Search for Rescue: an Application for the SWARM-BOT Self-Assembling Robot Concept

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Abstract

Semi-autonomous search for rescue in post-catastrophic environments is a typical example where self-assembling and self-reconfigurable robots can be quite efficient. In this paper we present the SWARM-BOT concept of a self-assembling robot along with the characteristics that make it well adapted to search for rescue after catastrophic events. SWARM-BOT has been designed for robust operation in rough terrain, based on the self-assembling capability of a swarm of simple and small mobile robots. These characteristics, together with the cost of the system, fit well with those needed for exploration in unstructured and unstable environments. After presenting the SWARM-BOT concept, we compare it with other families of robots that claim to address robust exploration of all-terrain environments, that is self-reconfigurable and collective robotics. We show that SWARM-BOT, combining the features of these two families of robots, has several interesting advantages over existing concepts.

Figure 1: *Catastrophic events generate unstructured, unstable and dangerous environments where fast and reliable intervention is needed.* *Courtesy National Information Service for Earthquake Engineering, University of California, Berkley, USA. Images from the Steinbrugge Collection.*

1 Introduction

Catastrophic events or major accidents generate unstructured and unstable environments where there is an urgent need of intervention, mainly to save lives or to prevent additional accidents. In this type of situation the typical operation are reconnaissance, exploration, search, monitoring, excavation, transport and rescue. This field is known as "Search and Rescue" (SAR) or, when dealing particularly with collapsed man-made structures, as "Urban Search and Rescue" (USAR).

Robotic tools for this type of operation are highly demanded, mainly because of the danger for human intervention. Moreover time and resources are critical in post-catastrophic operations, making the use of robots along with humans interesting. An increasing number of researchers and companies are performing research and tests in this field. A comprehensive overview of USAR and of resulting robot requirements recently made by Murphy et al. [30] indicates that there is a need for robots having an extreme mobility and keeping small dimensions. Good mobility is needed to pass very complex obstacles formed by the collapsed structure. Small dimensions are required because of the nature of the operation, such as the introduction of robots through small entries giving access to internal voids. The URBAN robot [28] is a good example of robot developed in the framework of USAR operation and now available on the market. This type of robot has on-board sensors and processing unit to perform autonomous behavior, but these features are used mainly for operator support.

Local use of sensor information and local control can help in providing fast and accurate actions very hard to achieve by the remote operator who has only a partial view of the environment. Research in this direction, such as the work performed at Sandia National Laboratories [4], indicates that some functionalities can be achieved more efficiently by the robot without external control. This is the case, for instance, of monitoring environmental characteristics, such as gas presence, where the operator needs only to be informed about specific particular events.

Although term USAR includes the "rescue" operation, it has to be noted that there is no literature on robots performing rescue, and this is not the goal of our research as well. Rescue is usually carried out by humans once robots have located the victims. Therefore USAR is often considered as the set of conditions and constraints to perform *search for rescue in post-catastrophic environments*.

In order to perform semi-autonomous or even fully autonomous post-catastrophic operation, mobile robots need to have at least the following characteristics:

- Rough terrain navigation. Unstructured environments need a very flexible and efficient all-terrain navigation combined with a small size.

- Robustness. Unstable and very complex environments require robustness to severe hardware failures.

- Versatility. The complexity of the task needs versatility of hardware shape and functionality.

- Reasonable cost. Loss of part of the system should be accounted for in the process of determining the final cost of the system.

- Efficient user interface. The information acquired by the robots has to be communicated in a fast and accurate way to the human rescue team.

In the next sections we will present the SWARM-BOT concept, which addresses the first four problems. The user interface aspect is not directly addressed in this first phase because of the focus on autonomous behavior. After an overview of the concept, a comparison is done with other families of robots, such as reconfigurable robots, articulated rovers, and collective robotics, that are often proposed as promising solutions for robust USAR.

