The SWARM-BOTS project

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Abstract. This paper provides an overview of the SWARM-BOTS project, a robotic project sponsored by the Future and Emerging Technologies program of the European Community (IST-2000-31010). The paper illustrates the robot hardware, and the results of experimental works in which distributed adaptive controllers are designed to allow the agents to perform a variety of tasks which require cooperation and coordination among the members of a group.

1 Vision

This paper introduces and illustrates the theoretical underpinning and the research agenda of the SWARM-BOTS project, a robotic project sponsored by the Future and Emerging Technologies program of the European Community (IST-2000-31010). The aim of this project is the development of a new robotic system, called a *swarm-bot*, based on *swarm robotics* techniques.

Swarm robotics is an emergent field of collective robotics that studies robotic systems composed of *swarms* of robots tightly interacting and cooperating to reach their goals [5]. Swarm robotics finds its theoretical roots in recent studies in animal societies, such as ants and bees. Social insects are a valuable source of inspiration for designing collectively intelligent systems comprised of a number of agents. Despite noise in the environment, errors in processing information and performing tasks, and no global information, social insects are quite successful at performing group-level tasks. Based on the social insect metaphor, swarm robotics emphasizes aspects such as decentralization of the control, limited communication abilities among robots, use of local information, emergence of global behaviour and robustness [3].

The work carried out within the SWARM-BOTS project is directly inspired by the collective behaviour of social insects colonies and other animal societies, and in particular it focuses on the study of the mechanisms which govern the processes of *self-organisation* and *self-assembling* in artificial autonomous agents. In order to pursue these objectives, a new type of robot, referred to as *s-bot*, has been developed. Hardware development runs in parallel with the development of distributed adaptive architectures that make the *s-bots* capable of autonomously carrying out individual and collective behaviour by exploiting local interactions among the *s-bots* and between the *s-bots* and their environment.

The *s-bots* are mobile robots with the ability to connect to and to disconnect from each other [15,13]. A *swarm-bot* is defined as an artifact composed of a swarm of assembled *s-bots* (see Figure 1). *S-bots* have relatively simple sensors and motors and limited computational capabilities. Their physical links are used to assemble into a *swarm-bot* able to solve problems that cannot be solved by a single *s-bot*. In the *swarm-bot* form, the *s-bots* are attached to each other and, when needed, become a single robotic system that can move and reconfigure. Physical connections between *s-bots* are essential for solving many collective tasks. For example, *s-bots* can form pulling chains to retrieve a heavy object. Also, during navigation on rough terrain, physical links can serve as support if the *swarm-bot* has to pass over a hole larger than a single *s-bot* (see Figure 1 right), or when it has to pass through a steep concave region. However, for tasks such as searching for a goal location or tracing an optimal path to a goal, a swarm of unconnected *s-bots* can be more efficient.

The design and realisation of both the hardware and the software of such a robotic system represents the scientific challenge of the SWARM-BOTS project.

Fig. 1. Graphic visualization of how the rigid gripper can be used to connect in a secure way *s-bots* among themselves so to form a *swarm-bot* for overcoming large obstacles or holes.

In what follows, we first give a brief description of the robot hardware, and of the experimental methodology employed to develop the *s-bots* controllers (see section 2). Then, in section 3 we describe the results of several experiments in which controllers have been designed to allow the *s-bots* to autonomously perform a variety of individual and collective behaviours in partially or totally unknown environments. Discussion and conclusions are drawn in section 4.

2 The hardware and the simulation environment

The construction of a number of artifacts (30-35) capable of self-assembling and self-organizing represents one of the most significant scientific challenges faced by the SWARM-BOTS project. In subsection 2.1, we briefly describe the hardware of the *s-bots*, with particular reference to its sensor and motor apparatus. A more detailed description of the hardware components can be found in [14]. In subsection 2.2, we briefly introduce the main features of swarmbot3d, a simulation environment employed to design the software which controls the *s-bots*[6].

2.1 The *s-bot*

An *s-bot* is the basic elementary unit of the *swarm-bot* (see Figure 2). Each *s-bot* 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* is able to communicate with other *s-bots* and physically connect to them, thus forming a so-called *swarm-bot*. A *swarm-bot* is able to perform tasks in which a single *s-bot* has major problems, such

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[6] Details regarding the hardware and simulation of the *swarm-bot* can also be found on the project web-site (www.swarm-bots.org).

