Social Integration of Robots into Groups of Cockroaches to Control Self-Organized Choices

J. Halloy, *et al.*
Science **318**, 1155 (2007);
DOI: 10.1126/science.1144259

24. D. G. Nair *et al.*, *Neuroimage* **34**, 253 (2007).
25. S. B. Frost, S. Barbay, K. M. Friel, E. J. Plautz, R. J. Nudo, *J. Neurophysiol.* **89**, 3205 (2003).
26. G. Cerri, H. Shimazu, M. A. Maier, R. N. Lemon, *J. Neurophysiol.* **90**, 832 (2003).
27. H. Shimazu, M. A. Maier, G. Cerri, P. A. Kirkwood, R. N. Lemon, *J. Neurosci.* **24**, 1200 (2004).
28. A. M. Martino, P. L. Strick, *Brain Res.* **404**, 307 (1987).
29. We thank E. E. Fetz, S. Perlmutter, N. Sadato, and B. Alstermark for comments on an earlier version of the manuscript and K. Isa, M. Mori, and K. Onoe for technical support. Supported by Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency (JST), as well as the Molecular Imaging Program on "Research Base for Exploring New Drugs" from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) and Grant-in-Aid for Scientific Research on Priority Areas–Integrative Brain Research–from the MEXT (project no. 17021041).

Supporting Online Material
www.sciencemag.org/cgi/content/full/318/5853/1150/DC1
Materials and Methods
Figs. S1 to S3
Table S1
References

2 July 2007; accepted 12 October 2007
10.1126/science.1147243

Social Integration of Robots into Groups of Cockroaches to Control Self-Organized Choices

J. Halloy,[1*†] G. Sempo,[1*] G. Caprari,[3] C. Rivault,[2] M. Asadpour,[3] F. Tâche,[3] I. Saïd,[2] V. Durier,[2] S. Canonge,[1] J. M. Amé,[1] C. Detrain,[1] N. Correll,[4] A. Martinoli,[4] F. Mondada,[5] R. Siegwart,[3] J. L. Deneubourg[1]

Collective behavior based on self-organization has been shown in group-living animals from insects to vertebrates. These findings have stimulated engineers to investigate approaches for the coordination of autonomous multirobot systems based on self-organization. In this experimental study, we show collective decision-making by mixed groups of cockroaches and socially integrated autonomous robots, leading to shared shelter selection. Individuals, natural or artificial, are perceived as equivalent, and the collective decision emerges from nonlinear feedbacks based on local interactions. Even when in the minority, robots can modulate the collective decision-making process and produce a global pattern not observed in their absence. These results demonstrate the possibility of using intelligent autonomous devices to study and control self-organized behavioral patterns in group-living animals.

Self-organization is a central coordination mechanism exhibited by both natural and artificial collective systems. Collective behavior and decision-making based on self-organization occur in eusocial insects (*1*–*3*), gregarious arthropods (*4*, *5*), and vertebrates (*6*–*8*). Self-organized mechanisms are characterized by nonlinear responses to stimulus intensity, incomplete information, and randomness (*1*). Self-organization coexists with guidance from environmental templates, networks of interactions among individuals, and various forms of leadership or preexisting individual specialization (*9*, *10*). Studies of animal societies (*1*–*8*) show that self-organization is used to coordinate group members, to reach consensus, and to maintain social coherence when group members have to choose between mutually exclusive opportunities.

[1]Université Libre de Bruxelles, Service d'Ecologie Sociale CP231, Avenue F. D. Roosevelt, 50, B-1050 Brussels, Belgium. [2]UMR 6652 Ethologie Evolution Ecologie, CNRS, Université de Rennes 1, Campus de Beaulieu, 35042 Rennes, France. [3]Autonomous System Laboratory, Swiss Federal Institute of Technology, ETH Zürich, Tannenstrasse 3, CH-8092 Zürich, Switzerland. [4]Swarm-Intelligent Systems Group, École Polytechnique Fédérale de Lausanne, EPFL IC ISC GR-MA, Station 14, CH-1015 Lausanne, Switzerland. [5]Laboratoire de Systèmes Robotiques, École Polytechnique Fédérale de Lausanne, EPFL STI IPR LSRO, Station 9, CH-1015 Lausanne, Switzerland.

