ROBOT-ANIMAL INTERACTION: PERCEPTION AND BEHAVIOR OF INSBOT

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ABSTRACT

This paper describes the hardware and behavior implementation of a miniature robot in size of a match box that simulates the behavior of cockroaches in order to establish a social interaction with them. The robot is equipped with two micro-processors dedicated to hardware processing and behavior generation. The robot can discriminate cockroaches, other robots, environment boundaries and shelters. It has also three means of communication for monitoring, logging, supervision of biological experiment and detecting other robots in short range. The behavioral model of the robot is a mixture of fusion in low-level and arbitration in high-level. In arbitration level a stochastic state machine selects the proper subtask. Then in fusion level, that subtask is decomposed to a hierarchy of sub-tasks. Each sub-task generates a potential field. The resultant force is then mapped to an action.

1 INTRODUCTION

Over the last decades, researchers in bio-inspired robotics have mimicked animals to design hardware and software structure of the robots. The RobotV (Kingsley et al. 2003), RHex (Sarnaly et al. 2001) , Biobot (Delcomyn and Nelson 2000), HEL-roach Kagawa and Kazerooni 2001) and the hexapod micro-robot (Guozheng 2002) are examples of legged-robots which have been mechanically inspired by cockroaches. Some projects are inspired from the behavior of cockroach and implemented their behavior on micro robots (Jost et al. 2004; Garnier et al. 2005).

Some researches have developed hybrid robots by mixing the artificial and biological systems. The PheGMot-III (Nagasawa et al. 1999) uses real cockroach antennas as a chemical sensor to follow pheromone tracks. Holzer and Shimoyama (Holzer and Shimoyama 1997) designed a system which controls the cockroach's actuators by electric stimulation.

Instead of building exactly the same mechanism as animals our goal in short-term is to have robots which integrate into a society of animals, live inside the society and interact with them. The focus of our work is in collective-level. So there is no need to have the same appearance as animals but the functionality of the robot must permit it integrate into their society and produce *statistically* same collective behaviors.

By "integration" we mean not only the animal's behavior is affected by the robots and other animals but also the robot's behavior is affected through interactions with the animals and other robots in the mixed-society. In fact every decision is made collectively by the whole system and a top-level observer will not see any difference between the animal society and the mixed one.

In our model the animal is thus considered as a black box and the important characteristics for our robot is to fit in the mathematical model of collective interactions among individuals involved in the group.

The long-term goal of the project, after the robots are accepted to the society of animals, is to manipulate the collective response of the society by modulating the behavioral parameters of robots. We hope then to propose guidelines towards a general methodology for performing such a control on mixed-societies.

Among the projects that are related to our work, we can mention the Robot Sheepdog (Vaughan et al. 1997) that controls a flock of ducks by moving them safely to a pre-determined position. Also, the W-M6 rat-like robot (Ishii et al. 2004) tries to create a symbiosis between creature and robot by teaching a rat to push a lever to access a food source. These projects are different from what we are investigating in that their robots are not trying to integrate into the society. Instead they are trying to affect or supervise the society in a centralized manner.

Böhlen developed a robot (Böhlen 1999) that interacts with three chickens in a cage. He manipulates some techniques to mechanically reduce chickens' anxiety towards moving machinery. The goal of the robot is to integrate with chickens but does not try to affect their behavior.

Our work is a part of the LEURRE European project which aims to study mixed-societies of animals and robots. This multi-disciplinary project gathers the competence of biologists, ethologists, chemists and engineers coming from different European universities: Université Libre de Bruxelles, Université Paul Sabatier, Université de Rennes and Ecole Polytechnique Fédérale de Lausanne.

Our team is mainly involved in design, building and programming the robots and tools needed to manage them. Behavior of robots is programmed according to the models developed by biological researches.

The preliminary tests run on the mixed-society of cockroaches and robots. More experiments will be done with other animals to verify the methodology.

In this paper we focus on the behavior generation issue and describe how we implemented the aggregation behavior of cockroaches on our insect-like robot, InsBots. More details on hardware aspects are found in (Colot et al. 2004; Tâche et al. 2005).

