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***Abstract*— We present the first attempt to accomplish a simple manipulation task by a set of randomly scattered modules that self-assemble into a modular robot. The manipulation consists in the transport of a heavy object towards a light beacon. The modules have no knowledge about their spatial arrangement. The object and the light beacon are detected by the modules' sensors.**

We present quantitative results obtained with up to six physical robots confirming the efficacy of the system.

I. Introduction

Modular robotic systems have received increasing attention from researchers in the last two decades as they hold the promise of versatility, robustness, and low cost [1], [2]. A *modular robot* is a robotic system composed of autonomous modules that can be connected in manifold ways. Typically, the number of module types is far less than the number of modules.

In some modular robotic systems, the reconfiguration of modules has to be carried out manually [3], [4]. However, most system are *self-reconfigurable*, that is, they can change the arrangement in which the modules are connected [5]–[8]. Based on their nature of reconfiguration, most self-reconfigurable robotic systems can be classified as *chain*, *lattice* or *mobile* reconfigurable systems [1]. While for the first two types, the system usually remains as one connected component, mobile modular systems self-reconfigure by having modules detach themselves and move independently to another location to reconnect.

In order to control a reconfigurable robot, centralized and decentralized architectures have been investigated. Some reconfigurable robots are capable of self-repair (i.e., to detect, reject and replace non-working modules) [9], [10], self-assembly (i.e., to aggregate independent modules and/or modular robots into a single body) [11]–[14], locomotion on a plane [15], [16], and all-terrain navigation [7], [17]–[19].

Little attention has been paid to interactions between a self-reconfigurable robot with its environment. In recent studies, modular robots are provided with sensory feedback, and can adapt to environments that are not known in advance [20]–[22]. Some works considered to manipulate the environment by a modular robot [15], [23]. However, in these cases, the modular robot is stationary and has explicit knowledge about the position of the object to manipulate. In contrast, we consider the mobility and the perceptual abilities of modular robots engaged in the manipulation of the environment.

In this paper, we address a simple manipulation task by a mobile, self-reconfigurable robot. The task consists in the transport of a heavy object towards a light beacon. It cannot be solved by a 1-module robot alone. The control of the modules is decentralized and homogeneous. The modules are not provided with any explicit knowledge about the positions of other modules, the object or the light beacon.

The paper is organized as follows. Section II introduces the experimental system. In Section III we study the manipulation of the object by modular robots that are manually arranged and connected to the object by the experimenter. We analyze the impact of frictional forces between the modular robots and the ground. Moreover, we examine the performance exhibited by the modules when being arranged in different patterns. In Section IV, we consider the case in which the robot modules are initially randomly scattered in the environment. We aim at controlling the modules so that they autonomously form modular robots which in turn manipulate the environment.

II. System Design

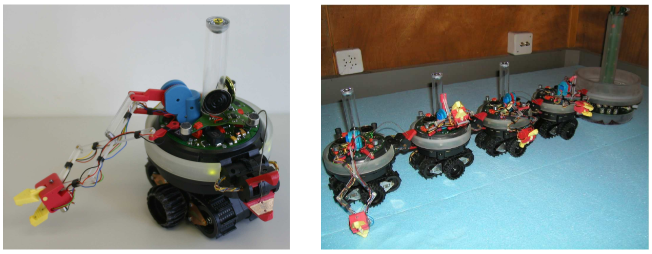
We are using a mobile self-reconfigurable robot called *swarm-bot* [24], [25]. The modules comprising a *swarm-bot*, called *s-bots*, are fully autonomous and mobile. S-bots can self-assemble, that is, they can autonomously connect to each other to form a modular robot. This ability was demonstrated on different types of terrain with up to 16 physical modules [14].

In the following the robot's hardware and control are detailed.

A. Hardware Design

Fig. 1a shows the physical implementation of the s-bot. It has a height of $19\,\mathrm{cm}$ (in total) and weighs $700\,\mathrm{g}$ approximately.