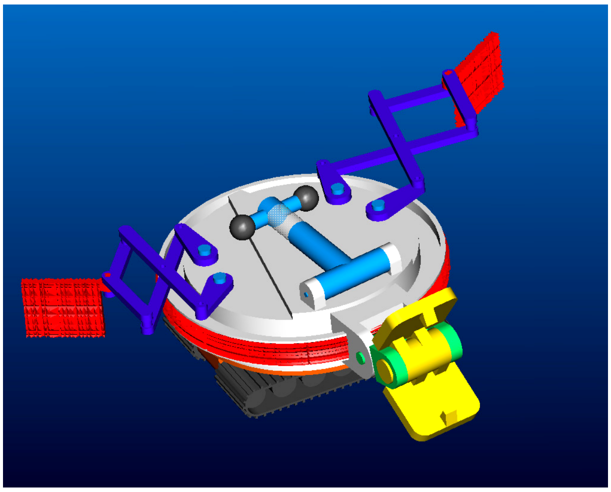

Figure 2: *A graphic visualization of the s-bot concept. The main body is equipped with passive and active gripping facilities, sensors and electronics. The lower body is equipped with tracks and hosts batteries. The diameter of the main body is 110 mm.*

2 The SWARM-BOT concept: Overview

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-organizing, 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-organizing and self-assembling capabilities shown by social insects and some other animal societies [9].

An important part of the project consists in the physical construction of at least one SWARM-BOT, that is, a self-assembling and self-organizing 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 (an example is given in figure 3). This hardware structure is combined with a distributed adaptive control architecture inspired upon ant colony behaviors.

This concept addresses directly and simultaneously the four aspects mentioned in the introduction, that

Figure 3: *The front gripper is used to connect in a secure way to other s-bots and form chains to pass large obstacles or holes.*

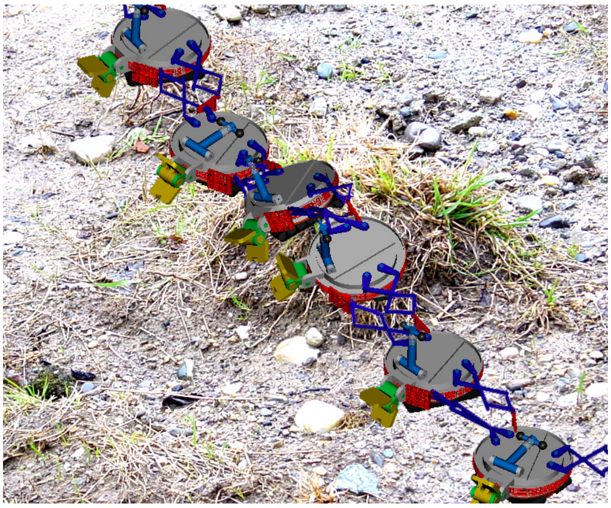

Figure 4: *Two lateral semi-flexible connections are used to keep relative mobility between s-bots while they are in a SWARM-BOT configuration.*

is, robustness, versatility, all-terrain navigation and cost. It would be therefore well adapted to operation in post-catastrophic operations. 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 and the self-assembling versatility can be used to climb obstacles and transport objects, also in situations where a single robot could not succeed. This gives SWARM-BOT a clear advantage over existing collective robotic systems in all-terrain conditions. Furthermore, distributed hardware and control gives some advantages over classical rovers and self-reconfigurable robots, permitting better robustness in all-terrain conditions. Even if the proposed concept cannot be used to form complex 3D structures, it fits well all-terrain situations and can better perform in search tasks where dynamic assembly and disassembly are required. Finally, the type of functionality, size and granularity of the modules enable an optimal cost of the system with respect to the performances provided.

In the next subsections we present the details of the SWARM-BOT concept within the context of post-catastrophic operations. The description is structured following the four main features needed by this type of robots: robustness, versatility, rough terrain navigation, and cost. In each section, a comparison is made between the SWARM-BOT and related state-of-the-art robots.

3 Robustness to hardware failures

In this section we consider robustness to physical damages of the system. In unstructured and unstable environments like those found in post-catastrophic situations, robustness to hardware failures plays a very important role. Unstable ground, fire, explosions, water, chemicals or other agents can cause damages to the robotic system. To ensure the most efficient task execution, the system has to be fault tolerant and ensure operation even if large part of the system, for instance half of the hardware, is lost.

