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The SWARM-BOTS Project

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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 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, and we report on results of experiments in which a group of s-bots perform a variety of tasks which require self-assembling, physical cooperation and coordination among the robots.

1 Introduction

The main scientific objective of the SWARM-BOTS project is the study of novel ways of designing and implementing self-organising and self-assembling artifacts, 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 [**?**]. 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 lack of global information, social insects are quite successful in performing group-level tasks. Based on the social insect metaphor, swarm robotics emphasises aspects such as decentralisation of the control, limited communication abilities among robots, use of local information, emergence of global behaviour and robustness [**?**].

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 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, we have designed and built small robots, that we call *s-bots*, with a large number of sensors and motors, several communication channels and onboard processing power (see Fig. 1). Additionally, these robots are endowed with self-assembly 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 to reconfigure when needed. For example, it might have to adopt a different shape in order to go through a tunnel or overcome an obstacle.


(a) (b)

Figure 1: (a) An *s-bot* and a 1 Euro coin. (b) Front view of an *s-bot*.

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 monolithic modular 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, the main innovation is that a *swarm-bot* is the first example of complex artifact controlled exclusively by swarm intelligence techniques. Another important innovation is in the integration of swarm intelligence and evolutionary computation. In fact, we use swarm intelligence principles to guide the definition of building blocks for the design and implementation of our self-organising systems, and evolutionary computation principles to guide the development of our *s-bot* controllers.

2 S-bots and Swarm-bots

S-bots are the basic components of a *swarm-bot*. 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* can communicate with other *s-bots* and physically connect to them, thus forming a *swarm-bot*. 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 motorised 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, coloured 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.

Rigid connections between two *s-bots* or between an *s-bot* and an object can be established by a gripper mounted on a horizontal active axis (see Fig. 2). Such a gripper has a very large acceptance area allowing it to realize a secure grasp at any angle and, if necessary, to lift another *s-bot*. The *s-bot* gripper can grasp other *s-bots* on a T-shaped ring placed around the *s-bot* turret. If it is not completely closed, such a grasp lets the two joined robots free to move with respect to each other while navigating on a rough terrain. If the grasp is firm, the gripper ensures a very rigid connection which can even sustain the lifting up of another *s-bot*.

In order to develop the controllers for the *s-bots*, we have implemented a 3D dynamics simulator called Swarmbot3d, based on the SDK Vortex$^{\text{TM}}$ toolkit by Critical Mass Labs, Canada, which provides realistic simulations of dynamics and collisions of rigid bodies in 3 dimensions.[1] Swarmbot3d provides *s-bot* models with the functionalities available on the real *s-bots* (see [?] for details). 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.

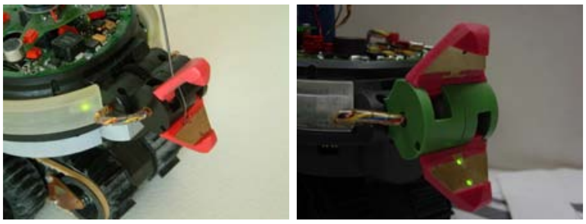

Figure 2: The *s-bot*'s rigid gripper.

3 An Overview of the Experimental Results

As a case study in which to test our design and implementation choices, we have defined the following experimental scenario (see Fig. 3): "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 $n > 1$."

To successfully carry out the scenario, the *s-bots* must be equipped with controllers that allow them to successfully navigate in a totally or partially unknown environment in or-

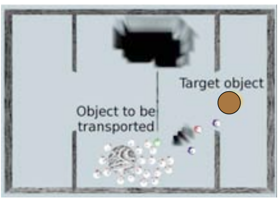

Figure 3: The scenario. The cylinder at the bottom represents the object to be transported; the landmark on the right represents the target location to which the object has to be transported. The three *s-bots* between the cylindrical object and the target location form a path which logically connects 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.

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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 4: (a) A *swarm-bot* made of 6 connected *s-bots*. (b) Six *s-bots* connected to an object to be transported.

der 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.

Over the course of this project we developed various controllers to allow the *s-bots* to successfully carry out all the tasks above mentioned. We now give, in the following subsections, a high level overview of our research activities and of the results obtained pertaining to the development of the basic behavioural capabilities above mentioned.

3.1 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, that is not self-evident as each *s-bot* is controlled independently, is achieved primarily through the use of the *s-bot*'s traction sensor, placed at the turret-chassis junction of an *s-bot*.

Our experimental work has focused on the evolution of artificial neural networks capable of controlling the behaviour 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 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 having access only 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 behaviour (when placed in an environment with obstacles), and scale well to *swarm-bots* of a larger size (see [**?**] for details). Additionally, they are robust to environmental changes such as varying terrain roughness or presence of moderately sized holes (see Fig. 4a).

Building on the coordinated motion behaviour, we were also able to synthesise controllers that allow the *s-bots* in *swarm-bot* formation to sense the presence of big holes or obstacles and avoid them [**?**].

3.2 Self-assembly and Cooperative Transport

The term self-assembly refers to the capability of the *s-bots* to autonomously connect to and disconnect from each other through some kind of device which makes the physical connections among the single robots possible. Self-assembly can enhance the efficiency of a group of autonomous cooperating robots in several different contexts. We focused on the study of self-assembly in relation to cooperative transport. The term cooperative transport describes the behavioural skills the *s-bots* need in order to transport objects that cannot be transported by a single robot, due to their mass, size, and shape. The *s-bots* have to exploit their self-assembling capabilities in order to connect to the object and to themselves in order to create a *swarm-bot* capable of achieving the task (see Fig. 4b). We designed artificial neural networks by artificial evolution to control the actions of a group of *s-bots* whose task was to approach, to connect to, and 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, the connection and the transport phase [**?**]. 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. We also studied [**?**] the situation in which some *s-bots* were able to locate the transport target, while the others (called *blind s-bots*) were not. 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, including terrains with holes.

3.3 Exploration and Path Formation

S-bots have rather limited visual capabilities and can perceive coloured 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 target to a starting location. This path is created by using the *s-bots* themselves as beacons; that is, the *s-bots* function as landmarks in order to form a chain from a starting location to a target. The path can be exploited by other *s-bots* or by a *swarm-bot* to find the way to the target and then back to the starting location. 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 [**?**]).

Each *s-bot* is controlled by a behaviour-based architecture. The *s-bot* can be in three different states: i) explorer, when the robot navigates along a chain to explore the environment; ii) chain member, when the robot is part of a chain; and iii) lost, when the robot has lost contact with a chain or with other robots. The state of a robot is determined by its state during the last time step and by its current perceptions. Transitions between states are triggered by probabilistic events and local perceptions. Three different control strategies were implemented and analysed. The first was the static strategy, in which a robot remains still once aggregated into a chain. The second was the aligning strategy, in which the members of a chain adjust their position in order to reach a certain distance and angle with respect to their neighbours, resulting in the alignment of the chain. The third was the moving strategy, which results in the collective movement of chains led by the last member of each chain.

3.4 The Whole Scenario

As a last step, we ran experiments in which all the components described above, coordinated motion on rough terrain, hole and obstacle avoidance, self-assembly, 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 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* (see [**?**]). The second problem is how to appropriately trigger the *s-bots*' self-assembly behaviour (see [**?**, **?**]).

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