

Animal and Robot Mixed Societies

Building Cooperation Between Microrobots and Cockroaches

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The European project LEURRE deals with cooperation between robots and animals in a social context. Its main objective is to demonstrate the possible control of such mixed societies. The control of interactions between artificial systems and living organisms is a key challenge in many scientific fields like medicine, agriculture, and ethology. All biological levels are concerned: the cellular level regarding, for example, interfaces between artificial systems and cells like neurons; the organism level regarding intelligent prosthesis; and the human level as it relates to cooperation between humans and robots.

The principle of experiments utilizing decoys or lures is to isolate from the other features of the interacting animal the stimulus inducing a specific behavior. Many ethological results show that it is possible to interact with animals not only by mimicking reality but also by making specially designed and often simple artifacts [1]. However, once the selected behavior has been performed by the animal, the interaction stops because the lure cannot “reply” (the ability to control and manage several related interactions), which is a key step in interacting with animals. Robots that can act as decoys and “respond” to animals by modulating their behavior accordingly offer an interesting opportunity for biology and robotics.

The main objective of the LEURRE project (visit <http://leurre.ulb.ac.be>) is to trigger the emergence of new collective responses or new global patterns by adding communicating robots to a group of social animals and proving that they can collaborate. Therefore, the main tasks of the project are to

- ◆ study behavioral models for mixed societies
- ◆ provide a validation of the behavioral model by confronting it with a real implementation of a mixed society composed of insects and insect-like robots
- ◆ control the global behavior of the society; we will show

that it is feasible to change the global behavior of a mixed society by introducing a limited number of robots

- ◆ provide a general methodology for the design and control of mixed societies
- ◆ demonstrate relevance of our results to quality of life and management of living resources. We aim to demonstrate that the methodology developed for insects is also applicable to groups of vertebrates, such as gregarious mammals or birds.

Some of the results will prove to be useful for collective robotics because a behavior programmed in the robot must cope with its natural counterpart in order to be accepted as a congener. This gives a better insight into the basic behaviors necessary in a mixed society.

The behavioral patterns based on self-organization in animal societies result from simple yet numerous interactions. The patterns create a “collective intelligence” among individuals distributed in the environment and having access only to local information. Each agent has simple sensorial apparatus and communication equipment that enable it to respond to two types of local stimuli: the stimuli from the nonsocial environment and those from the other members of the group that are, for example, attractive and activating (positive feedback regulations) or repulsive and inhibiting (negative feedback). In such systems, the signal itself constitutes the information, rather than being solely the physical support for an exchange of information [2]–[4]. The individual behavior adjusts to the signal itself rather than to its possible content of information.



The interaction between robots and animals in mixed societies is a challenging new research field. For many years, researchers have developed robots inspired by animals [5], [6] and robots that use biologic actuators [7]. Yet, only a few robots that interact with animals [8], [9] have been developed, and none attempt to be accepted as a member of the society.

The European Project LEURRE

The European project LEURRE started in September 2002. Complementary competencies are required for this project, and the teams include:

- ◆ CENOLI, Université Libre de Bruxelles (ULB), Belgium: core competencies in biology and complex systems both from experimental and theoretical points of view, particularly in self-organization and the dynamics of natural and artificial multiagent systems
- ◆ International Solvay Institutes for Physics and Chemistry, (ISI), Brussels, Belgium: core competencies in modeling complex systems and dissipative structures
- ◆ CNRS-EVE, Université de Rennes 1, France: core competency in biology, including behavior and the chemical communications of the cockroaches
- ◆ CNRS-CRCA, Université Paul Sabatier, France: core competencies in biology (mainly social insects and mammals), collective intelligence, and self-organization in biological societies
- ◆ Autonomous Systems Lab (ASL), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland: mainly involved in designing and building the robots and developing all the tools that are required to work efficiently with them. Another important task is to program the behaviors according to the models developed by the biologists and to fit them on the robot's CPU, taking into account the hardware limitations. In short, EPFL is involved in building something that can be used as a toolbox for ethologists.

