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SWARM-BOT: AN EXPERIMENT IN SWARM ROBOTICS

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ABSTRACT

This paper provides an overview of the SWARM-BOTS project, a robotics project sponsored by the Future and Emerging Technologies program of the European Commission (IST-2000-31010). We describe the *s-bot*, a small autonomous robot with self-assembling capabilities that we designed and built within the project. Then we illustrate the *cooperative object transport* scenario that we chose to use as a test-bed for our robots. Last, we report on results of experiments in which a group of *s-bots* perform a variety of tasks within the scenario which may require self-assembling, physical cooperation and coordination.

1. INTRODUCTION

The main scientific objective of our research is the study of novel ways of designing and implementing self-organizing and self-assembling artifacts. We are particularly interested in approaches that find their theoretical roots in recent studies in swarm intelligence [2], that is, in studies of the self-organising and self-assembling capabilities shown by social insects and other animal societies.

At the core of the research agenda presented in this paper is one bold idea: that one can design small mobile robots capable of autonomous physical aggregation into specific shapes so as to perform specific functions. To demonstrate our ideas we have designed and built small robots, that we call *s-bots*, with a number of sensors and motors, basic communication devices, and limited computational capabilities. Additionally, these robots are endowed with aggregation mechanisms that allow them to form collective physical structures and disband at will. We call these collective physical structures *swarm-bots*: a *swarm-bot* is an aggregate of *s-bots* that has the potential to exhibit capabilities that go beyond those of a single *s-bot*. A *swarm-bot* forms as the result of self-organising rules followed by each individual *s-bot* rather than via a global template and is expected to move as a whole and reconfigure along the way when needed. For example, it might have to adopt a different shape in order to go through a tunnel or overcome an obstacle.

Our approach to the design and realization of metamorphic robots is highly innovative—we have put together a number of concepts and ideas in an entirely novel way that has not been seen before in the robotics community. From the hardware point of view, the main innovation is in the fact that a *swarm-bot* is situated somewhere between a traditional monolithic robot and a colony of cooperating robots. A *swarm-bot* can be considered as a single complex robot composed of many detachable parts (the individual *s-bots*). In common with colonies of cooperating robots, however, each individual *s-bot* is also capable of autonomous, although limited, movement and control. The *s-bots* use their autonomy to act independently when they are not attached to each other, to self-assemble so to form a *swarm-bot* when necessary, and finally to implement autonomous reconfiguration and shape-changing activities when in *swarm-bot* configuration. Also, a *swarm-bot*, once assembled, is not limited to a single configuration, but can change its shape while moving, according to its needs (as imposed by the user or by environmental constraints). From the control point of view, with the *swarm-bot* we have pushed further the complexity of artifacts controlled solely by swarm intelligence techniques. To do so, we have exploited the integration of swarm intelligence with evolutionary computation,

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Figure 1. The *s-bot*.

Figure 2. A *swarm-bot* with a linear shape composed of four *s-bots* and moving on rough terrain.

as already suggested, for example, by Martinoli [14]. We have used swarm intelligence principles to guide the definition of building blocks for the design and implementation of our self-organising systems. We use evolutionary computation principles to guide the development of our *s-bot* controllers.

In the rest of this paper, after a brief introduction to the characteristics of the *s-bot*, we illustrate the experimental environment in which we chose to test our ideas and we report on some of the results we obtained.

2. S-BOTS AND SWARM-BOTS

S-bots are the basic elementary components of a *swarm-bot*. Each *s-bot* (see Fig. 1) is a fully autonomous mobile robot capable of performing simple tasks such as autonomous navigation, perception of the environment and grasping of objects. In addition to these features, one *s-bot* can communicate with other *s-bots* and physically connect to them, thus forming a *swarm-bot* (as shown in Fig. 2). A *swarm-bot* can perform tasks in which a single *s-bot* has major problems, such as exploration, navigation, and transportation of heavy objects on rough terrain.

