SWARM-BOTS: Physical Interactions in Collective Robotics

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Abstract

We present a new type of robot concept called *swarm-bot,* based on cooperative and swarm intelligence, that was developed within an interdisciplinary project sponsored by the Future and Emerging Technologies of the European Commission. A swarm-bot is an assembly of several mobile robots (called *s-bots*), which can operate both autonomously and as a group. The unique feature of the project is that s-bots can exploit physical interconnections to self-assemble into a bigger entity, a *swarm-bot*, capable of tackling environmental challenges that are too difficult for a single s-bot. The paper describes the development of the concept and gives an overview of the mechanical and electronic features of the first prototype. 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.

Introduction

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 perform successfully tasks such as displacement, exploration or object transportation

Swarm robotics, which can be considered an instance of the more general fields of swarm intelligence [1,2,3] and collective robotics [4], address 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. In this paper we briefly overview the outcomes of the SWARM-

BOTS project[1], whose goal is the development of a particular type of swarm robotic system, called *swarm-bot*.

A swarm-bot is defined as an artifact composed of a swarm of *s-bots*, mobile robots with the ability to attach/detach from each other. 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 so 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.

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.

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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 work of Kamimura et al. [5], or in the work of Yim et al. [7]. MTRAN and PolyBot use a large number of simple modules, have been physically 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 approaches known as Phase Automata [9].

The first 3D 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 re-adapts autonomously its behavioral role in the system.

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 large quantities (100).

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 just 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 to face in the design of the s-bots was the choice of connection types and their properties (flexible, rigid, number of degrees of freedom, etc.). 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-bots (wheels, legs, tracks, etc.)?

At first, we considered a cylindrical mobile robot capable of connecting to other robots by two rigid connections (figure 2 a-b). This solution seemed interesting because of the potential 3D 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 emerging complex behaviors.

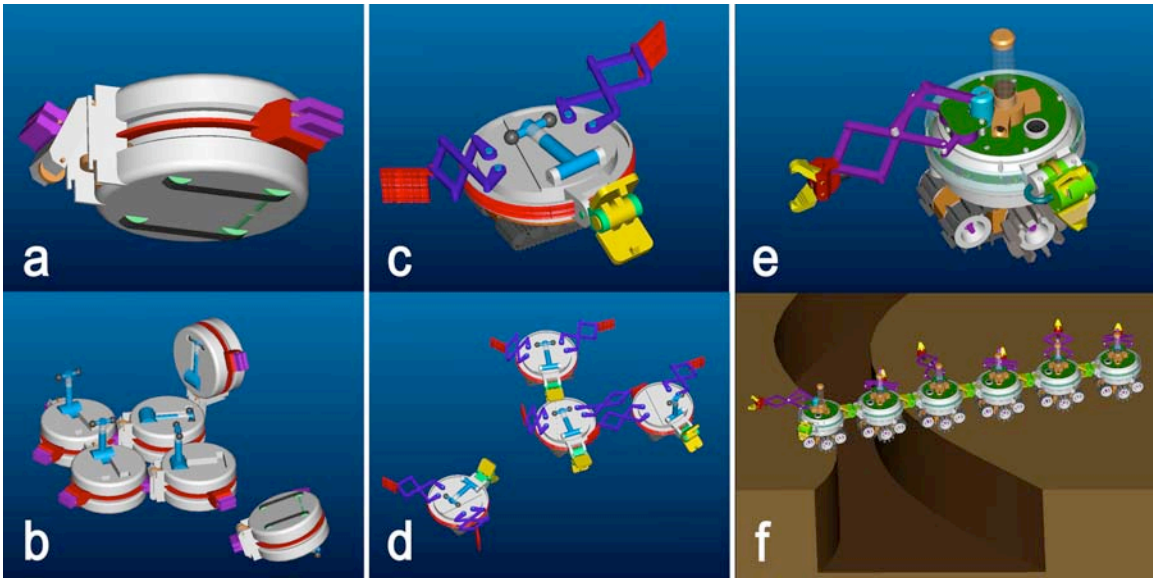

Figure 2: Evolution of the swarm-bot hardware design. (a-b): Results of the first brainstorming. (c-d): Introduction of flexible links and better mobility. (e-f): Choice of gripper-based connections and design finalization.