The s-bot has nine degrees of freedom (DOF), all of which are rotational, including two DOF for the traction system, one DOF to rotate the s-bot's upper part (called the *turret*) with respect to the lower part (called the *chassis*), one DOF for the grasping mechanism of the rigid gripper (in what we define to be the s-bot's front), and one DOF for elevating the arm



(a) (b)

Fig. 1. The swarm-bot concept: (a) a single module called s-bot capable of locomotion and perceiving the environment, (b) a modular robot called *swarm-bot* composed of four s-bots manipulating an object.

to which the rigid gripper is attached (e.g., to lift another s-bot). A versatile arm with four DOF is attached to the side of the turret and supports a second grasping device; the arm was not mounted when running the experiments presented in this paper. For the purpose of robot-robot communication, the s-bot has been equipped with eight RGB LEDs distributed around the s-bot, and two loudspeakers.

The s-bot's traction system consists of a combination of tracks and two external wheels, called *treels*©. When connected in a group, the chassis of an s-bot can be aligned in any (horizontal) direction. This allows for a coordinated motion of the modules in the group.

The s-bot is equipped with a surrounding ring matching the shape of the gripper (see Fig. 1). This makes it possible for the s-bot to receive connections on more than two thirds of its perimeter.

The s-bot is equipped with a variety of sensors, including 15 proximity sensors distributed around the turret, a VGA omni-directional camera, and optical light barriers integrated in the two grippers. Furthermore, proprioceptive sensors provide internal motor information such as the torque acting on each side of the tracks.

The proximity sensors can perceive other objects for distances up to $15\,\mathrm{cm}$. They can also be used to perceive a light beacon indicating the target location of the transport task. The omni-directional camera can detect s-bots and objects that have activated their LEDs in different colors. It can also be used to perceive the light beacon. The gripper is equipped with optical light barriers to test whether an object to grasp is present or not. By monitoring the torque of the internal motors (e.g., of the treels©), the s-bot gets additional feedback which can be exploited in the control design.

The s-bot runs a Linux operating system at $400\,\mathrm{MHz}$. A $10\,\mathrm{Wh}$ Lithium-Ion battery provides more than two hours of autonomy. For a more comprehensive description of the s-bot's hardware see [25].

B. Control Design

We aim at controlling a group of s-bots in fully autonomous manner to transport a heavy object towards a target.

The control system described in this section has been previously designed in a relatively simple simulation environment [26], and subsequently transferred to the real s-bot. The control is decentralized (i.e., fully distributed) and homogenous (i.e., all group members have identical control). It comprises two sub-modules: the "assembly" module, which is in charge of controlling the s-bot until it is connected to the object or to another s-bot; and the "transport" module, which allows the s-bot to move the object towards the target area once a connection is established. In the following, we detail the working of the two sub-modules.

Algorithm 1 Assembly module

```
1:  activate color ring in blue
2:  repeat
3:    (i1, i2) ← featureExtraction(camera)
4:    (i3, i4) ← sensorReadings(proximity)
5:    (o1, o2, o3) ← neural network(i1, i2, i3, i4)
6:
7:    if (o3 > 0.5) ∧ (grasping requirements fulfilled) then
8:      grasp
9:      if successfully connected then
10:       activate color ring in red
11:       halt until timeout reached
12:     else
13:       open gripper
14:     end if
15:   end if
16:   apply (o1, o2) to tracks
17: until timeout reached
```

1) Assembly module: We aim at controlling a group of s-bots in fully autonomous manner in such a way that they locate, approach and connect directly with an object that acts as a seed or with other *s-bots* already connected to the seed.