The *s-bot*'s innovative navigation system makes use of both tracks and wheels. One motor controls the wheel and track for a single side of the *s-bot*. The combination of the left and right side motors provides a differential drive system. This differential drive system allows efficient rotation on the spot due to the larger diameter of the wheels. It also gives the traction system a shape close to the cylindrical one of the main body (turret), thus avoiding the typical rectangular shape of simple tracks and improving the *s-bot*'s mobility.

The *s-bot*'s traction system can rotate with respect to the main body by means of a motorized axis. Above the traction system, a rotating turret holds many sensory systems and two grippers for making connections with other robots. In particular, each *s-bot* is equipped with sensors necessary for navigation, such as infrared proximity sensors, light sensors, accelerometers and incremental encoders on each degree of freedom. Each robot is also equipped with sensors and communication devices to detect and communicate with other *s-bots*, such as an omnidirectional camera, colored LEDs around the robot's turret, and sound emitters and receivers. In addition to a large number of sensors for perceiving the environment, several sensors provide each *s-bot* with information about physical contacts, forces, and reactions at the interconnection joints with other *s-bots*. These include torque sensors on most joints as well as traction sensors to measure the pulling/pushing forces exerted on the *s-bot*'s turret.

S-bots have two types of possible physical interconnections for self-assembling into a *swarm-bot* configuration: rigid and semi-flexible. Rigid connections between two *s-bots* are established by a gripper mounted on a horizontal active axis (see Fig. 3a). Such a gripper has a very large acceptance area allowing it to realize a secure grasp at any angle and, if necessary, allowing it to lift another *s-bot*. Semi-flexible connections are implemented by a gripper positioned at the end of a flexible arm actuated by three servomotors (see Fig. 3b). Note that in this paper we consider *s-bots* equipped only with the rigid gripper.

In order to develop the controllers for the *s-bots*, we have implemented a 3D dynamics simulator called Swarmbot3d and based on the SDK Vortex^{TM} toolkit, which provides realistic simulations of dynamics and collisions of

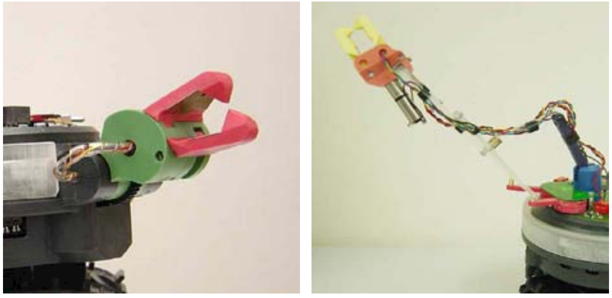
(a) (b)

Figure 3. (a) The *s-bot*'s rigid gripper. (b) The *s-bot*'s semi-flexible gripper.

rigid bodies in 3 dimensions.[1] Swarmbot3d provides *s-bot* models with the functionalities available on the real *s-bots*. It can simulate different sensor devices such as IR proximity sensors, an omnidirectional camera, an inclinometer, sound, and light sensors. It provides robot simulation modules at four different levels of detail. The less detailed models are employed to speed up the process of designing neural controllers through evolutionary algorithms. The most detailed models have been employed to validate the evolved controllers before porting them onto real hardware. A full description of the *s-bot*'s hardware as well as of the Swarmbot3d simulation environment is available in [15].

3. THE EXPERIMENTAL SCENARIO

As a case study in which to test our design and implementation choices, we have defined the following experimental scenario (see Fig. 4):

> A swarm of *s-bots* must transport a heavy object from an initial to a target location. There are several possible paths between these two locations; these paths may have different lengths and may require avoiding obstacles (e.g., walls and holes). The weight of the object is such that its transportation requires the coordinated effort of at least n *s-bots*, with $n > 1$.