Aside from the the global results of the project, each team will enhance its specific field of knowledge. From the biological point of view, it helps to understand animal behaviors since these behaviors will be tested through interaction with artificial systems. For researchers interested in complex systems, it is an opportunity to test the link between formal models and their implementation as well as to experimentally test the effect of the individual parameters on the global pattern. For engi-

neers, the challenge is to build very small robots that can be compatible with animals. Second, it is interesting to study perception and sensors for bio-interaction. Finally, since the project includes a collective intelligence, aspects of the results will be useful for collective robotics.

Mixed Society of Cockroaches and InsBots

For research dealing with animal societies, it is convenient to use animals that allow detailed analysis and modeling. For this reason, gregarious insects are a good choice. The artificial agent in the mixed society is an autonomous mobile robot. The recent results achieved in this field allow us to design a miniature robot with sufficient performance to interact with insects. We call it *InsBot* for "insect-like robot." To achieve these goals, we chose to use American cockroaches and miniature robots to form the experimental mixed society (Figure 1).

The study of this cockroach-InsBot model is new and has been selected for the following reasons. The social behavior of cockroaches involves such details as aggregation, collective decision, and parental care. Individuals are able in some situations to memorize visual cues and perform path integration [10]. Aggregation, one of the keystones of social phenomena, is a prerequisite for the development of other forms of cooperation

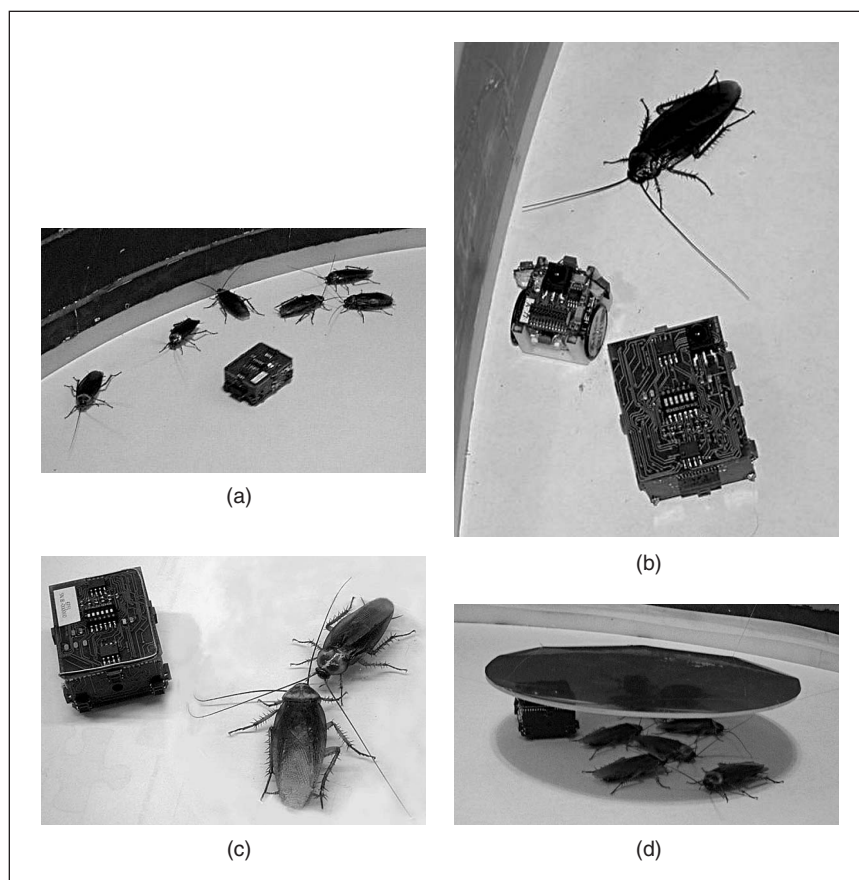


Figure 1. Robots and cockroaches together: (a) in the arena; (b) *InsBot*, *Alice*, and cockroach; (c) *InsBot* and cockroaches are of similar size; and (d) a mixed society under a shelter.

and is involved in many activities. In a homogeneous setup (see Figure 2), cockroaches are able to cluster to form characteristic patterns [11], [12]. However, in natural situations, cockroaches aggregate in places that present particularly interesting conditions. In tests carried out with large and identical shelters, the insects show a strong tendency to aggregate on a unique resting site [13], [14]. One common shelter is selected through this collective choice, and the individuals do not spread between the different potential shelters.

