Towards a Reliable Set-Up for Bio-Inspired Collective Experiments with Real Robots

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Abstract: This paper describes a set of tools developed at our laboratory that provide a reliable set-up for conducting bio-inspired experiments with real robots. We focus on the hardware tools needed to monitor team performances as well as those to achieve collective adaptive behaviours. We propose concrete solutions to some of the main problems in collective robotics. The four main results we derive are: *first*, the hardware modularity of the miniature robot Khepera [1] allows us to build a flexible set-up; *second*, the energy autonomy problem is solved in a reliable way for experimenting with real robots during several hours; *third*, the communication architecture among teammates and/or with a supervisor unit is designed to prevent bandwidth bottlenecks with bigger robot teams; *fourth*, the use of programmable active pucks (also called "seeds" below) extends the set of possible bio-inspired experiments without increasing the sensorial complexity of the robots. A simple bio-inspired collective experiment, the gathering and clustering of randomly distributed passive seeds, is presented as an example as well as a test-bed for the extended autonomy tool. The results are compared with those reported in [2, 3].

1. Introduction

In the last few years, we have observed a growing collaboration between biologists and engineers [4, 5]. Robots running bio-inspired controllers allow biologists to better understand living organisms, while engineers manage to solve problems which are hard to tackle using classical control methods. Unfortunately, the difficulty to build adequate and reliable set-ups for experiments with real robots prompts many researchers in autonomous robotics to carry out investigations with simulated robots in simulated environments. This is especially true in collective autonomous robotics, where the autonomy of the robots depends mainly on their on-board computational power and their energy supply. In many bio-inspired single-robot experiments, the robot is connected to a workstation through a cable, which supplies the required energy and supports intensive computing, such as learning algorithms [6]. With many robots using cables becomes impossible: they would become entangled. Two further robot features, not necessarily required in single-robot experiments but essential in collective robotics, are the capability to explicitly communicate with and distinguish the other teammates from the rest of the environment. Providing the robots with these capabilities in a noisy real environment is not a trivial task,

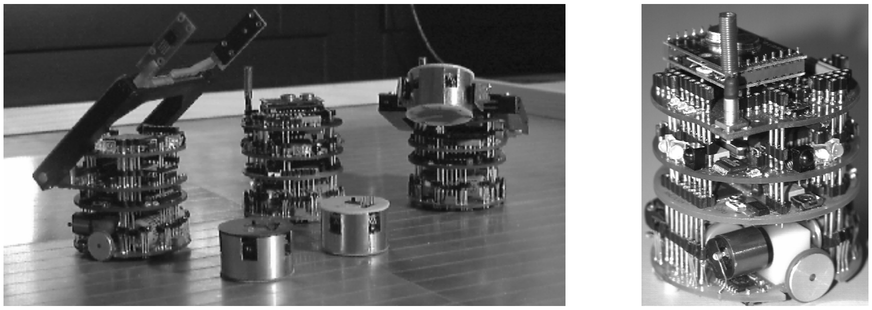
a) b)

Figure 1. a) Three Kheperas equipped with different combinations of modules on the energy supply board (from left to right): gripper and IrDA modules, IrDA and radio modules, and gripper and radio modules. The active seeds complete the set-up picture. b) A closer look at the Khepera with IrDA and radio modules.

particularly with miniature robots. This paper addresses these problems and describes the solutions developed and currently tested at our laboratory.

In the following paragraph we describe what we mean by bio-inspired collective robotics, and our motivation for developing this particular set-up (see fig. 1a).

1.1. Collective Behaviour Synthesis and Analysis in Bio-Inspired Experiments

Bio-inspired collective robotics favours decentralised solutions, i.e. solutions where coordination is *not* taken over by a special unit using private information sources, or concentrating and redistributing most of the information gathered by the individual robots. Inspired by the so-called collective intelligence demonstrated by social insects [7], bio-inspired collective robotics studies the robot-robot and robot-environment interactions leading to robust, goal-oriented, and perhaps emergent group behaviours.