In addition to the construction of the *s-bots*, the above scenario necessitated the construction of an experimental arena, shown in Fig. 5a. This arena, which measures approximately 5 m × 2.5 m, is modular in order to meet the different needs of experimentation. The center zone can be changed in different ways. The basement of the arena is made by gas concrete bricks (*Ytong*). This allows the addition of holes, slopes, tilted plans and different obstacles in a simple way. The bricks are covered by a synthetic carpet, to reduce friction. Additionally, two other different types of surfaces are available and can be added on top of the synthetic carpet to test more rugged terrain conditions:

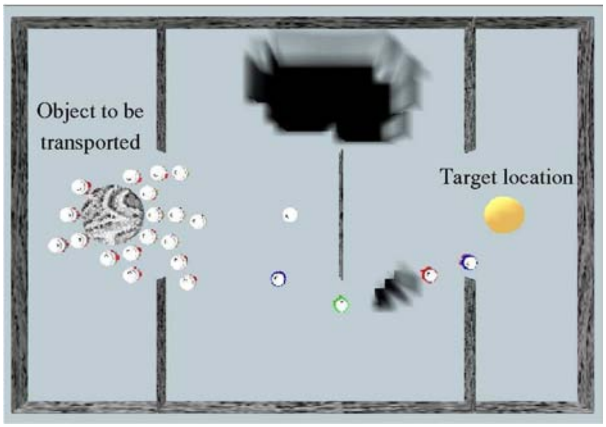

Figure 4. The scenario. The cylinder on the left represents the object to be transported; the landmark on the right represents the target location to which the object has to be transported. The four *s-bots* between the cylindrical object and the target location form a path which logically connects the former to the latter. This path is exploited by other *s-bots* to move back and forth between the target location and the object to be retrieved. Also visible are two types of obstacles: walls and holes.

- Brown plastic foils (see Fig. 6a) make a very regular rough terrain that remains mostly flat, but impossible to access for most standard wheeled robots. Only robots with tracks like the *s-bot* can move on it. The plastic foils are composed of a grid of cones, spaced 2.1 cm apart. The cones are 1.2 cm large and 0.7 cm high.
- White plaster bricks that look like stones (see Fig. 6b) can be used to cover the ground and generate more random rough terrain conditions. The bricks measure 13 cm × 28 cm, their height ranges between 0.9 cm and 2.1 cm.

The ambient light is generated by ten 20W halogen lamps, powered by an external regulated 12V DC power supply.

Last, we designed an item called *s-toy* (see Fig. 5b) that can be used either as object to be retrieved or as a landmark to localize a target location. The overall weight of the *s-toy* can easily be changed in the range of 1 to 3 kilograms. The *s-toy* has the same external ring as the *s-bots*, so that *swarm-bots* can connect to it. Its ring can change color in the same way as in the *s-bots* (red, green, blue and various combination). The central turret (which can be removed and was not used in some of the experiments presented in this

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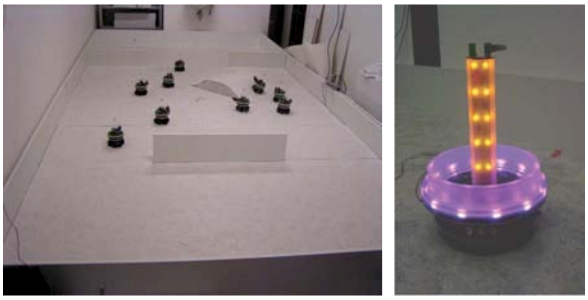
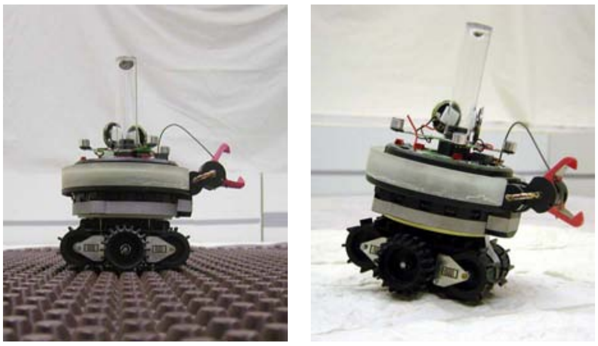
[1] At the time of writing a porting of the simulator in the open source ODE environment was nearly completed.