3.1 State of the art

A widely used technical solution for heavy hardware failures is redundancy. Most of the literature on fault-tolerant systems deals with minor failures that can be corrected with a robust control or with systems which have intrinsic redundancy, like communication networks. A typical example exploiting intrinsic redundancy is the failure of a node in a communication network. In this case the system, if well controlled, can continue to operate using the remaining working parts. To face this type of partial failure, which is the most common in engineering systems, the main design effort has to be placed in the control part of the system (for an overview see [34]). An efficient fault tolerant control is based on failure detection and correction. Both need a major design effort and an accurate model of the system. To correct major failures, additional and specific hardware redundancy becomes necessary.

In the case of robotic operation in post-catastrophic situations where the system must remain operational in partially changing and unpredictable situations, hardware failures can be frequent and major. Here robust control is not sufficient and redundancy has to be introduced at all levels. Explosions, collapse of structures, wrong movements or water can produce critical damage in electronics and mechanics, generating the failure of an entire robot. For this reason redundancy has to be introduced also at the robot level, building multi-robot systems.

The control, in the case of a multi-robot system, can be centralized or de-centralized. If centralized, it employs methods of robust control, failure detection and correction. This type of control system requires a major design effort and critically depends on the central control unit, which has to work properly and be continuously connected to each robot component. If de-centralized control is applied, the system need a higher level of hardware redundancy but can exploit simpler and more robust control strategies.

Most of the research work done in this direction is known under the name of *collective robotics* and represents a very active field (for an overview of the field, see for example [5]). A major focus of this community is distributed control, but there is little research on exploiting the collective aspect at the hardware level. The main motivation of collective robotics research is the coordination of several systems [6][21][29][20] and the robustness that can be achieved by the redundancy of the whole system [31][22]. An increasing number of applications plan to exploit this type of information processing, such as critical robotic missions [13][18] where there is a strong interest in using a more robust system.

Hardware modularity and redundancy can be found also in the field of *self-reconfigurable robots*. The research activity in this field is very complementary to collective robotics, the main focus being hardware modularity with very few research on autonomous perception and action in the environment.

Pioneering examples of self-reconfigurable robots are MTRAN [24] and PolyBot [17] (for an overview of existing systems and characteristics see [24][41]). Both use a large number of modules, exist physically and can self-reconfigure. Despite the very good hardware flexibility, both MTRAN and PolyBot have centralized control algorithms, which, in comparison to decentralized ones, have reduced robustness to failures. Currently, the only 3D self-reconfigurable robot with decentralized control is the CONRO hardware [12] with decentralized control by Støy et al. [36] or by Salemi et al. [33]. This system permit to change manually the position of the hardware modules in the structure while the system is running and each module autonomously readapts its behavioral role in the system. Although this demonstrates software robustness toward structure modifications and failures, automatic hardware failure correction is still not implemented and needs a major effort in design. Hardware failure detection and correction are known to be hard to implement in a reliable way [8].

3.2 The SWARM-BOT robustness

In the SWARM-BOTS project we decided to exploit distributed hardware and control, with a clear and strong influence from ant colony behaviors [11][9]. Each s-bot is therefore a simple but fully autonomous unit, capable of displacement, sensing and acting based on local information and decision. This is a clear distinction toward self-reconfigurable robots. The self-assembling ability is added on the top of this layer, enabling collective behavior at the level of the physically compact SWARM-BOT system. The global task execution is obtained by the exploitation of robot-robot and robot-environment properties, and is not achieved by centralized planning and control. Both the SWARM-BOT control strategy and the distributed hardware ensure good robustness to hardware failures.

The mechanical concept of an s-bot is presented in figure 2. The mobility of the system is ensured by two tracks, as illustrated in figure 5. Each track is controlled by a motor so that the s-bot can freely move in the environment and rotate on the spot. These tracks allow each s-bot to move in moderately rough terrain (obstacles 3-4 cm high, 30% slope, gaps not larger than 3-4 cm) 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 5. This ensures an independent movement of the upper part where the sensors and the physical connections to other robots are located.

A motorized pole on the top allows the robot to roll over if it falls on its back (figure 6). The same pole includes an omnidirectional camera used as sensor in standard conditions.

Each s-bot is equipped with 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 a large number of sensors for detection of the environment, several sensors will provide the s-bot with information about physical contacts, efforts and reactions at the interconnection joints with other s-bots. These includes torque sensors on most joints as well as effort sensors on the connection belt.

