The embodiment of cockroach behaviour in a micro-robot

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Abstract

Autonomous robots may some day be able to behave like an animal, be accepted by the animal as a conspecific and influence the individual as well as the collective behaviour of the animal and its conspecifics. With this objective in mind we report here the results of the first step in this direction, making the robot move like an animal. We programmed the Alice (sugar-cube) robot to behave qualitatively like a cockroach (random walk with wall-following behaviour). We then analyzed Alice displacement with the same standard techniques that were used for the cockroach studies (implemented in the free software R) and compared it to the underlying cockroach behvaviours: most were correctly reproduced both qualitatively and quantitatively. We finish by discussing how congregative behaviour will be implemented and mention potential applications of such an insbot (insect-like robot).

Introduction

The design of robots is often inspired from biology, in particular when nature has already solved a problem that the robot is supposed to attack and solve himself [1]. This applies not only on the hardware level but also on the software level [10]. But it is not only robotics that profits from biology, there is also a feedback from robotics to biology. First, behavioural algorithms are tested for their completeness and whether they actually let the robot achieve what the behaviour is supposed to lead to. Second, hardware constraints can reflect biomechanical or anatomical constraints that go unnoticed in simple computer simulations.

Social animals represent a particularly inspiring biological system for the decentralised organisation and coordination of many autonomous robots [13, 14, 3]. Nature has developped many strategies that solve collective problems (foraging, nest-site selection, nest construction, etc.) by self-organised mechanisms [4]. Such self-organised problem-solving is increasingly explored with many robots (e.g. [17, 2]).

Here we work towards a new goal that will represent a new feedback to biology: create a robot that is accepted by animals as a conspecific with whom they interact, thus permitting to infiltrate an animal society with an autonomous lure. Furthermore, such a lure could, through its own behaviour, influence or even control the collective behaviour of the animal society. This is the declared aim of the currently ongoing european research project LEURRE[1]. The work presented in this paper is a first step in this direction: make the robot move like an animal. The biological system is the german cockroach *Blattella germanica*, more precisely their 1^{st} instar larvae. A detailed and validated behavioural model exists for these larvae on the individual level [11] as well as on the collective level [12]. We will implement the single cockroach behavioural model in the Alice (sugar-cube) micro-robot [6] and develop a tool-package (in the statistical software R^2) to analyse the resulting robot displacement (the package can be requested from the authors) and compare it to the underlying behavioural model.

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[1] See `http://www.ulb.ac.be/sciences/leurre/` for further information on this project.

[2] See `http://www.r-project.org`

The biological system and the behavioural model

The german cockroach, *Blattella germanica*, is a world wide distributed urban pest and lives in close association with humans [16]. It can be commonly found in kitchens, restaurants or supermarkets. This species presents a rudimentary type of social organization and could be qualified as a presocial insect. *B. germanica* commonly forages at night. During the diurnal phase, individuals rest in hiding places (under kitchen appliances, sinks, behind baseboards, . . .) forming mixed and dense aggregates of individuals of both sexes and all developmental stages especially at low external humidity.

The behavioural model was developped from experiments conducted with first instar larvae of *B. germanica* (24 hours-old) in a uniform environment (a circular arena with diameter 11 cm and height 3 mm, covered by a glass plate). Animal displacement was recorded with a high definition camera (Sony CDR-VX 2000 E) and paths were digitized (one point every 0.68s, the time for a cockroach to move approximately its own body length) with an automatic tracking software (Ethovision®, version 1.90, Noldus information technology). See [11] for further details on these experiments and data anlysis.

The behavioural model

The radial repartition of cockroaches during the experiments showed that the larvae (that were dropped in the center of the arena) tended to reach the periphery of the arena and stay in an external ring (0.5 cm wide) during about 50% of their time (see figure 1). This is an example of thigmotactic behaviour, that is a tendency to decelerate upon contact with the arena wall and remain in antennal contact with it. We can thus subdivide the arena into a central zone and a peripheral zone. The analysis in [11] showed that cockroaches move (at approximately constant speed) in a correlated random walk when in the central zone, while they follow the arena wall when in the peripheral zone (with a constant probability to leave it and reenter the central zone). In addition, cockroaches can stop at any moment, stay motionless for some time and then move again.