In a second stage, we compensated those shortcomings by giving higher movement autonomy to individual s-bots and providing them with two types of connections (figure 2 c-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 body and lift it. They also had two flexible arms with a Velcro™ surface at their end 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, wood 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-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 on the motor base by combining tracks with wheels (treels©) to provide swift rotation and navigation on rough terrains. This final design includes 9 degrees of freedom: 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 3b) is based on the detailed design shown in figure 3a 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.

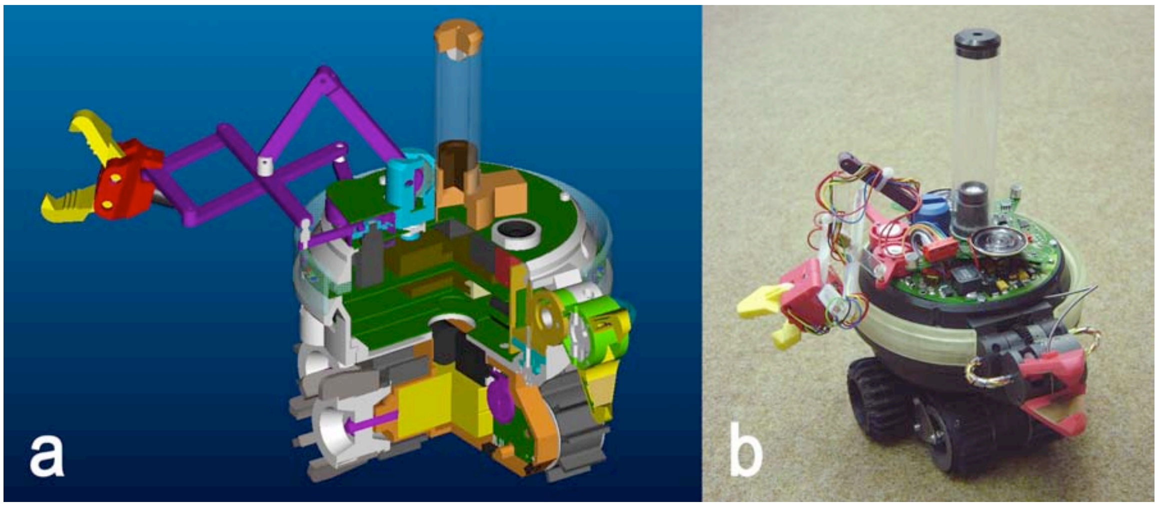

Figure 3: Detailed design and final implementation of an s-bot. The diameter of the robot is 120 mm.

The electronic brain and sensors of the s-bot have been designed to allow communication among robots, autonomous self-assembling, coordinated navigation of the 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 degrees of freedom, lateral and ground proximity sensors, inclinometers, humidity sensors for humidity gradient detection, light sensors, object sensors within the gripper, panoramic camera and microphones. In addition to actuators for the nine degrees of freedom, the robot is equipped with a transparent ring of color LED’s 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.