The self-organized aggregation and collective choice result from 1) an exploratory “random walk” and, hence, a random discovery of a cluster or a shelter and 2) some amplifications based on tactile and chemical communications. These amplifications are modulated by the probability of stopping correlated to the number of individuals already stopped in a local area of perception. The resting time increases according to the number of congeners present in the local neighborhood. Chemical cues are used for congener recognition and aggregation. In natural situations, the shelters are not identical, and they are characterized by different parameters that are more or less easily detected and integrated by an individual. Any parameter of a shelter that increases the individual resting time favors the formation of the cluster in that specific shelter. Due to the competition between shelters, most of the insects will aggregate at the site that has the highest resting time. These patterns of aggregation can be very diverse depending on parameter values, ranging from the gathering of all animals in a unique site to their splitting between several ones. We have demonstrated that the different collective patterns arise from the same generic rules based on the individual response to local signals, including the presence of conspecifics (positive feedback). The perception of the conspecific is based on tactile and chemical signals that are present on the surface of the insects [11]–[14].

The chosen species *Periplaneta americana* is a classical species used in biology (neurobiology, ethology, etc.). Their two long antennae (around 30 mm) are used as tactile and chemical

sensors. Their physical characteristics (including size and speed when calm) are similar to those of the InsBots. Moreover, the experimental spatial (about 1 m) and temporal scales (a few hours) of cockroach collective patterns make them suitable for our studies. The main problem in animal-robot interactions is that the signal emitted by animals must be detected by the robot and the robot must be able to emit signals detected by the animals. Thus, it is important to choose situations in which communications are simple and the signals used to communicate are easily detected by the robot’s sensors. We propose that the short-range interactions between cockroaches are mainly tactile and chemical, implying that it is possible to implement such short-range interactions somehow in robots as well. All these characteristics make the coupling of the microrobots with the cockroaches *Periplaneta americana* a useful and low-cost experimental environment.

Basically, each robot obeys simple rules that determine how it reacts as a function of the signals it receives from the environment, the other robots, or the animals. Its decision, position, and movement affect the decision, position, and movement of other members of the group, whether they are animals or robots. The robot can modify the general behavior of the mixed society, and this change can be measured in such cases where the probability of an aggregate in each shelter would be otherwise equal. One experimental idea is to influence the aggregate position by adapting the individual behavior of the InsBots. For example, in a natural situation of collective choice between shelters, the group of cockroaches preferentially select a shelter with lower light intensity. The InsBots can be tuned to settle in a brighter shelter and will be able to modify the choice of the group, leading the insects to choose this brighter shelter instead of the a darker one.

The Experimental Setup

The experimental setup is composed of a white plastic arena (1 m in diameter and 15 cm high), an overhead camera, and illumination (Figure 2). The same arena is used for experiments with or without shelters. Lighting features reduced infrared (IR) emission to avoid problems with the IR proximity sensors of the robot. For safety and experimental reasons, we have to prevent the insects from escaping the arena, so an electrical fence has been added. This low-power, low-voltage barrier is not harmful to the cockroaches; the shock is rapidly “forgotten” and does not alter their behavior. To reduce mechanical vibrations, a phonic layer has been added between the ground and the wooden layer. On the wooden layer, a paper sheet is added, and it is changed after each experiment. This change ensures that any chemical tagging left during the experiment will not influence the following experiments. It also allows us to remove dust or small dirty marks that could affect the mechanical parts of the robots; dust is a major problem with the robots’ very small open watch motors.