Most of these processes have the memory-less property, that is cockroaches have a constant probability per unit time to change state (moving straight to turning, moving to stopping, leaving the periphery). Thus the time to pursue in a given state is exponentially distributed and the rate of change can be estimated by survival curve analysis [9]. Only the stopping times (centre and periphery) followed a double exponential distribution. This can be explained by two stopping states, a short and a long one with a certain probability to be in one or the other. See figure 2 for a graphical summary of this behavioural model.

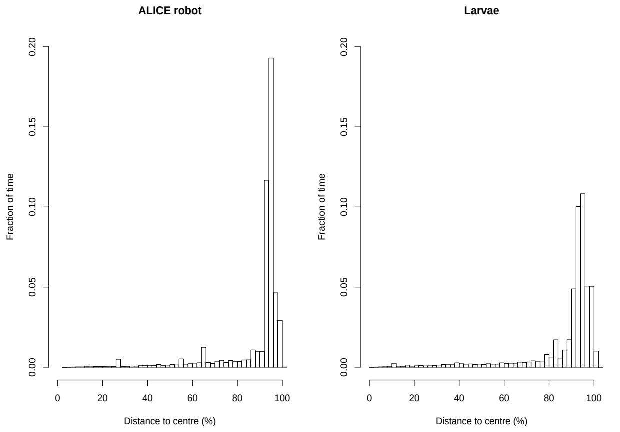

Figure 1: The radial distribution of cockroaches (on the right) and the Alice robot (left) expressed as the fraction of time spent at a given distance from the centre.

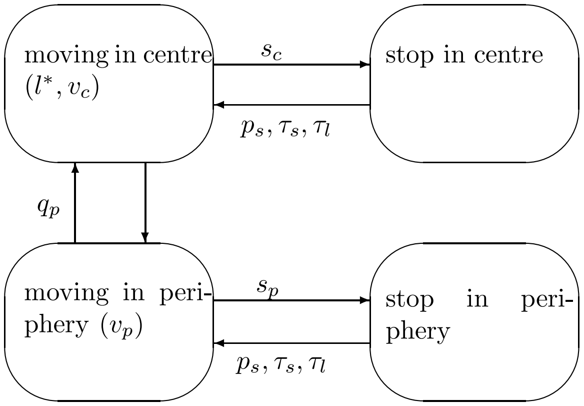

Figure 2: The behavioural model. Parameters are: velocity in centre v_c, velocity in periphery v_p, mean free transport path l^*, rate to quit periphery q_p, rate to stop in centre s_c or periphery s_p, probability to be in the short stop state p_s with mean short stopping time τ_s and mean long stopping time τ_l. The parameter values for the cockroaches [11] are listed in Table 1.

Implementation in the Alice robot

The Alice robot has 8K Flash EPROM memory, 368 bytes RAM and no built-in float operations. The implementation of the behavioural model should thus be as parsimonious as possible, rely on integer operations and avoid float operations (that have to be emulated with high memory usage) as much as possible. Programming is done with the IDE of the CCS-C compiler and the compiled programs are downloaded in the Alice memory with the free PIC-downloader software.

But before the implementation some thought must be given to scale. A cockroach is about 3mm long, while the Alice has 22mm length. Also, cockroaches move at approximately 1 cm s^{-1} while the Alice have a maximal speed of 4 cm s^{-1}. We choose to scale up from the experimental system by a factor of 4: Alice move at maximal speed, the arena has a diameter of 50 cm and all parameters with length units will be corrected by a factor 4. The Alice are on this scale still double the size of a cockroach, but this should not cause any problems for a single Alice moving around.

Displacement

The correlated random walk that was found for the cockroaches [11] is characterised by a series of straight moves (free paths) and turning angles. The lengths of the straight moves are distributed exponentially with a mean free path of length l. The distribution of turning angles (phase function) was found to be symmetrical and bell shaped. One could implement this random walk in the Alice by drawing repeatedly a random free path from an exponential distribution with a random turning angle from a fitted bell shaped curve.