Figure 5: *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 6: *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.*

Research on collective insects [11] 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 mainly have a very short range. Sound will have a much longer range. The camera, which is a passive sensor, is used both for long and short range sensing, depending on the features extracted from the image.

The control architecture of the SWARM-BOT consists of distributed algorithms based on local information and simple self-organization rules inspired upon ant colony behaviors [32]. Although this type of control algorithm does not need much computational power, the large number of sensors and degrees of freedom requires fast pre-processing and efficient control. Therefore s-bots will be equipped with a network of several processors, each of them responsible for a sub-task in the system. The main processor will be in charge of the management of the system

Figure 7: *The environment in USAR operation is composed of obstacles of very different size and shape, including wires, walls, tubes and gaps. Courtesy National Information Service for Earthquake Engineering, University of California, Berkley, USA. Images from the Steinbrugge Collection.*

and of the communication with a base station for monitoring purposes. This processor will run a standard real-time OS, permitting the use of standard development tools and allowing an easy porting of specific robotic development tools. S-bots will also be equipped with radio link to a base station for monitoring purposes (not for control).

4 Versatility

In USAR operation, the environment where the robot has to move includes a large number of obstacles in every kind of position and of very different type: from wires to walls, from long tubes to compact blocks, from fissures to deep vertical holes, etc. (see for example figure 7). For example, it may happen that robots must be introduced through small holes, then pass large gaps, descend a vertical duct ending in a large void, then pass again a narrow passage etc. Robots designed to cope with only one or two of these features, will be challenged by the other ones. To be successful, a robot has therefore to be very versatile, that is capable of dynamically changing shape and control functionality, depending on the situation to face.

4.1 State of the art

Modularity is a widely used technique to ensure versatility. At the control level, modularity is often implemented by distributed approaches on the structure of the control system [10][42] or on the control process itself, as in collective robotics. At the hardware level, modularity and versatility are clearly represented by self-reconfigurable robots.

In collective robotics, modularity provides versatil-

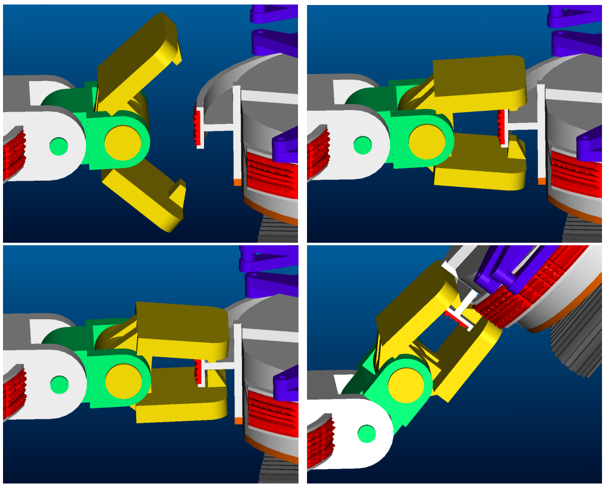

Figure 8: *The gripper of the s-bot provides large acceptance (top left), connects leaving some freedom of movement (top right), ensures a rigid connection (bottom left) and rotates around an horizontal motorized axis (bottom right).*

ity at several levels. A physically distributed system allows distributed sensing, acting and processing. Simultaneous distributed sensing delivers high flexibility in placing the sensors according to the configuration of the search space, thus improving search efficiency. A good example of this type of situation is given by Hayes et al. [23] where a very difficult search task, plume tracing, is performed using a swarm of robots equipped with odor sensors. Distributed acting allows versatility in transport tasks [25], exploiting the possibility to change the number of agents involved depending on the effort needed. Sorting is another example where multiple agents can improve versatility of the system [27]. Transport [16], sorting [15] or structure building [11] are typical tasks where collective robotics can take inspiration from social insects behavior[9] providing very efficient and versatile solutions.

