SWARM-BOT: A New Concept of Robust All-Terrain Mobile Robotic System

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Technical report

I2S - LSA - STI
Swiss Federal Institute of Technology, Lausanne, Switzerland

March 2002

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Abstract

This paper presents a new robotic concept, called SWARM-BOT, based on a swarm of autonomous mobile robots with self-assembling capabilities. This concept has been developed to ensure robust navigation, search and transportation in rough terrain. The SWARM-BOT concept takes advantage from collective and distributed approaches to ensure robustness to failures and to hard environment conditions. SWARM-BOT is provided with self-assembling and self-reconfiguring capabilities: each robot is able to connect and disconnect to another one building large flexible structures. This type of structure is designed to face all-terrain conditions in a very efficient way. This paper introduces the SWARM-BOT concept from a mechatronic prospective.

1 Introduction

Applications like semi-automatic space exploration [22], rescue [5] or underwater exploration [1] need robust all-terrain robotic systems. Most of these applications combine all-terrain exploration and navigation. Some of them can include transportation as well. Very few existing systems deal explicitly with all these aspects taking into consideration robustness and rugged terrain conditions. Most of the existing systems deal only with one of these two constraints or with part of the problem.

1.1 Robustness

Robustness, in the sense of tolerance to hard conditions or even partial failures, is mainly addressed by decentralized collective robotics. The classical example is fault tolerance in case of loss of part of the system. Multi-robot systems are affected only partially by this type of failure, ensuring the global success of the task at the population level [17][12]. Collective robotics is robust also in the sense that it can be used in situations where a single robot cannot achieve the entire task or reports worse performance. A good example of this type of situation is given by Hayes et al. [13] where plume tracing is performed using a swarm of robots equipped with odor sensors. Transport [8], sorting [7] or structure building [4] are also typical tasks where collective robotics, taking inspiration from social insects behaviour[3], is very efficient and robust. Collective robotics becomes especially interesting when the executed task goes behind the capabilities of the single robot, as illustrated in experiments where robots are asked to extract from the floor sticks that are buried deeper than the operating range of their gripper [14]. This property permits to achieve a task by many simpler robots, where each robot is more robust because of the simplicity of its design.

1.2 All-terrain navigation

Navigation in rough terrain conditions is mainly addressed with rover structures and self-reconfigurable robots. Good examples of rover development are the shrimp robot [11], the family of space exploration robots by ESA [22], the *pathfinder* rover used on Mars [19] as well as other specific rovers for missions like volcano explorations [2]. This type of research is mainly focussed on mechanical structures and their ability to pass obstacles. Even if most of these rovers are remotely controlled, research aims also at developing sensors for all-terrain applications (for instance [21]). In all these research activities, robustness, if addressed, is limited to failures of the algorithm or to hard environmental conditions. There are no rovers capable of dealing with partial hardware failures.
Some researchers consider multiple rovers for all-terrain exploration [6][10] with the goal of obtaining a more robust system. Nobody is trying to take ad-

vantage of the collective aspect for obstacle climbing.

Research in self-reconfigurable robots addresses the same problem in a totally different way, building modular systems that are flexible and can change shape depending on the environment. The best performing self-reconfigurable 3D robots are MTRAN [15] and PolyBot [9] (for an overview of existing systems and characteristics see [15]). Both claim to be robust, in the sense of tolerance to hard all-terrain conditions. The possibility to change configuration (from track to spider to snake to legged robot) helps clearly to deal with very different environmental conditions. However both systems include very few sensors, which are mainly used for sensing the state of the robot itself rather than the environment. They are therefore not yet ready to perform autonomous navigation. Moreover, both MTRAN and PolyBot have centralized control algorithms. The central control, in comparison to a decentralized one, has reduced robustness to failures and exploits only partially the hardware modularity.
The only 3D self-reconfigurable robot with decentralised control is actually the CONRO hardware with decentralized control from Støy et al. [20] or by Salemi et al. [18]. Despite some hardware weakness and difficulties in reconfiguring its shape, modules can be manually changed of place while the system is running and each module autonomously readapts its behavioural role in the system.

No research is done on the combination of collective robotics with self-reconfiguring features, resulting in a self-assembling system based on a swarm of robots. This is the aim of the SWARM-BOTS project presented in the next section.