However, since the final goal will be displacement on the collective level, there is a simpler solution. In fact, when averaged over many individuals, a random walk as described above is (nearly) equivalent to one where the turning angles are distributed uniformly in $(-180, 180)$ degrees (isotropic phase function) and the straight moves are distributed exponentially with mean free transport path l^* [7]. The latter is computed from l and the asymmetry parameter g by the formula $l^* = l/(1-g)$. g characterises the tendency of the individual to continue in the same direction $(1 \geq g > 0)$ or to make U-turns $(-1 \leq g < 0)$. See [11] for a more detailed description. Given the limited capacities of the Alice we choose to implement this simplyfied random walk.

Uniform random numbers were generated with a "Quick & Dirty" algorithm [15]. Exponential random numbers with mean l^* were created from a uniform random number $r \in (0, 1)$ transformed to $-log(r)l^*$ [15]. Letting the Alice move or turn at maximum speed we computed from these random numbers the time (in ms, which is the unit of the internal clock in the Alice) that it should move straight forward or turn. This process is repeated until the Alice detects with its infrared sensors an arena wall.

Upon wall detection the Alice switches into wall-following behaviour (which is provided with the Alice operating system, see [5]). The path length an Alice follows along the wall is also exponentially distributed [11], we thus computed the time the Alice should do so by the same algorithm as for the free path. Upon completion of this wall-following path the Alice returns to the centre area with a random angle between 17 and 78 degrees (as an approximation to the lognormal distribution measured in [11]).

Stopping behaviour

The probability to stop is constant in time (memoryless process), the above displacement algorithm was thus interrupted every 500 ms to draw a random number and to decide whether the Alice should stop or not. This probability is different when the Alice is in the centre (s_c) than when she is in the periphery (s_p). See Table 1 for numerical values of these parameters.

The stop duration has a double exponential distribution (see above). We first drew a random number to decide whether it will be a short stop (probability p_s) or a long stop, and then drew an exponential stopping time, either short (mean τ_s) or long (mean τ_l). After this stopping time the Alice continued displacement either with a random walk in the same direction as before the stop (centre) or by wall-following (periphery).

parameter	cockroach	Alice
v_c (cm s^{-1})	1.1	3.97 ± 0.01
v_p (cm s^{-1})	1.06	3.76 ± 0.03
s_c (s^{-1})	0.03	0.022 ± 0.002
q_p (s^{-1})	0.12	0.099 ± 0.008
s_p (s^{-1})	0.08	0.077 ± 0.004
l^* (cm)	2.32	43.1 ± 1.2
p_s	0.93	0.943 ± 0.005
τ_s (s)	5.87	7.33 ± 0.12
τ_l (s)	700	630 ± 76

Table 1: The behavioural parameters of the cockroaches [11] and their estimations from the analysis of the Alice's paths.

Analysis and comparison to cockroach displacement

Ten different Alice robots were recorded for one hour by the same digital camera as the cockroaches (see above). The paths were digitized with the Ethovision software with a sampling interval of 0.48 s. The analysis of these paths followed exactly the procedures explained in [11], we will only summarize here the major steps. These procedures were implemented in the open-source R software (they can be obtained from the authors upon request).

In a first step the paths over a whole hour were divided into the pieces in the centre area and the pieces in the periphery (all coordinates within less than 2.75cm from arena walls). In a second step these pieces were again subdivided into subpieces where the Alice moved or where it was at a stop (defined as less than 7 mm distance between two successive coordinates for at least 0.96 s).

Standard errors for all parameters were estimated by a non-parametric bootstrap method [8], taking the whole one hour recording of an Alice as the sampling unit. We first drew 10 random samples (with replacement) from our 10 recordings (as if a replication were done). Then the whole estimation procedure described below was applied to this bootstrap sample. This was repeated 100 times and the standard error was estimated as the standard deviation of these bootstrap parameter estimates.

Random walk parameters

Velocity in the centre was computed as the total length of a path subpiece divided by the total time it took the Alice to pass through it. The mean of these velocities gave 3.97 ± 0.01 cm s^{-1}.

Each path subpiece within the centre of the arena was decomposed into free paths and turning angles by the following algorithm:

- if the angle of the segment between the first two points and between the second and third point is below 10 degrees, drop the second point and connect the first point directly to the third one (considered now to be the second one),
- repeat the preceeding step until the angle exceeds 10 degrees,
- the segment between the first and the (final) second point is the first free path, start a new one from this second point,
- repeat the last three steps until the end of the path piece,
- compute the turning angles between successive free paths.

