MINI-TRANS: A Multi-robot System with Self-assembling Capabilities

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Abstract. Recently, reconfigurable multi-robot systems have gained interest due to advantages such as reconfigurability, robustness and modularity they offer in comparison with mono-robot systems. Self-reconfigurable multi-robot systems have potential applications in the fields of collective exploration, object transportation and rescue. However, the design of reconfigurable multi-robot systems presents many challenges such as the selection of materials, equipment, morphology and control to enable them to coordinate their actions, to assemble their bodies and to avoid collisions. This paper describes the development of a prototype of multi-robot system with self-assembling capabilities. Preliminary experimental results are also presented.

1 Introduction

Multi-robot systems refer to a group of integrated robots that work together. Modular robots are a subclass of multi-robot systems, they consist of self-assembling autonomous robots that have devices such as a grippers, attachment points or electromagnets to connect and disconnect to other robots. This capability enables modular robots to change the organization of their modules and is called reconfigurability. These kinds of systems have potential applications in rescue, object transportation and exploration of environments with irregular surfaces.

Reconfigurability can be static or dynamic. Static reconfigurable robots reorganize their structure off-line, whereas dynamic reconfigurable robots can reorganize their structure on-line, during run-time execution. A human user or another robot may assist dynamic reconfigurable systems with their reconfiguration. There are also dynamic self-reconfigurable systems able to achieve their reconfiguration by themselves.

Yim et al. [1] classified self-reconfigurable robots according to their form of configuration as described below.

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Mobile reconfigurable systems consist of mobile autonomous robots able to work independently of each other. Occasionally, these modules assemble to perform tasks they are unable to do individually, e.g. Millibot-trains [2].

Lattice reconfigurable systems are arranged in a cell form, the modules connect and disconnect to their neighbors within the limits of their structure, e.g. MTRAN [3].

Chain reconfigurable systems consist of semi-independent modules that must be connected at least to another module, e.g. Polybot [1].

Recently, reconfigurable multi-robot systems have gained interest due to the advantages such as reconfigurability, robustness and modularity they offer in comparison with mono-robot systems. Sometimes, these robots are also self-repairing and self-maintining, i.e. they are able to replace one damaged module with another one [4].

The design of reconfigurable multi-robot systems presents many challenges such as the selection of materials, equipment, morphology and control to enable them to coordinate their actions, to assemble their bodies and to avoid collisions.

Coordination is an important issue when designing multi-robot systems. As far as we know, the design of mechanisms that enable a group of mobile robots to interact with them, is an open problem in robotics. We denote **coordination** as the capability of the members of a multi-robot system to perform actions jointly to reach a common objective, avoiding collisions and conflicts among them.

In this paper, the progress in the development of a prototype of a mobile self-reconfigurable multi-robot system is presented. The rest of the paper is organized as follows: Section 2 presents related work; Section 3 describes the development of our prototype of a modular reconfigurable system: Mini-trans; Section 4 shows the results obtained from experiments using our prototype, and finally, Section 5 addresses conclusions and perspectives of this work.

2 Related Work

Because the prototype presented in this paper is a mobile self-reconfigurable multi-robot system, recent works on these systems are summarized below.

Swarm-bot is a project sponsored by the Future and Emerging Technologies program of the European Community [5]. The purpose of this project is to design and build physically a mobile reconfigurable system consisting of 30 to 35 small and autonomous robots called S-bots. S-bots are equipped with 50 sensors and 9 actuators. S-bots are able to perceive their environment, communicate with other S-bots and assemble themselves into flexible or rigid forms. Each S-bot is able to perform different tasks such as navigation, exploration and grasping objects. The system uses a distributed adaptive control architecture inspired on ant colony behaviors.

Carnegie Mellon University developed a group of robots called **Millibot-trains** with self-assembling capabilities [2]. Each Millibot is approximately $11cm.$ long and $6cm.$ wide. The modules of Millibot-trains system are equipped with sensors such as sonars, IR sensors and video cameras. They also have capabilities to navigate, to explore, to assemble and to communicate in a wireless network. Each Millibot consists of three modules: one module for movement, one for perception of the environment and one for control. Each Millibot can assemble another one using a pin-hole based device, which provides stability but demands a lot of exactness in connections.

SMC rover is a mobile reconfigurable system developed by Kawakami et al. [6]. This system consists of exploring and navigating robots. Each robot is integrated with various modules called Unirovers which are solar cell modules or other types of support modules. As well as Millibot-trains, Unirovers assemble together using a pin-hole device.