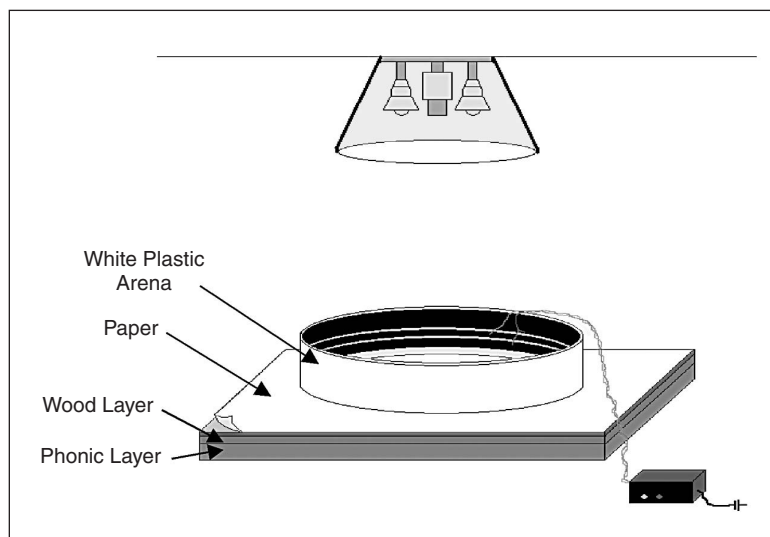


Figure 2. The experimental setup.

The insects are introduced in the arena and about 30 min is needed for them to calm. During this time, the robots are in standby mode. After this first phase, the experiment can start; at this point, there are many interactions and movements of the cockroaches and the robots. The first experiments performed without robots have shown that it takes about two hours before the appearance of an aggregation or a shelter selection.

The Robot InsBot

The developed robot fulfills the following requirements:

- ◆ to behave like the insects of the mixed society
- ◆ to be accepted by the insects as a congener
- ◆ to be able to influence the global behavior of the society.

Considering the description of the cockroaches and how the experiments will be performed, the major challenges are the robot's small size, the high level of integration (many sensors), and the darkness of the cockroach cuticle (IR sensors sensitivity). The number and duration of the experiments demand reliable robots and tools. However, the behaviors to be programmed are feasible with a simple microcontroller architecture. Finally, the most important information for all behaviors is proximity, which is well managed in minirobotics.

Design of the InsBot

During the initial part of the project, we have used Alice robots [15] to conduct some acceptance tests. The tests revealed that the robot (in particular, its IR emissions, vibration, and size) did not cause the cockroaches to flee. These preliminary tests showed that it is quite hard to detect the cockroaches because they are brown, a color that absorbs most of the IRs. To address this difficulty, we increased the power of the emitters. We also found that we required some wireless communication modules for monitoring, some additional sensors, more computational power, and much greater memory than incorporated in Alice. This is why we finally decided to develop a new robot (Figure 3) dedicated to our mixed society application.

Many sensors might be interesting when experimenting with animal interaction. Here is a short summary of what we had imagined. In Table 1, potential sensors are given rankings from 1 to 6 based on computational power, energy consumption, and complexity. Because of the limitations on the size of the robot, its autonomy, and computational power, we finally decided to implement sensors 1, 2, 4, and 7 in the InsBot.

Chemical Sensors

For this project, both the emission and reception of chemical signals must be taken into account. The emission of the "cockroach chemical signal" is rather simple. Indeed, the molecules are present on the surface of the cockroaches. This is

why we decided to use only a passive chemical communication with some medium impregnated with the synthesized cuticle pheromones of the cockroach. The difficult tasks are to identify and synthesize this blend of chemicals. The reception of chemical signals using a "chemical nose" is much more complicated. This is still a major research field, and there are currently no industrial sensors that can be found for the type of chemicals used in insect communication. One strategy is to mimic the reaction to the signal using the other sensors and to implement only chemical emission. The chosen final solution is to cover the robot with a paper containing cockroach odor and to feel the insects through proximity measures.