The paper is organized as follows: The required functionality of the InsBot is summarized in the next section. Then a short review on the perception of the robot is presented. In section 4, the behavioral architecture of the robot is explained in detail. Finally the test results followed by conclusion and future works are explained.
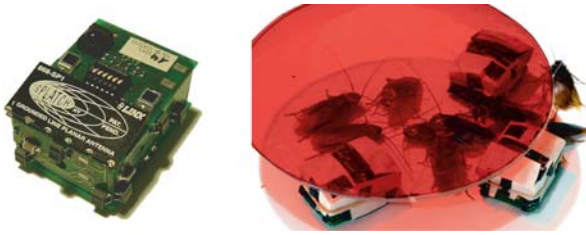

Figure 1-Left: InsBot without cover. Right: InsBots with their covers aggregated with cockroaches under a shelter (Copyright ULB)

2   FUNCTIONALITY OF INSBOT

As mentioned earlier, InsBot requirements do not specify that the robot should look like a real cockroach. Instead it should:

- Behave like a real cockroach among its group.
- Get accepted by them as a congener.
- Be able to influence their collective behavior.
- Be equipped with monitoring and debug facilities

InsBot (Figure 1) is a 41x30x19 mm^3 robot. Its rigid body is composed of PCBs that allow mechanical and electronic connections at once. It has a 190 mAh Li-Polymer battery that allows autonomy of at least 3 hours (required for the biological experiments) and 2 miniature differential-drive step-motors for locomotion. It weighs 17gr and can move up to 5cm/s.

It has several sensors and communication tools:

- 12x Infrared (IR) proximity sensors, 3 in each side of the robot. They are placed at different heights to allow discrimination of different environment objects. They are also used for local communication between the robots.
- 2x Photodiodes on top, for detection of the shelters.
- 1x linear camera (102 pixels) in front to enhance cockroach detection.
- 1x IR receiver to remotely control the robot.
- 1x radio transceiver (@868MHz) to communicate with an external computer. It is used mainly for debug or monitoring.
- 2 PIC18F6720 micro-processors (@16MHz) with

128K program memory, 3840 byte SRAM data memory and 1024 byte ROM.

One of the processors, called "The Hardware Processor", is connected to (almost all of) the hardware resources. It prepares the sensory data by noise-filtering, scaling and calibrating their values. This information is then transmitted through a 400 KHz I^{2}C bus to "The Behavior Processor", which hosts the behavioral algorithms.

To enhance the acceptance of the robot into the cockroach's colony, it is covered by a paper impregnated with cockroaches' pheromone (Figure 1, right).

3   PERCEPTION

In this section we focus on the detection algorithm that has been tuned for optimal environment perception.

3.1   Experimental Setup

The perception methods described in this section have been tuned for the particular setup shown in Figure 2. It is a circular white plastic arena (1m diameter, 20cm high) with an electrical fence to prevent the escape of the cockroaches. The floor is composed of anti-vibrations materials covered with a white paper. The paper is changed after each experiment. The illumination is given by 4 neon light bulbs with low IR emission to reduce the interference with IR sensors.

There are two circular suspended shelters under which cockroaches aggregate. The shelters (called "dark shelter" and "bright shelter" hereafter) are composed of dark plastic layers hanged at 5cm from the ground. To create different levels of shadow different number of layers are grouped.
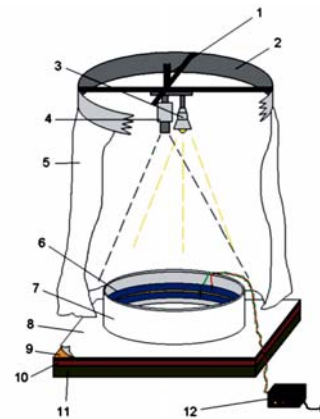

Figure 2-Experimental setup composed of neon light (3), camera (4), electrical fence (6, 12), white plastic arena (7), paper layer (8), phonic layer (9) and wooden layer (10). Shelters are absent (Copyright ULB).

