The Cooperation of Swarm-Bots

Physical Interactions in Collective Robotics

BY FRANCESCO MONDADA,
LUCA MARIA GAMBARDELLA, DARIO FLOREANO,
STEFANO NOLFI, JEAN-LOUIS DENEUBOURG,
AND MARCO DORIGO

Several advanced robotics applications, such as rescue and planetary or underwater exploration, must cope with very unstructured and partially unknown environments. Robots operating in such environments should display a high degree of mobility, versatility, and robustness to very different and time-varying operating conditions in order to successfully perform tasks such as displacement, exploration, or object transportation.

Swarm robotics, which can be considered an instance of the more general fields of swarm intelligence [1]–[3] and collective robotics [4], addresses mobility, versatility, and robustness in a novel way, combining different aspects such as distributed control, self-assembling mechanisms, and collective behavior. This novel research field addresses the design and implementation of robotic systems composed of swarms of robots that interact and cooperate to reach their goals. In a swarm robotics system, although each single robot of the swarm is a fully autonomous robot, the swarm as a whole can solve problems that single robots cannot deal with because of limited capabilities or physical constraints. Swarm robotics researchers use the social insect metaphor as their main source of inspiration and emphasize concepts such as control decentralization, limited communication bandwidth, coordination via local information, emergence of global behavior, and robustness.

This article describes the development of the concept and briefly overviews the outcomes of the SWARM-BOTS project, including the mechanical and electronic features of the developed robots. It also presents a physics-based simulator suitable to investigate time-consuming adaptive algorithms and shows examples of cooperative behaviors, both in simulation and in hardware. The project was sponsored by the Information Society Technologies-Future and Emerging Technologies Programme (IST-FET) of the European Commission.

A swarm-bot is defined as an artifact composed of a swarm of several mobile robots (called *s-bots*) that can operate both autonomously and as a group. In addition to standard sensors, motors, and limited computational capabilities, what best characterizes s-bots is that they are equipped with grippers that can be used to create physical links with other s-bots to assemble into a swarm-bot able to tackle challenges that are too difficult for a single s-bot. In swarm-bot formation, s-bots are attached to each other and the robotic system becomes a single whole that can move and reconfigure as needed. For example, the swarm-bot might change its shape in order to traverse a narrow passage or climb an obstacle. Physical connections between s-bots play a particularly important role in the solution of many collective tasks. For example, in a navigation task, physical links can serve as support if the swarm-bot has to pass over a hole larger than a single s-bot or when it has to pass through narrow passages in complex situations, as illustrated in Figure 1. S-bots could also exploit physical links to form pulling chains in an object retrieval scenario. However, there might be situations where a swarm of unconnected s-bots is more efficient; for example, when searching for a goal location or when tracing an optimal path to a goal.

Flexibility and modularity are features that have already been explored in robotics under the label of *self-reconfigurable robotics*. Pioneering examples of self-reconfigurable robots are MTRAN [5] and PolyBot [6]. An overview of existing systems and characteristics can be found in the works of Kamimura et al. [5] and Yim et al. [7]. MTRAN and PolyBot use a large number of simple modules, have been physically

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implemented, and can self-reconfigure. Despite their very good hardware flexibility, both MTRAN and PolyBot have been designed with a centralized control perspective, which features less robustness to failures when compared to a decentralized approach. The latest articles on these two research projects show that MTRAN is staying with the centralized control approach [8] while PolyBot is incorporating a new decentralized approach known as *Phase Automata* [9].

The first three-dimensional (3-D) self-reconfigurable robot with decentralized control has been the CONRO system [10], which operates on decentralized control systems [11], [12]. These controllers allow the robotic hardware modules to change their relative positions while the system is running. During this dynamic change, each involved module autonomously readapts its behavioral role in the system.


(a)

(b)

Figure 1. *Swarm-bots in situations of extreme all-terrain navigation where chain formation is exploited for (a) passing a gap and (b) going through a narrow passage.*

One of the most recent developments in the field of self-reconfigurable robotics is the ATRON module of the HYDRA project [13]. This module is very simple, with one degree of freedom, but displays high-precision mechanics and is manufactured in hundreds of units.

Although self-reconfigurable robots display an impressive flexibility, they are all based on modules without individual mobility and autonomy with respect to the environment. Therefore, they are not capable of autonomously self-assembling, which is a main feature of swarm-bots.