The process of self-assembling is governed by the attraction and repulsion among s-bots, and between s-bots and the seed. The color ring of the seed is permanently activated in red. Initially, all s-bots set the ring color to blue. The controller lets the s-bots avoid blue objects, and approach/connect with red objects. Thus, the process is triggered by the presence of the seed. Once an s-bot has established a connection, the color of its ring is set to red. Therefore, it becomes itself an object with which to establish a connection. The basic principle of signaling the state (of being connected or unconnected) allows the emergence of (global) connection patterns of dimensions beyond the s-bot's (local) sensing range.

Algorithm 1 details the control module for self-assembly. The main component is a feed-forward two-layers artificial neural network (line 5) that maps sensory inputs to motor commands. At each control cycle, the network takes as input the values i_1, i_2, i_3 and i_4. $i_1 \in \{0,1\}$ and $i_2 \in \{0,1\}$ are set by extracting and pre-processing data from the s-bots vision system (line 3). The input variables $i_3 \in [0,1]$ and $i_4 \in [0,1]$ take the reading of the front-left-side and front-right-side s-bot's proximity sensors (see Algorithm 1, line 4). The network's output (o_1, o_2, o_3) is used to control the speed of the left and the right wheels (see line 16) and the connection mechanism (see lines 7 to 15). By default, the tuple (i_1, i_2) is

Algorithm 2 Transport module

```
1:  repeat
2:    α ← computeTargetDirection(camera)
3:    if (stagnation) then
4:      execute recovery move
5:    else
6:      if (risk of stagnation) then
7:        turn on the spot towards α
8:      else
9:        move, softly re-aligning towards α
10:     end if
11:   end if
12: until timeout reached
```

assigned $(0, 0)$. Any other assignment indicates the presence of red objects (in the front, or to the left or right side). If, an obstacle (a blue object) is present in between, i_1 and i_2 remain zero. The network's weights have been shaped by artificial evolution in the context of a cooperative transport task. For a more comprehensive description of the assembly module see [14], [26].

2) Transport module: Algorithm 2 describes the transport module which allows a connected s-bot to align its chassis towards the light beacon indicating the target, and to apply pushing/pulling forces in order to move the object towards the target.

The transport module exploits either the camera vision system or the proximity sensors to detect the angular position of the light beacon with respect to the s-bot's heading. By adjusting the orientation of the chassis with respect to the s-bot's heading (i.e., the orientation of the turret) the s-bot's controller sets the direction of motion α. The realignment of the chassis is supported by the motion of the tracks. We implemented two different types of realignment referred to as "hard" and "soft" alignment. The hard alignment makes the s-bot turn on the spot (see Algorithm 2, line 7). The soft alignment makes the s-bot turn while moving forward (see Algorithm 2, line 9).

During the transport, the s-bot monitors the magnitude of the torque acting on its tracks and on the turret. If the torque values exceed a certain threshold, there is stagnation. In this case, a recovery move is performed to prevent the hardware from being damaged. The recovery move lasts about $160\,\mathrm{ms}$. During this time the s-bot moves slowly forward and backward.

III. Transport by Modular Robots

In this section we study simple object manipulation by modular robots (consisting of s-bots) that are manually connected to the object by the experimenter. The more complex situation in which modules have to self-assemble before manipulating the object is considered in the subsequent section. The task is to pull or push the object towards a light beacon. We analyze the impact of frictional forces between the modular robots and the ground. Moreover, we examine the performance exhibited by the modules when being arranged in different connection patterns.

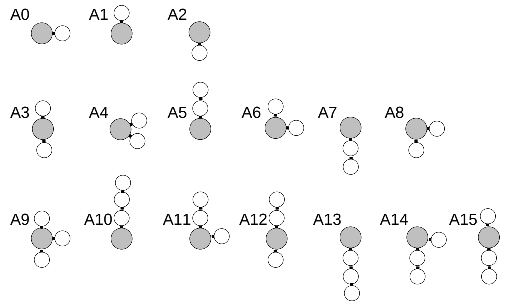


Fig. 2. Experimental setup. An object has to be transported towards a target (on the right side, not shown). S-bots are manually attached to the object in one of the spatial arrangements shown in the figure. In each arrangement, every s-bot has visual contact with the target.