Fig. 2. Graphic visualization of the *s-bot* concept. The main body (turret) is equipped with passive and active gripping facilities, sensors and electronics. The lower body (traction system) is equipped with tracks and hosts the batteries. The diameter of the main body is 116 mm.

as exploration, navigation, and transportation of heavy objects on very rough terrain.

As far as it concerns the mobility of the *s-bot*, an innovative system has been developed which makes use of both tracks and wheels as illustrated in Figure 2. Wheel and track on a same side are driven by the same motor, building a differential drive system controlled by two motors. This combination of tracks and wheels is labeled *Differential Treels*© *Drive*[7]. Such a combination has two advantages. First, it allows an efficient rotation on the spot due to the larger diameter and position of the wheels. Second, it gives to the traction system a shape close to the cylindrical one of the main body (turret), avoiding in this way the typical rectangular shape of simple tracks and thus improving the *s-bot* mobility.

The *s-bot*'s traction system can rotate with respect to the main body by means of a motorised axis. Above the traction system, a rotating turret holds many sensory systems and the 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 and humidity 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 omni-directional camera, colour LEDs all around the robot, local colour detectors, 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, efforts, 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 forces exerted on the *s-bots* body and/or chassis through the hinge joint.

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 Figure 2). 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 servo-motors.

2.2 The simulation environment: swarmbot3d

Swarmbot3d is a 3D dynamics simulator of our multi-agent system of cooperating robots, based on the SDK Vortex™ toolkit (Critical Mass Labs, Canada), which provides realistic simulations of dynamics and collisions of rigid bodies in 3D. Swarmbot3d provides *s-bot* models with the functionalities available on the real *s-bots* (see [14] for details). It can simulate different sensor devices such as IR proximity sensors, an omni-directional camera, an inclinometer, sound, and light sensors.

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[7] Treels is a contraction of TRacks and whEELS

A fundamental feature of the swarmbot3d simulator is that it provides robot simulation modules at different levels of detail. In particular, it provides a hierarchy of four *s-bot* reference models with increasing levels of detail. The less detailed models have been 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 on real hardware. The advantages of such a simulation environment are multiple: it works as an aiding tool for accurately predicting 3D kinematics and dynamics of a single *s-bot* in a *swarm-bot*; it has been employed to evaluate possible new options for hardware parts; it represents a "plastic" world model which allows the design of new experimental set-ups in 3D; it has been employed to quickly evaluate new distributed control ideas before porting them to the real hardware. Furthermore, the simulator provides on-line interactive control during simulation, useful for rapid prototyping of new control algorithms. Swarmbot3d allows to handle a group of robots either as independent units or in a *swarm-bot* configuration, which can be thought of as a graph, in which each node represents a connected *s-bot*. The connections can be created and released dynamically at simulation time. Connections may be of a rigid nature giving to the resulting structure the solidity of a whole entity.

3 Results

In this section, we briefly summarise the methods and the results of experimental work in which controllers have been designed to allow the *s-bots* to autonomously perform a variety of individual and collective behaviours in partially and totally unknown environments. These basic behaviours represent different lines of investigation which are pursued in parallel, and are focused on: 1) aggregation; 2) co-ordinated motion; 3) collective and co-operative transport of a prey item; 4) exploration; 5) adaptive task allocation; 6) navigation on rough terrain; 7) functional self-assembling. These research lines have been identified by looking at the kind of requirements that either a single *s-bot* or an aggregation of *s-bots* must fulfill in order to successfully perform the tasks involved in a complex scenario. The latter requires a swarm of up to 35 *s-bots* to transport heavy objects from their initial location to a goal location in an environment which presents difficulties of various nature, such as obstacles and holes on the ground. Moreover, the weight and/or size of the objects to be transported are such that these objects can not be transported by a single *s-bot* (see Figure 3).

To be capable of accomplishing 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 and retrieve a target. The *s-bots* must also be capable of aggregating and self-assembling in a *swarm-bot* formation. The *swarm-bot* might be of fundamental importance for passing 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 following subsections illustrate the research activities concerning the development of the basic behavioural capabilities above mentioned.

