Group locomotion of mobile robots based on auditory information

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We propose to study the efficiency of our mobile robot control architecture — the so-called **"trend" architecture**, derived from Brooks' subsumption architecture — applied to the locomotion of a group of miniature Khepera robots. In our experimental set-up, each robot is equipped with a sophisticated auditory system, allowing it to communicate its position to its near neighbours by means of short sound messages.

1 Introduction

Collective robotics — and more specifically group locomotion — deals with lots of mobile robots, interacting either directly or indirectly through the environment. Because of this interaction, each robot has to deal with an important flow of sensory input. This is best handled by a reactive or behaviour-based system, often used for mobile robot control, because of its quick responsiveness and moderate computing power requirement.

Co-ordinating the operation of several robots moving in a tight space is not a trivial task. Distributing the co-ordination among the robots is the only viable means of mastering the flow of sensory input acquired by each

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robot [1]. A centralised control system would break down as soon as the global communication channels (usually radio links) get saturated.

Mataric has experimented with groups of real mobile robots moving together using a distributed control system [2], but for technical reasons, she had to rely on a global radio link (the robots exchanged their absolute position with the others). Her set-up proved to be only a faked distributed architecture and, in fact, it did not scale well above 5 robots.

Distributed architectures should rely only on local communication channels (e.g. infrared communication by means of IrDA) in order to solve local conflicts. No global communication should be required. We propose to use sound as a support for this local communication.

Lund, Webb & Hallam have successfully used sound to actively drive a miniature Khepera robot into the direction of a live cricket [3]. Animals extensively rely on sound to locate each other, so why not apply the same principle to mobile robots ?

Sound has advantages over light : it can easily go round small obstacles and the communicating robots need no longer be facing each other, as is required by a conventional IrDA system. Robots can communicate while they are moving and they need not know the exact position of their partner.

Sound has also some drawbacks : as soon as two nearby robots communicate, every other not too distant robot will be able to follow the conversation. Moreover, two simultaneous conversations held by near robots will interfere, unless some extensive filtering is used.

2 The "trend" architecture

We have developed a novel mobile robot control system, called the *"trend" architecture*, in order to provide an easy means of combining several basic behaviours.

Our "trend" architecture is derived directly from Brooks' *subsumption architecture* [4] [5]. Basically, the subsumption architecture is based on a layered network of basic behaviours. Each layer connects sensory input (or data coming from a lower level layer) to actuators (or to inputs of a higher level layer), as presented in **figure 1**. There is neither a central control nor a shared representation.

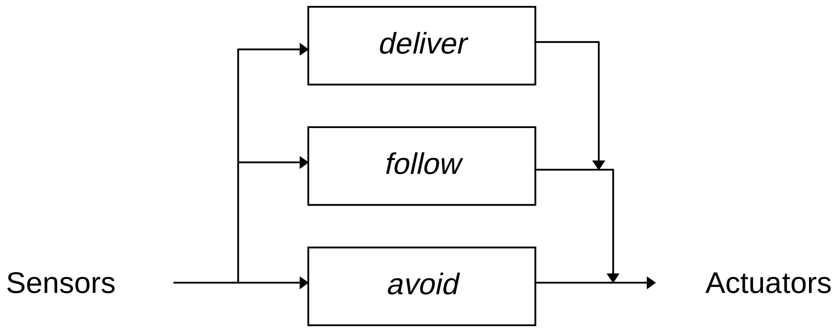


Figure 1 : A robot based on the subsumption architecture is based on a layered network of basic behaviours (avoid, follow, etc.)

The basic behaviours communicate through connections by means of simple message forwarding. Messages usually consist of small numbers (for example a sensor value, motor speed, yes-or-no Boolean value, etc.) in Brooks' implementation.

Higher level layers can assume that the lower level layers are active and operating correctly. For example, a phototropic behaviour (attraction by a light source) does not need to deal with obstacle avoidance, if there is a lower level layer that is responsible for avoiding collisions.