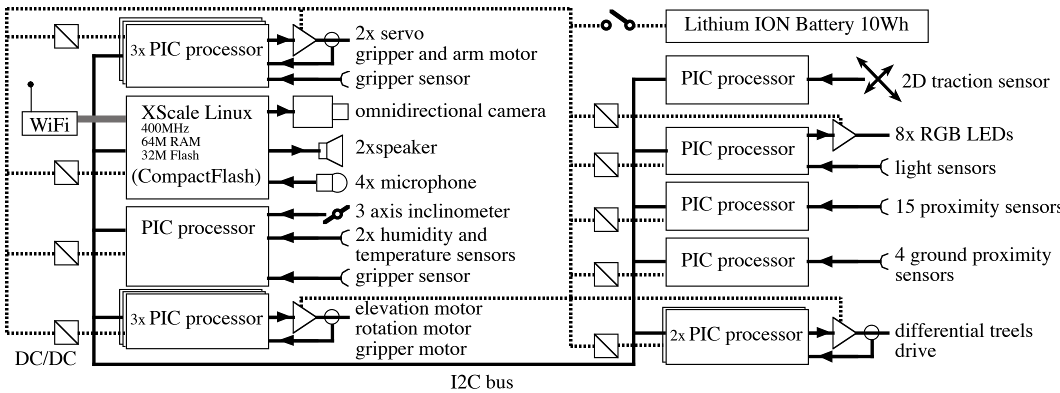

Figure 4: Schematic structure of the s-bot electronics. Fourteen processors distributed all around the robot body manage all the sensor and actuator devices.

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 14th processor, an Intel XScale™ processor running LINUX at 400MHz, plays the role of the master controlling the whole robot. This processor has direct control on sound devices and camera. It can also communicate with an external PC by means of a WiFi connection. A set of rechargeable batteries within the motor base provides autonomy for about three hours in normal activity (this duration is decreased if the robot lifts other robots several times).

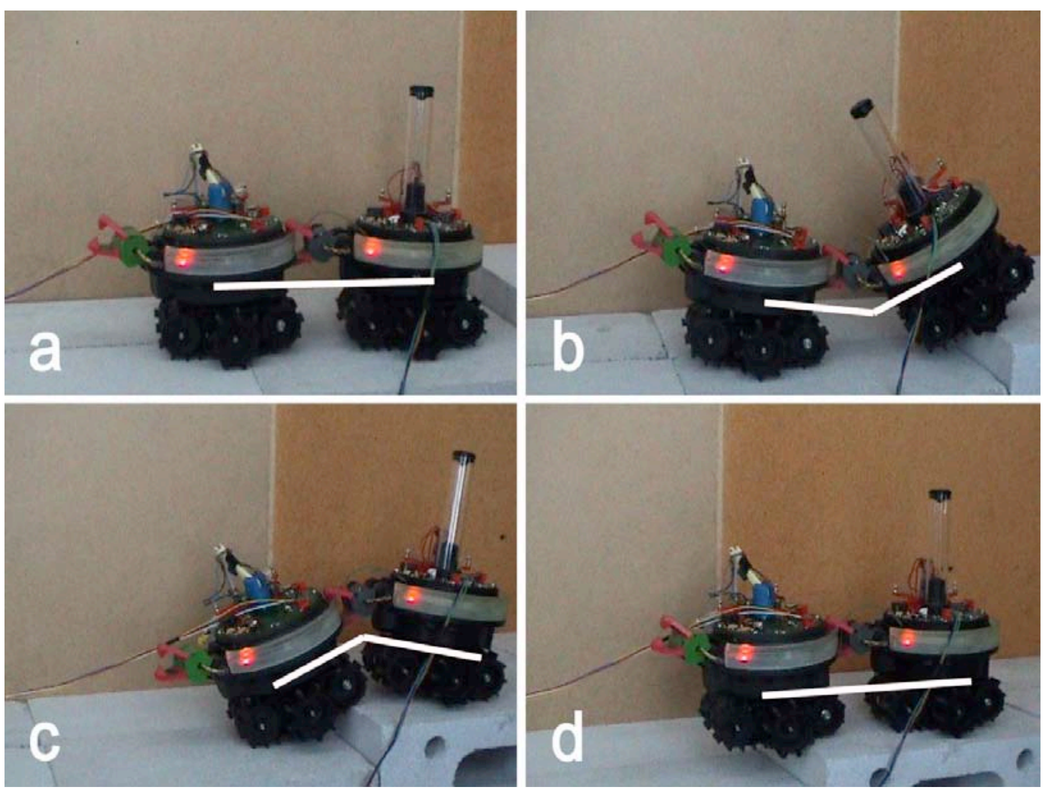

Figure 5: Example of a task that two s-bots can perform together, but not in isolation. Using the rigid connection between them, (a) one s-bot is helped to pass the step (b). As soon as the first s-bot has passed, it helps the second to pass the step too (c and d).