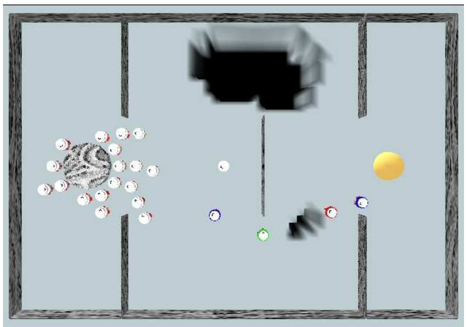

Fig. 3. The scenario: a swarm of up to 35 *s-bots* must transport a heavy object from an initial to a goal location. The cylinder on the left side represents the object to be transported; the landmark on the right side represents the target location where the object has to be transported. The four *s-bots* between the cylindrical object and the target location form a path which logically connects the former to the later. 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.

3.1 Aggregation

Within the SWARM-BOTS project, aggregation is of particular interest since it stands as a prerequisite for other forms of cooperation. For instance, in order to assemble into a *swarm-bot*, *s-bots* should first be able to aggregate. Several experiments have focused on the design of scalable aggregation behaviours by means of sound signaling (see [2,16] for details). Artificial neural networks shaped by evolutionary algorithms control the behaviour of a homogeneous group of *s-bots* (i.e., within a group, all the *s-bots* share the same controller). During the evolutionary phase, the groups are randomly placed in a square arena. The agents are equipped with a simulated speaker that can emit a tone for long range signaling. *S-bots* can perceive the intensity of sound using three sound sensors that simulate three directional microphones. The *s-bot* controller takes as input the state of the *s-bot* proximity sensors, and the state of the sound sensors. Two output nodes control the *s-bot*'s motors. Controllers that exploit sound to let a group of *s-bots* aggregate are evolved using a fitness function that selectively rewards those groups which minimise the average distance of all the *s-bots* from the group center of mass.

The evolved controllers show quite robust aggregation strategies. In particular, the *s-bots* exploit the sound signal both to get closer to each other, and to remain aggregated. In general, all evolved strategies rely on a delicate balance between attraction to sound sources and repulsion from obstacles, the former being perceived by sound sensors, the latter by proximity sensors. A qualitative analysis of the evolved controllers reveals that different replications result in slightly different behaviours. In particular, the evolved solutions differ mainly in the behaviour of *s-bots* when they are close to each other.

Further evaluation tests concerning scalability of the evolved solution, have shown that controllers evolved for groups of four *s-bots* can successfully bring forth aggregation in groups with a higher number of *s-bots* (up to 40 *s-bots*). The best scalable strategy was the one in which the controller creates an aggregate that moves across the arena. This is a result of the complex motion of *s-bots* within the aggregate, which in turn is the result of the interaction between attraction to sound sources and repulsion from obstacles. The slow motion of the aggregate across the arena leads to scalability, as an aggregate can continue to move joining solitary *s-bots* or other already formed aggregates, eventually forming a single cluster of *s-bots*.

3.2 Co-ordinated motion

Coordinated motion represents another basic ability for a *swarm-bot* formed of connected *s-bots* that, being independent in their control, must coordinate their actions to choose a common direction of motion. The coordinated motion ability is essential for an efficient motion of the *swarm-bot* as a whole. Our experimental work has focused on the evolution of artificial neural networks capable of coordinately controlling the behaviour of a *swarm-bot* (a collection of assembled *s-bots*). In this kind of experiments, the problem that the *s-bots* have to solve is

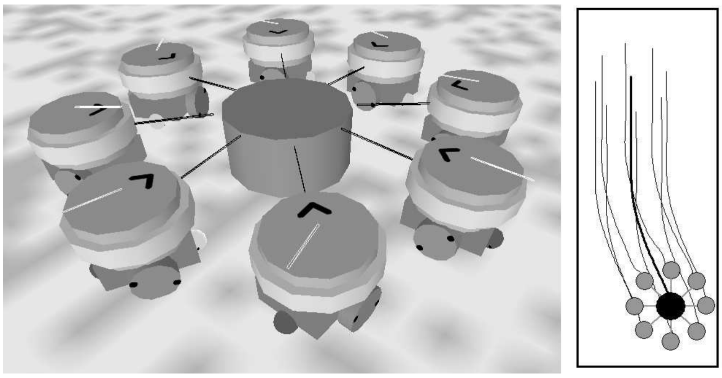
(a) (b)