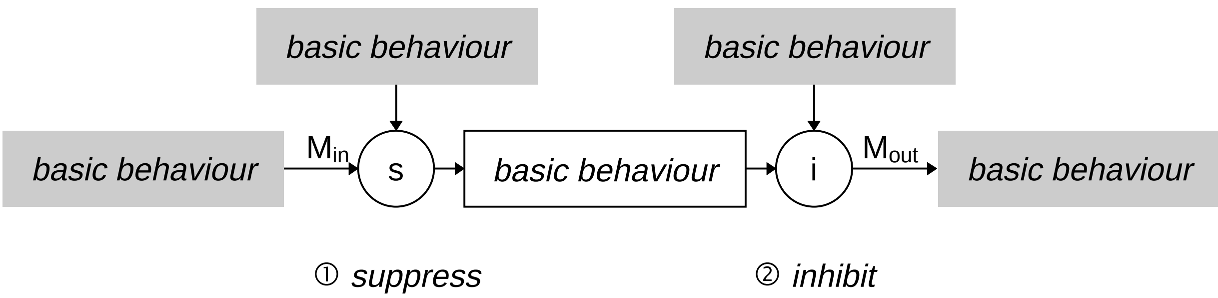


Figure 2 : Suppressing and inhibiting side-taps in the subsumption architecture.

It is possible to extend an existing subsumption architecture based system by adding new basic behaviours and connecting them to the existing network as shown in **figure 2**. The additional behaviours can (1) *suppress* or (2) *inhibit* messages by attaching their outputs as *side-taps* to the network connections. When a message arrives on an inhibitory side-tap, it will not be transmitted further. Again, when a message arrives on a suppressing side-tap, it will not be transmitted; instead, it will be replaced by the suppressing message, which will be forwarded as if it had come from the original source [Brooks 93]. Both inhibitory and suppressing side-taps need a continuous flow of inhibiting or suppressing messages in order to stay active. They return to their *pass-through* state only a short time after having received the last inhibitory or suppressing message.

The "trend" architecture is similar to the subsumption architecture. It is also the result of the interconnection of basic behaviours. Whereas in the subsumption architecture, basic behaviours transmit simple messages, the "trend" architecture associates a *priority information* P_i to each *message* M_i, as shown in **figure 3**.

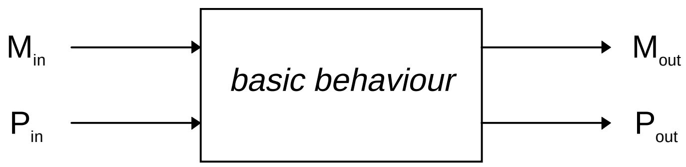
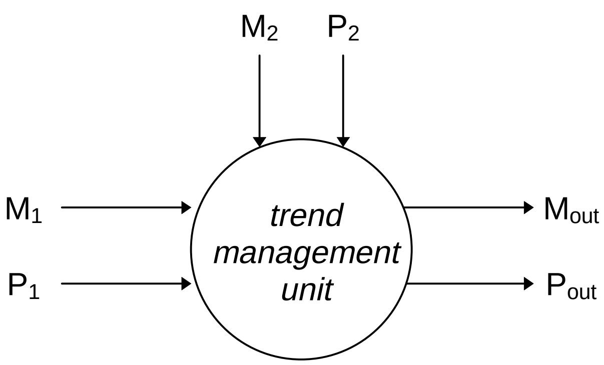


Figure 3 : Basic behaviour block of the "trend" architecture. A priority P_i is associated to each message M_i.

The subsumption inhibitory and suppressing side-taps are replaced by a *trend management unit* — shown in **figure 4** — which basically provides the same functionality.



$$M_{out} = \frac{M_1 \cdot P_1 + M_2 \cdot P_2}{P_1 + P_2}$$

$$P_{out} = \mathbf{max}\ (P_1, P_2)$$

Figure 4 : Trend management unit. The output message is the weighted sum of the input messages.