Preliminary results showed that two s-bots can autonomously connect together and perform tasks that one s-bot alone cannot carry out. An example is illustrated in figure 5, where two connected s-bots (figure 5a) pass a step that one robot alone could not pass. The rigid connection with its vertical degree of freedom is used to help one s-bot to pass the obstacle (figure 5b) and then pull the second over the step (figure 5c and d). This behavior has been obtained with a simple state machine based on the data coming from the proximity sensors situated under the robot that point at the ground. The data measured and the resulting actuation of the gripper elevation is illustrated in figure 6. We can observe that the frontal ground sensors is the first sensor to detect the step and triggers the elevation of the gripper, helping the s-bot to pass the step. Once the robot has reached the upper edge of the step the value of the that frontal sensor decreases. We can then observe two peaks for each of the down-looking sensors as soon as they pass over the edge of the step. Once the second down-looking sensor has passed the step, the s-bot is considered to be over the step and the gripper elevation is modified to help the following s-bot to pass the step. The first s-bot can then move forward and find its normal configuration when the distance traveled corresponds to the second robot having passed the step.

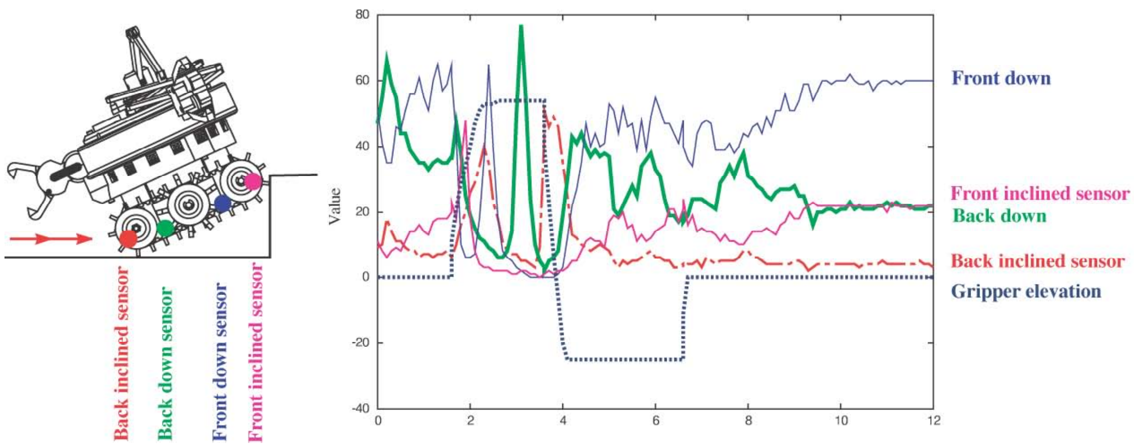

Figure 6: Activation of ground distance sensors and actuation of the gripper elevation for the first of the two s-bots in the step-passing problem illustrated in figure 5.

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 3D 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 3D space.