*These authors contributed equally to this work.
†To whom correspondence should be addressed. E-mail: jhalloy@ulb.ac.be

These biological findings have stimulated engineers to investigate novel approaches for the coordination of autonomous multirobot systems (*11*–*14*). Swarm-robotic systems, in contrast with other multirobot systems, explicitly exploit self-organization as a main coordination mechanism. Often, the controller of individual robots is designed using reactive, behavior-based techniques (*15*): Robots act and interact with their close environment, which sends immediate feedback to their receptors in response to their own actions and the actions of others. Behavior-based techniques allow for real-time implementation of the social nonlinear feedbacks influencing the whole system, minimization of onboard computational resources under tight volume constraints, and suitable support for the injection of stochastic behavioral rules.

Autonomous robots, perceived as congeners and acting as interactive decoys, are interesting research tools. By their ability to respond and adapt to animal behavior, they open possibilities to study individual and social animal behaviors. Robots, or any artificial agents, could then be used to implement new feedback loops, leading to new collective patterns in these mixed natural-artificial systems. Here we describe an experimental study that makes a step toward building such mixed societies of artificial and natural agents, using real and robotic cockroaches.

Our experimental setup consists of a circular arena endowed with two shelters (Fig. 1). In the presence of two identical shelters, each large enough to host the entire group, all the cockroaches choose collectively to rest under one of the shelters (*16*, *17*). When one shelter is darker than the other, cockroaches select the darker shelter by amplifying their individual preference through interindividual interactions. This self-organized choice does not require leadership, reference to the final pattern, or explicit comparison between the shelters. This mechanism leads to shelter selection and optimal group formation (*17*).

A mathematical model in quantitative agreement with the experiments was developed (*17*) considering the following experimental facts: (i) Individuals explore their environment randomly and thus encounter sites randomly; (ii) they rest in sites according to their quality, in this case determined mainly by darkness; and (iii) they are influenced by the presence of conspecifics through social amplification of resting time, all individuals being considered equal. This model also forms the core behavioral module of the robots, enabling them to respond stochastically to social stimuli according to Eqs. 1 to 4 (below). The robots are designed to discriminate (i) cockroaches from other robots, these two types of agents being considered here as conspecifics; (ii) shelters from the rest of the arena and shelter darkness; and (iii) the wall around the circular arena and other obstacles (*18*). The model is used as a quantitative explanation as well as overall guidance for the design of the robot.

The model describes mixed groups where robots and cockroaches exhibit similar behavior. The differential equations giving the time evolution of the number of individuals in the shelters and outside are

$$dx_i/d_t = R_i x_e - Q_i x_i \quad i = 1,2 \tag{1}$$

$$dr_i/d_t = R_{ri} r_e - Q_{ri} r_i \quad i = 1,2 \tag{2}$$

$$C = x_e + x_1 + x_2 \tag{3}$$

$$M = r_e + r_1 + r_2 \tag{4}$$

Variables x_i and r_i represent the numbers of cockroaches and robots present in shelter i, respectively, and x_e and r_e the numbers outside the shelters. Parameters C and M correspond respectively to the total numbers of cockroaches and robots. The functions R and Q, giving

