Orlando, Florida - May 2006

Transport of an Object by Six Pre-attached Robots Interacting via Physical Links

Roderich Groß*, Francesco Mondada†, and Marco Dorigo*
*IRIDIA, Université Libre de Bruxelles, 1050 Brussels, Belgium,
Email: {rgross,mdorigo}@ulb.ac.be
†Autonomous System Lab (ASL), École Polytechnique Fédérale de Lausanne,
1015 Lausanne, Switzerland, Email: francesco.mondada@epfl.ch

***Abstract*— This paper addresses the cooperative transport of a heavy object by a group of mobile robots. We present a system in which group members lacking knowledge about the position of the transport target exploit physical interactions with other members of the group that have such knowledge. This is the first such system to achieve a performance superior to that of a passive caster. The system is fully decentralized and the information flow between the robots is limited to physical interactions. The robots have no knowledge about their relative positions. A comprehensive experimental study with up to six physical robots confirms the effectiveness, reliability, and robustness of the system. Finally, the system is examined in rough terrain conditions.**

I. Introduction

Multi-robot systems have received increasing attention from researchers in the last two decades. Groups of mobile robots have been controlled to display a wide repertoire of task-oriented behaviors, for instance, aggregation [1], exploration [2], group motion [3], and object manipulation [4]. It is this latter class of behaviors that we focus on in this work.

Recently, a new type of multi-robot system called *swarm-bot* has been proposed [5], [6]. *Swarm-bot* is a distributed robotic concept lying in-between collective and self-reconfigurable robotics. The robots comprising a swarm-bot, called *s-bots*, are fully autonomous and mobile (see Fig. 1a). However, they can also grasp each other to form a modular robot that can self-reconfigure its shape.

The ability of a group of six physical s-bots to autonomously connect to an object and/or to each other has been experimentally validated on different types of flat and rough terrain [7], [8]. The performance of the system has shown to scale well with group size. Experiments were conducted with up to 16 physical robots, and up to 100 in simulation [7], [8].

In this paper we address the problem of controlling a group of s-bots to transport an object towards a target location (see Fig. 1b). We assume the s-bots to be physically connected to the object with their grippers. We study a leader-follower system of N mobile robots of which $N - N_B$ robots are leaders, capable of perceiving the target, while N_B robots are followers, that is, they have no knowledge about the position of the target. We aim at controlling the follower robots so that they contribute to the performance of the group.

Such heterogeneity can either be designed into the system, or might arise during task execution if, for instance, some robots of the group have hardware failures of their sensing system. Or, it might be due to the nature of the environment: for example, the presence of obstacles, teammates, or of the object being manipulated can make it impossible for some of the robots to perceive the target.

(a) (b)

Fig. 1. (a) The s-bot robot. (b) Problem description. A group of two robots has to transport an object towards a target location. The robot on the left has no camera and therefore cannot see the target, while the robot on the right can see the target. The task requires cooperation of the two robots. The robots can sense each other's physical interactions with the object. This provides a means of communication.

The paper is organized as follows. Section II overviews the related work on group transport by mobile robots. Section III details the hardware and control of our robotic system. In Section IV, we show that, in a group of two robots, a *blind* robot, that has no knowledge about the position of the transport target can exploit physical interactions to achieve a performance superior to that of a passive caster. This allows the group to transport an object that otherwise cannot be moved by the *non-blind* robot alone. In Section V, we address the problem of scalability. We examine the performance of a single blind robot when being part of a bigger group. Moreover, we investigate whether multiple blind robots may display cooperative behaviors that contribute to the performance of the group. Finally, in Section VI, we study group transport in rough terrain conditions.

II. Related Work

In the following we briefly review studies on group transport by physical, mobile robots. The related work is partitioned into the two main approaches to solve the task, that is, pushing/caging strategies and grasping/lifting strategies. Note that there are also a few other approaches, for instance, strategies that let robots make use of tools such as a rope [9],

[10], that are not considered here.

1) Transport by Pushing or Caging: Pushing behaviors have the advantage that they allow robots to move objects that are hard to grasp. In addition, multiple objects can be pushed at the same time. On the other hand, it is difficult to predict the motion of the object and of the robots, especially, if the ground is not uniform.[1] Therefore, the control typically requires sensory feedback.

Most studies consider two robots pushing a wide box simultaneously from a single side [4], [12]–[15]. To coordinate the robots' actions, robots are specifically arranged [4], [12], [14], [15], control is synchronized [12], relative positions are known [4], [14], explicit communication is used [12], [14], or individuals tasks are generated by a designated leader agent [13], [15]. Only few systems considered more than two robots, pushing a wide box simultaneously [16]–[19]. In these cases, the control is homogeneous and decentralized. In addition, the robots make no use of explicit communication.