We dubbed our architecture the "trend" architecture because it relies on behavioural trend fusion rather than behavioural competition or exclusion : (1) active behaviours do not compete in the sense that they do not mutually exclude each other and (2) several antagonist behaviours can be active simultaneously. Each behaviour generates a set of *wishes* or *trends*, which are combined by a trend management unit, thus producing a single, more complex behaviour.

The subsumption architecture can be viewed as a *subset* of the "trend" architecture :

- An inhibiting side-tap can be modelled using a trend management unit with M_1 connected to the message source, P_1 set to 1, M_2 set to 0 and P_2 connected to a Boolean inhibitory message source. When P_2 is set to 0, the trend management unit just forwards the messages received on M_1. When P_2 is set to ∞, M_2 will be forwarded, which effectively results in a null message.

- A suppressing side-tap can be modelled just like the inhibiting side-tap, but in this case, M_2 is connected to the real inhibitory message source.

The "trend" architecture offers an advantage over the simpler inhibiting and suppressing subsumption architecture : it is possible to merge two actions rather than choosing just one of them. For example, suppose that a mobile robot is driving towards a light source along an oblique wall, as shown in **figure 5** :

a) With the subsumption architecture, the robot drives towards the light source (1) until it gets too close to the wall; at this point, the obstacle avoidance behaviour becomes active (2) and suppresses the phototropic behaviour : it drives the robot away from the wall until it is safe; the phototropic behaviour becomes active again (3) and drives the robot nearer to the wall, etc.

b) With the "trend" architecture, the robot drives towards the light source (1); as it approaches the wall, the obstacle avoidance behaviour becomes more and more active (2), until an equilibrium is established between the phototropic behaviour and the obstacle avoidance behaviour (3).

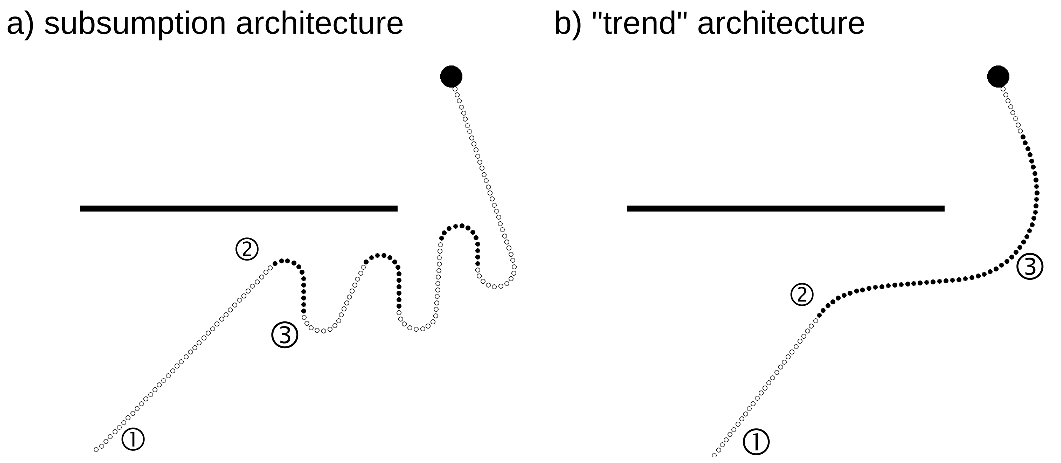


Figure 5 : Simulation of a vehicle attracted by light controlled by (a) the subsumption architecture and (b) the "trend" architecture.

In this simulation, we have set the priority of the wall avoidance behaviour to be inversely proportional to the distance between the robot and the wall, whereas the behaviour driving the robot towards the light has a constant priority of 1.

The "trend" architecture provides a **smoother overall behaviour** than the traditional subsumption architecture.

3 Proposed experiment

In order to study the efficiency of the "trend" architecture, we propose to set up an experiment based on the miniature mobile robot Khepera. The basic robot is equipped with two additional auditory turrets, as shown in **figure 6**.

This configuration provides the robot with infrared sensory input for obstacle avoidance, odometric sensory input for simple position estimation and auditory sensory input for local robot communication.