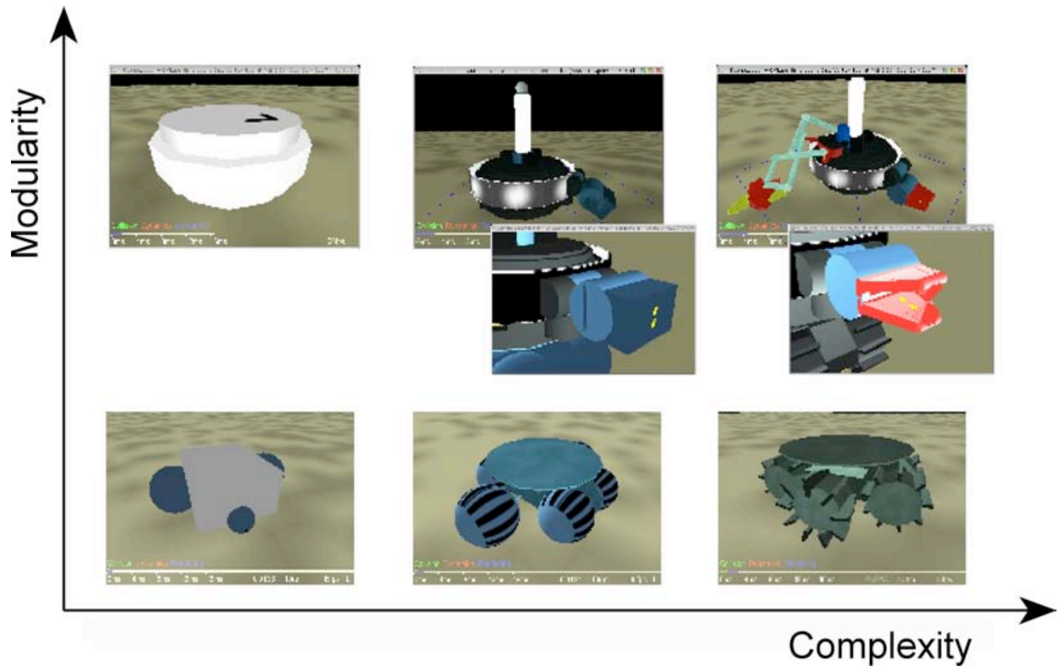

Figure 7: The simulation of the s-bot hardware is structured into various modules, each of them modeled at several levels of complexity. These features allow a very flexible simulation, adjusting in an optimal way the simulation complexity to the experiments.

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 details, as described in figure 7. This allow the user to build the simulated robot according to the experimental constraints, for example by focusing on 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 8) have been implemented in which the detailed model replicates exactly the geometrical blue prints of the real hardware as well as masses, centre of masses, torques, acceleration, and speeds. The other models have been designed combining basic modules with decreasing level of details and increasing simulation speed.

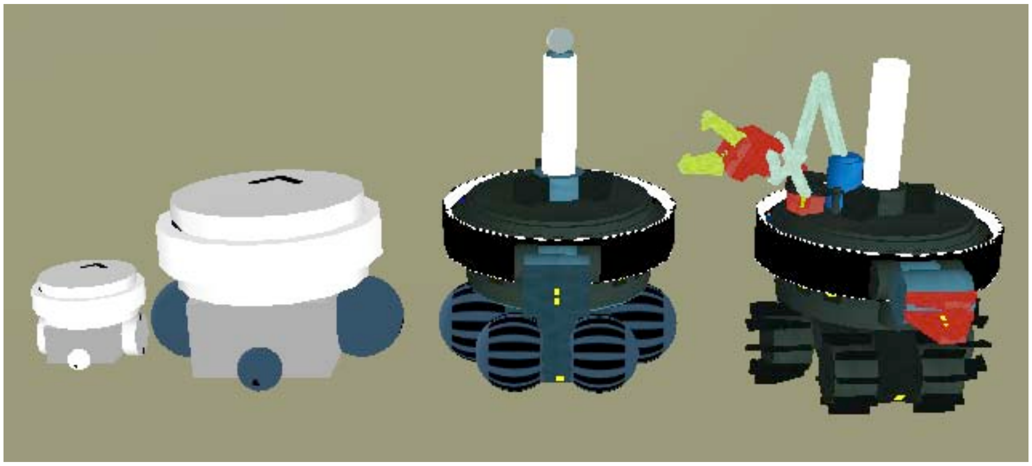

Figure 8: To simplify the exploitation of the simulator modularity, four reference models have been pre-defined and made available to the user.

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 around 60 degree, 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 5 and 9).