(a) (b)

Figure 5. (a) The experimental arena with nine *s-bots* and some obstacles. (b) The *s-toy*.



(a) (b)

Figure 6. (a) An *s-bot* moving on the brown rough terrain. (b) An *s-bot* moving on the white rough terrain.

paper) has two different color LEDs (green and red). The external diameter is 20 cm, the height 30 cm. The *s-toys* can also emit sounds that might be used by *s-bots* to localize them.

4. AN OVERVIEW OF THE EXPERIMENTAL RESULTS

Over the course of the project we developed various controllers for the *s-bots*. These controllers were designed to enable the *s-bots* to perform tasks in the context of the experimental scenario described above. In this section we briefly summarize our methods and results.

To act successfully in the scenario, the *s-bots* must be equipped with controllers that allow them to successfully navigate in a totally or partially unknown environment in order to find an object and retrieve it to a target location. The *s-bots* must also be capable of self-assembling into a *swarm-bot* formation. The *swarm-bot* might be necessary to pass over a hole larger than a single *s-bot*, or to retrieve objects that can not be transported by a single *s-bot*. Finally, a group of *s-bots* should be capable of adaptively allocating resources to different tasks to be carried out either sequentially or in parallel. For example, if two heavy objects must be transported, a group of *s-bots* must be capable of splitting into two sub-groups each of which formed by the number of *s-bots* appropriately chosen with respect to the nature of the object the group aims to transport.

The methodology that we followed to develop the *s-bots* controllers has been to first split the overall scenario in a number of tasks and then to either design or evolve the basic behaviors that allow the *s-bots* to solve these tasks. Once this done, we have hand-written simple behavior arbitration mechanisms that allocate the *s-bots* control to the different behaviors as necessary. Most of the choices involved (e.g., how to split the overall scenario in basic behaviors, whether to design or to evolve them, how to select which behavior should be active at a given moment) have been made following a very pragmatic approach. For example, an attempt to design controllers for the different basic behaviors has always been done, and the choice of resorting to evolved neural nets was taken whenever it was not easy to produce an efficient controller by hand-coding.

Another important decision has been to let, for each basic behavior, all the *s-bots* be controlled by the same program. In other words, we work with homogeneous swarms of *s-bots* which can switch from one behavior to another.

In the following subsections, we give a high level overview of our research activities and of the results obtained pertaining to the development of the basic behavioral capabilities above mentioned. Ongoing research is discussed in the subsequent section.

4.1. Coordinated motion

Coordinated motion is a basic ability required of a *swarm-bot*. To allow the *swarm-bot* to move, the constituent *s-bots* must coordinate their actions to choose a common direction of motion. This coordination is not self-evident, as each *s-bot* is controlled independently. The required coordination is achieved primarily through use of the *s-bot*'s traction sensor, which is placed at the turret-chassis junction of an *s-bot*. The traction sensor returns the direction (i.e., the angle with respect to the chassis' orientation) and the intensity of the force of traction (henceforth called "traction") that the turret exerts on the chassis. Traction results from the movements of the *s-bot*'s own chassis as well as the movements of other *s-bots* connected to it. Note that the turret of each *s-bot* physically integrates the forces that are applied to the *s-bot* by the other *s-bots*. As a consequence, the traction sensor provides the *s-bot* with an indication of the average direction toward which the group as a whole is trying to move. More precisely, it measures the mismatch between the direction in which the *s-bot*'s own chassis is trying to move and the direction in which the whole group is trying to move.