3.2   Calibration

Due to several facts a calibration phase should be repeated once after each setup changes: First, the program is running on multiple robots and robots are slightly different in hardware devices. Then, the inclination angle of proximity sensors is hard to adjust

precisely. They are not also perfectly placed at the same height so they have different initial values. The floor paper and its roughness highly affect the bottom sensors. The illumination conditions vary in each experimental setup and the amount of light under each shelter changes as well. Orientation of shelters varies in each setup. It changes the gradient of light under the shelters.

The calibration procedure developed for proximity sensors and shelters are activated via TV remote control upon the user request. The computed calibration vectors are saved in the EEPROM and loaded after each restart. During regular process, these vectors are used to adjust the value of the sensors and cut the noise off.

3.3 Object Detection

To behave like a real cockroach, the robot must first be able to detect the relevant features of the experimental setup. These features are the two heterogeneous shelters, the living cockroaches, the wall and the other robots.

For detection and differentiation of shelters, the light intensity is measured by 2 photodiodes mounted on top of the robot. Then their value is compared with thresholds learned during the calibration procedure.

The cockroaches used in the mixed-society experiments are *Periplaneta Americana*. They are (24-44mm long and shine red-brown. They have 6 legs and 2 long (around 3cm) antennas. Due to the dark color of their skin, they are hardly detected by IR sensors from far distance. But thanks to carefully sensor placement on the robot, the calibration procedure and some heuristic rules, they can be distinctively detected from 1.5cm distance.

There are 3 IR proximity sensors on each side of the robot (Figure 1). The two lateral sensors are close to the ground (called "bottom sensors" hereafter). The other one is placed at top-center of each side (called "top sensor" hereafter). Due to the shorter height of the cockroach, the top sensors are less affected by them than the bottom sensors.

There are some situations where IR sensors can not provide reliable information to well discriminate different objects, especially when a cockroach is located along the wall. In this situation using the linear camera helps reducing the misdetections of cockroaches.

The difference between values of IR sensors mounted in different heights is used also to detect the wall. Due to taller height of the wall comparing to the cockroaches, the top sensor shows a value close to the mean of the two bottom sensors.

Depending on the position and orientation of other robots, they can be seen as a wall or a cockroach. To distinguish them from cockroaches and walls a local communication protocol using IR sensors as transceiver has been implemented. The scheduler keeps track of timing and coordinates the use of IR sensors as both proximity sensor and communication media.

3.4 Local Communication

Local communication is the exchange of information among the robots within a limited distance via their infrared proximity sensors. The purpose is to declare the presence of the robots to their neighbors. The transferring message is a 6-bit data containing the unique ID of the sender. Knowing the position of the sensor that received the signal and the proximity value of the IR sensors, the robot can then indicate whether the around object is a robot or not.

The low-level protocol is described in detail in (Tâche et al. 2005). Since the communication baud rate is very low the robots may not have the chance to communicate quite often. Therefore it must be combined with software solutions to provide a short term memory of the robots in neighborhood.

The information the robot gets out of local communication is saved in a log table. It is tagged with timestamp and the sensor that received the message (the sensor indicates roughly the position of the sender). The robot then has at its disposal, information about when, where and who has been around him.

The log table has a limited size. In case of experimenting with a large group of robots the table can hold only a part of signals. The table should then hold only the fresh signals. If a robot that is already registered in the table is detected at another time, its corresponding record in the table will be updated with the most recent data. Otherwise the oldest record is overwritten.

A fixed time window of T seconds is used as a criterion to specify the neighborhood region. Only the robots that have been around within the last T seconds are counted. By setting T to a bigger value the neighborhood range expands.

4 BEHAVIOR

The control architecture of the robot is a behavior-based controller (Arkin 1998) distributed on two processors. It consists of a collection of behaviors. Each behavior can take inputs from the robot's sensors and/or from other behaviors, and send outputs to the robot's actuators and/or to other behaviors.