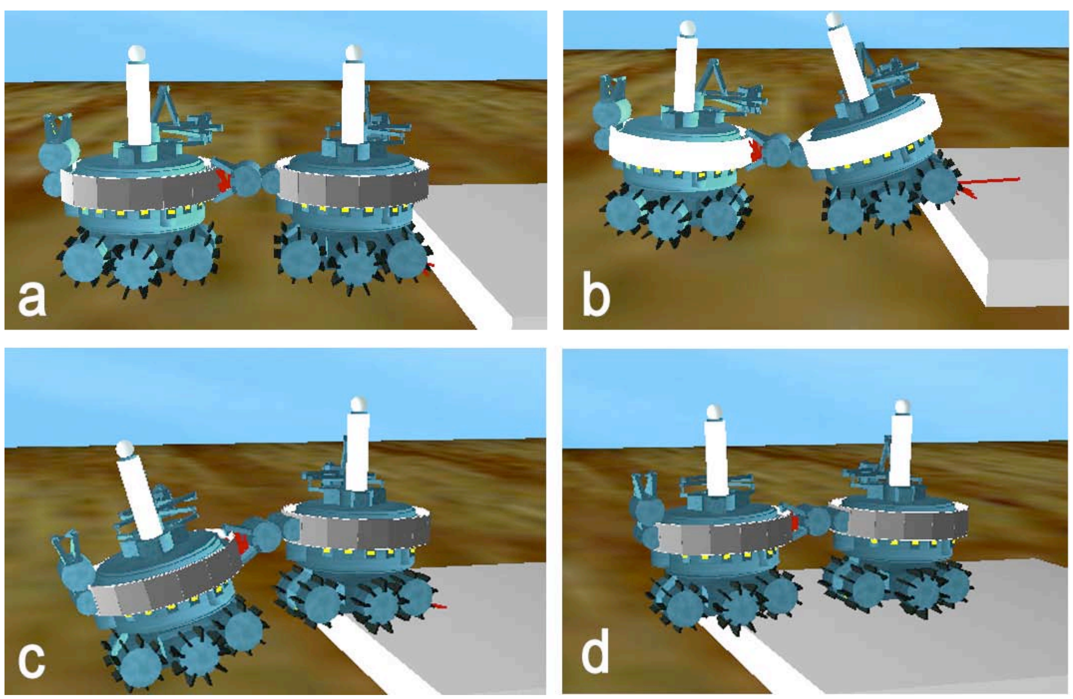

Figure 9: Replication of the four phases illustrated in figure 5 using 3D physics based simulation.

These collective capabilities are currently investigated in experiments in which the goal is to move heavy objects in complex environments with terrains of different level of roughness. In these experiments we face two differ requirements: In 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 case of behaviors actively exploiting physical connections, one may use a more refined simulated robot. 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 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 in this way simulation faster. In addition, in case of experiments based on artificial evolution [14], where a large number of evaluations is required, it is possible to run fast evaluations using the simple model and to re-evaluate some situations (or parts of them) by using a more detailed s-bot.

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References

[1] E. Bonabeau, M. Dorigo, and G. Theraulaz. *Swarm Intelligence: From Natural to Artificial Systems*. Oxford University Press, New York, NY, 1999.
[2] E. Bonabeau, M. Dorigo, and G. Theraulaz. *Inspiration for optimization from social insect behavior*. Nature, 406:39-42, 2000.
[3] G. Beni and J. Wang, *Swarm Intelligence*, Proceedings of the Seventh Annual Meeting of the Robotics Society of Japan, RSJ press, Tokio, Japan, 1989, pp. 425—428.