One way to generate robust collective behaviours is to apply bio-inspired adaptive algorithms at the team level. We believe that the integration of learning methods can contribute strongly to design a team of self-programming robots in view of predefined task. In the last few years reinforcement learning and genetic algorithms have been used to produce adaptive behaviour in the context of single-robot applications [8, 6]. In multiple-robots applications, where fitness is measured at team level, robots are faced with the *credit assignment problem*, which means the problem of deciding to what extent their own behaviour has contributed to the team's overall score [9]. Two ways for bypassing this problem have been proposed. *First*, by integrating *global communication* among teammates [10]. However, this is not a completely decentralised solution and does not match the above definition of bio-inspired robotics. Furthermore, depending on the environmental conditions, global communication is not always possible and tends to bottleneck with great team sizes. *Second*, by measuring each robot individual performance instead of team performance [11]. A main drawback of this approach is to force collective behaviour to be the sum of identical individual behaviours, which is not necessarily the optimal strategy for every boundary condition of the shared mission.

We can achieve *real team solutions*, whose form depends strongly on task boundary conditions (such as the number of robots involved in the experiment or their functionalities), only at the price of dealing with the credit assignment problem. Attempts in this direction in simulated environments have been recently published [9, 12]. In order to implement the learning process according to this approach on a team of real robots, enough energy autonomy and a reliable communication with the workstation (learning supervisor) is required. Via radio link, the team performances are computed on the supervisor unit and the adapted parameters are sent back to the robots.

Let us consider now behavioural analysis. Currently, autonomous mobile robotics is dominated by the experimental approach. Very few researchers have performed quantitative measurements of robot performances. This is also true for collective robotics. However, recently, the research community in this field has focused on this problem [3, 13, 14]. In [3, 14] the environmental key parameters were collected by filming or by observing the team behaviour. It would be of great interest to automatically collect robot key parameters, parallel to the environment evolution, i.e. to quantitatively correlate team strategies with team performances. A first attempt in this direction has been conducted in [13]. The authors demonstrated that a quantitative measurement of the interference rate can be used as tool for evaluating the multi-robots controller.

2. Experimental Set-Up

2.1. The Robots

Khepera is a miniature mobile robot developed to perform "desktop" experiments [1]. Its distinguishing characteristic is its small size (55 mm in diameter). Other basic features are: important processing power (32 bits processor at 16 MHz), energetic autonomy of almost half an hour, precise odometry, and light and proximity sensors. The wheels are controlled by two DC motors with an incremental encoder, and can rotate in both directions. The simple geometrical shape and the motor layout allow Khepera to negotiate any kind of obstacle or corner. Modularity is another characteristic of Khepera. Each robot can be extended with several modules: a gripper module which can grasp and carry objects with a maximum diameter of 50 mm and a weight of 20 grammes, a radio module, an IR local communication module, a vision module, a KPS (Khepera absolute Position System) module, and other general purpose or custom modules. Thanks to its size, Khepera is a convenient platform for both single- and multi-robot experiments: 20 Kheperas can easily work on a 2 m^2 surface, which is equivalent to a workspace of 10 × 20 m for robots with a 50 cm diameter.

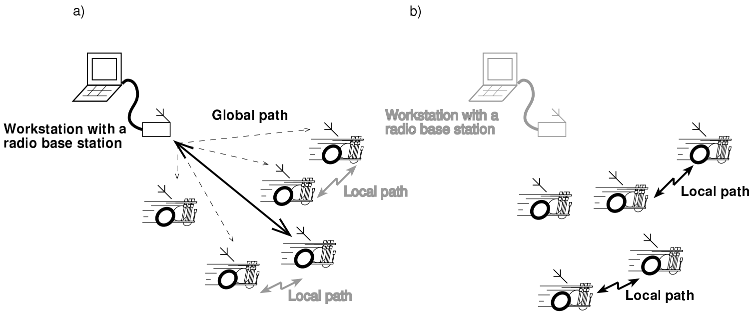

Figure 2. a) Global communication path. b) Local communication path.