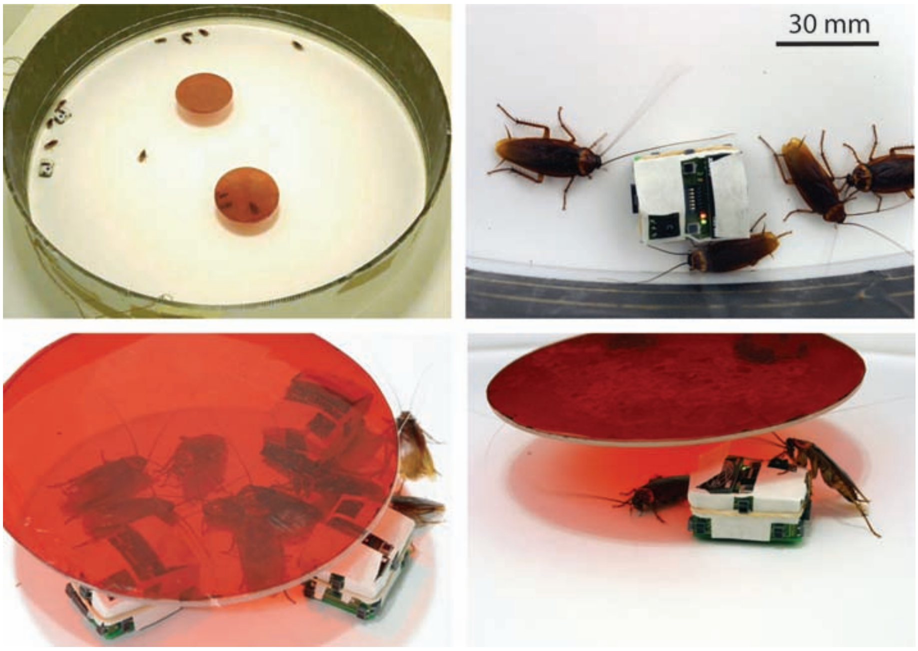

Fig. 1. Experimental setup showing the cockroaches (*Periplaneta americana*) and the robots. Two shelters (150 mm) made of plastic disks covered by red film filters are suspended (30 mm) above the floor of a circular arena (diameter 1 m). The darkness under the shelter is controlled by the number of layers of red film. Cockroaches aggregate under the shelters (*18*).