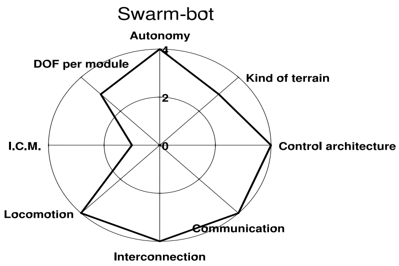
Figure 1 summarizes the main features of the modular robots reviewed above. The main features of Mini-trans, our prototype which is described in Section 3, are also presented in this figure. Important notions used in this paper are precised below.

- A robot that is able to make decisions based on its own perception and processing is considered autonomous. On the other hand there are the complete remote-controlled or non-autonomous robots. A semi-autonomous robot is able to make decisions based on external processing. A mainly remote-controlled robot is able to make certain decisions but it could also be controlled by a human operator.
- The communication based on explicit exchanges is considered direct communication, whereas the communication based on the observed behavior is considered indirect communication.
- The control architecture that depends on the multiple robot interactions is considered decentralized. The control architecture that depends on a central scheduler is considered centralized and fixed. A hybrid architecture comprises two layers, one containing centralized mechanisms able to plan actions, and other containing decentralized mechanisms able to react at immediate events. A centralized control architecture based on a non-fixed hierarchy is considered a dynamic hierarchy.

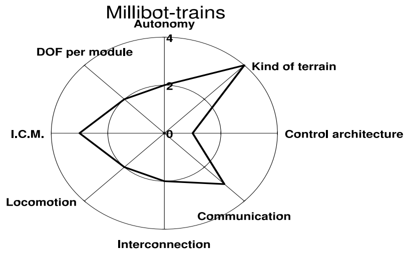
3 Mini-trans System

The Mini-trans system consists of three homogeneous and autonomous modules with self-organizing and self-assembling capabilities. Its development is divided into six steps: 1) design and building of one prototype, 2) definition of the system behaviors, 3) experimentation, 4) analysis of results, 5) modification and improvement and 6) generalization of behaviors. This work is in progress, its development is currently in step 5.

This section presents the design, implementation and control of the system.



(a)



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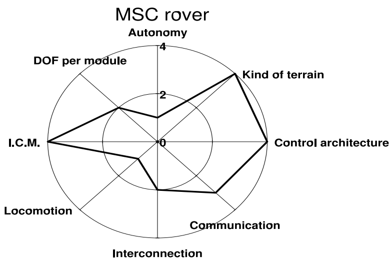

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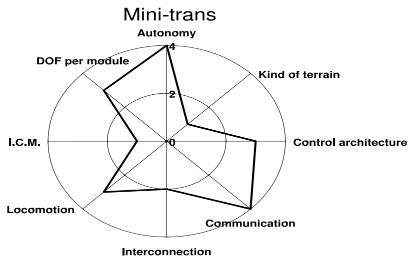


(d)

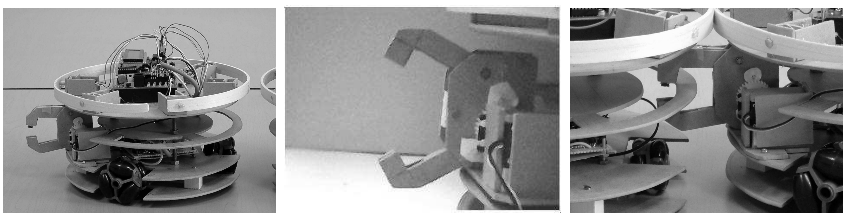
	Self-reconfigurable systems			
Feature	**Values**			
	1	2	3	4
Autonomy	Completely remote-controlled	Mainly remote--controlled	Semi-autonomous	Autonomous
DOF	1	2	3	> 3
Individual capabilities per module (I.C.M.)	Homogeneous hardware & software	Homogeneous hardware, heterogeneous software	Heterogeneous hardware & software	Complementary heterogeneous hardware & software
Locomotion	Wheels	Tracks	Omnidirectional wheels	Wheels & tracks
Interconnection	Rigid	Semi-rigid	Flexible	Rigid & flexible
Communication	Without communication	Indirect	Direct	Direct & Indirect
Control architecture	Centralized & fixed	Centralized based on a dynamic hierarchy	Hybrid	Decentralized
Kind of terrain	Flat	Few rough	Rough	Extremely rough