2.2. The Communication Tools

In collective robotics, communication is crucial for coordinating behaviour among robots. Furthermore, a communication link between the workstation and teammates enables supervision of the robots. In bio-inspired robotics, team behaviour is obtained with a completely decentralised control, which limits communication to neighbouring teammates. These considerations have facilitated the definition of a hierarchical communication strategy which optimises robot-to-robot (local path) and workstation-to-robot (global path) communication (see fig. 2). The multi-microcontroller architecture of Khepera has a software layer which supports any kind of communication turrets. Specific communication implementation is taken in account by an on-board dedicated microcontroller connected to Khepera by its standard local network.

According to the multi-microcontroller architecture of Khepera, the size of the environment, the possible number of robots involved in the experiments and the technological constraints, the choice of the global and local communication paths have led to radio and infrared physical implementations (see fig. 1b). Notice that, due to the completely different range of the these two physical links (see further paragraphs), implementing the local path using radio communication would imply that the robots are aware of their absolute position (see [10] as example). This is not coherent with our definition of bio-inspired robotics and would further reduce the available bandwidth for local and global communications.

2.2.1. The Radio Turret

The radio communications are managed by a low speed star topology network. Two possible modes are available: standard (the communication master is the base unit) and robot-based (the communication master is a Khepera). In the *standard mode*, which is currently used for the bio-inspired collective experiments, all the transactions are started and controlled by the radio base unit which can address either a single Khepera (selective standard mode) or all the Kheperas used in the experiment (broadcasting standard mode). In this mode only messages which use the standard ASCII protocol of Khepera (see [1]) can be sent. In the *robot-based mode*, no protocol is a priori defined. Each Khepera can start a transaction with another Khepera (selective robot-based mode) or

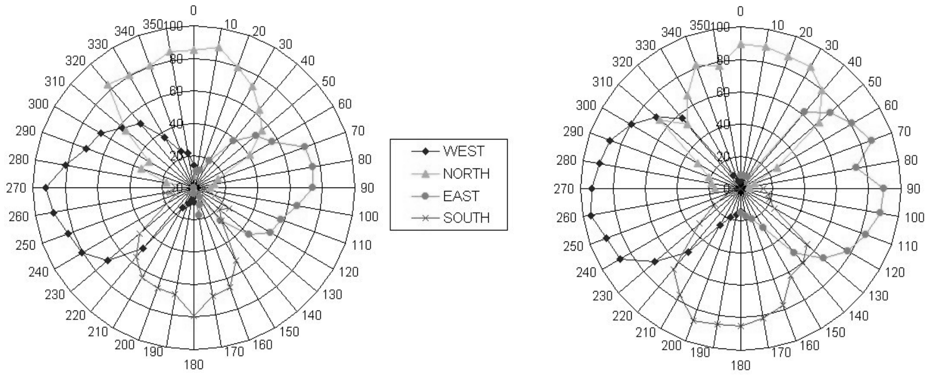

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Figure 3. a) Reception covered area of the IrDA turret. b) Emission covered area of the IrDA turret. Data registered with low emission power and high sensitivity level (level 3, see fig. 4).