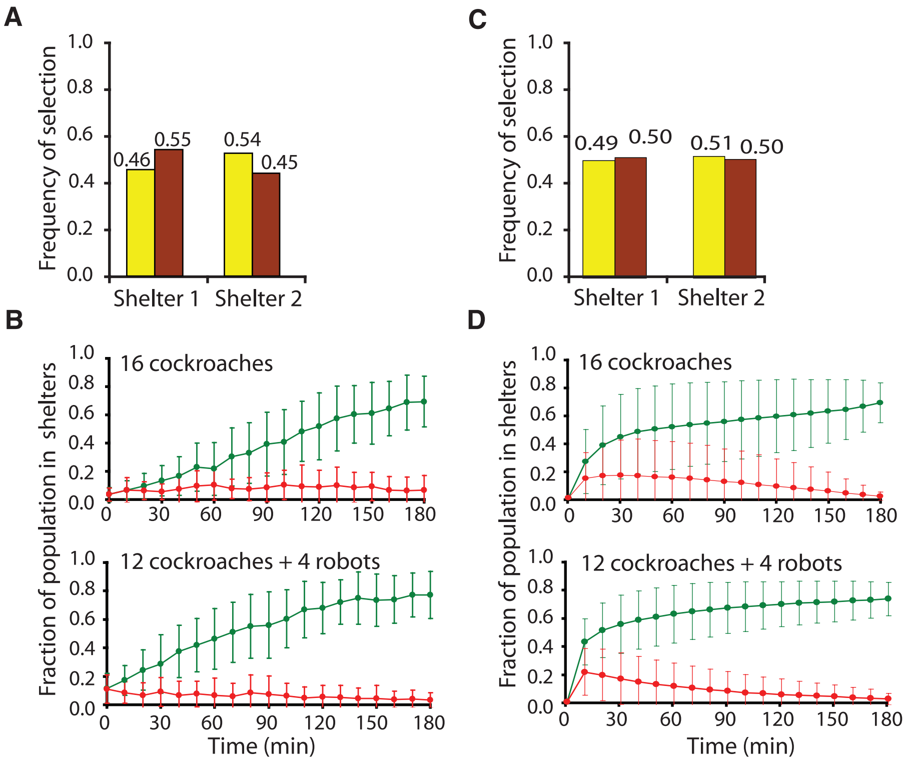

Fig. 2. Shared collective choice between two identical shelters. (**A** and **B**) Experimental results for 30 trials. (**C** and **D**) Computer simulations of Eqs. 3 and 4 (*18*). Groups of 16 cockroaches (brown bars) selected one of the two shelters. Mixed groups of 12 cockroaches and four robots (yellow bars) presented the same distribution, demonstrating that the mixed groups made the same collective decision as cockroaches alone. The probability of selecting one of the shelters is about 0.5, in accordance with a dynamics leading to stable multiple states (*16*, *17*). In (B) and (D), the fraction of the group present under the shelters (mean ± SD) in relation to time shows that selection has similar dynamics in both types of group. Green lines represent the selected shelter (randomly shelter 1 or 2 in different trials), the red lines the shelter not selected.

respectively the rate per individual of entering or quitting shelters, are

$$R_i = \mu_i\{1 - [(x_i + \omega r_i)/S_i]\} \quad (5)$$

$$R_{ri} = \mu_{ri}\{1 - [(x_i + \omega r_i)/S_i]\} \quad (6)$$

$$Q_i = \theta_i/\{1 + \rho[(x_i + \beta r_i)/S_i]^n\} \quad (7)$$

$$Q_{ri} = \theta_{ri}/\{1 + \rho_r[(\gamma x_i + \delta r_i)/S_i]^{n_r}\} \quad (8)$$

Each cockroach outside shelters has a rate R_i of entering shelter i (R = 1/mean exploring time); the equivalent rate for robots is R_{ri}. Because these functions (Eqs. 5 and 6) take into account a crowding effect, they decrease with the ratio between the number of individuals present in shelter i and its carrying capacity S_i. The carrying capacity corresponds to the maximum number of cockroaches that can be hosted in shelter i. In Eqs. 5 and 6, parameter ω represents the surface of one robot expressed as a multiple of the surface of one insect. The term μ_i represents the maximal kinetic constant of entering the shelter for insects; μ_{ri} is the equivalent term for robots.

Each cockroach in shelter i has a rate Q_i of leaving it to start exploring (Q = 1/mean resting time); the equivalent rate for robots is Q_{ri}. The parameter θ_i is the maximal rate of leaving a shelter for cockroaches (θ_{ri} for robots); the parameters ρ and n take into account the influence of the cockroaches' conspecifics (ρ_r and n_r for robots). When both shelters are identical, the parameters characterizing them are equal: $S_1 = S_2$; $\mu_1 = \mu_2$; $\mu_{r1} = \mu_{r2}$; $\theta_1 = \theta_2$; $\theta_{r1} = \theta_{r2}$. When one shelter is darker than the other, then $\theta_1 \neq \theta_2$; $\theta_{r1} \neq \theta_{r2}$.

Parameters γ, β, and δ correspond respectively to the influence of insects on robots, of robots on insects, and of robots on robots. The greater they are, the greater the mutual influences. The influence of insects on insects is imposed by biology and is not modulated in our experiments. However, parameters γ, δ, and β could be modulated by changing the hardware and/or software of the robots. As in insect societies, the interattraction between cockroaches is chemotactile and is mainly based on a blend of hydrocarbons coating their body (*19*–*22*). The robots are coated with this blend, and the higher the pheromone concentration, the higher the value of β.