At the hardware level, advanced modularity and versatility is shown by self-reconfigurable robots. These systems are built with a large number of physical modules acting together in a unique body. Each module provide few degrees of freedom. Assembled together, these modules give the body extraordinary physical versatility. An additional feature is given by the possibility of the system to connect or disconnect modules autonomously, enabling self-reconfiguration. Based on this feature, a robot can change shape depending on the environment, as shown by PolyBot [40] and by other robots such as MTRAN [24]. The structure of the modules and of the possible configurations change very much across existing systems. The most advanced systems show 3D configurations like snakes, tracks, spiders, and quadruped legged systems. Both PolyBot and MTRAN have displayed transition between shapes in hardware.

4.2 The SWARM-BOT versatility

In SWARM-BOT versatility is given by the presence of many entities that can self-assemble in a unique body and can disassemble again when necessary. This feature combines the properties of control versatility found in collective robotics with some hardware versatility found in self-reconfiguring robots. Since each s-bot is a fully autonomous mobile robot, the SWARM-BOT can not only self-reconfigure, but also self-assemble. S-bots can leave the SWARM-BOT configuration, move around and join again the SWARM-BOT when necessary. This is a major additional feature with respect to existing self-reconfigurable robots, which form a unique and monolithic structure.

S-bots have two types of possible physical interconnections to self-assemble into SWARM-BOT configurations: rigid and semi-flexible.

Rigid connections (figure 8) 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 [26]. The large acceptance area is a very significant aspect for connections that take place in rough terrain between independent 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 SWARM-BOT where freedom to connect at several angles and with less precision is required.

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 lets the two robots move with respect to each other in order to navigate on rough terrain, for example. If completely closed, the gripper ensures a rigid connection and can be used to lift other s-bots.

An s-bot, with its gripper, is capable of lifting only one s-bot. This is the major difference between SWARM-BOT and self-reconfigurable robots, which instead can form complex 3D shapes in order to move and pass obstacles. SWARM-BOT does not require complex 3D shapes because its mobility is provided

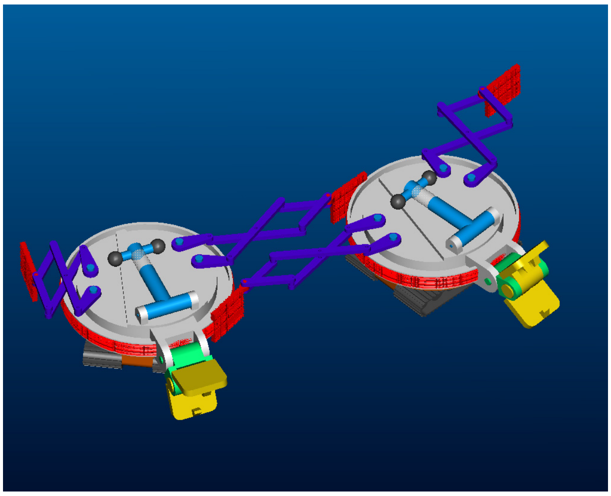

Figure 9: *Two s-bots connected using semi-flexible connections.*

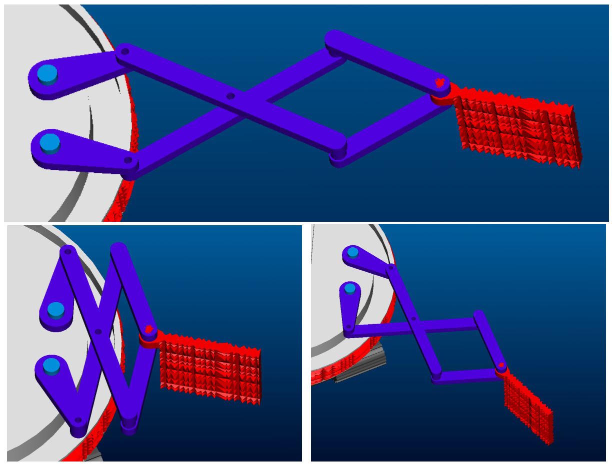

Figure 10: *The semi-flexible connection can be extended, retracted, and moved laterally. The surface at the end of the arm is covered with Velcro©.*

by the combined effort of each s-bot.