The behaviors are arranged in a hierarchy where behaviors on higher levels integrate or arbitrate the behaviors on lower levels. At the highest level a centralized arbiter decides which behavior to execute. At the next level the selected behavior activates one or more behaviors from the lower levels. The decomposition continues downward until the primitive behaviors in the lowest layer. Therefore behavior coordination is competitive at the highest level and cooperative at lower levels. The final output is the result of cooperation among the activated behaviors.

The centralized arbiter runs on the behavior processor. It is a finite state machine that implements aggregation of robots in mixed-society (hereafter referred as mixed-aggregation). The remaining behaviors run on the hardware processor. Hereafter we call them *reactive*

behaviors in the sense that they map a stimulus directly to a response. They have faster access to sensors and actuators. The running cycle of the reactive behaviors is 10 times faster than the centralized arbiter (50 ms vs. 500 ms).

4.1 Reactive Behaviors

Reactive behaviors are generated by means of potential field fusion method (Arkin 1998; Reynold 1994). Each behavior generates a potential field. Potential fields map sensory space into motor space through attraction or repulsion force vectors *(rx, ry)*. The final direction and velocity of robot corresponds to the resultant force *(Rx, Ry)*, which is the weighted sum of these force vectors. The weights are specified empirically. The resultant force is then transformed to the speed of wheels.
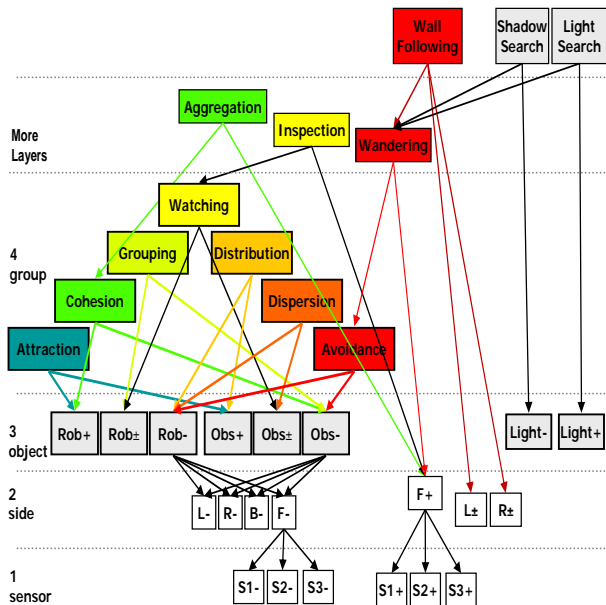

Figure 3- An example of the behavioral architecture. Rob, Obs, L, R, B, F , +, -, and ± stand for robot, obstacle, left, right, back, and front, attraction, repulsion, and following (combination of attraction and repulsion), respectively. It is assumed that the typical robot has 3 sensors at each side, where S1, S2, S3 are located at front. Weights and some other details are not shown.

4.1.1 Behavior Layers

The lowest layer deals with a specific sensor. This layer provides the primitive behaviors. Each primitive behavior assign different levels of attraction or repulsion to value of a sensor *S,* i.e. *(rx, ry) = F(S)*. *F* can be constant, binary, or proportional attraction/repulsion, or combination of them.

The second layer deals with sides i.e. left, right, etc. Here a group of primitive behaviors of the first layer are combined to generate a force toward/from a direction. For instance *move-forward* behavior is achieved by assigning a constant attraction force to the front-side sensors.

The third layer deals with objects, i.e. wall, cockroach, robot, or unknown object. For instance *obstacle-avoidance* is *left-avoidance* behavior *if* an obstacle is detected at left plus *right-avoidance if* an obstacle is

detected at right, etc (Figure 3, layers 2 and 3).

The fourth layer deals with a group of objects. This layer composes collective behaviors like *dispersion*, *cohesion*, *watching*, etc. For instance *watching* behavior is the result of following all objects.

It is possible to add more layers and create more complex behaviors. For instance *light-search* behavior is built from *wandering* and *light-attraction,* where *wandering* is composed of *avoidance* and *move-forward.*

As a summary, a typical architecture of behaviors for a robot equipped with only IR proximity sensors is shown in Figure 3. To fit in one figure the types of distinguishable objects with IR sensors were limited to robots, obstacles, and ambient light. Also some of the behaviors in the 3 first layers are not shown.