Fig. 1. Comparison of main features in four self-reconfigurable systems: Swarm-bots (a), Millibot-trains (b), SMC rover (c) and Mini-trans (d). Low values in the table (1 and 2) represent low adaptability, whereas high values (3 and 4) represent high adaptability. Swarm-bots is, as shown in Figure (a), the best performing system according to this classification. (d) Shows the features of the system proposed in this paper, which is described in Section 3

3.1 Hardware

Various versions of Mini-trans were designed and tested. The definitive version of the modules consists of four $26cm$ diameter wooden circular plates. These plates are arranged one over another supported by screws. Locomotion elements were placed on first plate. A gripper was placed on second plate. The fourth plate contains a contact sensor belt, an IR reflective optosensor and a Handyboard©. For its locomotion, the robot uses 3 motors and 3 commercial omnidirectional wheels of $6cm$ placed in form of a tricycle. This robot is able to move omnidirectionally and avoid obstacles. This version was equipped with 1 gripper, 2 IR reflective optosensors, and 1 IR emitter and 1 IR receiver for communication, whose range is of approximately $1.20m$.

The design and building of a gripper was a very important challenge in the building of Mini-trans due to the precision required in a servomotor to operate the gears that open and close the gripper. In order to design and build an efficient gripper for modular robots, an important number of issues should be considered. The form and size of the assembling devices, the length of opening, the resistance and position where the gripper will be fixed, are for instance, key issues to be considered. Five grippers were designed and built. The definitive gripper of Mini-trans is able to hold another robot through one of the three cuts located on the third plate of each module of Mini-trans. This way of assembling does not require the precision of a pin-hole or other specific connection devices. Figure 2 shows one module of Mini-trans (a), its gripper (b) and a connection between two modules (c).



(a) (b) (c)

Fig. 2. Module of Mini-trans system (a). Each module is equipped with one gripper (b). Connection between modules (c)

3.2 Individual Capabilities

To summarize, each module of Mini-trans system is a mobile and autonomous robot able to send and receive messages, connect and disconnect to other modules at any of its attachment points. These modules are also able to move omnidirectionally and detect collisions around themselves. Finally, robots are able to identify a black circle on the floor that represents an objective region (see Figure 5 (c)).

3.3 Collective Capabilities

The modules of Mini-trans system have collective capabilities such as communication, self-assembling and coordinated motion that are described below.

Communication. The modules can communicate sending and receiving different IR coded signals. While sending a signal, a robot is unable to receive any signal, and vice versa. The messages used by robots are "connect", "disconnect", "ready", "wait", "stop" and "move".

Self-assembling. Each module is able to assemble another through one of the three cuts on the third plate. When one module receives the message "connect" from another module, the module closes its gripper. Once the gripper is closed, the module detects that the assembling was done. Then, the module communicates to another module that the connection was successful. On the other hand, when the message "disconnect" is received, the module opens its gripper and moves away from the other module and notifies that the disconnection was successful. Two or more connected modules can assemble another one, making then a linear formation.

Coordinated motion. When two or more modules are connected in linear formation, they can move keeping this formation. The module that is connected to another one is considered a `follower module`. In contrast, the module to which a module is connected is considered a `leader module`.
When modules are connected, the `leader` communicates the `follower` that the collective movement will start. Then, the `follower` moves forward until the gap between itself and the `leader` is full up. If the `leader` collides with an obstacle, it stops and communicates "disconnect" to the `follower`. `Follower` disconnects from the `leader` and moves away from it.

4 Experiments and Results

In this section, some experiments designed to measure the performance of Mini-trans are presented. These experiments were conducted using two modules of the Mini-trans system.

The experiments were conducted in a $1.5m \times 1.5m$ area. Both robots started at the same time. The `leader` robot searched a goal position indicated by a black circle painted on the floor while the `follower` robot waited for a signal. When this signal was perceived, the `follower` robot went towards the `leader` robot which was waiting. When the `follower` robot reached the `leader`, it informed its arrival to the `leader`. Then, the `leader` robot requested the `follower` to connect to it. The `follower` connected and notified `leader` that its connection had been done. Then, `leader` requested `follower` that motion must start and both robots started to move keeping the connection until an obstacle was perceived by `leader`. When the `leader` collided against an obstacle, it stopped and requested `follower` a disconnection. When `follower` received the message "disconnect", it disconnected from `leader`, moved away and notified to the `leader` that disconnection had been done. Then, both robots continued their exploration individually. The control of both robots is illustrated in Figure 3.