TABLE I
Friction coefficients for the grounds G_0 and G_1.

	object	s-bot (lateral)	s-bot (longitudinal)
ground G_0	0.46	0.57	0.58
ground G_1	0.41	1.30	1.80

A. Experimental Setup

We examine the transport of an object by a homogeneous group of s-bots (see Fig. 1b) . The object has a weight of $813\,\mathrm{g}$. It has to be transported towards a target (i.e., a light beacon). Object and target are placed at the opposite sides of an arena. The initial distance between the object and the target is $250\,\mathrm{cm}$.

In this study, groups of 1–3 s-bots are used. The s-bots are physically connected to the object from the beginning. The connection of an s-bot can be made either directly to the object or indirectly via one or more connected s-bots. In the latter case, the s-bots form a modular swarm-bot robot. We studied 16 distinct spatial arrangements $\{A_0, A_1, \ldots A_{15}\}$ as illustrated in Fig. 2. All arrangements ensure that at the beginning the target is visible for each s-bot.[1]

We examine the performance of the system on two different grounds (G_0 and G_1). Both grounds are flat. Friction coefficients have been determined experimentally and are listed in Table I. For ground G_0, we consider the friction coefficient between the s-bot and the ground as moderate. For ground G_1, horizontal forces applied to the s-bot cause the s-bot either to topple down or they will displace the s-bot by a sequence of irregular movements. We consider ground G_1 as a very difficult test-bed, since a group of s-bots connected to each other and/or the object might easily get stuck, if individual actions are not coordinated properly.

[1] At the time of experimentation, the s-bot camera device driver was not yet available. Therefore, the proximity sensors have been used to detect the target. Contrary to the omni-directional camera, the proximity sensors cannot perceive a light beacon if an s-bot is located in between.

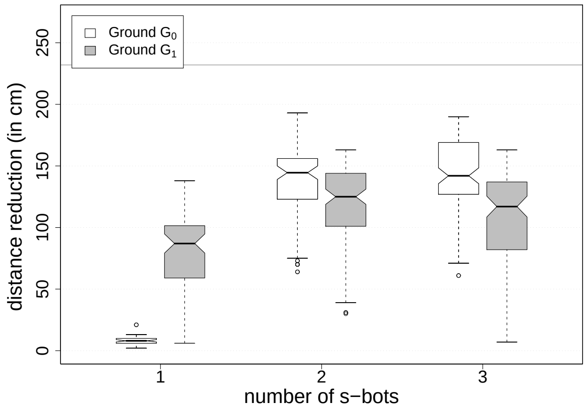


Fig. 3. Box-and-whisker plot [27] showing the observed distances (in cm) by which the object approached the target during the test period of $15\,\mathrm{s}$. Observations are grouped according to the number of s-bots and the type of ground used. Observations per box (from the left to the right): 42, 75, 90, 120, 105 and 105. The horizontal line on top indicates an upper bound for the transport performance assuming a weightless object (for details see text). If the notches of two plots do not overlap this is *strong evidence* that the two medians differ [27].

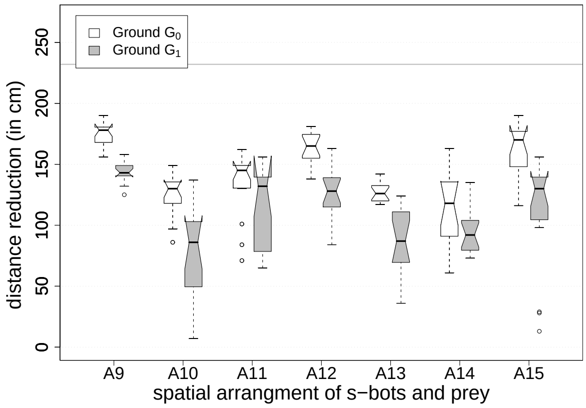


Fig. 4. Box-and-whisker plot [27] showing the observed distances (in cm) by which the object approached the target during the test period of $15\,\mathrm{s}$. Observations of three s-bot experiments grouped according to the spatial arrangement used (15 observations per box). If the notches of two plots do not overlap this is *strong evidence* that the two medians differ [27].