Behavior layers are designed carefully to maintain scalability and reusability of components both in higher levels and even on another robot. We have implemented the same architecture on Alice micro robots (Caprari 2003). It is scalable via adding more layers or modules.

4.1.2 Transformation of Force to Speed

Finally, the resultant force *(Rx, Ry)* is transformed to the speed of the wheels. Inspired by the law of physics, we can write the following relations for Figure 4.

$$\begin{cases} \sum F = 0 \Rightarrow R_y = F_L + F_R \\ \sum \tau = 0 \Rightarrow R_x.L' = (F_L - F_R).L \end{cases} \overset{L'/L=k}{\Longrightarrow} \begin{cases} F_L = \dfrac{R_y + kR_x}{2} \\ F_R = \dfrac{R_y - kR_x}{2} \end{cases}$$
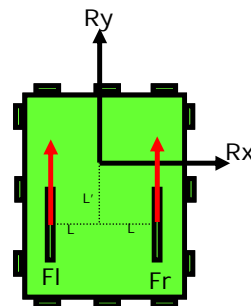

Figure 4-Converting resultant force to speed vector

The vector *(FL, FR)* is a force vector that must be simulated by the wheels so that an observer perceives a force vector *(Rx,Ry)* affecting the movement of the robot. The force vector *(FL, FR)* is mapped to a feasible speed vector *(VL, VR)*. We used *k=1* in our application. Bigger *k* values create sharper turnings since Rx is magnified.

4.2 The Arbiter

The mathematical model of the mixed-aggregation asks for a stochastic state machine that at each time step (here 500 ms) selects the next macro-action among *move*, *turn*, and *stop* action set (Figure 5). These actions are mapped to reactive behaviors in hardware processor. If the robot is moving near periphery, the *move* action means *wall-*

following behavior and *turn* means *escaping-from-wall*. In the center of the arena they mean regular *obstacle-avoidance* and regular *turning* respectively.

Actions are selected based on a probability table. Entries of the table assign a probability to each macro-action based on the state of the robot, i.e. position, shelter type, and number of cockroaches and/or robots around. The probability table is extracted by extensive statistical data gathering on real cockroaches using visual tracking software and adapted to create similar behavior as the cockroaches.
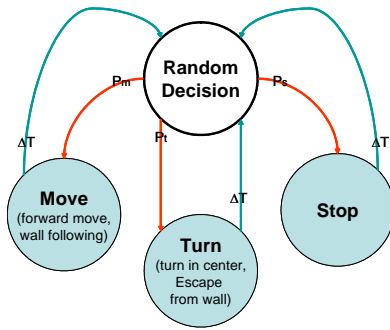

Figure 5-The finite state machine for mixed-aggregation

5   RESULTS

Based on the discussed facts, the detection algorithm combines the different responses of the top and bottom IR sensors, the local communication and the linear camera to distinguish cockroaches from arena walls and robots. Here we show the test results.
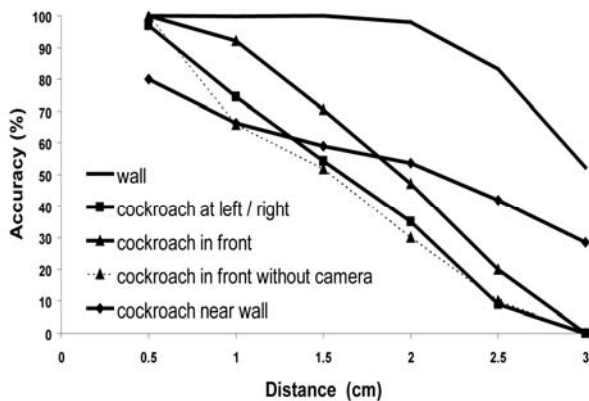

Figure 6- Cockroach/wall detection accuracy vs. robot-cockroach/wall distance

5.1   Cockroach and Wall Detection

Figure 6 displays the accuracy of the cockroach/wall detection algorithm implemented on the InsBot. These results were obtained by manually analyzing 900 different situations of a movie taken by the overhead camera and information of the wireless communication interface. For cockroach detection the distance is measured from the robot (body-border) to the closest point of the cockroach body (excluding legs and antennas).