From Theory to Practice

When we started the project at the end of 2001, we knew that we were going to bring into robotics the self-assembling and self-reconfiguration abilities displayed by colonies of ants when they transport objects, build a nest, or make living bridges to cross large gaps. The first challenge in designing the s-bots was the choice of connection types and their properties (flexible, rigid) and number of degrees of freedom (DOF). Another important issue was the mobility of the swarm-bot with respect to individual s-bots. Should the swarm-bot move by acting on the s-bot connections (rotate like a track or a ball made of s-bots) or by relying on the mobility of each individual s-bot (wheels, legs, and tracks)?

At first, we considered a cylindrical mobile robot capable of connecting to other robots by two rigid connections [Figure 2(a) and (b)]. This solution seemed interesting because of the potential 3-D configurations of the swarm-bot and of the possibility of self-reconfiguration of a single s-bot without disconnecting from the swarm-bot (a functionality that has been exploited also by Kamimura et al. [5]). The first full-size wood model showed that the resulting structure was hyperstatic and would have required precise control and strong coordinated planning of the actions of each s-bot. This was not in line with the spirit of the project, which aimed at developing decentralized and loosely coupled robotic systems where simple computational abilities would give rise to complex behaviors.

In a second stage, we compensated for those shortcomings by giving higher movement autonomy to individual s-bots and providing them with two types of connections [Figure 2(c) and (d)]. Better mobility was achieved by introducing bigger tracks. For connections, s-bots were equipped with a strong gripper capable of grasping another s-bot anywhere around its

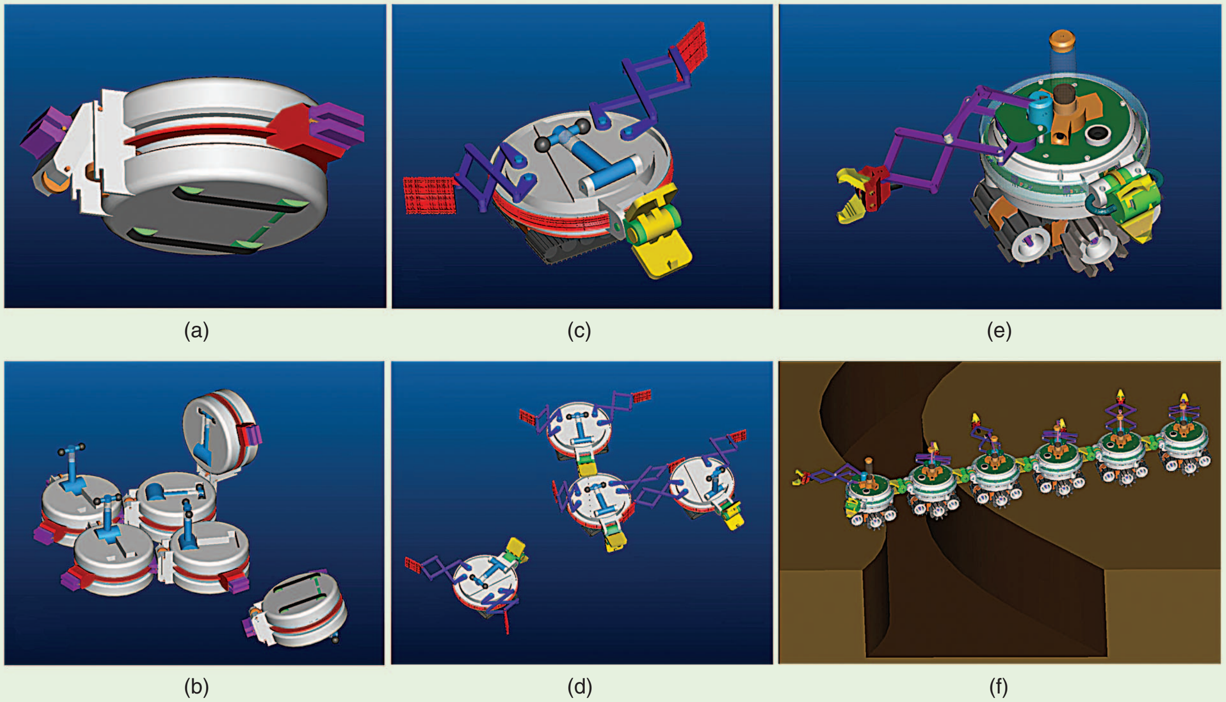

Figure 2. *The evolution of the swarm-bot hardware design: (a)–(b) results of the first brainstorming, (c)–(d) introduction of flexible links and better mobility, and (e)–(f) the choice of gripper-based connections and design finalization.*