B. Experimental Results

To assess the performance of the group on the grounds G_0 and G_1, in total more than 500 trials have been performed. In each trial, the object has to be transported towards the target within a fixed time period of $15\,\mathrm{s}$. The performance metric we use is the difference of the initial and the final distance (in cm) between the object and the target.

The distance an s-bot can cover on ground G_0 or G_1 during the time period of $15\,\mathrm{s}$ is about $232\,\mathrm{cm}$.[2] On ground G_0 an s-bot can move the object within $15\,\mathrm{s}$ for about $8\,\mathrm{cm}$ by pulling it backwards with maximum speed. However, a chain of two s-bots can pull the object for about $210\,\mathrm{cm}$. Since a group cannot transport a load faster than the maximum speed of each group member, a chain of two s-bots is sufficient for reaching near optimal performance (i.e., 91% of the theoretical upper bound).

Fig. 3 plots the distance (in cm) by which the object approached the target. The white boxes refer to the transport performance of groups of $1-3$ s-bots on ground G_0. One s-bot was nearly incapable of moving the object in all trials. On the contrary, two and three s-bots have transported the object during each of the 90 trials for more than $60\,\mathrm{cm}$. The whiskers of the plot cover observations in the intervals [2, 13], [75, 193] and [71,190], respectively.

The gray boxes in Fig. 3 refer to the transport performance of groups of $1-3$ s-bots on ground G_1. The whiskers cover observations in the intervals [6, 138], [39, 163] and [7, 163].

Due to the better grip the tracks have on the ground G_1, a single s-bot itself is already capable of transporting the object. Nevertheless, for the group sizes 2 and 3, the system performs significantly better for ground G_0. Note that the magnitude of the force necessary to move the object on ground G_0 is slightly bigger than for ground G_1 (see Table I).

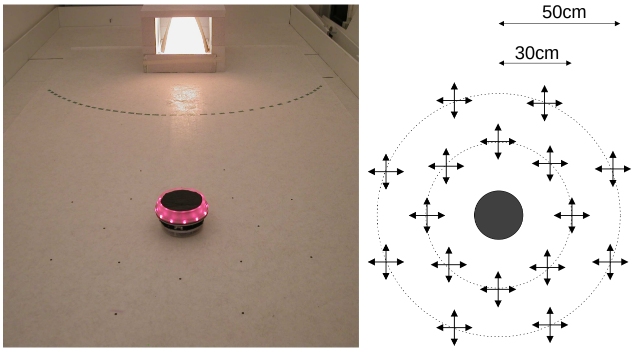
[2]The maximum speed of the wheels is chosen as for the transport controller.

As discussed previously, the task can be solved near optimally by two s-bots. There seems to be no gain in performance by adding the third s-bot. On the other hand, the third s-bot does not disrupt the performance either.

In the following we examine the results for groups of three s-bots in more detail. The box-and-whisker plot shown in Fig. 4 groups observations belonging to the same spatial arrangement. The white boxes refer to trials performed on ground G_0, while the gray ones refer to trials performed on ground G_1. For all different spatial arrangements, the median performance on ground G_0 is superior to the median performance on ground G_1. Although the performance of a single s-bot is superior on ground G_1 which provides the s-bot's tracks with a better grip, a group of s-bots performs better on ground G_0. On ground G_0 the tracks of the s-bot may slide more easily when compared to ground G_1. Therefore, individual misalignments of the tracks might results in a lower decrease in performance.