Semi-flexible connections (figure 9) are implemented by flexible arms actuated by two motors positioned at the point of attachment on the main body. The two degrees of freedom allow to extend and move laterally the arm, as illustrated in figure 10. This structure is a bi-dimensional version of the DELTA robot [14]. Vertically, the arm will have sufficient flexibility to be bent and support connections in all-terrain conditions. 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. A complementary Velcro© surface is positioned on the "T" shape belt of each s-bot (figure 11). The size of the contact surfaces ensures also for this connection a large acceptance area.
Connections of this semi-flexible link take place tangentially to the belt, as illustrated in figure 11. 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.
To ensure a reliable connection, two s-bots have to mutually connect with their flexible arm, as illustrated in figure 9. This implies the decision of both robots to stay connected. As soon as one robot decides to disconnect, it can rotate its upper part and disconnect. The other robot will not be able to keep the connection alone and will become soon disconnected too.

Rigid and semi-flexible connections have complementary roles in SWARM-BOT. The rigid connection is mainly used to form solid chains in order to pass large gaps, as illustrated in figure 3. The semi-flexible connection is useful for configurations where s-bots must remain close to each other but also move with respect to each other. An example is illustrated in figure 4. Swarm-bot can also have mixed configurations, including both rigid and semi-flexible connections, as illustrated in figure 12.

Rigid and semi-flexible connections are not designed to create complex 3D structures. Most configurations will be closer to the examples of figures 3 and 4. However, the rigid connection allows the creation of simple 3D structures, for instance where peripheral s-bots are placed vertically to help the SWARM-BOT better dealing with obstacles. This type of 3D flexibility will be mainly exploited to climb obstacles that are too steep for the tracks of single s-bots.

5 Rough terrain navigation

In unstructured environments like those found in USAR operation, the robot must be capable of navigating across rough terrain as well as get through cavities and narrow passages. Within this context, SWARM-BOT offers an innovative solution in improving mobility by exploiting physical collaboration of a collective system.

5.1 State of the art

Navigation in rough terrain conditions is mainly addressed by articulated rovers and reconfigurable robots. Examples of these types of rover include the *shrimp* robot [19], the family of space exploration robots by ESA [39], the *pathfinder* rover used on Mars [35], as well as other specific rovers for mis-

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

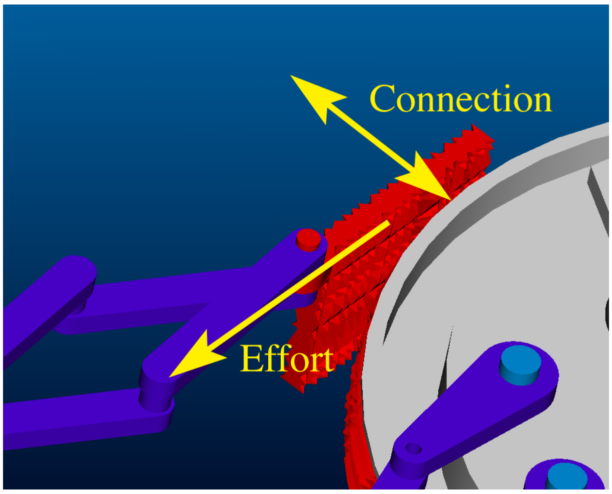

__Figure 11:__ The semi-flexible connection is based on a Velcro© fastener. The effort is supported tangentially to the s-bot body, the connection and disconnection is made radially.