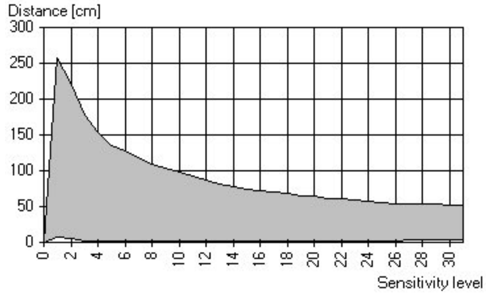

Figure 4. Covered range as a function of the sensitivity level of the IrDA device. The grey zone represents the useful range for reliable communication.

with all other Kheperas in the experiment (broadcasting robot-based mode). The supervising communication algorithm is then running on the transmitting teammate. The radio turret is composed of a 418-MHz FM radio module and a microcontroller at 8 MHz, which establishes the interface with the local network. A 32000 bits/s half-duplex protocol, similar to HDLC (High-Level Data Link Control), is used to ensure reliable communications. The real user throughput at hand is about 4800 bits/s which can slightly decrease if the environment is too polluted (e.g. strong electro-magnetic field generated by poorly shielded computers). Of course, the real user throughput represents the available bandwidth of the radio channel and it has to be divided by number of robots to have the full global bandwidth by robot. The area covered by the radio network is about $100\,\mathrm{m}^2$.

2.2.2. The IrDA Turret

The infrared communication is based on the standard IrDA (Infrared Data

Association) physical layer. The implementation allows selective point-to-point communication. The local emitting-receiving area of each turret is divided in four regions (south, north, east, and west). The IrDA turret is composed of a microcontroller and four IrDA devices, whose placement creates an omnidirectional local path (similar to the solution proposed in [15], see fig. 3).

The physical specifications of IrDA devices allow for a very high bandwidth, typically above 100000 bits/s. However, the real throughput is determined by the hardware implementation of the whole turret. Currently, the baudrate is 20833 bits/s. Notice that the real throughput is not decreased by the number of robots engaged because the channel is shared by only two Kheperas at a time. According to the IrDA chip specifications, the emission power and reception sensitivity can be set to obtain the desired range. The area covered can be modified from $0.03\,\mathrm{m}^2$ to $7\,\mathrm{m}^2$ (see fig. 4).

A greater area can be covered using higher level of sensitivity. However, due to the IR activity of Khepera's proximity sensors, the communication is only reliable from a distance of 15 cm. If the required range lies between a few centimetres and the maximal obtainable distance (about 250 cm), a spatial filter must to be added to the Khepera's infrared receiver, to suppress the influence of the proximity sensors.

2.3. The Extended Autonomy Tool

As mentioned in the introduction, our idea is to apply adaptive bio-inspired algorithms to self-programming in a team of robots with a shared mission. Due to the many iterations currently required by these algorithms to converge (hours or days), the robots should have a long autonomy. That is why we have developed a supply floor board and have modified the Khepera basic module to get energy from it.

2.3.1. General Description of the Device

To achieve extended autonomy, we have considered two possible solutions, using a special floor board as an interface between an external supply source and the robots. In the first option, energy is transmitted by electrical contact. An original contact and floor board layout (see next paragraph) allows each robot to take advantage of the external supply source, regardless its position. In the second option energy is transmitted by induction [16]. The idea is to equip Khepera with secondary windings of a multiple transformer whose primary windings are placed on the special floor board. The latter option has two advantages: no additional friction is added between the robots and the board (the odometry is not influenced) and there are no contact rebounding problems. However, the induction option is significantly more expensive and difficult to miniaturise; obtaining a high energy transmitting ratio is not trivial. We are currently investigating both options, but focus on the first, more advanced solution.

The extended autonomy tool is composed of a common supply generator, a special floor board, and a modified Khepera basic module. When the robot is moving on the supply floor board, it is able to keep its own batteries charged and, if necessary, to recharge them during the experiment, without stopping to work. This suppresses pauses and the need of special behaviours for recharging (with the batteries and charger currently used, about 45 minutes are necessary for 30 minutes of work); the power supply level is constant during the whole experiment which can last hours or days. Furthermore, thanks to its on-board batteries, the robot preserves its traditional autonomy which can be useful for short experiments or demonstrations. Past experience has revealed a further reason to preserve the batteries on the robot: the 100% efficiency in energy transmission can be assured only if all the robot poles are permanently in contact with the floor board surface. Short transient fluctuations can be filtered with condensers but if dust has been accumulating, power failure could occur at any moment. We have conducted tests without batteries during one week with a robot moving on the arena in a pseudo-random way: it stopped on the average every half hour. To restart the robot, it was sufficient to slightly push it.