[4] R. C. Arkin and G. A. Bekey, editors. *Robot Colonies*. Kluwer Academic Publishers, 1997.
[5] A. Kamimura, S. Murata, E. Yoshida, H. Kurokawa, K. Tomita, and S. Kokaji. *Self-reconfigurable modular robot - experiments on reconfiguration and locomotion.* In T. J. Tarn et al., editor, Proc. of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems IROS2001, pages 606–612, IEEE Press, Piscataway, NJ, 2001.
[6] D. Duff, M. Yim, and K. Roufas, *Evolution of PolyBot: A Modular Reconfigurable Robot*. In: Proceedings of COE/Super-Mechano-Systems Workshop, 2001, Tokyo, Japan.
[7] M. Yim, Y. Zhang, and D. Duff, *Modular Robots*. IEEE Spectrum 39(2), 2002, pp. 30–34.
[8] H. Kurokawa, A. Kamimura, E. Yoshida, K. Tomita, S. Kokaji, and S. Murata, *M-TRAN II: Metamorphosis from a Four-Legged Walker to a Caterpillar*. In: C. S. G. Lee and J. Yuh (eds.): Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robot and Systems (IROS 2003), 2003, IEEE Press, Piscataway, NJ, pp. 2454–2459.
[9] Y. Zhang, M. Yim, C. Eldershaw, D. Duff, and K. Roufas, K., *Phase Automata: A Programming Model of Locomotion Gaits for Scalable Chain-type Modular Robots*. In: C. S. G. Lee and J. Yuh (eds.): Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robot and Systems (IROS 2003), 2003, IEEE Press, Piscataway, NJ, pp. 2442–2447.
[10] A. Castano, W.-M. Shen, and P. Will, *CONRO: Towards Deployable Robots with Inter-Robot Metamorphic Capabilities*. Autonomous Robots 8, 2000, pp. 309–324.
[11] K. Støy, W.-M. Shen, and P. Will, P, *Global Locomotion from Local Interaction in Self-Reconfigurable Robots*. In: C. T. M. Gini, W.-M. Shen and H. Yuasa (eds.): Proceedings of the 7th International Conference on Intelligent Autonomous Systems (IAS-7), 2002, IOS Press, Amsterdam, The Netherlands, pp. 309–316.
[12] Salemi, B., Shen, W.-M., and Will, P., *Hormone Controlled Metamorphic Robots*. In: Wook H. Kwon et al. (ed.): Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2001), 2001, IEEE Press, Piscataway, NJ, pp. 4194–4199.
[13] D. J. Christensen, E. H. stergaard, and H. H. Lund. *Metamodule control for the atron selfreconfigurable robotic system*. In Proceedings of the 8th Conference on Intelligent Autonomous Systems (IAS8), IOS Press, 2004. Conference, Amsterdam, The Netherlands, March 10-14, 2004, pages 685-692.
[14] S. Nolfi and D. Floreano. *Evolutionary Robotics. The biology, intelligence, and technology of Self-Organizing Machines*. MIT Press, 2000.

Short BIOs

Francesco Mondada has an MSc in Microengineering and a PhD from the Swiss Federal Institute of Technology (EPFL), Lausanne (Switzerland). He is a member of the group who developed the Khepera mobile robot. He is co-founder of two companies: K-Team (robotics) and Calerga (scientific software). He has been president and director of K-Team for 5 years. He is currently senior researcher at the Autonomous System Laboratory of the Swiss Federal Institute of Technology (EPFL), Lausanne. 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 Research Director at 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 optimisation 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 national (Swiss) and European level.

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Marco Dorigo received the Laurea (Master 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, Milan, Italy, and the title of Agrégé de l'Enseignement Supérieur, from the Université Libre de Bruxelles, Belgium, in 1995. From 1992 to 1993 he was a research fellow at the International Computer Science Institute of Berkeley, CA. In 1993 he was a NATO-CNR fellow, and from 1994 to 1996 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 Universit´e Libre de Bruxelles. He is the inventor of the ant colony optimization metaheuristic and one of the founders of the swarm intelligence research field. Its current research interests include metaheuristics for discrete optimization, swarm intelligence and swarm robotics. Dr. Dorigo is an Associate Editor for the journals: 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 journals, 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, MIT Press, 1998; Swarm Intelligence, Oxford University Press, 1999; and Ant Colony Optimization, MIT Press, 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.