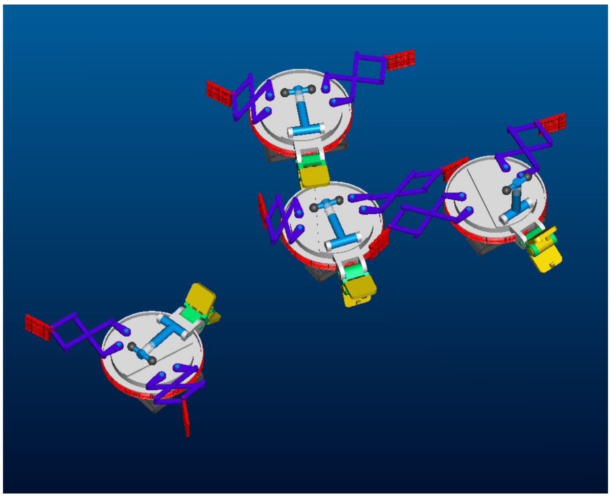

__Figure 12:__ Most swarm-bot configurations will include both rigid and semi-flexible connections.

sions like volcano explorations [7]. This type of research is mainly focussed on mechanical structures of articulated wheels and tracks and their ability to pass obstacles. Although most of these rovers are remotely controlled, research aims also at developing sensors for autonomous operation (for instance [38]) or to help the remote operator [28].
Some researchers consider multiple rovers for all-terrain exploration [13][18] exploiting distributed hardware and, in some cases, distributed control to obtain a more robust system and better exploration performances [4]. To the best of our knowledge, nobody has yet tried to take advantage 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 walk, creep, and roll in rough environment conditions. Simulations of PolyBot have been based on an all-terrain scenario [40] and the typical goal of the CONRO system is earthquake search-and-rescue and battlefield surveillance and scouting [12]. Despite these goals, the sensors included in these developments are mainly used for perception of the internal state of the system and there is practically no perception of the environment. This is motivated in some cases by pure tele-operation. But pure tele-operation seems not to be sufficient for efficient operation [30][28]. Semi-autonomous tele-operation, especially in this type of complex environment, is necessary to achieve the task in an efficient way. There is therefore a need for including sensors on this type of robots, as shown by recent work on the CONRO system [36].
Another problem still under development and unclear in all-terrain operation of self-reconfigurable robots is the contact of the robot with the ground. Although snake-like configurations can be quite efficient, performance is less evident in legged configurations. In this latter case, the contact to the ground is made by the end of the chain of modules, which hosts the inter-modules connector. This part of the module, the connector, is the most sensitive part of the system and would be damaged if used as foot of the robot. For this problem, solutions still have to be found.

5.2 SWARM-BOT ability to deal with rough terrain

In SWARM-BOT, overall mobility is provided by the mobility of each single s-bot. We do not plan to use s-bots as modules of a leg, for instance, as in the case of self-reconfigurable robots. The gripper used for the interconnection between robots will not have sufficient torque to support this type of structure. The configurations displayed by SWARM-BOT will be mainly bi-dimensional, with the possibility to lift lateral s-bots in order to pass large obstacles. The tracks of the s-bots will therefore always be the point of contact with the ground for the SWARM-BOT. The possibility of rotating the tracks with respect to the main body (figure 5) will ensure suitable mobility of the entire structure when s-bots are connected.

The control of the swarm-bot structure in all-terrain conditions is strongly based on insect behavior [26][32]. Most structures will be built of chains of s-bots combined with lateral connections for overall stability of the structure. The process of passing an obstacle will be based on local push-pull operations. The self-assembling feature will be strongly exploited: A swarm-bot structure will be assembled if necessary and disassembled as soon as possible, using as much as possible the s-bots as independent units.

Finally, the size of the elementary components of the SWARM-BOT, the s-bots, fits very well the constraints of USAR operation. The small size of the s-bot permits its introduction in very small entry points, giving SWARM-BOT access to internal voids. The SWARM-BOT, if necessary, can then self-assemble to achieve other navigation tasks.

6 Cost

Operation in post-catastrophic environments can easily result in loss of several robotic units. Furthermore, the large redundancy of the system rises the question of cost.

6.1 Situation of existing systems

Several researchers suggesting to use self-reconfigurable robot for flexible all-terrain navigation argue that their solution is cheap[37][36][40]. The main argument is that small, identical, and mass-produced modules are cheaper to build than big custom robots. Since SWARM-BOT employs a modular approach, we have been looking for elements giving indications on the cost of modular systems.

Without taking into consideration the complexity in connectivity added by the modular approach, it is interesting to look at the price of mass-produced small systems in comparison with bigger systems produced in smaller quantities. Figure 13 shows the price of fourteen mobile robots available on the market versus their volume. We considered only fully programmable mobile robots used by universities for research and education. Two types of prices are given: total price of the system and volumic price, that is price per unit of volume. This graph shows that mass-production of small modules alone does not help in getting better volumic prices. It is interesting to see that the volumic price of a mass-produced robot like LEGO Mindstorm© [1] is similar or even higher than volumic price of most of the very complex research robots systems like Koala© robot by K-Team [3] or ATRV micro© by iRobot [2]. This means that the mass-fabrication of modules for a modular robot is not necessarily cheaper than fabrication of a single, larger, more complex, and customized robot.