IR Sensors

The IR sensors are used for both proximity and brightness measurement. This is the most important type of sensor because every behavior is mainly based on proximity information. Not only is the type of sensor important, but so is the position of the sensor itself. The sensors have been specially positioned in order to distinguish between an obstacle and a cockroach. This is why we decided to place one sensor on the top of each face and two on the bottom. The top sensor is higher than a cockroach. Therefore, in the case of an obstacle, the top and bottom sensors are activated, but in the case of a cockroach, only the bottom sensors are activated. One top and one bottom sensor

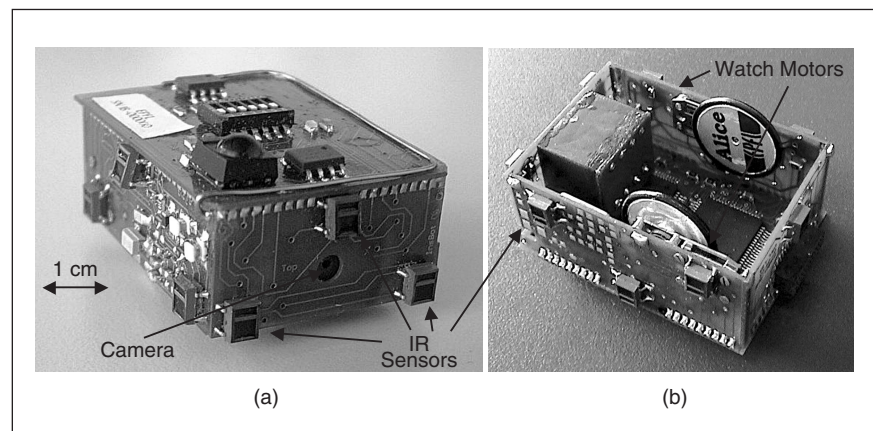


Figure 3. (a) The robot InsBot and (b) the robot upside down without battery and bottom cover.

Table 1. Sensor types for "biorobots."

N	Type	CPU Power	Energy	Complexity
1	IR proximity	2	3	1
2	Light sensor	1	1	1
3	2-D color camera	6	5	4
4	Linear camera	3	4	3
5	Tactile antennae	2	1	4
6	Vibration sensor	1	1	3
7	Temperature	1	2	1
8	Chemical	4	3	6
9	Humidity	2	2	2
10	Gas sensor	2	2	2

could potentially have been sufficient, but because of the sensor opening angle, the length, and the width of the robot, it would have been difficult to perceive obstacles. Moreover, the robot

also needs to distinguish another InsBot from a wall. In this case, it uses local communication with the IR sensors. The nearby robot also emits IR signals, whereas the border of the arena does not. The measure of the brightness using the same 12 IR sensors is used by InsBot to detect the shelters. It is capable of detection if it is partially or completely under a shelter and, thus, will try to enter or leave this dark area.

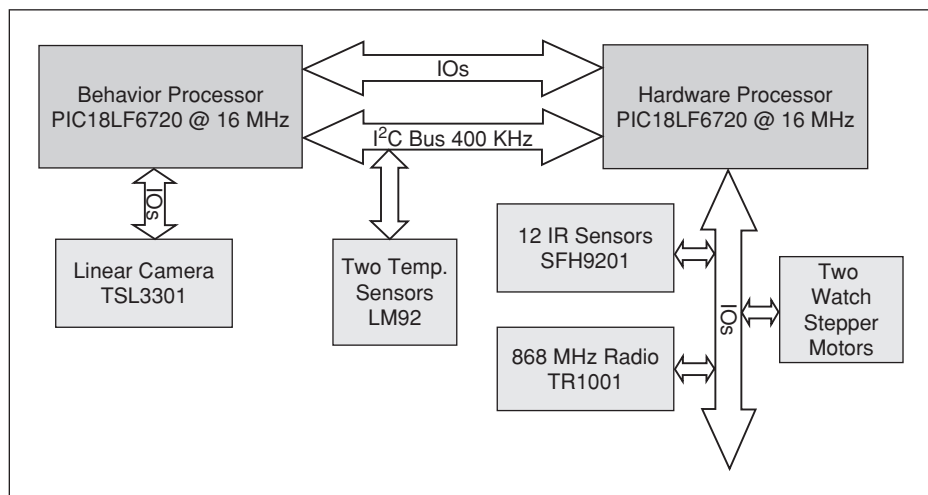


Figure 4. Hardware architecture of InsBot.