Acceptance of robots within a cockroach group is related to the ability of robots to bear the correct chemical signal and to behave appropriately. Chemical analyses and behavioral tests were performed to identify the main molecules constituting the odor that carries cockroach identity (*18*). This odor was then collected from male cockroaches and calibrated to a known concentration used to condition filter papers dressing the robots. The concentration on the filter paper (per cm^2) was the same as that on one cockroach. Therefore, natural and artificial agents were equally attractive to one another. Tests with encounters between robots and cockroaches showed that cockroaches were lured to, and interacted with, chemically dressed robots. Comparisons with unmarked robots showed the importance of this chemical message (*18*).

Pheromone luring was used here to allow acceptance of the robot in the group and not to attract the insects to a specific shelter. As robots become members of the group, they can take part in and influence dynamically the collective decision-making process. Not only do these robots explore their environment autonomously, but they are also able to tune their resting time in relation to the presence of cockroaches, as cockroaches do (*16*, *17*). In turn, the insects are influenced by the presence of robots, closing the loop of interaction between animals and machines. The shelter selection emerges from the social interactions between natural and artificial individuals.

The first set of experiments showed the sharing of the collective decision-making for shelter selection in mixed cockroach-robot groups. The robots were programmed to select dark shelters as cockroaches do. Interactions between robots and cockroaches led to the selection of a common shelter (Fig. 2). Given the choice between two identical dark shelters, both types of groups chose to rest under one of the shelters and behaved as a whole, irrespective of their natural or human-made origin. In most trials, both cockroach groups and mixed groups selected one of the shelters. In 28 of 30 trials (93%), mixed groups presented a clear choice for one of the shelters, and 75% of cockroaches and 85% of robots aggregated under the same shelter. Comparisons of these results with computer simulations of the model confirmed that the choice corresponds to the coexisting stable states of a nonlinear system (Fig. 2, A and C).

The second set of experiments was designed to show the control of the collective choice by mixed groups when shelters differed in attractiveness—in this case, darkness (Fig. 3). Cockroaches prefer to aggregate under the darker shelter (brown bars in Fig. 3A). This selection process is explained by the same model as above, with a bias induced by the darkness level of the shelters ($\theta_1 \neq \theta_2$, $\theta_{r1} \neq \theta_{r2}$; Fig. 3C). When cockroach groups selected one of the shelters (22 of 30 trials), the darker shelter was selected in 73% of the cases and the lighter one in only 27% of the cases (Fig. 3A). As in the first set of experiments with two identical dark shelters, these proportions correspond to the coexistence of multiple stable states in a nonlinear system.

In the case of mixed groups (yellow bars in Fig. 3A), the robots were programmed to prefer the lighter shelter, contrary to the cockroaches. This effect was obtained by keeping the same behavioral model and swapping the parameters controlling the robot response to darkness with respect to those measured for cockroaches. Given the choice between a dark and a light shelter, robots were able to induce a change of the global pattern by inverting the collective shelter preference. Under these conditions, the shelter less preferred by the cockroaches (i.e., the lighter one) was selected by mixed groups in 61% of the trials, versus only 27% of the trials done without robots. Despite the individual preference of robots for lighter shelters, they were socially driven by the cockroaches into the darker shelter in 39% of the trials (Fig. 3A). These results are explained by the nonlinear mechanism governing the self-organized choice, as shown by stochastic simulation of the model (Fig. 3B). In some trials the choice was induced by the robots, and in others by the cockroaches. The robots did not act as a mere attractant but were integrated into the decision-making process of the society.

These experimental results show the possibility of shared and controlled collective actions between machines and animals. At the technical level, we introduced lures able to perceive animal response and able to respond to it. The robots were designed to interact and to collaborate autonomously both with the animals and with one another. This work could be extended to vertebrates, taking into account sound, visual cues, and social organization. Possible ways to identify individual behavioral algorithms could be to replace some animals within a group by robots or other artificial devices and to compare collective responses in "mixed" and "natural" groups (*23*–*26*). They could also be used to test