2.3.2. Layout Optimisation of the Floor Board and Robot Contacts

The floor board should fulfill the following requirements: modularity (the size of the useful surface can be chosen by the experimenter), work surface as flat as possible to avoid contact rebounding, and simple layout pattern. The robot contacts should fulfill the following requirements: matched with the floor board for high energy transmission efficiency, rotation symmetric placement of poles as well as low friction (the odometry of the robot should be not influenced), minimal rebounding, and possible miniaturisation for matching with the active seeds size (see next section).

Copper has been chosen both for the robot poles and floor board surface. This offers good contact (resistance smaller than 0.3 Ohm) and low friction. The isolated gaps between the conducting bands are made of unconnected conducting surfaces, achieving minimal discontinuity between bands.

How many poles are needed and how should they be placed in order to fulfill the mentioned requirements? How should the floor board upper surface be designed? We solved this optimisation problem with an atypical procedure, using first simple geometric considerations, then selected the optimal solutions with a genetic algorithm and finally we demonstrated their validity mathematically. The width of floor board band and the placement of the robots' poles were encoded in a genome string. The fitness function was the number of "external powered" positions in a set of samples generated with discrete translations and rotations of the robot. Some noise was added to simulate the mechanical vibrations of the contacts. The obtained set of solutions assures the 100% efficiency with 4 poles if transient mechanical phenomena (rebounding and dust on the pole-board contact surface) are neglected.

2.3.3. Test Results

We have tested the performances of the extended autonomy tool with an obstacle avoidance algorithm (mean power consumption of about 1.5W) and with the clustering algorithm presented in [3] (mean power consumption of about 1.7W). The batteries were recharged at a very low rate (C/10) during the experiment. The tests consist of three phases: working on the floor board without

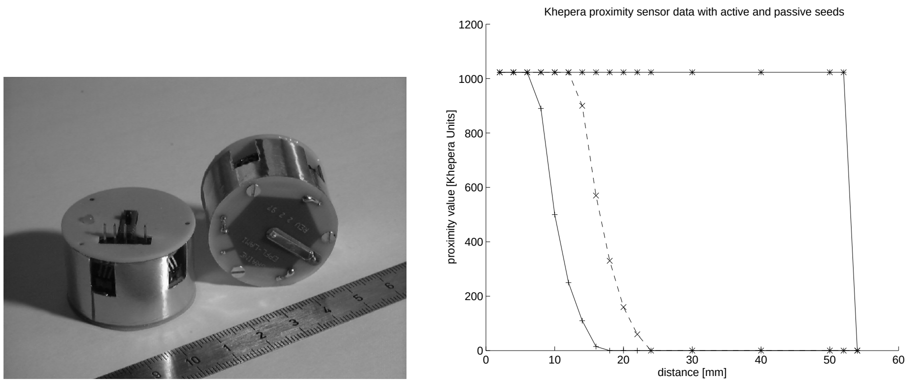

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Figure 5. a) Front and bottom view of an active seed. b) Seed detection range (values of Khepera's proximity sensors): "*-*" represents the emitting seed signal, "+-+" the idle active seed, and "x-x" the passive reference seed (small wood cylinder).

external supply until the batteries are discharged, working on the floor board for a hour with external supply starting with charged batteries, and replaying phase 1 immediately after phase 2, without recharging the batteries. The tests were conducted several times with several robots running the two different algorithms and the discharging time of phase 1 and 3 were compared. The results show that the power consumption during phase 2 was always smaller than 5% of the whole batteries power. Managing to charge the batteries faster should lead to open end autonomy.