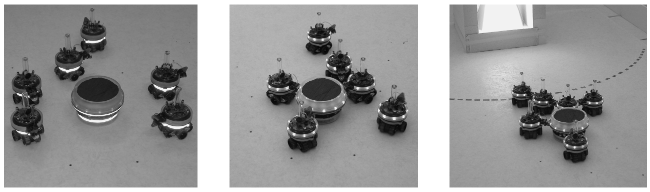
By comparing the patterns of the white and the gray boxes, it can be recognized that the spatial arrangement of the s-bots affects the performance. Overall, it seems that the arrangements A_9, A_{12} and A_{15}, which are those in which at least one s-bot is located on both sides of the object (with respect to the target) result in a better performance than the others. This is plausible, since these arrangements are more stable and the forces exerted by the s-bots result in a translation of the object rather than a rotation. In addition, if an arrangement is stable from the beginning, all s-bots can perceive the target during the whole duration of the transport. On the contrary, if a structure rotates, s-bots may lose visual contact to the target. Consequently, the performance can decrease.

In the only symmetric case (arrangement A_9), the *lowest* transport distance observed over all trials on ground G_0 (G_1) is still 67% (54%) of the distance a single s-bot moving straight without any load can cover within the same amount of time.



(a) (b)

Fig. 5. (a) Overview of the arena with the object located at a distance of $225\,\mathrm{cm}$ from a light bulb which represents the center of a circular target zone. (b) Potential starting points and orientations of the s-bots around the object.



(a) (b) (c)

Fig. 6. These pictures shows a sequence of actions, during a trial, in which a group of six s-bots randomly placed around the object (a), initially locates, approaches and connects to the object (b) and finally, once assembled, transports the object to the target zone (c).

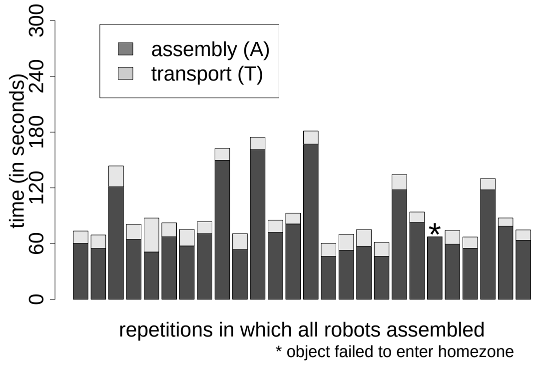


Fig. 7. Time necessary for a group of six robots to self-assemble and transport the object inside the target zone.

IV. Transport by Modular Robots that Self-assemble

In this section we consider the case in which the s-bots are initially randomly scattered in the environment. We aim at controlling the modules so that they autonomously form modular robots which in turn manipulate the environment.

A. Experimental setup

The manipulation task requires the s-bots to locate, approach and grasp the object—that has to be subsequently transported from its initial location to a target zone. The experimental setup is shown in Fig. 5a. The object is initially located at a distance of $225\,\mathrm{cm}$ from a light beacon. The target zone is a circular area centered around the beacon. The group is considered to be successful if the s-bots manage to move the object inside the target area within $300\,\mathrm{s}$. If moved in a straight line, the distance covered by the object to enter the target zone is $125\,\mathrm{cm}$.

At the beginning of each trial, six s-bots are positioned in the vicinity of the object. The initial position of each s-bot is assigned randomly by uniformly sampling without replacement from a set of 16 specific starting points. The s-bots initial orientation is chosen randomly from a set of 4 specific directions. The 64 potential placements (16*4) of a single s-bot are illustrated in Fig. 5b. The s-bots do not have any knowledge about their starting positions.