Our experimental work has focused on the evolution of artificial neural networks capable of controlling the behavior of a *swarm-bot* in a coordinated manner. In this kind of experiments, the problem that the *s-bots* have to solve is that their traction systems (wheels plus tracks) might have different initial directions or might mismatch while moving. In order to coordinate, *s-bots* should be able to collectively choose a common direction of movement whilst only having access to local information. Each *s-bot*'s controller (i.e., an artificial neural network) takes as input the readings of its traction sensor and as output sets the status of the *s-bot*'s actuators.

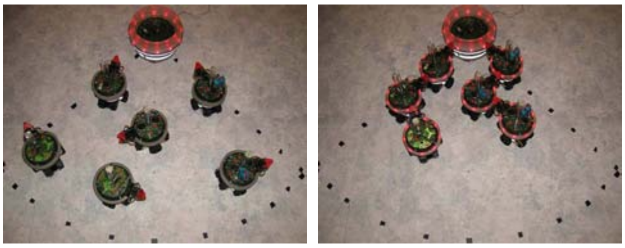
The results obtained show that evolution can find simple and effective solutions that allow the *s-bots* to move in a coordinated way independently of the topology of the *swarm-bot*. Moreover, it was found that the evolved *s-bot* controllers also exhibit obstacle avoidance behavior (when placed in an environment with obstacles), and scale well to *swarm-bots* of a larger size (see [1, 4] for details). Additionally, they are robust to environmental changes such as varying terrain roughness or presence of moderately sized holes (i.e., holes too big for a single *s-bot*, but small enough to be passed over by the *swarm-bot* itself; e.g., see Fig. 7).

Building on the coordinated motion behavior, we were also able to synthesize controllers that allow the *s-bots* in *swarm-bot* formation to sense the presence of big holes and avoid them [21, 20, 24].

Figure 7. A *swarm-bot* composed of four *s-bots* in square formation passing over a trough.

4.2. Self-assembly

Probably the most characteristic capacity of the *swarm-bot* system is that it can self-assemble; that is, move from a situation characterized by the activity of a number $n > 1$ of *s-bots* to a situation in which these n *s-bots* physically connect to each other to form a *swarm-bot*. To develop controllers capable of letting *s-bots* self-assemble we used a perceptron-type neural network whose weights were evolved using an evolutionary algorithm (for more details see [7, 10]). These controllers were synthesized in simulation using up to 5 simulated *s-bots* and then ported to the real *s-bots*. In short, self-assembly works as follows. The start of the process is triggered by the presence of an *s-bot* which turns on its red lights. The *s-bots* which are closer to the red *s-bot* perceive the red light and approach it until they are close enough to connect by grasping the red *s-bot* ring with their gripper. If the connection is successful, they turn their red lights on so as to attract other *s-bots*. If an *s-bot* encounters difficulties during the approach phase, it launches a recovery procedure which consists of the *s-bot* moving backward and approaching the red *s-bot* again. Experiments have shown that this procedure can reliably control the *s-bots* so that they connect to each other or to an *s-toy* with red lights turned on (e.g., see Fig. 8). The procedure is scalable, as it works for increasing numbers of *s-bots* (experiments with up to 16 *s-bots* were run successfully), and robust, as it can control self-assembling *s-bots* moving on both flat and moderately rough terrain (see Fig. 6).



(a) (b)

Figure 8. (a) Six *s-bots* at the start of a self-assembling experiment on flat terrain. (b) Two self-assembled *swarm-bot*, each comprised of three *s-bots*, connected to the *s-toy*.

4.3. Cooperative transport

Artificial neural networks were designed by artificial evolution to control the actions of a group of *s-bots* whose task was to pull and/or push a heavy object in an arbitrarily chosen direction. In this case, the *s-bots* could only interact through their physical embodiment to coordinate their actions during the approach and transport phase [9]. In a second study, we designed artificial neural networks to control a group of *s-bots* that had first to connect to the object and then transport it towards a target location. The best of the evolved controllers efficiently transported the object as required. Furthermore, these controllers proved robust with respect to variations in the size and shape of the object they had to transport [8].