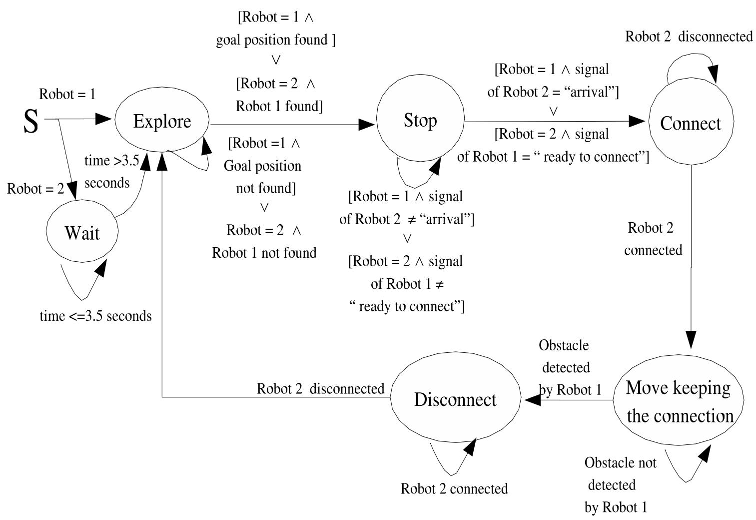


Fig. 3. Automaton that summarizes the general behavior of Mini-trans system. Behaviors such as **Wait**, **Explore**, **Stop**, **Connect**, **Move keeping the connection** and **Disconnect** are constantly executed. A robot may take one of two roles: `leader` (Robot 1) or `follower` (Robot 2). Robot 1 is the robot which waits for Robot 2 to connect to it. **Wait** consists in staying immobile during 3.5 seconds. **Explore** consists in moving within the environment until the goal position, an obstacle or robot 2 is found. **Stop** consists in finishing any activity. **Connect** is the process applied to connect to another robot using the gripper. **Move keeping the connection** consists in the movement executed by two connected robots until an obstacle is found by `leader`. Finally, **Disconnect** is the process applied to disconnect the modules of the system. **Connect**, **Move keeping the connection** and **Disconnect** require the exchange of messages and the waiting of certain time to send or receive a signal

The time that robots spent doing each behavior in 10 1-minute experiments is shown in Table 1.

Figure 4 illustrates the average time taken by the behaviors that were programmed, as well as the average time when robots exchanged messages and executed connection and disconnection. As this figure shows, robots are able to swap from individual action (**explore**) to collective actions (**connect**, **move keeping the connection** and **disconnect**) and to individual action again.

Table 1. Time in seconds spent by two robots, R1 and R2, during 10 tests. Robots had to go towards a goal position, connect, move connected, disconnect when an obstacle was perceived, and continue to explore individually during a constant time. Second robot (R2) had to wait 3.5 seconds before to start its operation

		Behaviors							
No. test		Wait	Explore	Stop	Connect	Move keeping the connection	Disconnect	Explore	Duration of the experiment (seconds)
1	R1	0.00	3.80	4.60	10.03	12.83	10.48	10.00	
	R2	3.50	4.91	3.26	10.81	12.20	13.98	10.00	58.66
2	R1	0.00	3.57	4.38	12.18	12.04	9.27	10.00	
	R2	3.50	4.97	4.14	13.34	9.15	13.98	10.00	59.08
3	R1	0.00	4.21	6.24	16.28	11.55	8.51	10.00	
	R2	3.50	3.94	10.32	14.86	8.72	13.98	10.00	65.32
4	R1	0.00	3.48	4.78	9.13	11.45	9.48	10.00	
	R2	3.50	2.75	4.90	10.43	11.18	13.97	10.00	56.73
5	R1	0.00	3.47	5.50	9.95	12.42	8.42	10.00	
	R2	3.50	5.58	4.30	11.07	9.53	13.98	10.00	57.96
6	R1	0.00	3.34	3.62	9.11	12.76	9.48	10.00	
	R2	3.50	4.13	6.26	10.30	11.57	13.97	10.00	59.73
7	R1	0.00	3.45	4.52	10.13	12.86	8.52	10.00	
	R2	3.50	4.47	3.07	12.96	10.14	13.97	10.00	58.11
8	R1	0.00	3.37	3.62	10.01	12.58	8.51	10.00	
	R2	3.50	3.90	7.40	10.45	11.80	13.98	10.00	61.03
9	R1	0.00	3.45	3.80	9.12	12.75	8.52	10.00	
	R2	3.50	4.31	4.14	10.29	9.95	13.97	10.00	56.16
10	R1	0.00	3.30	3.47	9.53	12.63	8.49	10.00	
	R2	3.50	3.53	3.24	12.12	9.76	13.98	10.00	56.13
$\bar{x}$	R1	0.00	3.54	4.45	10.55	12.39	8.97	10.00	
	R2	3.50	4.25	5.10	11.66	10.40	13.98	10.00	58.89

Figure 5 shows a sequence of snapshots taken during an experiment where robots were controlled by the automaton illustrated in Figure 3.