Fig. 4. (a) Eight *s-bots* connected to an object through rigid links. (b) Traces left by the *s-bots* (thin lines) and the object (thick line) during 150 simulation cycles. The gray and black circles represent the initial positions of the *s-bots* and of the object.

that their wheels 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 having access only to local information.

The results show that evolution can find simple and effective solutions that allow the *s-bots* to move in a coordinate way independently of the topology of the *swarm-bot* and of the type of link with which the *s-bots* are connected (flexible or rigid). Moreover, it is shown that the evolved *s-bots* also exhibit obstacle avoidance behaviour (when placed in an environment with obstacles) and object pulling/pushing behaviour (when assembled to or around an object, see Figure 4), and scale well to *swarm-bots* of a larger size (see [1,6] for details).

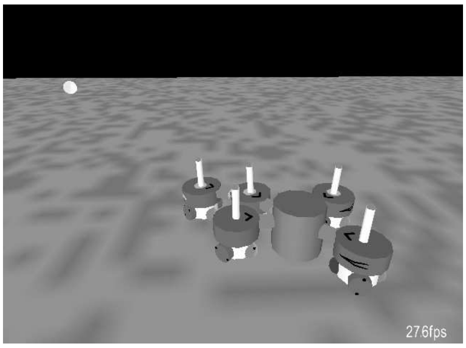

Fig. 5. These pictures show *s-bots* connected to each other and to an object.

3.3 Collective and co-operative transport of a prey item

By taking inspiration from the behaviour of ants, the SWARM-BOTS project aims to build autonomous agents which by solely relying on local information, are capable of cooperatively and collectively carrying objects which can not be moved by a single agent. The members of a group have to coordinate their actions to achieve the desired outcome. In particular, due to the nature of the object (i.e., its shape, dimension, and weight) the *s-bots* might be required to connect to each other in *swarm-bot* formation and/or to the object itself for transporting it (i.e, gripping the object with the fixed gripper, see Figure 5).

In a preliminary series of experimental work, artificial neural networks have been evolved to control the actions of a single homogeneous group of *s-bots* which is required to pull and/or push an object in an arbitrarily chosen direction. During the evolutionary phase, the *s-bots* are located in a boundless arena, in the proximity of objects of various shape, dimension, and weight. Only indirect communication through the environment can be exploited to attain coordination. The evolved controllers exhibit rather good transport performances. Certain controllers show scaling properties: they can be applied to larger groups of *s-bots* to move bigger and heavier prey objects. However, the controllers' performances are very sensitive to the size of the prey (see [8]).

A follow-up work focused on the self-organization of *s-bots* into assembled structures and the transport of heavy prey by groups of assembled *s-bots* to a target. To facilitate the process of assembling, the *s-bots* are provided with the ability to detect team mates; in addition, the presence of assembled structures is favoured by the fitness function employed. The best evolved controller proved fairly robust with respect to different combinations of size and shape of the prey (see [7]).

Recently the situation has been studied in which some *s-bots* are given the opportunity to localize the transport target, while the others (called the *blind* ones) are not. To enable a blind *s-bot* to contribute to the group's performance, it has been equipped with sensors to perceive both whether or not it is moving, and traction forces on its turret. For group sizes ranging from 2 to 16, it is shown that blind *s-bots* make an essential contribution to the group's performance. For the best evolved solution the performance scales well with group size, making possible the transport of heavier prey by larger swarms of blind and non-blind *s-bots* (see [9]).