After analysing all path subpieces in the centre the free paths are grouped together and analysed as a survival curve (the proportion of free paths exceeding length d, plotted on log-linear scale as a function of d, see Fig 3 top). The inverse of the slope of this survival curve gives a mean free path $l = 6.29 \pm 0.40$ cm. The distribution of the turning angles is shown in Fig. 3 (bottom). Contrary to what was implemented it is not uniform but show a Gaussian shape. This phase function has $g = 0.85$, we get thus a mean free transport path $l^* = l/(1-g) = 43.1 \pm 1.2$ cm.

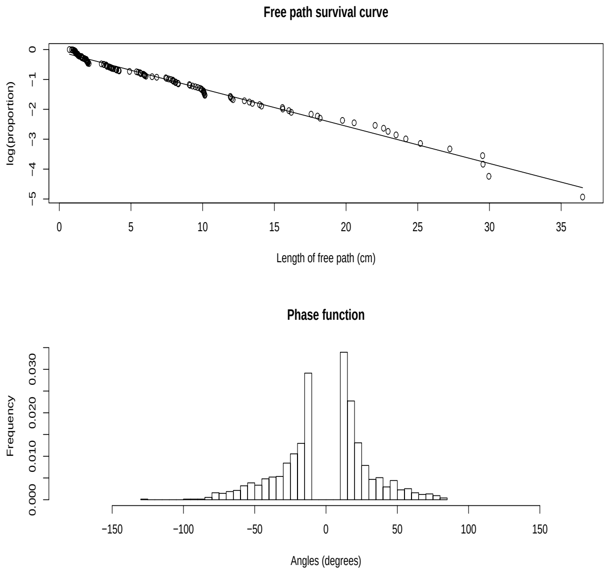

Figure 3: Survival curve of the Alice free paths (top) and the phase function of turning angles.

Wall-following paramaters

Velocity in the periphery was computed as detailed above, giving a mean velocity 3.76 ± 0.03 cm s^{-1}. The rates to stop in or to quit the periphery were estimated together by first drawing the survival curve of the all times during which an Alice followed the arena wall before either stopping or quitting it (Fig 4). Given the proportion of these wall-following path pieces that ended by a stop in the periphery one can decompose the slope of this survival curve into the rate to quit the periphery and the rate to stop in it (see [11] for the details). This procedure gave a rate to stop of 0.077 ± 0.004 s^{-1} and a rate to quit of 0.099 ± 0.008 s^{-1}.

The turning angles by which an Alice quit the periphery had a strong tendency to be below the 17 to 78 degree that were programmed (mean …), the same problem that we had already encountered for the phase function. We will come back to this problem in the discussion.

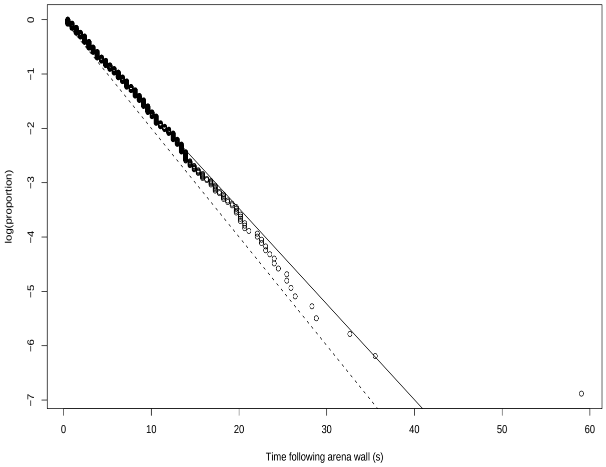

Figure 4: Survival curve of the Alice wall following time with the fitted regression line (solid) and the original cockroach regression line (dashed).

The rate to stop in the periphery was already computed above. The rate to stop in the centre is computed similarly from the survival curve of the times an Alice, after quitting the periphery, took before either stopping in the centre or reentering the peripheral zone. Additional theoretical results (for which we refer to [11]) permit to compute the stopping rate from the slope of this curve, the fraction of paths that ended by a stop in the centre, the mean velocity of the Alice and the central zone diameter. The resulting rate was $0.022 \pm 0.002\ \mathrm{s}^{-1}$.

