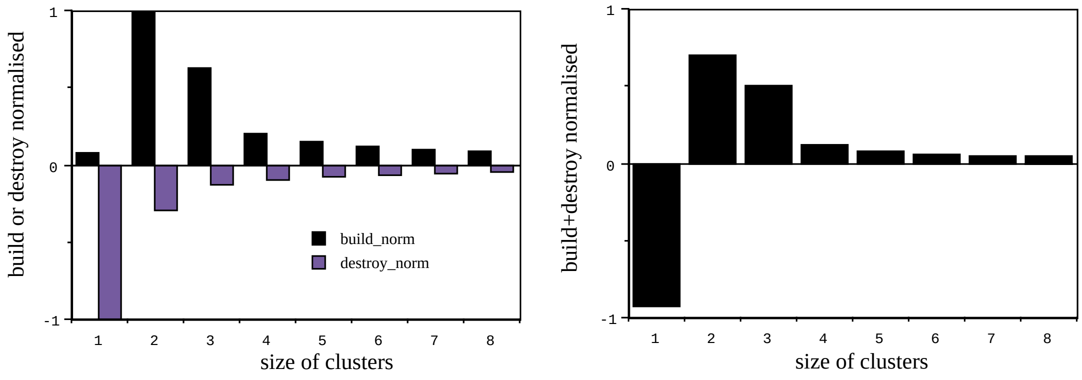
experiment, we notice that a major density of robots on the arena causes only an increasing rate of destructive interferences (e.g., avoidance of the other robots, false perception of the object to grasp), as demonstrated in the first and more reliable part of the experiment. Therefore, the results of this experiment contribute to the proof that a collective but noncooperative task can not always be achieved with better performances (in this case the judgement criterion was the relative speed) increasing the density of robots.

Let us analyse in more detail the process rules of the first experiment. Figure 4 presents a geometrical explanation of the building-destroying mechanism. We draw the access area in order to perform one action or the other. We consider the cluster and the robot gripper geometry. The cluster building area is always greater than the cluster destroying area. The size of these areas is directly proportional to a sort of mean global probability; hence, we can assert that the building process is more probable than the destroying one and the result is, as illustrated by figure 3a, a final dynamical equilibrium.

In figure 5, the normalised results of figure 4 are presented. The probability of building a two objects cluster from two single object clusters (i.e., destroying them) is very high. On the other hand the probability to build greater clusters is inversely proportional to their size. In effect, it is a question of conditional probability: an 8 objects cluster can only be built if a 7 objects cluster previously exists.

3.2. Second Experiment

The setup of the second experiment is depicted in figure 6. The event showed in figure 6c has occurred almost every 20 minutes. How we mentioned above, this experiment implements a collective cooperative task, this means that the stick can not be removed by a single Khepera. Because of the very low rate of collaboration, it is difficult to formulate any consideration concerning the optimal density of robots on the arena. Furthermore, there are more destructive interferences during this



a) b)

Figure 5. a) Histogram of the probability to build or destroy a cluster with a given number of objects. b) Sum of both probabilities for a given cluster size.

a) b) c)

Figure 6. a) Setup for the second experiment. b) Detail of the setup: Khepera in front of a stick. c) Collaboration between two robots in order to achieve the task.

experiment than during the first one, because there are fewer objects to grasp, more robots are moving towards the sticks and therefore more collisions occur.

3.3. Remarks

Some drawbacks in the basic behaviour of robots emerge from both experiments. Often it occurs that the perception algorithm does not operate correctly: a robot is not always differentiated from an object. Very often a robot drops an object in front of another robot and the latter grasps the object (object exchange). For the same reason, the robots try to grasp each other and it often occurs that they become tangled for a few seconds. The default opening width of the gripper is too large in order to grasp only a single object: sometimes the robot grasps two objects at once but it can not carry them and therefore fall.

4. Conclusion

Our first experiment shows that only an absolute time speed-up can always be reached. The performance expressed in "work achieved" versus "time * robots" usually decreases with an increasing number of robots. This results from the fact that the task achieved in this case is purely collective and noncooperative. The

the contrary, the collective aspect introduces many destructive interactions, such as collisions between robots, errors of detection due to moving obstacles, conflicting situations, etc. Probably the single robot performance, which represents the top limit in this type of task and with this kind of performance measurement, can only be improved by groups of robots if some kind of differentiation of the individual behaviour is introduced.

The results of the second experiment show that a good interaction between the robots and the environment, also with a very simple behaviour, can give rise to a collective task where a real cooperation is present.

These two experiments show interesting characteristics of collective performances where the individual behaviour is very simple and the same on every robot of the group. The interactions between many robots and between the robots and the environment play a crucial role in the performances of the group. A very simple modification of these relationships, as illustrated in the two experiments, can radically modify the performances and the behaviour of the group. Both types of working organisations (cooperative and noncooperative) can be very useful in robotics to extend the capacity of a single robot. To exploit this group structure in new design methodologies and apply it to real useful applications, we still need to better understand the basic mechanisms of collective work.

5. Acknowledgements

We would like to thank Edo Franzi and André Guignard for the important work in the design of Khepera, and Paolo Ienne for the review of this paper. Alcherio Martinoli and Francesco Mondada have been partially supported by the Swiss National Research Foundation (project FN and PNR23).

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