We plan to apply the "trend" architecture to a group locomotion task, based on a *leader/follower* model : a single robot (the *leader*) is responsible for the global path planning; the other robots (the *followers*) just need to follow the leader. The leader emits short sound messages, which can be

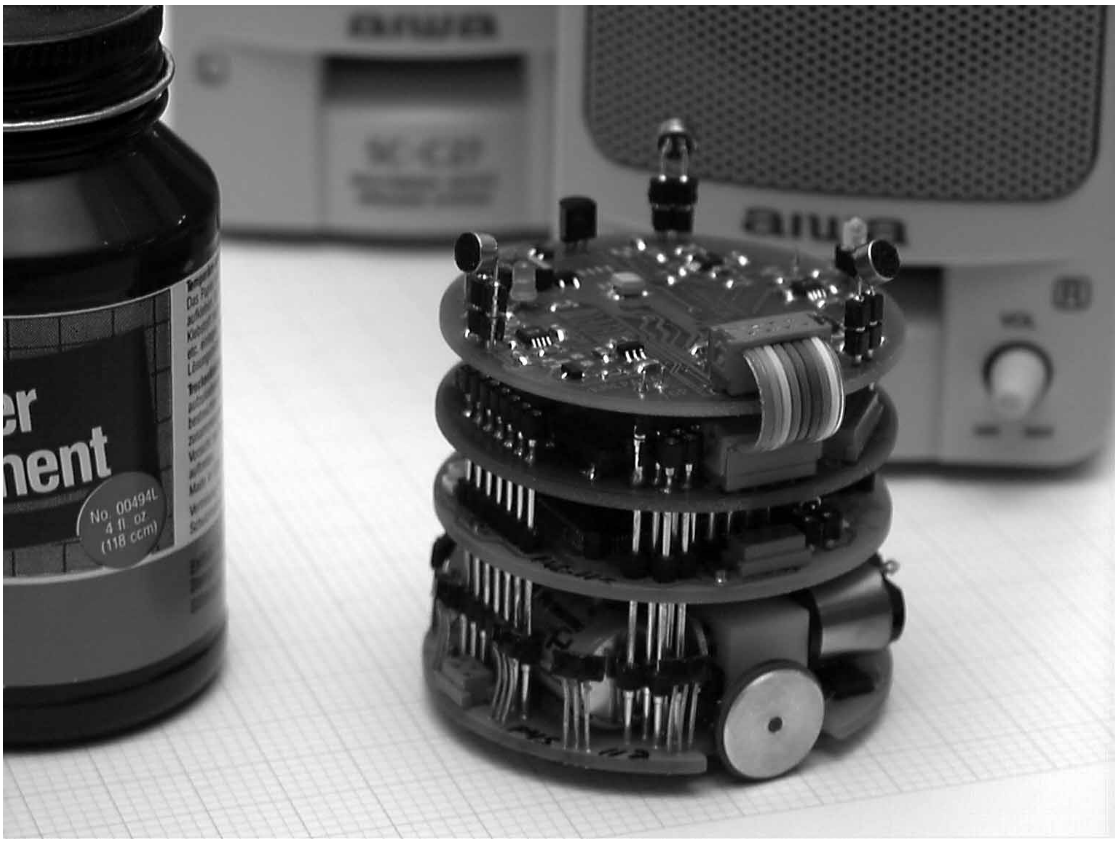


Figure 6 : Khepera robot with its two auditory turrets (∅ 55 mm, height 65 mm). Three miniature microphones can be seen on the topmost turret.

used by the followers to locate it. The sound messages do not carry any intrinsic information. Nevertheless, they allow the followers to compute the relative direction and distance to the leader.

4 Developed hardware

The hardware consists of two Khepera turrets, shown in **figure 7**. A schematic diagram of the electronic circuitry is shown in **figure 8** :

- The bottom turret hosts a small but powerful *digital signal processor* : an embedded Motorola DSP 56302. This processor consumes 5 mA in standby mode and only 110 mA at 3.3 V when running at full speed. It provides a very high execution speed (up to 8 operations per clock cycle at 80 MHz). The DSP can communicate with the top turret thanks to a serial link. The Khepera host processor accesses the DSP as if it were a standard peripheral.