2.4. The Active Seeds

Khepera's 8 proximity sensors allow obstacle detection at a maximal distance of 6 cm in nearly all directions, depending on the obstacle size and material [17]. This basic configuration has demonstrated its reliability in simple tasks such as obstacle avoidance. However, the limited number of sensors as well as their variable sensivity generate vague information about the form and the size of the encountered objects. Object-gathering experiments with real Kheperas showed the difficulty to distinguish seeds, the objects to gather, from obstacles, i.e., arena walls and other teammates (see [3]). A possible solution to improve the discriminating capabilities of Khepera, without increasing the complexity of its hardware, was to develop active seeds easily recognised by the proximity sensors.

2.4.1. General Description of the Device

The "active" seed (see fig. 5a) has a diameter of 30 mm, is equipped with 5 IREDs whose overlapped spatial lobes cover all the required 360 degrees. It is able to synchronously respond to the IR pulses of the Khepera's proximity sensors. By emitting at a given rate, for instance one pulse for each two received, the seed is seen by the robot as a "blinking" object. The IREDs are controlled by a low-power RISC microcontroller which allows great flexibility. Currently, three basic operation modes are implemented: answer once each 2, each 3 and each 4 pulses received. A LED on the seed top signals to the experimenter its activity and selected mode. These modes and their temporal validity can be completely and permanently reprogrammed in a few seconds by connecting a dedicated programmer to the seed. Four other interesting features distinguish our active seed. *First*, their robustness: the sensitivity is adapted to the ambient lighting conditions. *Second*, their complementary features for recognition: each type of seed is provided by another software conditioned “internal” resistance, which Khepera is able to measure with the gripper resistivity sensor. *Third*, their energy autonomy: the primary supply source is represented by 2 replaceable 225 mA/h lithium coin cells. Moreover, the seed’s lower face is equipped with 4 contacts, whose placement is identical to those on Khepera. If used together with the extended autonomy tool, the seeds can take advantage of their secondary supply source (the floor board) bypassing the on-board batteries. Without the extended autonomy tool, the batteries last about 3 days of continuous operation, depending on the seed’s activity and the lighting conditions. *Four*, their weight and mechanical stability: an active seed weighs only 17 grammes, can be lifted without problem by Khepera’s gripper and does not impede the movements of the robot. The seed centre of mass is very low. As a consequence, even after inaccurate dropping operations the seed body tends to keep its upright position.

2.4.2. Test Results

We have conducted a series of tests to evaluate the spatial range of the seed prototype. We should be able to assure a 5 cm detection under various lighting conditions. Fig. 5b shows the useful detection range of a seed measured with a Khepera.

3. Seed Clustering: The Bio-Inspired Test Experiment

A biologically inspired experiment concerned with the clustering and gathering of scattered seeds was presented in [2] and replaid in [3]. We can summarise the resulting robot behaviour with the following simple rules. The robot moves on the arena looking for seeds. When its sensors are activated by an object, the robot begins the discriminating procedure. Two cases can occur: if the robot is in front of a large obstacle (a wall, another robot or an array of seeds), the object is considered as an obstacle and the robot avoids it. In the second case, the object is identified as a seed. If the robot is not already carrying a seed, grasps the seed with its gripper; if the robot is carrying a seed, it drops the seed close to the one it has found; then, in both cases, it turns about 180 degrees and begins searching again.