Stopping times

Stopping times were also analysed as a survival curve (see Fig. 5) and showed, as the cockroach data, a double exponential distribution. Fitting a double exponential curve to this survival curve gave a probability to be of the short type $p_s = 0.943 \pm 0.005$, a mean short stop duration $\tau_s = 7.33 \pm 0.12$ s and a mean long stop duration $\tau_l = 630 \pm 76$ s.

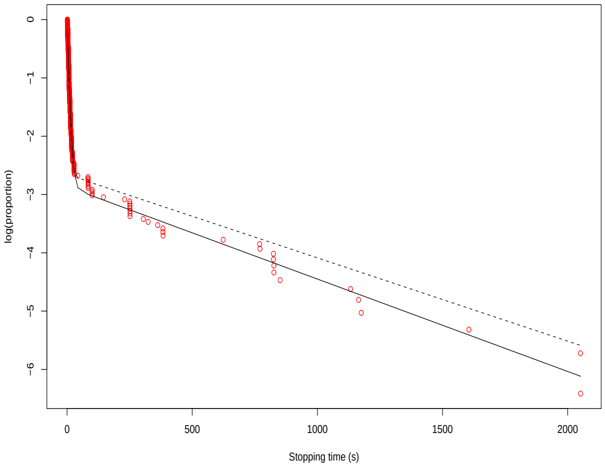

Figure 5: Survival curve of the Alice stop times. Line patterns as in Fig. 4 but with double exponential distributions.

Discussion and perspectives

In this paper we report about the implementation of a detailed quantitative behavioural model of cockroach larvae in the Alice ‘sugar cube’ micro robot. As can be seen in Table 1, most behavioural parameters of the Alice robot are very close to the corresponding cockroach parameters (taking the approximate scaling factor 4 into account). This concerns in particular the rates of changing from one state into another (stopping, moving) and the times to do a particular action (wall-following, stopping times). However, there is one major discrepancy concerning all actions that involve a local rotation of the robot (phase function and periphery exiting angle) and that are closely correlated with these rotations (mean free path in the centre).

We think that this is due to our assumption that acceleration from zero to maximal rotational speed are close to instantaneous. Thus all computed times to rotate at maximal speed result in a smaller physical rotation. Our next task will thus be a calibration curve that relates time of rotation to actually effected rotation. However, this unexpected physical constraint might also be used to model non-uniform phase functions (in particular normally distributed ones similar to the one that emerged in our study) with a minimal computational load (recall that a single uniform random number was used, compared to the complexity of a normal random number generator). This latter perspective might be particularly interesting for robots much smaller than the Alice with less performing but cheaper microchips.

Our next task will be to implement a program that lets the Alice behave collectively similar to cockroaches (aggregation). Again, a detailed behavioural model already exists [12] and will serve as a benchmark. This model requires that each Alice robot has an idea how many other Alice are in its immediate vicinity. We are currently implementing this feature by using the robot's infrared sensors for direct communication between Alice in order to let them tell the difference between a simple obstacle and another Alice. These infrared sensors are placed on each side of the Alice, they could thus communicate with a maximum of four other Alice. By providing an identification number to each Alice this technique can thus give a rough estimate of local Alice density. In cockroach larvae this density modulates the probabilities to stop or to start moving, which has been identified as the major mechanism leading to self-organised aggregation [12]. First results of this approach are shown in the little movie that accompanies this paper.

Once such an artificial lure could be successfully infiltrated into an animal society currently ongoing simulation work shows that a small number of robots with slightly different behaviours can completely change the collective behaviour, maybe even control it in a desired direction. Experiments with this aim will be conducted in an ongoing european research project (LEURRE) with the cockroach *Periplaneta americana* that is slightly larger than an Alice.

In conclusion, this paper has shown that Alice robots can behave very similar to cockroaches once a detailed but simple behavioural model is available for direct implementation. Particular attention has to be given to physical constraints such as acceleration of movement or rotation. Such a biomimetic robot will serve as a base for infiltration in real animal societies to modify their collective behaviour, offering new perspectives in pest-management and the management of living resources.

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