body and lifting it. They also had two flexible arms with a Velcro surface at their ends to provide loose but easy connectivity to other s-bots. In addition, the upper part of the s-bot (including the connections) could rotate with respect to the motor base in order to allow local adjustments in swarm-bot configuration. This design was getting closer to the original aim and also captured the functionality of mandibles and legs used by ants to lift heavy objects and establish connections to other ants, respectively. However, prototypes of Velcro-equipped arms showed that the connection could easily break up if two s-bots rotated in certain directions.

Eventually, we decided to replace the two arms with a single flexible arm equipped with a small, toothed gripper [Figure 2(e) and (f)]. This flexible arm could be used to establish connection with another s-bot as well as grasp objects on the floor. Another improvement has been made at the level of the motor base by combining tracks with wheels (treels) to provide swift rotation and navigation on rough terrains. This final design includes 9 DOF: two for the treels, one for the rotation of the body with respect to the treels, two for the strong gripper (elevation and aperture), three for the flexible arm, and one for the gripper mounted on it.

Mechatronic Implementation

The mechanical structure [Figure 3(b)] is based on the detailed design shown in Figure 3(a), with the main parts made of plastic and molded in our workshop. This manufacturing process allows fast reproduction of parts without extra machining in order to build 35 s-bots. Plastic parts also allow the construction of relatively light robots (660 g) that can be lifted by other robots. An s-bot is made of approximately 100 main parts.

The electronic brain and sensors of the s-bot have been designed to allow communication among robots, autonomous self-assembling, coordinated navigation of the

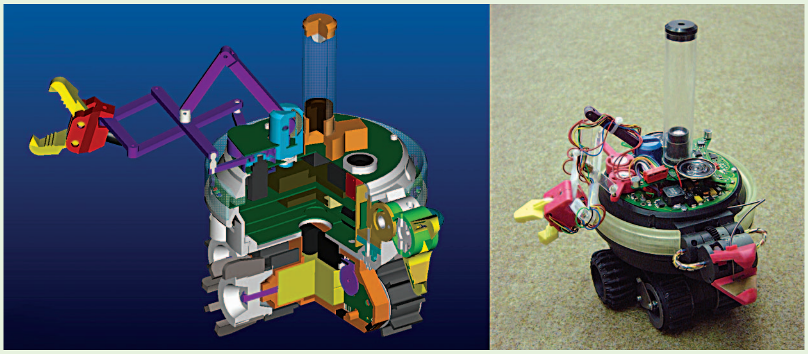

Figure 3. *The (a) detailed design and (b) final implementation of an s-bot. The diameter of the robot is 120 mm.*