- The top turret hosts the miniaturised analogic circuitry, including three tiny microphones, a loudspeaker and an infrared sensor for synchronisation. A four channel analogic to digital converter digitises the signals from the three microphones and from the infrared sensor. Up to 200’000 samples per second can be acquired and transmitted to the DSP. This turret uses less than 20 mW when in active listening mode.

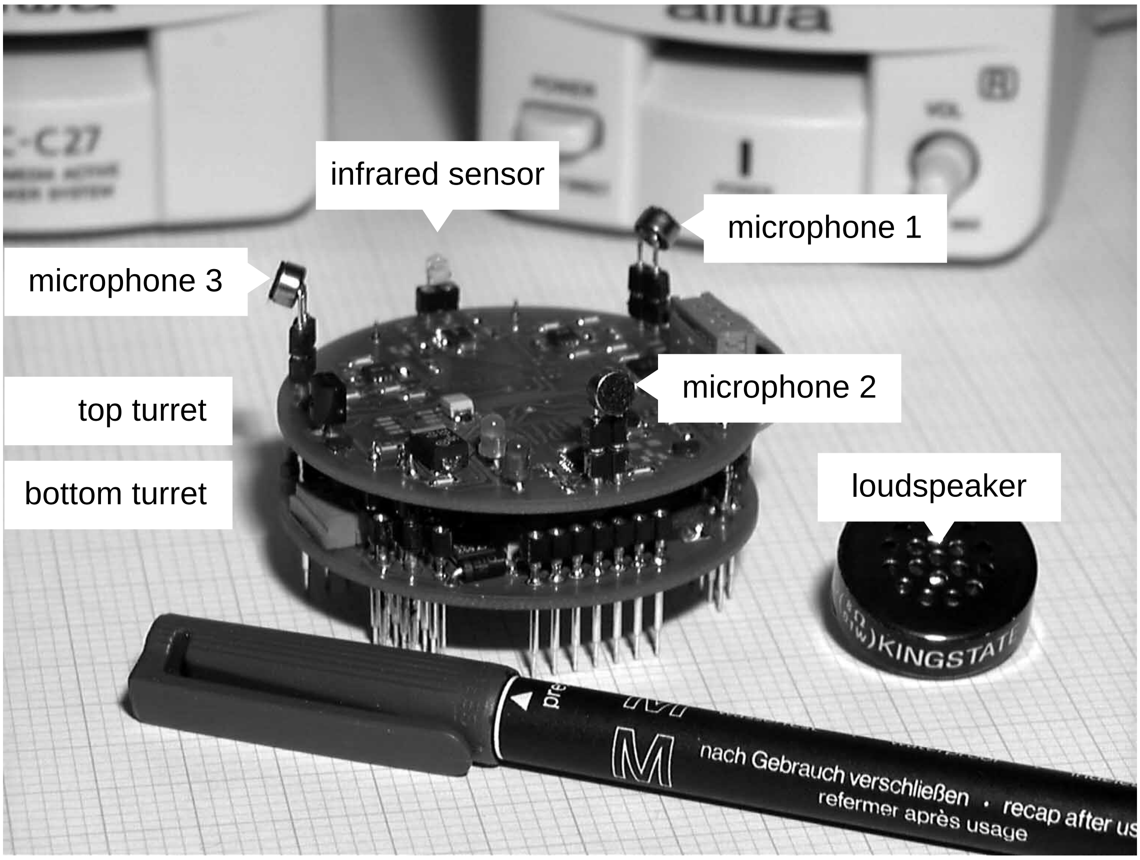


Figure 7 : The auditory system consists of two Khepera extension turrets : a turret hosting the analogic circuitry (top) and a turret hosting the DSP (bottom).

We use 3 microphones in order to resolve ambiguities related to symmetry (is the sound coming from the front or from the rear ?) and increase the precision of the measurements.