The object weighs $2310\,\mathrm{g}$ and cannot be moved by less than four s-bots. However, even four s-bots may not be sufficient to perform the task. In fact, the performance also depends on the way in which the s-bots are connected to the object and/or to each other. Four s-bots, connected in a “star-like” formation around the object can move it with an average speed of about $1\,\mathrm{cm\,s^{-1}}$. Regardless the way in which they are connected, a group of six s-bots pulling and/or pushing the object is always capable of moving the object.

B. Experimental Results

In this section, we report data which represents a quantitative description of the performance of the s-bots engaged in the cooperative transport task. Recall that in this task, six s-bots are required to self-assemble and transport the object from its initial position to a target zone. A trial can be divided in two different phases. In the first phase, the s-bots are controlled by the assembly module. Thus, they try to establish a connection either directly to the object or indirectly via a chain of other s-bots. To enable all s-bots to establish a connection before the object starts moving, connected s-bots transport the object only when they do not perceive any unconnected teammates (i.e., if no blue object is perceived; see also Section II-B.1). The assembly phase terminates once every s-bot has successfully established a connection. In the subsequent phase, all s-bots are controlled by the transport module to push/pull the prey towards the target. This phase terminates when the object enters the target zone.

We performed 30 replication of the experiment—i.e., 30 trials. A trial begins with the s-bots randomly placed around the object, and it ends (a) successfully if the s-bots manage to transport the object inside the target zone within the time limit (i.e., $300\,\mathrm{s}$), or (b) unsuccessfully if, for any reason, the s-bots fail to transport the object to the target-zone within the time limit. Fig. 6 shows a sequence of three pictures taken from a successful trial.

In 26 out of 30 trials, all six s-bots connected. In trials n. 3, n. 12, and n. 29, a single s-bot failed to connect. In trial n. 18 two s-bots failed to connect. Thus, out of the 180 connections required by the 30 trails—i.e., six connections per trial times 30 trials—we recorded only 5 failures. Due to one or two s-bots that remain unconnected, in 4 out of 30 trials the s-bots did not manage to reach the transport phase. In fact, in these unsuccessful trials, several s-bots did not activate the transport module as they perceived an unconnected s-bot. Recall that connected s-bots start transporting the object only if they do not perceive any unconnected teammate.

Fig. 7 shows the amount of time per trial spent by the s-bots in the two phases of the experiments mentioned above. Data concerning the four unsuccessful trials in which one or more s-bots fail to establish a connection are not shown. In 20 out of the 26 trials, the whole group could successfully self-assemble within 83 s, in the other trials self-assembly was successfully completed within 167 s.

Only in a single case out of those in which the s-bots connected successfully, the group failed to transport the object entirely inside the target zone. In this unsuccessful trial, the transport was interrupted in the proximity of the target zone. This failure during the transport phase was probably due to the light reflections in the immediate vicinity of the beacon which indicates the target zone. In fact, a too high intensity of the light disrupts the mechanism used by each s-bot to establish the direction of movement. Therefore, it may happen that, in the immediate vicinity of the target, the entire group loses efficiency in moving the object.

In all other cases, the object entered the target zone within a short period of time; the average transport speed was $8.20\,\mathrm{cm}$ per s, which is about 55% of the maximum speed of a single s-bot moving without any load.

V. Conclusion

This paper reports on a series of experiments that present a first attempt to perform a manipulation task by a non-stationary modular robotic system.

In a first experiment, modules were manually arranged and connected with the object to manipulate. We analyzed the impact of frictional forces present in the environment and the spatial arrangement of the modules on the system performance.

In a second experiment, we demonstrated the ability of modules that are randomly scattered in the environment to self-assemble into modular robots which in turn manipulate the object.

We presented quantitative results obtained with up to six physical modules confirming the validity of our approach. We showed that mobile self-reconfigurable robots can organize themselves in large pulling structures such as chains. This allows to manipulate heavy objects which provide only limited surface for direct robot-object interactions.

Future work has to face the question on how to adapt the shape of the robot and the number of its modules according to the changing demands of unknown environments.

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