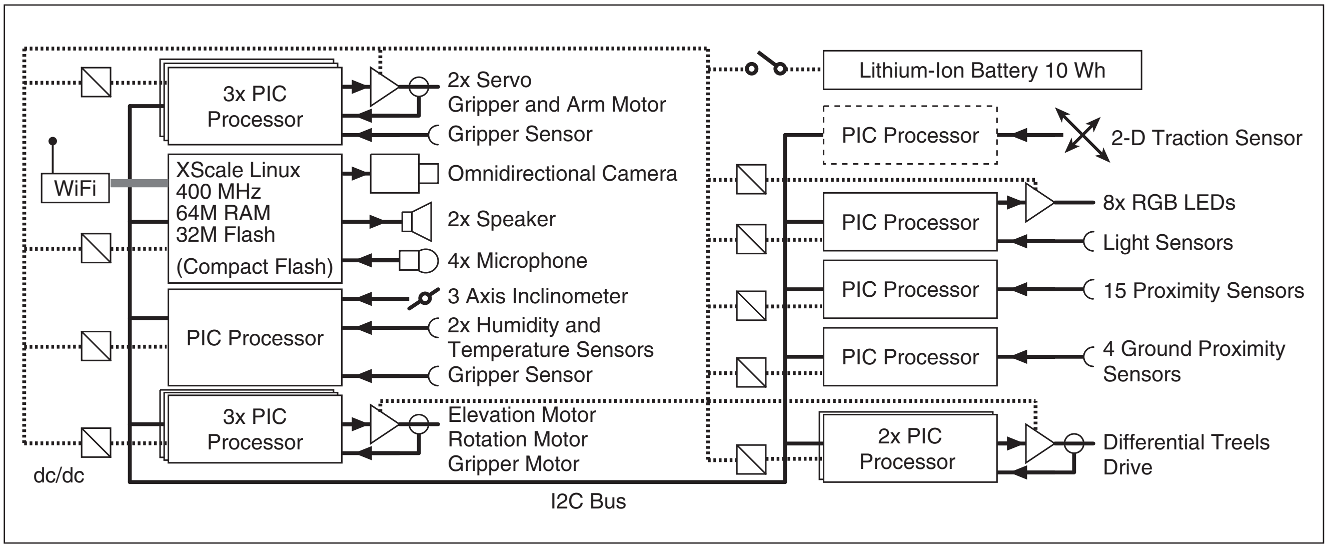

Figure 4. *Schematic structure of the s-bot electronics. Fourteen processors distributed all around the robot body manage all the sensor and actuator devices.*

s-bots in swarm-bot configuration, and monitoring of the entire system for data analysis on an external computer. To ensure all these functionalities, the s-bot has been equipped with 50 sensors, including position and torque sensors on most DOF, lateral and ground proximity sensors, inclinometers, humidity sensors for humidity gradient detection, light sensors, object sensors within the gripper, a panoramic camera, and microphones. In addition to actuators for the 9 DOF, the robot is equipped with a transparent ring of color light-emitting diodes (LEDs) around its body and loudspeakers. The color ring, which also serves as connection area, can be used by s-bots to express their state and guide the approaching and grasping of other s-bots. The loudspeakers can be used to call other robots or emit alert signals.

Fourteen processors within the s-bot ensure the control of all these devices, as illustrated in the diagram of Figure 4. Most of them (13) are small PIC processors acting as slaves for local management of sensors or actuators. The fourteenth processor, an Intel XScale processor running LINUX at 400 MHz, plays the role of the master, controlling the whole robot. This processor has direct control on sound devices and cameras. It can also communicate with an external PC by means of a wireless ethernet connection. A set of rechargeable batteries within the motor base provides autonomy for approximately three hours in normal activity (this duration is decreased if the robot lifts other robots several times).

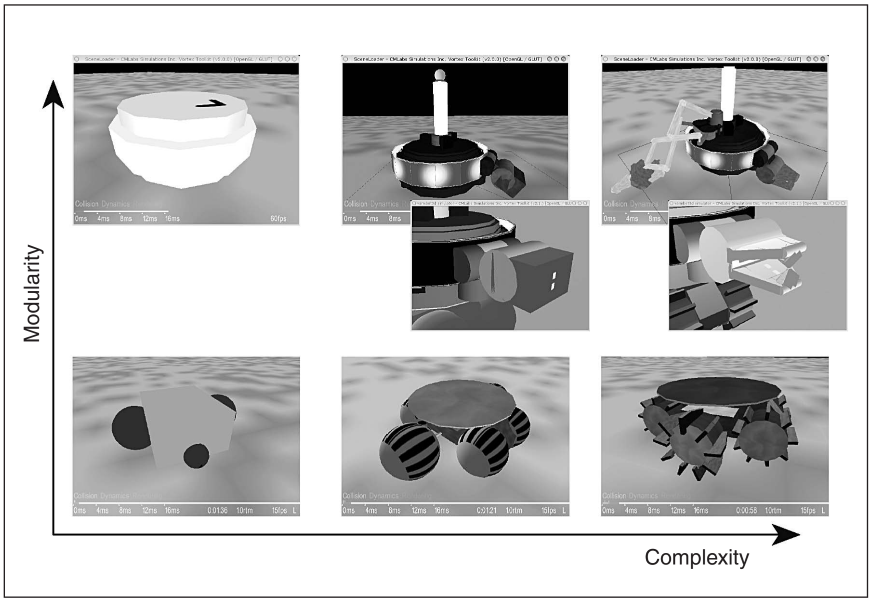

Figure 5. *The simulation of the s-bot hardware is structured into various modules, each of them modeled at several levels of complexity. These features allow a very flexible simulation, adjusting in an optimal way the simulation complexity to the experiments.*

Simulation

Swarmbot3D is the simulation platform developed during the swarm-bots project to support the evaluation of different hardware components, to help the design and the validation of distributed swarm control policies, and to reproduce kinematics and dynamic robot 3-D behaviors on terrains with different levels of roughness. Since no commercial or research prototype simulation tools were able to provide all these features together, we decided to implement Swarmbot3D starting from Vortex, an engine that allows the simulation of rigid objects and their dynamics in a 3-D space.