We also studied [10] the situation in which some *s-bots* were able to locate the transport target, while the others (called *blind s-bots*) were not. To enable a blind *s-bot* to contribute to the group's performance, it was equipped both with sensors to perceive whether or not it was moving and sensors to detect the traction forces acting between its turret and its chassis. For group sizes ranging from 2 to 16, it was shown, in simulation, that blind *s-bots* make an essential contribution to the group's performance.

The controllers for cooperative transport have been ported and validated on the real *s-bots*, using groups of up to 6 *s-bots* (e.g., see Fig. 9). In the experiments involving blind *s-bots*, it was verified that the blind *s-bots* do not behave disruptively. On the contrary, it was shown that they can make an essential contribution to the performance of the group. The same controllers also proved successful at transporting the object over various types of rough terrain. Furthermore, the controllers also enabled the *swarm-bot* to navigate over terrain with holes in it. (Some of these holes were sufficiently large that they defeated even a chain of two *s-bots*.)

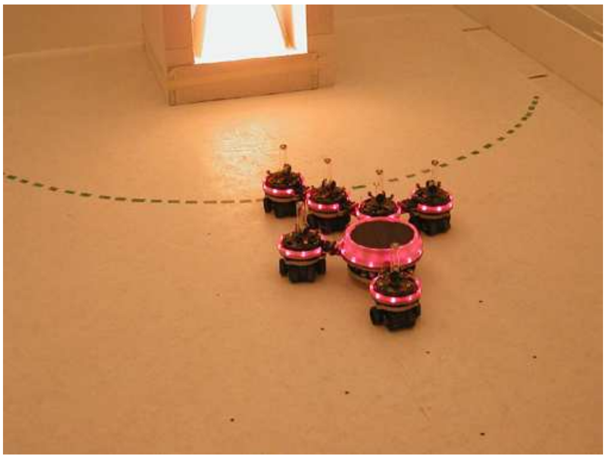


Figure 9. Six *s-bots*, four of which forming a *swarm-bot*, are transporting the *s-toy* towards the target location.

4.4. Exploration and path formation

S-bots have rather limited visual capabilities and can perceive colored objects at a maximum distance of 40 cm. In order to be able to retrieve an object they first have to find it. Then, in order to facilitate the retrieval task, they build a path connecting the object to the target location. This path can be exploited by other *s-bots* or by a *swarm-bot* to find the way to the object and then back to the target location.

The approach we have followed in our research is inspired by the path formation behavior of ants (for a somehow related approach see [18]). Ants deposit pheromones on the ground while walking and this gives raise to paths shared at the colony level. As our *s-bots* cannot deposit pheromones, they build visual paths as follows. They start from the target location identified by a blue *s-toy* and randomly explore the space around it. When they reach a maximum distance (given by a parameter) from the *s-toy* they become beacons of the forming visual path. This means they stop moving and turn on their light. Other *s-bots* continue the random search around the beacon and can become beacons themselves extending in this way the visual path. The direction of growth of the visual path is therefore random and is not guaranteed to reach the object to be retrieved. However, visual paths under formation have some probability of dissolving (given by another parameter of the visual path formation procedure) and therefore unsuccessful searches (that is, incomplete visual paths that do not reach the object to be retrieved) can restart until a complete visual path is constructed. Once this stochastic procedure finds a visual path connecting the target location to the object to be retrieved, the visual path can be exploited by the *s-bots* to reach the *s-toy* and then to retrieve it (see Fig. 10). The main advantage of this exploration strategy is that it relies on local information and simple rules and does not require the *s-bots* to create a map-like representation of the world (more details can be found in [17]; the original algorithmic idea was proposed in [6] where it was tested in simulation).