Figure 6 confirms that cockroaches are visible from 2.5cm, but optimal detection is only reached when they

get closer to the robot. The better performance in front side is due to introducing the linear camera. The dashed curve represents the same result without the use of the linear camera. It is clear that the detection accuracy is close to detection in left/right side. This graphics also shows that walls are detectable at further distances than cockroaches with higher accuracy thanks to their better reflective properties.

The rather poor performance of cockroach detection at even short distances comes from several facts: Firstly, certain parts of the cockroach's body are less visible than others. Its head well reflects the IR signals, whereas the rear side of its body composed of thin horizontal wings reflects the IR signals upwards. Also some positions around the robot are not well covered by IR sensors. Better performance is achieved by adding the linear camera as the graph with diamond marks shows.

5.2   Robot Detection

Robot detection mainly depends on the reliability of local communication protocol, which is rather difficult to characterize. The communication rate depends on distance and relative orientation of robots. Figure 7 (left side) shows communication rate between two robots. Each point represents the number of received messages by a fixed robot from another robot in different distances and orientations during a 30s test. Brighter points correspond to higher rates. Figure 7 (right side) shows the success rate i.e. the percentage of correct messages out of the received ones. The success rate is rather high (70-100%) even where the baud rate is low.
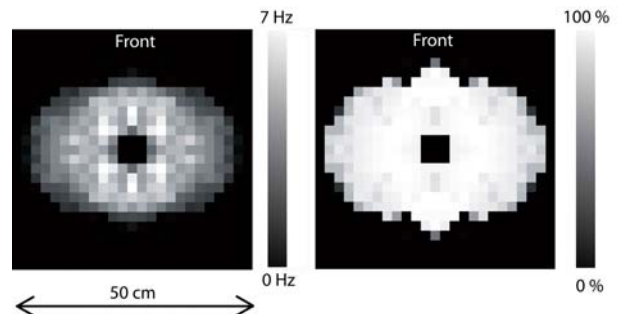

Figure 7- Local communication between 2 robots. Left: communication rate. Right: success rate

6   CONCLUSION

In this paper details of the perception and behavior implementation of the miniature robot InsBot were explained. Due to the limitation in the size of the robot, and the required long-time autonomy, the hardware parts and processing algorithms have been highly optimized. Different problems arisen from the imposed simplifications and limited sensory information were explained and the solutions were described.

The sensor fusion methods combined with heuristic rules that came from our knowledge about the experimental setup allowed the robots have good discrimination among different objects in the environment. Cockroaches and walls are now detected by using the infra-red proximity sensors mounted in different heights all around

the robot.

To have less collisions and thus a more friendly behavior with cockroaches, a linear camera was introduced on the front side of the robot that enhanced the detection quality.

A simple local-range communication protocol through infra-red sensors was established for robot detection. However more investigation is necessary to completely solve the raised problems. Using local communication introduces noise on the proximity value of sensors of other surrounding robots. The noise disturbs the detection procedure and we are working on appropriate filters to reduce it.

We also explained the scalable and reusable architecture of behaviors. The layers start from some primitive low-level behaviors. The higher layers combine the behaviors in lower layers and build new behaviors. We have distributed the behavior layers between two processors, hardware and behavior processors. The hardware processor provides a library of reactive behaviors. The behavior processor provides the possibility to combine the behaviors in the library and compose more complex even deliberative behaviors. The biology researchers who try to model the behavior of animals and implement it on the robot will need to modify only the behavior processor.

The biological experiments showed that the robots are accepted by the group of cockroaches and that the mixed-society of robots and cockroaches has statistically close behavior to a pure cockroach society. The results of these biological experiments will be submitted to biology conferences.

Acknowledgment

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