2 The SWARM-BOT concept

The objective of the SWARM-BOTS project is to study a novel approach to the design, hardware implementation, test and use of self-assembling, self-organising, metamorphic robotic systems called *swarm-bots*. This approach finds its theoretical roots in recent studies in swarm intelligence, i.e., in studies of the self-organising and self-assembling capabilities shown by social insects and other animal societies.

An important part of the project consists in the physical construction of at least one swarm-bot, that is, a self-assembling and self-organising robot colony composed of a number (30-35) of smaller devices, called *s-bots*. Each s-bot is a fully autonomous mobile robot capable of performing basic tasks such as autonomous navigation, perception of the environment and grasping of objects. In addition to these features, an s-bot is able to communicate with other s-bots and physically connect to them in flexible ways, thus forming a swarm-bot. The swarm-bot is able to perform exploration, navigation and transport of heavy objects in very rough terrain, where a single s-bot has major problems to achieve the task. This hardware structure is combined with a distributed adaptive control architecture inspired upon ant colony behaviors.

This concept address directly and simultaneously the two aspects mentioned in the introduction, that is, robustness and all-terrain navigation. The algorithmic robustness exploited by collective robotics is extended here to the physical level by allowing s-bots to self-assemble into a swarm-bot. The collective robustness can therefore be used to climb obstacles and transport objects that are not feasible for a single robot. This gives a swarm-bot a clear advantage over existing collective robotic systems in all-terrain conditions. Furthermore, distributed hardware and control gives an advantage over classical rovers and self-reconfigurable robots, permitting better flexibility and robustness in all-terrain conditions.

In the next sub-sections we present some details of the concept. The swarm-bot built for this project is also a research platform for distributed algorithm applied to self-assembling robots. It has therefore to satisfy some major requirements of monitoring during experiments, flexibility, and reliability.

2.1 Mechanical concept

The mechanical concept of an s-bot is presented in figure 1.

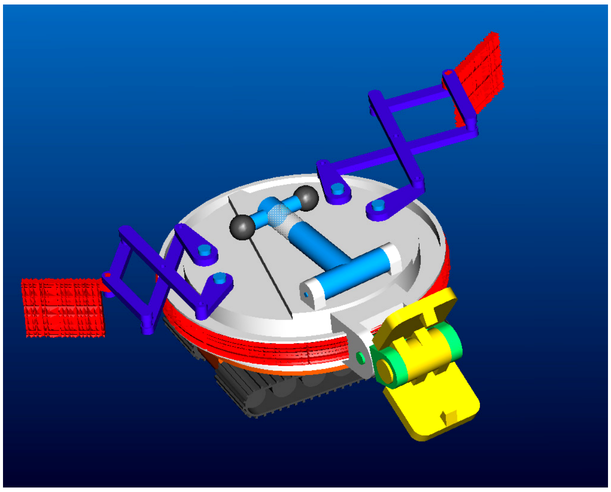

Figure 1: *A graphic visualisation of the first s-bot concept. The diameter of the main body is 110 mm.*

Mobility. The mobility of the system is ensured by tracks, as illustrated in figure 2. Each track is controlled by a motor so that the s-bot can freely move in the environment and rotate on the spot. This is a relatively simple solution for all-terrain navigation, and fits therefore very well with the SWARM-BOT concept composed of many simple s-bots. These tracks allow each s-bot to move in moderately rough terrain, with more complex situations being addressed by swarm-bot configurations.

The motor base with the tracks can rotate with respect to the main body by means of a motorized axis, as illustrated in figure 2. A motorized pole on the top let the robot roll over if it falls on its back (figure 3). The same pole includes an omnidirectional camera used as sensor in standard conditions.

Interconnections. S-bots have two types of possible physical interconnections: rigid and semi-flexible.

Rigid connections (figure 4) between s-bots are implemented by a gripper mounted on a horizontal active axis. This gripper has a very large acceptance area that can securely grasp at any angle and lift (if necessary) another s-bot. Similar connections are made by ants to build bridges or other rigid structures [16]. This is a very important aspect for connections that take place in rough terrain between autonomous robots. It has to be considered that interconnecting robots to build a self-assembling swarm-bot is a very different action than interconnecting modules in a self-reconfigurable robot. Self-reconfigurable robots can compute the exact position of each module in order to ensure precise positioning during interconnection. This is not the case in self-assembling robots like the swarm-bot where one needs freedom to connect at several angles and in less controlled situations.