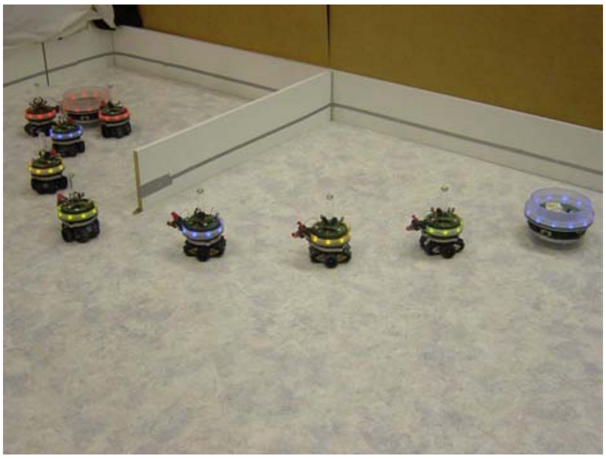


Figure 10. A chain of five *s-bots* connect the red object on the left to the target location (represented by the blue *s-toy* on the right). Two *s-bots* have reached the red object and are preparing to transport it to the target location.

To implement the exploration and path formation strategy we have employed a behavior-based approach. We have shown that by varying parameters of the *s-bots* controller it is possible to generate a variety of exploration strategies. Different strategies are better adapted to particular environments. In particular, we have implemented two strategies.

In the simpler one, we have static visual paths: the *s-bots* beacons do not move. In the other setup, the *s-bots* that form a visual path move in a coordinated way without breaking the path. The controllers developed in simulation have been ported successfully on the real *s-bots*. In the experimental scenario setup described in Section 3, real *s-bots* were able to find the object and build a chain connecting it to the target location. The time required to build the chain is a function of the complexity of the environment and in particular depends on the presence, or absence, of obstacles.

4.5. The whole scenario

As a last step, we run experiments in which all the components described above, coordinated motion on rough terrain, hole and obstacle avoidance, self-assembling, cooperative transport and environment exploration and path formation, were executed by a group of up to 18 *s-bots* (video recordings of these experiments are available on-line at `www.swarm-bots.org`). These experiments were very successful and make our work the current state-of-the-art in swarm robotics. However, there are still many challenges facing designers of swarm robotic systems. Ongoing research on the *swarm-bot* platform is focused on two particular problem areas. The first problem is how to efficiently allocate tasks to different *s-bots*. The second problem is how to appropriately trigger the *s-bots*' self-assembling behavior. These two problems are discussed in the following sections.

5. ONGOING WORK

5.1. Adaptive task allocation

Task allocation and division of labour are two important research areas in collective and swarm robotics. Previous studies have shown that an increasing group size does not necessarily implies an increase in the efficiency with which a collective task is performed [19]. However, inherent inefficiency of large robot groups can be avoided if such large groups are equipped with an adaptive task allocation mechanism which distributes the resources of the group based on the nature of the task and the diversity among the individuals of the group. In our research we are obviously interested in designing an adaptive task allocation mechanism which allocates a sufficient number of *s-bots* to each task, without reducing the efficiency of the entire group. In particular, we have been working on a mechanism which adaptively tunes the number of active robots in a foraging task: that is, searching for objects and retrieving them to a nest location. The robots, controlled by a behavior-based architecture, use a simple adaptive mechanism which adjusts the probability of each robot being a forager based on the current success rate of the individual in carrying out the task. As a result of this simple adaptive mechanism, a self-organized task allocation is observed at the global level. That is, not all the robots end up being active foragers. The same mechanism is also effective in exploiting mechanical differences among the robots inducing specialization in the robots activities. More details are given in [12, 13].

5.2. Functional self-assembly

We call *functional self-assembly* the self-assembling into a *swarm-bot* of a group of *s-bots* triggered by environmental contingencies that prevent a single *s-bot* from performing a given task [22]. The term "functional" is motivated by the fact that the self-organized creation of a physically connected structure is a function of the particular task to be performed.