Swarmbot3D implements a modular description of the s-bot, based on basic modules such as the treels system module, the rotating turret module, the front-arm gripper module, and the flexible side-arm gripper module. Each module has been implemented in different models, each model having a different level of detail, as described in Figure 5. This allows the user to build the simulated robot according to the experimental constraints, for example, by focusing on a few details for high simulation speed in case of time-consuming experiments or by using the full description to carry out experiments requiring detailed models. Four different reference models—fast, simple, medium, and detailed (see Figure 6)—have been implemented in which the detailed model replicates exactly the geometrical blueprints of the real hardware as well as masses, center of masses, torques, acceleration, and speeds. The other models have been designed combining basic modules with decreasing level of details and increasing simulation speed.

Many tests have been carried out to validate the simulation in case of swarm-bot behavior in complex environments. Porting a simulated experiment to the real robot is quite easy since simulated and physical systems use the same control primitives. Both the detailed model and the real s-bot were able to carry out a successful traversal up to a maximum gap of about 45 mm, to climb slopes up to about 60°, and to overcome steps up to 23 mm. Experiments with simulated and physical robots have shown that two connected s-bots are able to overcome gaps and to pass steps that are larger and higher than the capability of a single s-bot (see Figures 7 and 8).

These collective capabilities are currently investigated in experiments in which the goal is to move heavy objects in complex environments with terrains of different levels of roughness. In these experiments, we face two different requirements. In the case of flat terrain, the user does not need a detailed simulation of the interaction with the ground and may therefore adopt a simple and fast reference model. In case of rough terrain, or in the case of behaviors actively exploiting physical connections, one may use a more refined simulated robot.

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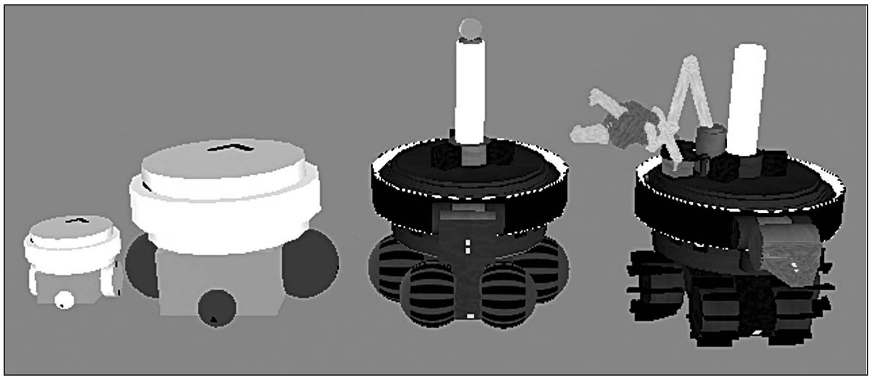
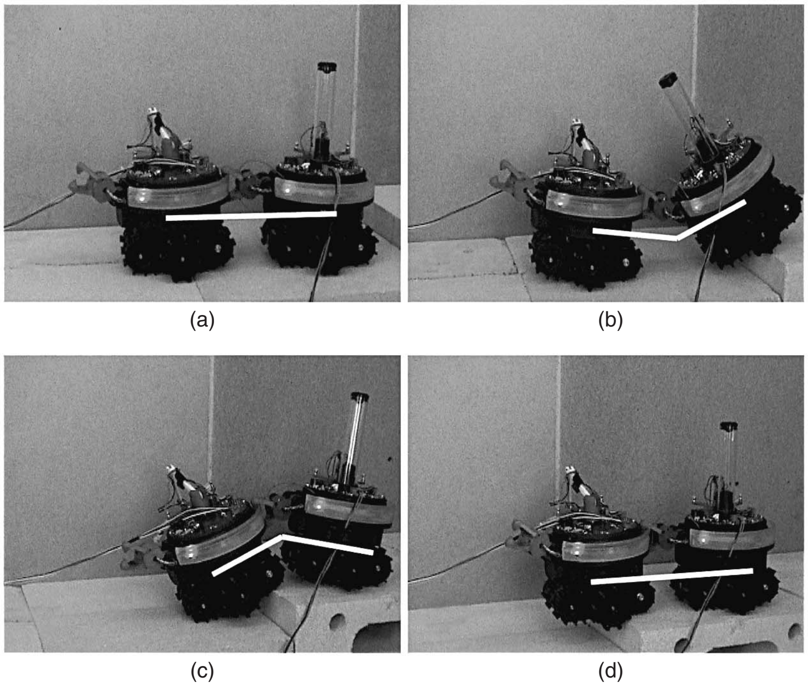