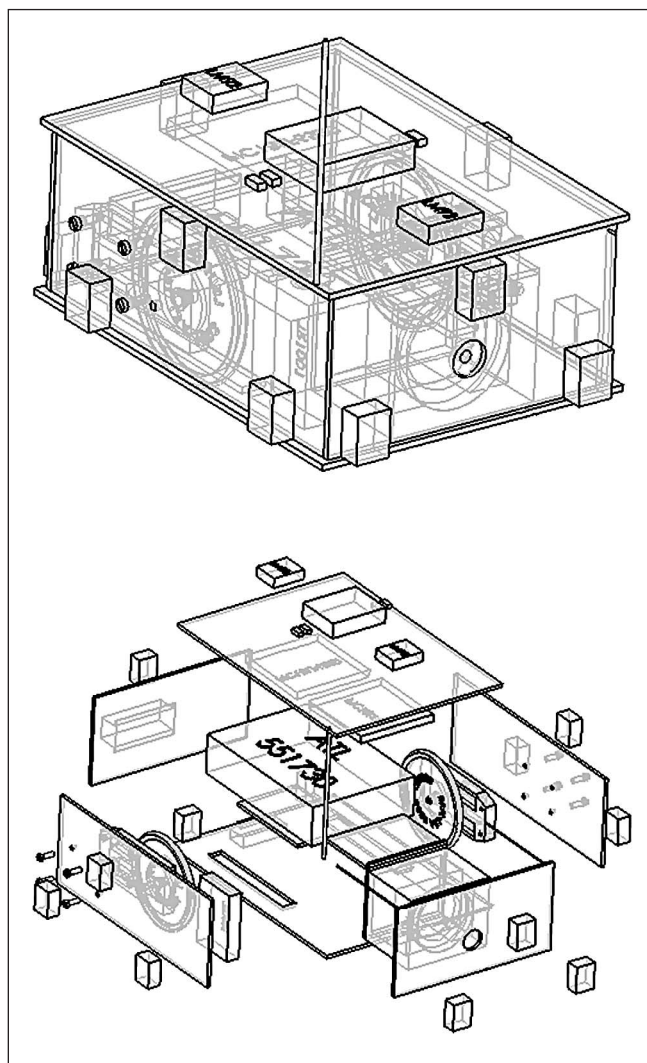


Figure 5. A three-dimensional model of InsBot.

Linear Camera

The linear camera is useful for detecting objects or groups of cockroaches at a longer distance than the IR sensors. Dark spots are assumed to be groups of individuals.

Temperature

Temperature information is used to adapt the behavior according to the temperature if needed, but

mainly to follow a temperature gradient as seen in cockroaches. This is why we have implemented two temperature sensors placed at the extremities of the InsBot.

Control and Electronics

The control consists of a behavior level and a hardware level implemented on two processors (Figure 4). The first, called the *hardware processor*, is connected to most of the hardware resources (wireless communication, IR sensors, and motors). Its basic tasks are to control all these features and preprocess the sensor information for perception. This processor is mainly programmed by the engineers. The second, called the *behavior processor*, can access all resources through a fast I²C bus (400-KHz) but can also be interrupted by the hardware processor with digital in-outputs. The camera is the only hardware device connected to the behavior processor because of the limited number of IOs on the other processor and because this makes the information directly accessible to high-level algorithms.

Energy

Energy is delivered by a small 190-mAh, Li-polymer battery for up to 4 h in the worst case (i.e., when all features are continuously working). We chose Li-polymer technology because this currently has the highest volumetric capacity among rechargeable batteries, is available on the market, is affordable, and boasts a very fast charging time (1 h for a fast full charge).

Mechanics

The robot must be very small and integrate many electronic parts. Therefore, we decided to use the printed circuit board (PCB) as the mechanical structure (Figure 5). Connections between each PCB are soldered for both electrical and mechanical connection. For locomotion, we chose a differential drive configuration, as was chosen for the Alice robot.

Three-Dimensional Drawing

Because of the very small size and the high level of integration, we first developed a three-dimensional (3-D) model of InsBot (Figure 5) to determine the size and position of each PCB. The 3-D model is also very important for visualizing the position of each sensor and the feasibility of the assembly.