The gripper can connect to other s-bots on a "T" shaped ring around the main s-bot body. If not completely closed, the connection leaves some degrees of freedom, which are very important for positioning and physical interaction between robots. If completely closed, the gripper ensures a rigid connection and can be used to lift other s-bots.

Semi-flexible connections (figure 5) are implemented by flexible arms actuated by two motors positioned at the point of attachement on the main body. The two degrees of freedom allow to extend and move laterally the arm, as illustrated in figure 5. The arm ends with a surface covered by Velcro©[1]. The orientation of this surface is kept in a default position by springs but can rotate freely.
The complementary Velcro© surface on the other robot is on the "T" shape belt illustrated in figure 4. The size of the contact surface ensures also for this connection a large acceptance area.

[1] The "Velcro" trademark is the property of its owner.

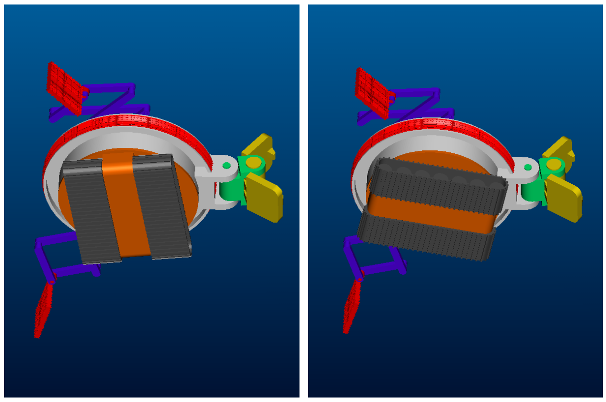

Figure 2: *Bottom view of the s-bot concept. Two independent tracks ensure the displacement of the s-bot. The motor base with the tracks can be oriented independently from the main body.*

Figure 3: *The pole situated on the top of the robot is equipped with an omnidirectional camera and can be used both as sensor and as a mechanical help when the robot falls on its back.*

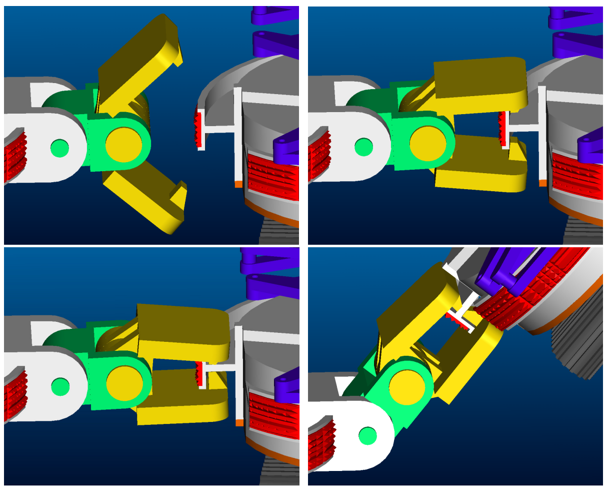

Figure 4: *The gripper of the s-bot provides large acceptance (top left), connects leaving some freedom of movement (top right), ensures a rigid connection (bottom left) and rotates around an horizontal motorized axis (bottom right).*

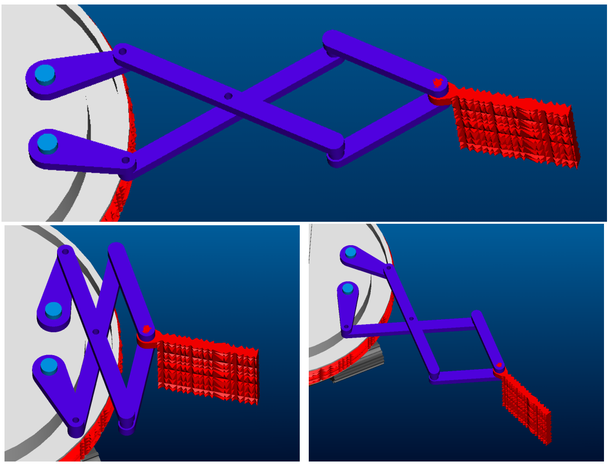

Figure 5: *The semi-flexible connection can be extended, retracted, and moved laterally. The surface at the end of the arm is covered with Velcro©.*