Figure 6. *To simplify the exploitation of the simulator modularity, four reference models have been predefined and made available to the user.*



(a) (b) (c) (d)

Figure 7. *An example of a task that two s-bots can perform together but not in isolation. Using the rigid connection between them, (a) one s-bot is helped to pass the step; (b) as soon as the first s-bot has passed, it helps the second to pass the step too, as shown in (c) and (d).*

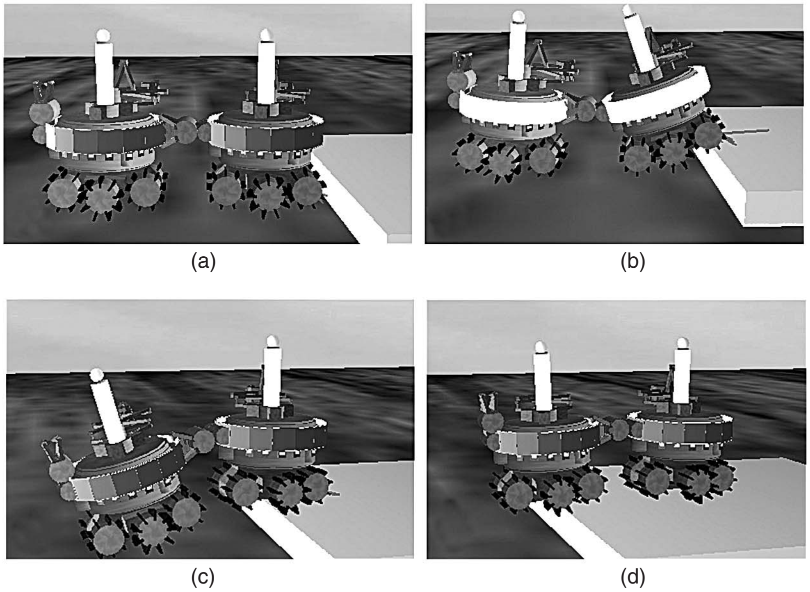


Figure 8. The replication of the four phases illustrated in Figure 5 using 3-D physics-based simulation.