5 Conclusion and Perspectives

In this paper, the progress in the development of a multi-robot-system that consists of two modules with self-assembling capabilities has been described. The existing self-reconfigurable robots involve, as this paper has reviewed, considerable resources in the number of sensors and actuators, as well as in the

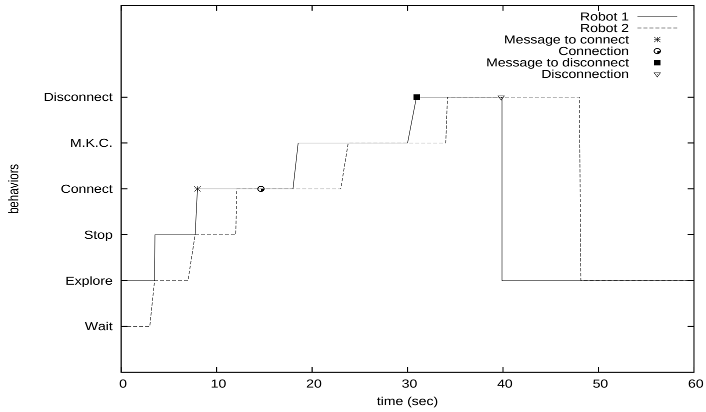


Fig. 4. Average duration of behaviors and average time in which robots exchange messages during the experiments described in Table 1. The alternation of behaviors illustrates the synchronization in the robots operation. M.K.C. means move keeping the connection

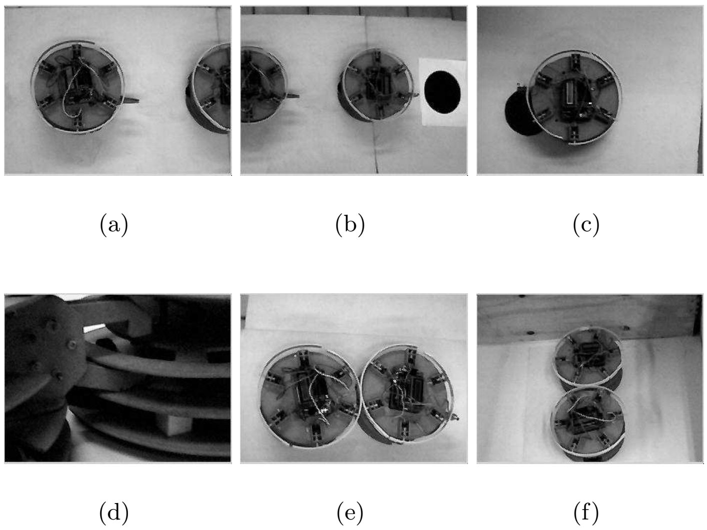


Fig. 5. Experiment divided into 6 steps: Wait (a), Explore (b), Stop (c) Connect (d), Move keeping the connection (e), Disconnect (f). The `leader` robot finds a goal position indicated by a black circle. When this position is found, the `leader` stops and waits for the `follower` robot. The `follower` robot waits 3.5 seconds to start, and then searches for the `leader` robot. When the `follower` finds the `leader` robot, both robots connect their bodies and move coordinating their movements. When the `leader` robot finds an obstacle, it stops and they disconnect their bodies. In order to coordinate their actions, robots exchange messages such as "ready to connect", "successful connection" and so on through their IR sensors

electronics to control them. Our prototype is much simpler compared with these systems. Various tests have been made in order to select and validate experimentally the simplest materials that are required to build a mobile reconfigurable multi-robot system.

The development of the Mini-trans system is in progress. Future work will focus on the design and implementation of more complex coordination mechanisms to enable robots to adapt their arrangement to the form of an object they are pushing, as well as to cope with obstacles when they are moving in assembled form. A third module is almost finished and ready for integration into the Mini-trans system.

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