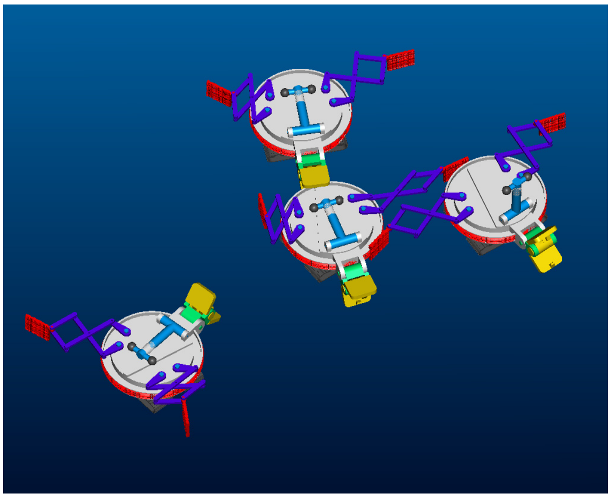

Figure 6: *Most swarm-bot configurations will include both rigid and semi-flexible connections.*

Connections of this semi-flexible link take place tangentially to the belt, as illustrated in figure 6. This is the typical effort that Velcro© can withstand very well. As soon as the relative position of the robots changes and transforms the efforts from tangential to radial, the Velcro© fixation becomes less resistant and the robots, when pulling, can disconnect.

Rigid and semi-flexible connections have complementary roles in the functioning of the swarm-bot. The rigid connection is mainly used to form rigid chains that have to pass large gaps, as illustrated in figure 7. The semi-flexible connection is adapted for configurations where each robot can still have its own mobility inside the structure. An example is illustrated in figure 8. The swarm-bot can of course also have mixed configurations, including both rigid and semi-flexible connections, as illustrated in figure 6.

It is important to consider that in the swarm-bot concept, the mobility of the global swarm-bot is provided by the mobility mechanism of each s-bot. We do not plan to use the s-bots as modules of a leg, for instance, as in the case of self-reconfigurable robots. The tracks of the s-bots are the best point of contact with the ground for the swarm-bot, and will be used for this purpose. In self-reconfigurable robots, the point of contact with the ground is often the end of the chain of modules, that is, a module connector. This is not always an optimal solution, the module connector being a very sensible and fragile part of the robot.

The connections available on the s-bot are not designed to create complex 3D structures. Most configurations will be closer to the examples of figures 7 and 8. However, the rigid connection allows the creation of simple 3D configurations. This type of 3D flexibility will be mainly exploited to climb obstacles that are too steep for the tracks of the single s-bots. This is another major difference with existing self-reconfigurable robots.

Figure 7: *The rigid connection can be used to form chains and pass very big obstacles and large gaps.*

Sensors. Each s-bot is a fully autonomous mobile robot and is equipped with all the sensors necessary for navigation, such as infra-red proximity sensors, accelerometers and incremental encoders on each degree of freedom. In addition to these basic features, each robot is equipped with sensors and communication devices to detect and communicate with other s-bots. Typical devices implementing these features are the omnidirectional camera, color LEDs all around the robot, local color detectors and sound emitters and receivers. In addition to long-range de-

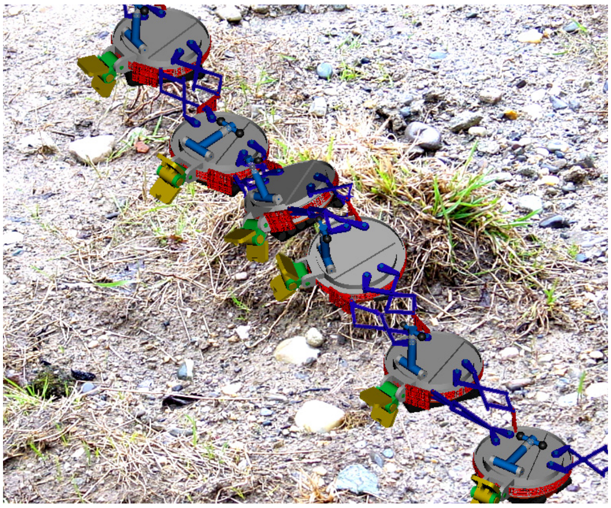

Figure 8: *The semi-flexible connection is used to keep relative mobility between s-bots while they are in a swarm-bot configuration.*