In a preliminary set of studies, we have focused on the evolution of neural controllers for self-assembling *s-bots* required to solve a simple scenario. In particular, we have investigated a scenario which requires the *s-bots* to approach a light source located at the end of a corridor. To get there the *s-bots* must traverse a zone in which they navigate more effectively if they self-assemble into a *swarm-bot*. So, when individual *s-bots* enter this zone, they should first aggregate (approach each other) and then assemble using their gripper element. This experimental setup allowed us to investigate the basic mechanisms that underpin functional self-assembly.

The results of our empirical work shows that integrated (i.e., not modularized) artificial neural networks can be successfully synthesized by evolutionary algorithms. *S-bots* equipped with the evolved controllers successfully displayed individual and collective obstacle avoidance, individual and collective photo-taxis, aggregation and self-assembling. To the best of our knowledge, these experiments represent one of the first works in which (i) functional self-assembling in a group of robots has been achieved and (ii) evolved neural controllers successfully cope with a complex scenario, producing different individual and collective responses. These responses, that consist of appropriate control of the state of various actuators, are triggered by local information coming from various sensors. More details on this research can be found in [23].

6. DISCUSSION

When given the task of building a robotic system, the main decisions to be taken by the research engineers concern the architecture of the hardware and of the control system. In this paper we have presented the results of a project directed at evaluating two particular choices. From the hardware point of view, we considered a robotic system comprised of many autonomous robots with the particularity that they can attach to (and detach from) each other so as to form bigger, physically connected structures. From the control point of view, we considered fully distributed controllers that exploit only local information. These choices are motivated by the desire of giving our robotic system, called a *swarm-bot*, characteristics of robustness and versatility,[2] as well as the ability to navigate rough terrain.

Our research, which falls between collective robotics and self-reconfigurable robotics, is loosely bio-inspired, in the sense that many of our choices and techniques have as inspiration some natural process or biological observation. However, we do not try to replicate faithfully any of the inspiring principles: we are content to take our inspiration from natural processes and let these principles guide our engineering choices.

As in collective robotics, we are concerned with the performance of groups of cooperating robots. Unlike collective robotics, however, we are interested in the study of self-assembling structures and in their exploitation for the solution of problems for which cooperation through physical connection is a necessity.

As in self-reconfigurable robotics, we study robotic structures (i.e., *swarm-bot*s) that can change their shape as a function of the task they are performing. Unlike self-reconfigurable robotics, however, the units composing our self-reconfigurable robot are autonomous units that can perform tasks independently of each other or in cooperation, as required by the particular task considered.

7. CONCLUSIONS

In this paper we have illustrated the most important features of a novel robot concept, called a *swarm-bot*. A *swarm-bot* is a self-organising, self-assembling artifact composed of a variable number of autonomous units, called *s-bots*. As illustrated in Section 2, each *s-bot* is a fully autonomous robot capable of displacement, sensing and acting based on local information. Moreover, the self-assembling ability of the *s-bots* enables a group of them to execute tasks that are beyond the capabilities of the single *s-bot*.

Hardware versatility and robustness is ensured by the presence of many autonomous entities which can assemble into a single body and disassemble back into disparate elements as required. Because of this self-assembly/disassembly capability, supported by a great number of sensors and actuators, the *swarm-bot* is more versatile than other robotic systems composed of small elementary units capable of reconfiguring themselves (see [3, 5, 11, 16, 25]).

In the development of the *s-bot* controllers, extensive use was made of artificial neural networks shaped by evolutionary algorithms. The solutions found by evolution are simple and in many cases generalize to different environmental situations. This demonstrates that artificial evolution is able to produce a self-organized system that relies on simple and general rules, a system that is consequently robust to environmental changes and that scales well with increasing numbers of *s-bots*.

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[2] By saying that a robot is versatile we mean that it is capable of dynamically changing shape and control functionality depending on the situation it faces.

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