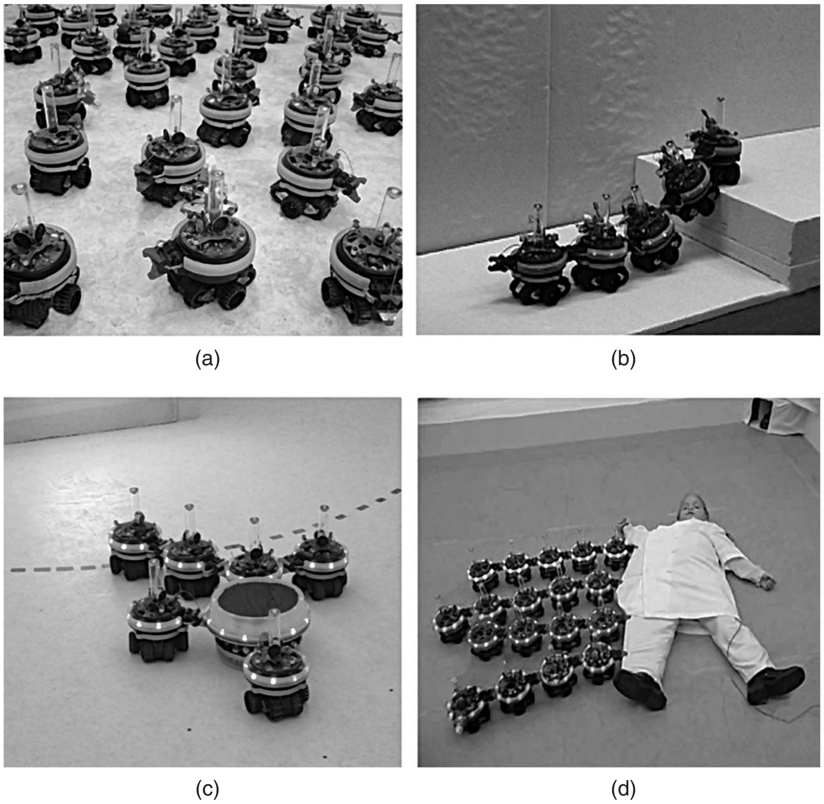


Figure 9. Major results of the project: (a) the production of 35-s bots, (b) the demonstration of passing a 14-cm step with a swarm-bot composed of five s-bots, (c) s-bots self-assembling and transporting an object towards a goal in a self-organized manner, and (d) transporting a child in a structured manner.

Swarmbot3D introduces the possibility to dynamically change at run-time the s-bot representation models. This allows the user to use the simulation with the simplest abstraction level as the default and let it automatically switch to a more refined model when the environment or the interaction among s-bots requires a more detailed simulation. Dynamic model changing allows Swarmbot3D to introduce complexity only when needed, making simulation faster. In addition, in the case of experiments based on artificial evolution [14], where a large number of evaluations are required, it is possible to run fast evaluations using the simple model and to reevaluate some situations (or parts of them) by using a more detailed s-bot.

Results

The project achieved very interesting results concerning the implementation and the validation of the mechatronic concept of self-assembling systems, the design of control algorithms, and the exploration of the potential impact of the approach.

A total of 35 s-bots were produced [Figure 9(a)] in three batches of about 12 robots each. The first batch was produced after four prototyping iterations. Despite the sufficient quality of the robots in this first batch, we improved them in the second and third batches, allowing better and more complex experiments. Until now we carried out experiments involving up to 20 s-bots.

A swarm-bot in a chain configuration displayed the ability to pass obstacles of the same height of a single s-bot robot [Figure 9(b)]; a video of this experiment is available at: http://www.swarm-bots.org/ram05.html. This type of operation has been carried out under tele-operation and still has to be tested in fully autonomous mode. It nevertheless shows the potential flexibility of this type of system in all-terrain conditions.

S-bots are capable of autonomous self-assembly by combining vision for long-range information, proximity sensors for local adjustments, and sensors in the gripper for secure grasping.

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The control strategies that allow a swarm of connected s-bots to move in a coordinated fashion were evolved in physics-based simulation and successfully used with the real robots. Those strategies are sufficiently universal to generalize to the different shape (chain, square, triangle) and size of the swarm-bot. They are also useful for the coordinated transportation of a heavy object toward a goal, exploiting a combination of vision and lateral force sensors on the robot body [Figure 9(c)]; a video of the combination of these two behaviors is available at http://www.swarm-bots.org/ram05.html.

All these capabilities were exploited in an experiment where 20 s-bots self-assemble into four swarm-bots to pull a child on the floor [Figure 9(d)]; a video of this experiment is available at http://www.swarm-bots.org/ram05.html. The experiment was carried out in semiautonomous mode. The user specifies the number of swarm-bots, the distribution of the s-bots in the swarm-bots, the global localization of the child, and the global actions timing. The s-bots perform in autonomous mode the precise localization of the grasping location on the child, the approach, and the self-assembling process.

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Keywords

Swarm-bots, self-assembling, collective transport, child pulling.

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Francesco Mondada received an M.Sc. in microengineering. He received his Ph.D. from the École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland. He is a member of the group who developed the Khepera mobile robot. He is cofounder of two companies: K-Team (robotics) and Calerga (scientific software). He has been president and director of K-Team for five years. He is currently a senior researcher at the Autonomous System Laboratory of EPFL. His interests include miniature robotic design, mechatronics, bio-inspired robotic research, the development of tools to perform this research, and the transfer of robotics technology to industry.