Implementation

After the design and modeling stages, we have finally built an InsBot to validate all assembly aspects. The robot is composed of nine PCBs (0.6 mm thick) as shown in Figure 6.

The first six units have been manually assembled. Because of the very small size of the components and the very precise mechanical parts, it takes about 6 h to fully assemble one InsBot. Additional units are in production to perform all the mixed society experiments. Table 2 summarizes the general characteristics of the InsBot as well as the main components.

Software

The source code of the InsBot is written in C and is compiled with the C compiler by CCS, Inc. (<http://www.ccsinfo.com>). The compiled hex file is then uploaded to the robot by means of a serial boot-loader, so that the user does not need a hardware programmer. Table 3 presents the software architecture and processor tasks of the InsBot.

Tools

Through a programming board, the two InsBot processors can communicate and be programmed with a PC through a serial port. In most recent laptop PCs, there are no serial ports; consequently, we decided to implement a USB hub and two USB-serial converters in order to use just one USB port on the PC. The programming board also includes two in-circuit debugging (ICD) connections for a full reflash of the processors. The final feature is a fast charger that allows a full battery charge in one hour.

A multirobot charger block has been developed because we plan to work with colonies of 20 InsBots. This device includes the same charger as the programming board, but it permits four InsBots to be recharged simultaneously. It also monitors the battery charging level and other problems. The state is signalized with two LEDs.

To enable wireless communication to the robot, we use a radio base station on the PC side. With this board, we can communicate both with one specific InsBot (defined by its address) or with all InsBots. The robots can also communicate together. As stated previously, we are not using this wireless link to globally control the behavior of all the InsBots, but only to monitor the experiments. We have used a USB-serial converter to be compatible with any computer (Windows, MacOS, and Linux) and to

power this module directly from the PC. All existing applications communicating using a classical serial port (e.g. Hyperterminal, MatLab, or any C program) are also compatible because the USB-serial converter emulates a virtual serial port on the computer. The graphical user interface was developed using SysQuake (<http://www.calerga.com>).

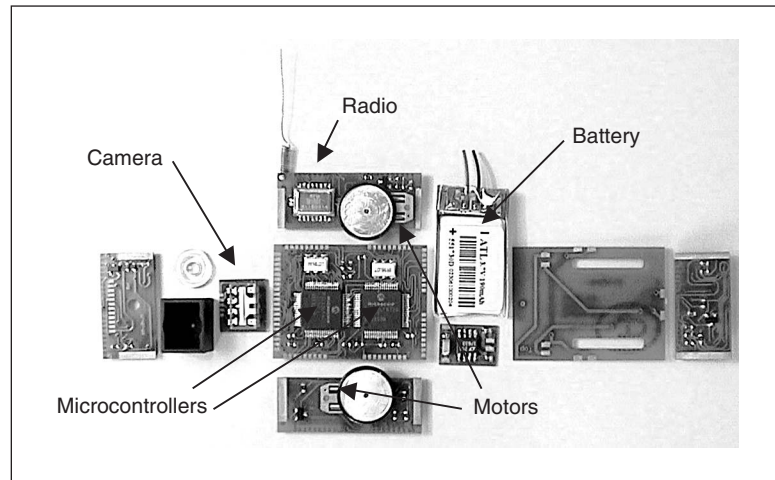


Figure 6. The robot before the final assembly. The nine PCBs from inside the robot are shown.

Table 2. Specifications.

Weight	15 g
Maximum speed	5 cm/s
Autonomy	4 h minimum
Linear camera	102 pixels, 8 bits gray level
Processor	2 × PIC18LF6720 (64 Ko Flash) @ 16 MHz
Temp. sensors	0.33°C accuracy, two units
Proximity sensors	Up to 8 cm (white paper), 12 units
Wireless link	125,000 baud, 20 m
Size	41 mm × 30 mm × 19 mm
Cost	About €200 (without assembly)

Table 3. Software architecture and processor tasks.