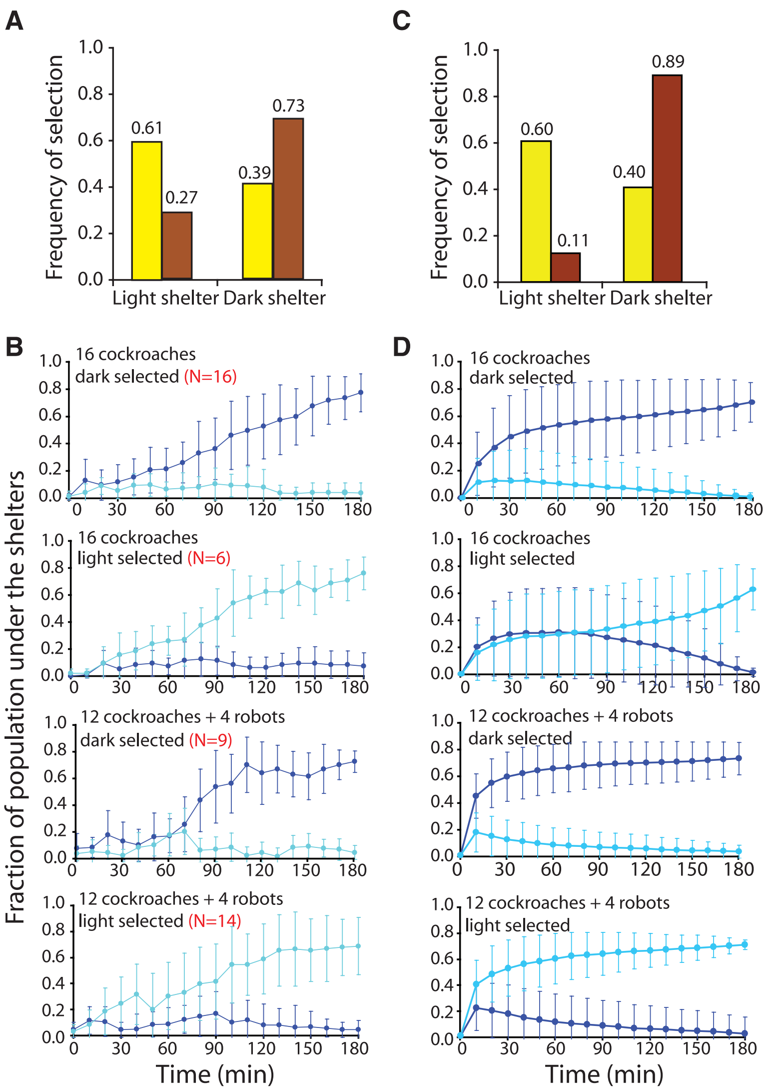

Fig. 3. Controlled collective choice between dark and light shelters. (**A** and **B**) Experimental results; (**C** and **D**) computer simulations (*18*). (A) Groups of cockroaches without robots (brown bars) selected the dark shelter in 73% and the light shelter in 27% of the trials. Mixed groups with robots programmed to prefer the light shelter (yellow bars) selected it in 61% of the trials. The robots induced a change of the collective choice by modulating the nonlinear collective mechanism. Nonetheless, the dark shelter was still selected in 39% of the trials because the robots also socially responded to the cockroaches. In all selections, robots and cockroaches shared the same shelter. In (B) and (D), the fraction of the group present under the shelters (mean ± SD) as a function of time shows that the selection has similar dynamics in both types of group (dark blue, dark shelter; light blue, light shelter). *N* values in (B) (red) are number of selections out of 30 trials.

hypotheses about the origin of cooperation among group members. At the conceptual level, we exploited the nonlinear dynamical properties of regulatory feedbacks to introduce a form of control that can require only a small number of social lures. Artificial agents such as robots or networks of sensors and actuators could also be used to introduce new regulatory feedback loops (or modulate existing ones) at the social level (*27*, *28*), inducing new patterns of collective behavior. Animal societies could be one of the first biological systems where autonomous artifacts cooperate with living individuals to solve problems.