tection, several sensors will provide the s-bot with information about physical contacts, efforts and reactions due to interconnections with other s-bots. This includes torque sensors on most joints, effort sensors on the connection belt, and a motion detector implemented on the omnidirectional camera.

Research on collective insects [4] shows that collective robotics requires multi-range and multi-modal sensing in order to perceive and exchange signals at multiple levels and in several circumstances. For this reason, as well as for more practical reasons of interferences, infra-red proximity (active) sensors will have a very short range. Sound will have a much longer range. The camera will be used both for long and short range sensing, depending on the features extracted from the image.

These sensors characteristics are clearly very distant from those of existing self-reconfigurable robots.

CPU and control electronics. The control architecture of the swarm-bot will consist of distributed algorithms based on local information and simple self-organization rules inspired upon ant colony behaviors. Although this type of control algorithm will not need much computational power, the large number of sensors and degrees of freedom will require fast pre-processing and efficient control. The type of experiment that will be conducted on this system, very similar to biological experiments, will also need very good monitoring and collection of large quantity of data for software development and experiment analysis. For all these reasons the s-bots will be equipped with a network of several processors, each of them responsible for a sub-task in the system. The most powerful processor will be in charge of the management of the system and of communication with a base station for monitoring purposes. It is planned to connect all the s-bots with a base station using a radio link.

3 Status of the project

After the definition of this concept, we are now (March 2002) designing the s-bot in detail and prototyping the principal parts for preliminary tests. The project will provide a full prototype of some s-bots for the end of this year. These prototypes will be used for intensive testing and for the definition of an eventually new or improved concept.

In parallel to this hardware development, other groups involved in the project are working on simulation tools and control algorithms.

4 Discussion and conclusion

This paper presents the main aspects of the swarm-bot concept. This new self-assembling robotic concept extends the robustness of existing collective robotics to a physical level. This characteristic allows physical collaboration between robots, for instance to navigate over difficult obstacles and gaps in all-terrain conditions. Moreover, the characteristics of the interconnections may help the robot to use their physical characteristics to simplify the behavioral algorithms.

The modularity of the system and its ability to deal with all-terrain conditions is a typical characteristic of existing self-reconfigurable robots too. We have therefore presented in detail the type of interconnections between our s-bots, showing fundamental differences with those found on self-reconfigurable robots. Swarm-bots have a much more flexible structure and can assemble and disassemble autonomously, the basic element being a fully autonomous robot.

Although swarm-bots are not intended to form complex 3D shapes like those found in self-reconfigurable robots, the swarm-bot concept will have very good mobility and a much better contact with the ground. The mobility of the swarm-bot is built over the mobility of each single s-bots, avoiding the problem found in self-reconfigurable robots where robots have to roll or walk on their connectors.

Finally we presented the sensors and CPU concept of the SWARM-BOTS project, clearly close to existing collective robotics but extended to consider physical connections.

The next step of this project consists in building a prototype and its test in realistic conditions. This phase is in progress at the time of writing.

Acknowledgments

Many thanks to Pierre Arnaud, Gianluca Baldassarre, Gianni Di Caro, Andrea Danani, Ivo Kwee, Thomas Halva Labella, Giovanni Pettinaro, Philippe Rasse, Andrea Rizzoli, Erol Sahin and Vito Trianni for their comments and ideas.

The SWARM-BOTS project is funded by the Future and Emerging Technologies programme (IST-FET) of the European Community, under grant IST-2000-31010. The information provided is the sole responsibility of the authors and does not reflect the Community's opinion. The Community is not responsible for any use that might be made of data appearing in this publication. The Swiss participants to the project are supported under grant 01.0012 by the Swiss Government.

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