The price of miniaturization is another interesting aspect shown in figure 13. Miniaturization brings higher volumic prices for volumes lower than 1000 cubic centimeters. This is mainly due to the technology involved, which has to be customized and optimized when the volume of the system becomes so small. For comparison, the volume of some self-reconfigurable robot modules is given in table 1.

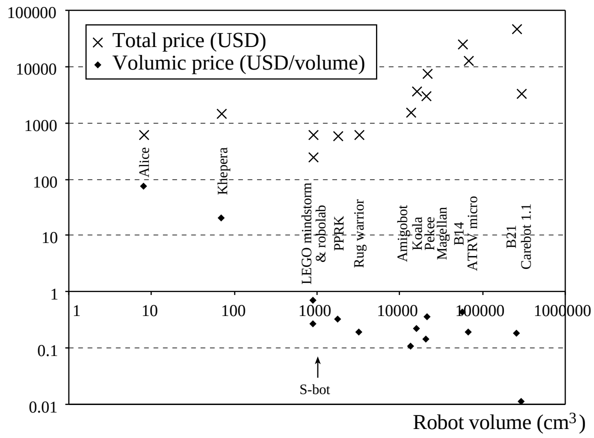

Figure 13: *Price of fourteen mobile robots used in research activities versus their volume. Crosses give the total price of the system and dots give the price per unit of volume. The system name corresponding to each point on the graph is given in the same order as the points.* *All mentioned names are trademark and are property of their owner.*

It is hard to apply in detail these remarks to the cost of modular systems, but the claim of cheaper system seems difficult to support. On the other side it has to be noticed that modular systems bring higher versatility than single custom robots, which could justify the higher cost due to modularity and miniaturization.

Table 1: *Volume of some modules used in self-reconfigurable robots.*

	Volume in cm^3
MTRAN	575
I-Cubes	430
CONRO	300
PolyBot G3	115

6.2 The SWARM-BOT cost

We do not claim that SWARM-BOT will be a cheap system, but it will bring very interesting features for a reasonable cost. Two elements can be used for this argumentation. One should consider that SWARM-BOT has a modularity enabling the use of each s-bot both independently and in swarm-bot configuration. This is an interesting advantage over collective robotics and self-reconfigurable robots, because it allows a better versatility with the same number of units. This feature brings also additional costs, the s-bot being more complex than the modules found in self-reconfigurable robots. A better comparison will be possible when self-reconfigurable robots will include sensors for environment perception, which will be a major complexification of the design.

Another interesting point of the s-bot is its size. The s-bot will have a size of about 1000 cm^3, which is larger than modules used in existing self-reconfigurable robots, but smaller than existing robots with similar features used in collective robotics. This size, as seen on figure 13, fits well with the actual technology, allowing small design with a good volumic price.

7 Conclusions

In this paper we presented the SWARM-BOT concept in the context of the four major characteristics needed for post-catastrophic operation of semi-autonomous or even fully autonomous mobile robots:

- Robustness.
- Versatility.
- Rough terrain navigation.
- Reasonable cost.

A fifth characteristic, the need of a very efficient user interface, has not been described in this paper, due to the focus on the new SWARM-BOT concept. For each characteristic, we compared SWARM-BOT with existing systems.

SWARM-BOT, with its self-assembling capability, opens a new research field situated between self-reconfigurable and collective robotics. The concept combines hardware versatility found in self-reconfigurable robots with control versatility found in distributed control for collective robotics. This fundamental property of SWARM-BOT plays a key role in USAR operation and allows SWARM-BOT to face complex environments found in post-catastrophic conditions.

The second fundamental property of SWARM-BOT is robustness, provided by distributed hardware and control. This feature is also essential for USAR operation where the unstable environment can cause loss of robotic units.

Finally the SWARM-BOT concept is compatible with technological constraints, ensuring a reasonable cost.

After the definition of this concept and the preliminary tests in simulation, we are now prototyping the principal parts for preliminary tests. We expect to have a fully functional prototype of some s-bots by the end of the year 2002.

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