References and Notes

1. S. Camazine *et al.*, *Self-Organization in Biological Systems* (Princeton Univ. Press, Princeton, NJ, 2001).
2. D. J. T. Sumpter, *Philos. Trans. R. Soc. London Ser. B* **361**, 5 (2006).
3. J. L. Deneubourg, S. Goss, *Ethol. Ecol. Evol.* **1**, 295 (1989).
4. R. Jeanson, J. L. Deneubourg, G. Theraulaz, *Anim. Behav.* **67**, 531 (2004).
5. J. Buhl *et al.*, *Science* **312**, 1402 (2006).
6. J. K. Parrish, L. Edelstein-Keshet, *Science* **284**, 99 (1999).
7. I. D. Couzin, J. Krause, *Adv. Stud. Behav.* **32**, 1 (2003).
8. I. D. Couzin, J. Krause, N. R. Franks, S. Levin, *Nature* **443**, 513 (2004).
9. J. H. Fewell, *Science* **301**, 1867 (2003).
10. L. Conradt, T. J. Roper, *Trends Ecol. Evol.* **20**, 449 (2005).
11. E. Bonabeau, M. Dorigo, G. Theraulaz, *Swarm Intelligence: From Natural to Artificial Systems* (Oxford Univ. Press, New York, 1999).
12. G. Beni, *Lect. Notes Comput. Sci.* **3342**, 1 (2005).
13. A. Martinoli, K. Easton, W. Agassounon, *Int. J. Robot. Res.* **23**, 415 (2004).
14. F. Mondada *et al.*, *Auton. Robots* **17**, 193 (2004).
15. R. A. Brooks, *Science* **253**, 1227 (1991).
16. R. Jeanson *et al.*, *Anim. Behav.* **69**, 169 (2005).
17. J. M. Amé, J. Halloy, C. Rivault, C. Detrain, J. L. Deneubourg, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 5835 (2006).
18. See supporting material on *Science* Online.
19. T. D. Wyatt, *Pheromones and Animal Behaviour* (Cambridge Univ. Press, Cambridge, 2003).
20. I. Saïd, G. Costagliola, I. Leoncini, C. Rivault, *J. Insect Physiol.* **51**, 995 (2005).
21. I. Saïd, C. Gaertner, M. Renou, C. Rivault, *J. Insect Physiol.* **51**, 1384 (2005).
22. G. Caprari, A. Colot, R. Siegwart, J. Halloy, J. L. Deneubourg, *IEEE Robot. Autom. Mag.* **12**, 58 (2005).
23. A. Michelsen, B. B. Andersen, J. Storm, W. H. Kirchner, M. Lindauer, *Behav. Ecol. Sociobiol.* **30**, 143 (1992).
24. G. L. Patricelli, J. A. Uy, G. Walsh, G. Borgia, *Nature* **415**, 279 (2002).
25. G. De Schutter, G. Theraulaz, J. L. Deneubourg, *Ann. Math. Artif. Intel.* **31**, 223 (2001).
26. H. Ishii, T. Aoki, M. Nakasuji, H. Miwa, A. Takanishi, in *2004 IEEE International Conference on Robotics and Automation* (IEEE, Piscataway, NJ, 2004), pp. 2758–2763.
27. R. Vaughan, N. Sumpter, J. V. Henderson, A. Frost, S. Cameron, *Robot. Auton. Syst.* **31**, 109 (2000).
28. Z. Butler, P. Corke, R. Peterson, D. Rus, *Int. J. Robot. Res.* **25**, 485 (2006).

29. This research, named the Leurre project, was financed by the Future and Emerging Technologies branch in the Information Society Technologies priority of the European Community Research Programme.

Supporting Online Material

www.sciencemag.org/cgi/content/full/318/5853/1155/DC1
Materials and Methods
Figs. S1 and S2
Tables S1 to S4
References
Movies S1 and S2

25 April 2007; accepted 6 September 2007
10.1126/science.1144259