Luca Maria Gambardella is a research director of the Dalle Molle Institute for Artificial Intelligence (IDSIA). His major research interests are in the area of optimization, simulation, robotics learning, and adaptation applied to both academic and real-world problems. In particular, he has studied and developed several ant colony optimization algorithms to solve scheduling and routing problems. In these domains, the best known solutions for many benchmark instances have been computed. He is responsible for IDSIA robotics projects. He has led several research and industrial projects, both at the Swiss national and European levels.

Dario Floreano is a professor of intelligent systems at the École Polytechnique Fédérale de Lausanne (EPFL) where he is also director of the Institute of Systems Engineering. His research activities include artificial neural networks, evolutionary computation, swarm intelligence, biomimetic electronics, autonomous robotics, and artificial life. He is one of the pioneers in the field of evolutionary robotics, and his book with Stefano Nolfi on this topic was reprinted by MIT Press three times since 2000. He is on the editorial board of the journals *Neural Networks*, *Genetic Programming and Evolvable Machines*, *Adaptive Behavior*, *Artificial Life*, *Connection Science*, *Autonomous Robots*, and *IEEE Transactions on Evolutionary Computation*. He is also the cofounder and codirector of the International Society for Artificial Life, a member of the board of governors of the International Society of Artificial Neural Networks, and a member of various international societies. He frequently serves as advisor to the Research Division of the European Commission, to the U.S. National Science Foundation, and to other governmental and private institutions.

Stefano Nolfi is the head of the Laboratory of Artificial Life and Robotics of the Institute of Cognitive Science and Technologies (CNR). His research interests are in the field of neuroethological studies of adaptive behavior in natural and artificial agents and include: evolutionary robotics, artificial life, complex systems, neural networks, and genetic algorithms. The main themes underlying his work are behavioral strategies and neural mechanisms are understood better when an organism (living or artificial) is caught in the act (i.e., when one considers situated and embodied agents in their interaction with the environment), and in order to understand how natural agents behave and to build useful artificial agents, one should study how living organisms change, phylogenetically and ontogenetically, as they adapt to their environment. Nolfi has published more than 90 peer-reviewed articles and a book on evolutionary robotics.

Jean-Louis Deneubourg is codirector of the department of social ecology at the Université Libre de Bruxelles (ULB) and researcher for the Belgian National Fund for Scientific Research (FNRS). He obtained his Ph.D. from the ULB in 1979 with a thesis on mathematical models of animal and human behavior. He is the author or coauthor of about 170 papers, the coeditor of two books, and the coauthor of one book (*Self-Organization in Biological Systems*).His research concerns the collective intelligence in animal societies.

Marco Dorigo received the Laurea (master's of technology) degree in industrial technologies engineering in 1986 and the doctoral degree in information and systems electronic engineering in 1992 from Politecnico di Milano, Italy, and the title of Agrégé de l'Enseignement Supérieur, from the Université Libre de Bruxelles, Belgium, in 1995. He was a research fellow at the International Computer Science Institute of Berkeley, California, a NATO-CNR fellow, and a Marie Curie fellow. Since 1996, he has been a tenured researcher of the FNRS, the Belgian National Fund for Scientific Research, and a research director of IRIDIA, the artificial intelligence laboratory of the Université Libre de Bruxelles. He is the inventor of the ant colony optimization metaheuristic and one of the founders of the swarm intelligence research field. His current research interests include metaheuristics for discrete optimization, swarm intelligence, and swarm robotics. He is an associate editor for the publications *Cognitive Systems Research, IEEE Transactions on Evolutionary Computation, IEEE Transactions on Systems, Man, and Cybernetics,* and *Journal of Heuristics*. He is a member of the editorial board of numerous international publications, including *Adaptive Behavior*, *AI Communications*, *Artificial Life*, *Evolutionary Computation*, *Information Sciences*, and *Journal of Genetic Programming and Evolvable Machines*. He is the author of three books: *Robot Shaping*, 1998; *Swarm Intelligence*, 1999; and *Ant Colony Optimization*, 2004. In 1996, he was awarded the Italian Prize for Artificial Intelligence and in 2003, the Marie Curie Excellence Award for his work on ant colony optimization and ant algorithms.

Address for Correspondence: Dr. Francesco Mondada, École Polytechnique Fédérale de Lausanne (EPFL), Autonomous Systems Lab, EPFL - STI -12S - LSA, Office MEB330, Station 9, CH-1015 Lausanne, Switzerland. E-mail: francesco.