In [2], due to the difficulty for the recognition algorithm to distinguish between a seed and another robot, a robot often dropped a seed in front of a fellow, and the latter grasped the seed (seed exchange) or a seed was dropped in an isolated position in the middle of the arena or beside the wall. For the same reason, the robots tried to grasp each other and often became entangled

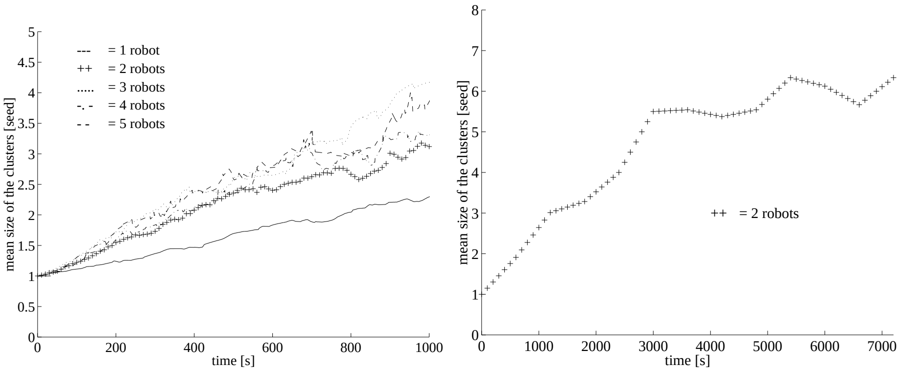

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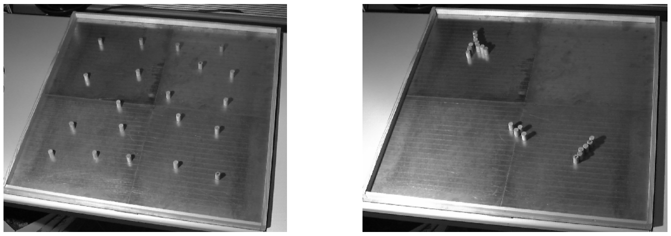
Figure 6. a) Team performances in the clustering bio-inspired experiment in in [3] (average over 5 replications) and b) with the help of the extended autonomy tool for 2 robots (average over 3 replications).



a) b)

Figure 7. The arena at the beginning (a) and at the end of the experiment (b).

for a few seconds. The experiment was conducted with a group of 1 to 5 Kheperas equipped with the gripper module and 20 scattered seeds in an arena of 80 × 80 cm. The measured team performance was the average size of the cluster created in about 30 minutes. Due to the low reliability of the distinguish algorithm, the performance evolution showed a saturation phase after about 10 minutes.

In [3] we carried out the same experiments with a group of 1 to 10 Khepera, different arena sizes, different number of seeds, and with a more reliable distinguishing algorithm. Furthermore, in order to improve the discrimination, each robot was equipped with an IR reflecting band: the size of the robots indicated by the proximity sensors was therefore increased and, at a distance of 4-5 cm a robot was already recognised as an obstacle by the other robots. The team performance evolution did not saturated, even after more then 16 minutes (see fig. 6a).

The question arises spontaneously: what would happen after 16 minutes? A simple probabilistic model developed in [3] suggests that, because of the geometry conditioned probabilities of building or destroying a cluster, the size of the clusters should continuously increase until all the seeds are gathered together. The model forecast does not take in account the interference phenomena, which play a crucial role in experiments with real robots. With the help of the developed extended autonomy tool, we have performed an experiment with two robots, using the same algorithm as in [3]. The experiment lasted 2 hours and was replicated 3 times. As we can see in fig. 6b, the cluster size does not increase very much after 80 minutes. Fig. 7 shows a typical scattering of the seeds at the beginning and at the end of the experiment.

4. Conclusion

We presented a set-up for bio-inspired experiments in collective robotics. The four main results we derive are: *first*, the hardware modularity of Khepera allows us to build a flexible set-up; *second*, the energetic autonomy problem is solved in a reliable way for experimenting with real robots during several hours; the seed clustering experiment has demonstrated the efficiency of the developed tool; *third*, the communication architecture among teammates and/or with a supervisor unit is designed to prevent bandwidth bottlenecks with bigger robot teams; *fourth*, the use of programmable active seeds extends the set of possible bio-inspired experiments without increasing the sensorial complexity of the robots. We hope that the design ideas described in this paper will help other researchers to develop their own set-up.

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