Software Processor	Hardware Processor
Library of functions	Multitask and real-time OS
Random generators	Motors control
–Uniform	Sensors processing:
–Normal	–Proximity
–Exponential	–Brightness
Hardware access	Time in ms (4 B)
High-level behaviors	Automatic behaviors:
	–Obstacle (avoidance-attraction)
	–Wall following (left-right)
	–Light (avoidance-attraction)
	–Temperature (avoidance-attraction)
	Local communication (IR)
	Global communication (radio)

Chemical Marking

The most important factor is to ensure that the robot is recognized as a congener. The InsBot not only has to be accepted in the near environment of cockroaches but has to be identified as a conspecific because it is bearing the specific chemical pheromone. The cuticular surface of insects represents a rich reservoir of chemical molecules, some of which have a high informational value and some of which are superfluous. Informational molecules are mainly cuticular hydrocarbons that function as intra- and interspecific signals for insects and, in particular, social insects. The identification of these compounds involves several steps: the development of adequate behavioral bioassays for the proposed role of a given blend of chemical compounds, the role of the different groups of compounds in the aggregation behavior, and the localization of the secretion source and the identification of the efficient molecules. This chemical blend has been identified by extracting cuticular chemicals, followed by gas chromatography and mass spectrometry analysis. At this stage, this pheromone blend is not chemically synthesized, but rather extracted from the insects. Our tests have already shown that, indeed, the insects prefer to collaborate with a chemically tagged robot and try to avoid nontagged robots. This system allows us to study the role of chemical communication in robot-animal interaction. Moreover, it can be further developed to study the use of chemical communication in collective robotics.

Ongoing and Future Work

We are now tuning the behaviors implemented in the InsBot in order to mimic the insects. The biologists extracted the trajectories of the cockroaches using a tracking system and quantified the different parameters of the individual behavioral model. The first goal is to have a robot that moves like an individual cockroach and that presents a resting time that is modulated by the number of insects present in its perception area.

After this first phase, the robot will be introduced into the colony, and we will try to analyze the most important parameters (size, noise, behavior, chemicals, etc.) that enable the InsBots to collaborate and influence the insects.

The final phase will be to upgrade the individual behavior of the InsBots to control the global behavior of the mixed society. The typical experiment in this sense is to attract the cockroaches to a place or shelter they would not choose spontaneously without the presence of the robot. At this point, it will be possible to study and test the parameters and the strategies that permit the control of the whole group.

Conclusion

After about six months of analysis with an existing minirobot (Alice), we have been able to define specifications for a new robot to be used in a mixed society of cockroaches and robots. Due to the limitation on the physical dimensions and the large number of necessary sensors, some trade-offs had to be made. The number of features included in InsBot makes it an example of a highly integrated system. Moreover, this is one of the first robots devoted to interaction with small insects. It is a prelimi-

nary step in understanding the mechanisms that underlie complex societies of social animals and may potentially lead to the possibility of controlling such mixed societies.

Most problems that occur in animal societies have a strong self-organized component: synchronization of activities, aggregation, sorting, etc. Social imitation plays a key role in these species, and most of the collective patterns result from positive feedback [1], [16]. The analysis of collective behavior in these terms implies a detailed observation of both individual and collective behavior, combined with mathematical modeling to link the two. This is why the study of different examples of collective behavior is an important task in this project.

Despite this simplicity, the emerging collective pattern may be of remarkable interest [17], [18]. In such a context, a relatively simple robot is able to control the spatial distribution of these wild animals.

Most self-organized systems are very sensitive to small changes at the individual level or at the level of a small fraction of the population. It is possible that a number of robots interacting within the group might be the source of small differences inducing the whole group to escape from some sub-optimal solution [1]. This offers the opportunity to introduce new collective behaviors and/or to "push" the group towards new patterns; in this way, it may be possible to improve breeding conditions, animal welfare, pest management, and so on. A few outstanding questions remain to be addressed: What are the rules which must govern the behavior of such robots and how should these rules be tuned to generate different patterns and efficient solutions? How may robots modify the organization of the group, leading to new patterns?

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Keywords

Mixed society, artificial life, life control, gregarious animals, miniature mobile robots, insect-like robots, basic behaviors, complexity and control, emergence, self-organization.

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