The relative distance is measured thanks to an external synchronisation mechanism : an infrared light pulse is emitted at the same time as the *beep*.

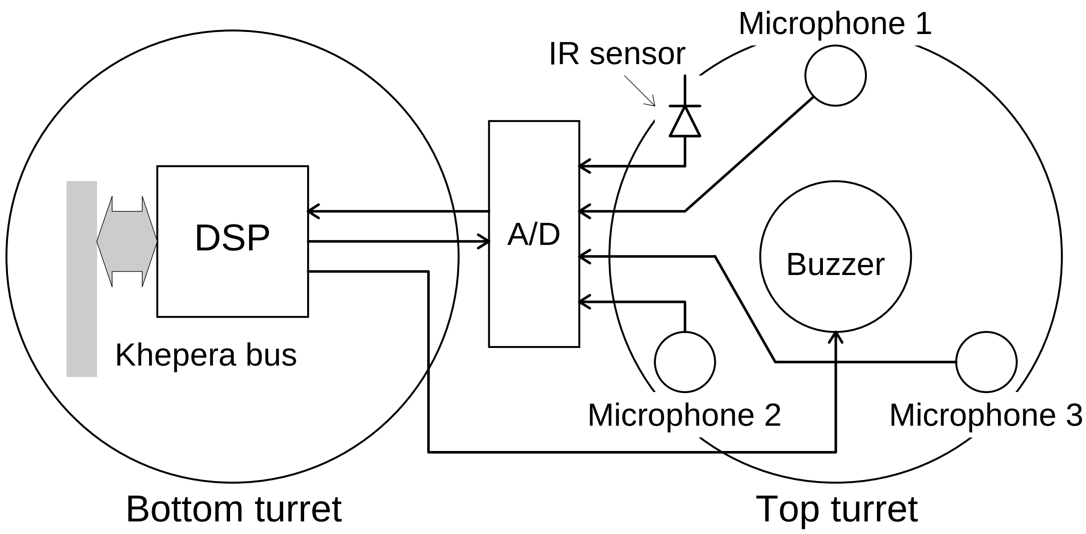


Figure 8 : Schematic diagram of the two auditory turrets.

The digital signal processor provides enough computational power to do extensive filtering and signal analysis.

5 Results

By the end of June 1998, we had only one set of auditory turrets available, which means that we could not design experiments with several robots[1]. We therefore only present results obtained with a single robot.

We have measured our auditory turrets to have a mean resolution of about 50 µs in the signal detection (signal correlation and phase detection), which gives the robot an accuracy of ± 10 mm for the measured distance and ± 7° for the direction, depending on the relative orientation between the robot and the sound source.

A correct detection of the sound source is possible as far as 1 meter away while the robot's motors are active. The noise produced by the motors is attenuated by software, thanks to the phase correlation algorithm used by the robot.

[1] The latest results are available on the net : http://diwww.epfl.ch/lami/team/arnaud/

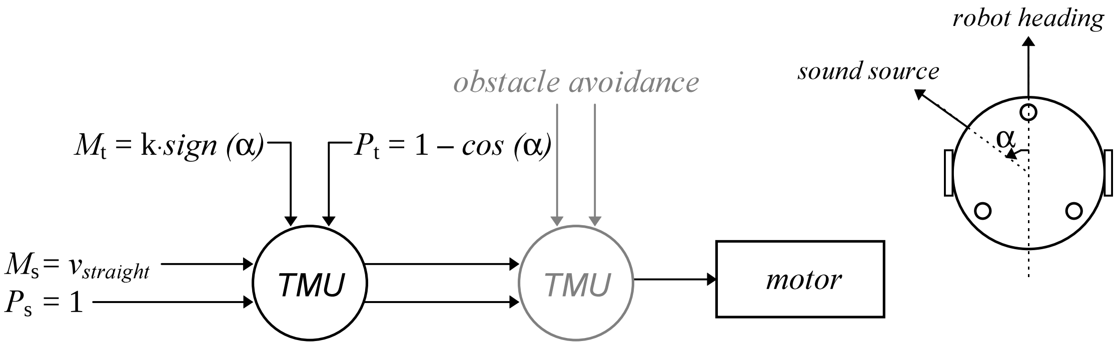


Figure 9 : "Trend" architecture used for the experiment; k *is a positive (right motor) or negative (left motor) constant,* α *is the angle between the robot heading and the sound source.*

In order to test our design, we have applied the "trend" architecture described in **figure 9** to a few simple tasks involving the auditory turrets : namely *homing*, *following* and *escaping*.