3.4 Exploration

This subsection illustrates the mechanisms employed by the *s-bots* to efficiently explore a partially or totally unknown environment. Our approach is based on the exploitation of the collectivity, and it requires that some *s-bots*–referred to as *s-bot* beacon—should be capable of positioning themselves in the environment in order to work as beacons for other *s-bots*–referred to as *s-bot* explorer—that move back and forth from a starting position to a goal location. The *s-bot* beacons should form a chain which connects different locations that cannot be perceived both at the same time by a single *s-bot*. In this way, a path between a goal and a home location is established, and it can be subsequently exploited by the *s-bot* explorers. The main advantage of this exploration strategy, is that it does not require the s-bots to create a map-like representation of the world.

The status of these experiments, in which a behaviour-based approach is employed to design the *s-bots* controllers, is still preliminary. However, simply by varying two parameters of the *s-bots* controller (i.e., the probability of each single agent to become a beacon and the probability of a robot beacon to become an explorer) it is possible to bring forth a variety of exploration strategies each of which results more adaptive in certain types of environment than in others. Up to date, two different strategies have been implemented. In the simplest setup, we have static chains: the *s-bots* that form a chain do not move. In the other setup, the *s-bots* that form a chain move coordinately without breaking the chain. We are currently working on the development of an adaptive mechanism which autonomously sets these parameters with respect to the characteristics of the environment experienced by the *s-bots.*

3.5 Adaptive task allocation

Task allocation and division of labour are two important research areas within collective robotics. Previous studies have shown that small groups of robots might perform a collective task better or not worse than a larger group. However, this efficiency loss can be avoided if large groups of robots are equipped with an adaptive task allocation mechanism which distributes the resources of the group with respect to the nature of the task and the diversity among the individuals of the group. Within the SWARM-BOTS project we are obviously interested in designing an adaptive task allocation mechanism which allocates to each task a sufficient number of *s-bots* without reducing the efficiency of the entire group. In particular, we have been working on a mechanism which adaptively tunes the number of active agents in a foraging task: that is, searching for objects and retrieving them to a nest location. The agents, controlled by a behaviour-based architecture, use a simple adaptive mechanism which adjusts the probability of each agents to be a forager with respect to the current success rate of the individual on the task. Owing to this simple adaptive mechanism, a self-organized task allocation is observed at the global level. That is, not all the agents end up being active foragers. The same mechanism is also effective in exploiting mechanical differences among the robots inducing specialisation in the robots activities. More details are given in [11,12].

3.6 Navigation on rough terrain

Navigating on rough terrain is an important feature for an adaptive autonomous system, that can open many possible application scenarios, like space exploration or rescue in a collapsed building. Within the SWARM-BOTS project, several experiments have been run on an instance of the family of navigation on rough terrain tasks, that is, hole avoidance. A *swarm-bot* is required to perform coordinated motion in an environment that presents holes too large to be traversed. Thus, holes must be recognized and avoided, so that the swarm-bot does not fall into them. The difficulty in this task is twofold: first, *s-bots* should coordinate their motion. Second, *s-bots* have to recognize the presence of a hole, communicate it to the whole group and re-organize to choose a safer direction of motion. The results demonstrate that the evolved controllers (i.e., artificial neural networks) manage to efficiently manoeuvre a *swarm-bot* in the proximity of holes in the ground. Evolution is able to produce a self-organizing system that relies on simple and general rules, a system that is consequently robust to environmental changes and to the number of *s-bots* involved in the experiment. The evolved strategies strongly rely on the traction forces produced by those *s-bots* that feel the presence of a hazard (see [17] for details).

3.7 Functional self-assembling

These studies focus on the design of controllers for robots capable of physically connecting to each other, each time environmental contingencies prevent a single robot to achieve its goal (see [18] for details).

4 Discussion and conclusions

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

As far as it concerns the hardware, the presence of many of such autonomous entities that can self-assemble in a single body and disband any time the union is no longer required, makes the system extremely versatile and robust to failure. Contrary to the *swarm-bot*, other robotic systems composed of small elementary units capable of reconfiguring themselves are less versatile and less robust, due to the fact that each unit has no or very limited mobility, very limited sensing capabilities, and acts often under the control of a central unit (see [19,4,10]).

As far as it concerns the *s-bots*' controllers, we have developed them making an extensive use of artificial neural networks shaped by evolutionary algorithms. The solutions found by evolution are simple and in many cases they generalize to different environmental situation. This demonstrates that 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 the number of *s-bots* involved in the experiments.

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