When the sound source is approximately in front of the robot, α is small and $P_t \rightarrow 0$. The motor speed is therefore governed mainly by M_s. When |α| increases, P_t increases and M_t progressively replaces M_s, either slowing down or increasing the motor speed, depending on the sign of α and k. Since the Khepera uses a differential gear, this will make it turn either left or right.

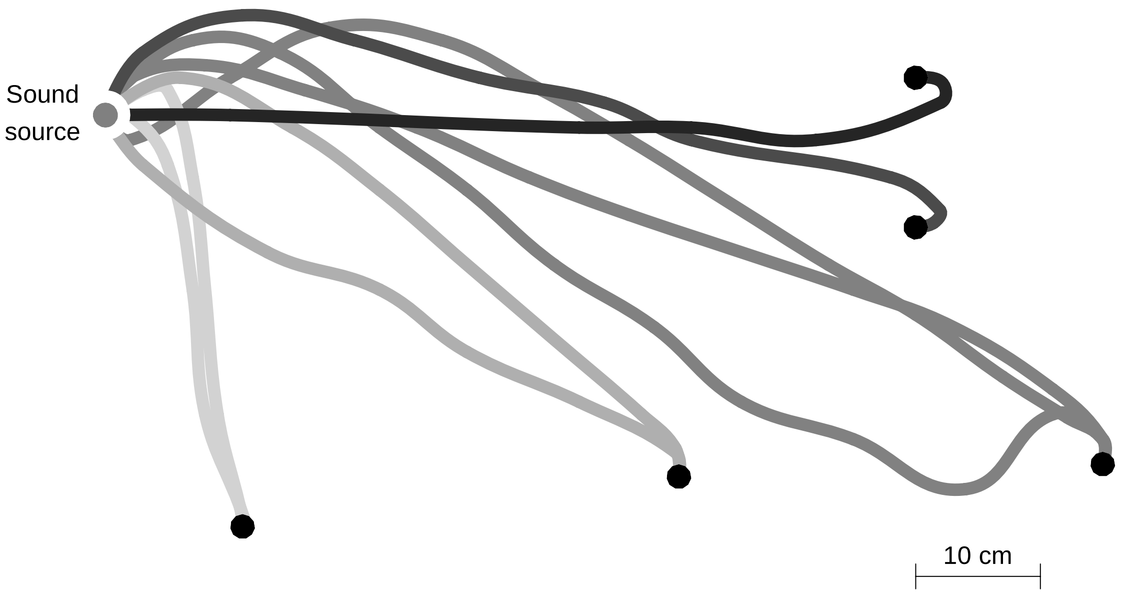


Figure 10 : Homing experiments. The robot starts at the black dots and moves towards the sound source on the left.

1. **Homing**.

The robot is placed at a certain distance of the sound source and it has to drive towards it. The robot simply moves forward at a constant speed, turning either right or left, depending on the phase difference of its three microphones.

This experiment, which resulting trajectories are presented in **figure 10**, is similar to Lund, Webb and Hallam’s.

2. **Following**.

Following is based on the same principle as homing, but the sound source is moving. In our case (see **figure 11**), the robot tries to follow a circling sound source, moving faster than the robot.

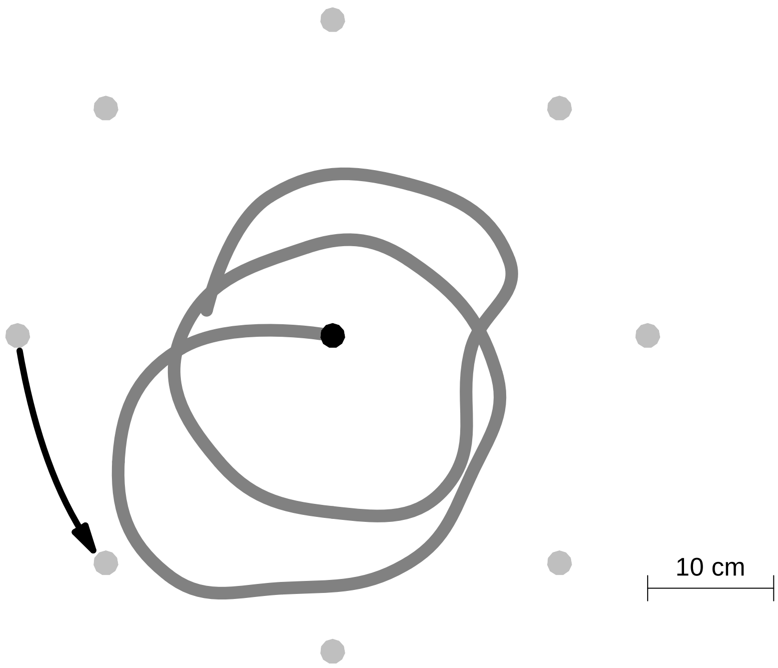


Figure 11 : Following experiment. The sound source moves faster than the robot. At the beginning, the robot is at the centre of the circling sound’s trajectory and facing the sound source.

3. **Escaping**.

Escaping is the opposite of homing and following. In order to get this behaviour, we have changed the sign of both M_s and constant k : the robot moves backwards, always facing the sound source (**figure 12**).

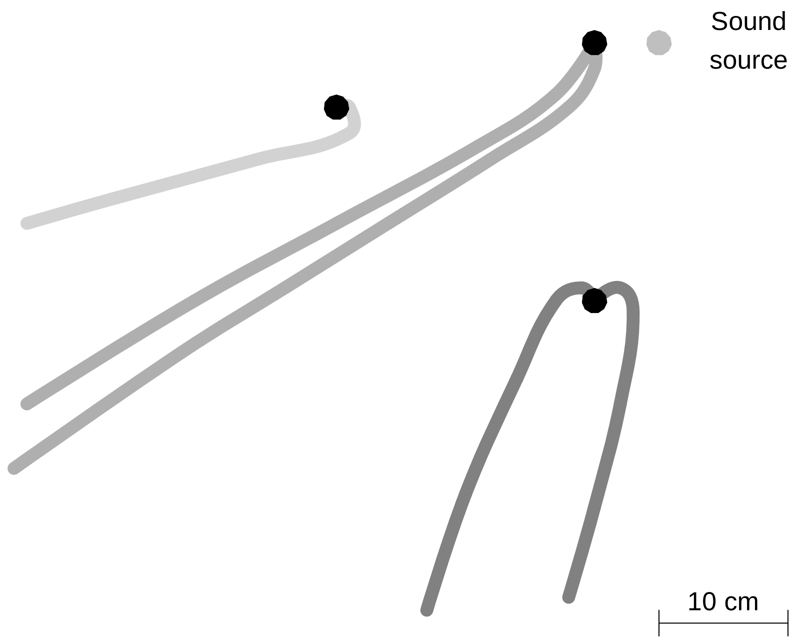


Figure 12 : Escaping experiment. The robots orient themselves and then move away from the sound source in a straight line.

6 Conclusion

The results of our experiments with a single Khepera robot equipped with the auditory turrets are promising : they have proved that the use of sound as a media to communicate the relative position of miniature mobile robots is a practical solution.

We have also verified the aptitude of the "trend" architecture to give good results both in simulations and in experiments with real robots.

Obstacle avoidance and following behaviours are the key to the formation of herds of mobile robots. We have shown that these behaviours work for a single robot; we will focus our further research on a group of such robots, demonstrating that it is possible to build fully decentralised and distributed group behaviours without resorting to explicit inter-robot communication.

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