Kube *et al.* [18], [19] reported that if the object is small compared to the size of the pushing robots the performance decreases drastically with group size as the object offers only limited contact surface. A few other studies with multi-robot systems consider objects of the size of a single robot or less [20], [21]. However, in these cases the objects were light enough for a single robot to move them alone.

Recently, researchers considered a special case of multi-robot box-pushing in which the movable area of the object is bounded by the robots. This condition is referred to as *object closure* and the manipulation concept is denoted as *caging* [22]–[25]. Typically the object is light enough for a single robot to move it alone. In some systems a single robot can constrain the object in several directions using multiple contact points [23], [24]. To test and maintain the condition of object closure, decentralized control algorithms have been proposed [25], [26].

2) Transport by Grasping or Lifting: Many studies considered the transport of an object by multiple, mobile robots grasping and/or lifting it [27]–[39]. In some systems the desired trajectories are given prior to experimentation to all robots of the group. The object is transported as each robot follows the given trajectory by making use of dead-reckoning [27]. In other systems, the manipulation is planned in real-time by an external workstation which communicates with the robots [33], [35], [37]. Often, instead of an external computer, a specific robot called the *leader* knows the desired trajectory or the goal location. The leader robot can send explicit high- or low-level commands to the *followers* [32], [34]. However, in many leader-follower systems explicit communication is not required [29]–[31], [36], [38], [39]. Typically, this is realized in systems in which the object is lifted by the robots; the followers simulate the behavior of a virtual caster. None of these works considered the transport of an object by groups of more than four physical robots.

[1]For a theory on the mechanics of pushing see Mason [11].

III. System Design

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 approximately $700\,\mathrm{g}$.

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 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. 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 oriented 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. An omni-directional VGA camera can be used to detect the direction of a light source in the environment (e.g., the target of transport). A 2 DOF force sensor provides an estimate of the magnitude and orientation of the horizontal component of the force that acts on the hinge joint between the turret and the chassis of the s-bot. This force is affected by the s-bot's actions and by the force exerted by all the objects that are physically linked to the s-bot. Furthermore, proprioceptive sensors provide internal motor information such as the torque acting on each side of the traction system.

The s-bot runs a Linux operating system on an X-Scale processor 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 [6].

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 robots are physically connected to the object from the beginning. They have neither explicit nor implicit knowledge about their relative position. The system is fully decentralized. No explicit communication is used. Some robots (called the *non-blind* ones) are capable of perceiving the direction of the target (i.e., a light source), while others (called the *blind* ones) are not. In the following the corresponding controllers are detailed.

1) Controller for Non-Blind Robots: The transport module allows a connected s-bot to align its chassis towards the light source indicating the target, and to apply pushing/pulling forces in order to move the object towards the target. It is detailed in Algorithm 1.

During the transport, the s-bot monitors the magnitude of the torque acting on its traction system and on the turret. If

Algorithm 1 Transport module for non-blind robots

1: **repeat**
2: $\alpha \leftarrow$ compute target direction (camera)
3: $M \leftarrow M_{\text{max}}$
4: **if** (stagnation) **then**
5: execute recovery move
6: **else**
7: **if** (risk of stagnation) **then**
8: hard alignment (α)
9: **else**
10: soft alignment (α) and forward motion (M)
11: **end if**
12: **end if**
13: **until** timeout reached

the torque reading values exceed a certain threshold, there is *stagnation*. In this case, a short recovery move is performed to prevent the hardware from being damaged.

The transport module uses the camera vision system to detect the direction of the light source 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 controller sets the direction of motion α. The realignment of the chassis is supported by the motion of the traction system. 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. The soft alignment makes the s-bot turn while moving forward. The hard alignment is executed if there is risk of stagnation. This is the case, for instance, if the angular mismatch between the current and the desired orientation of the chassis exceeds a certain threshold. The parameter M_{max} is the maximum speed we set to an s-bot's traction system.

2) Controller for Blind Robots: The controller for those robots that have no knowledge about the target location can be derived from Algorithm 1. The only difference is in the lines 2 and 3: an Elman neural network [40] with four hidden nodes is executed in each iteration of the control loop. This network takes the input vector $(f_0, f_1, f_2, f_3, s, \theta)$. f_0, f_1, f_2, and $f_3 \in [0, 1]$ correspond to the sensor reading values of the 2 DOF force sensor with respect to four preferential directions; $s \in \{0, 1\}$ indicates whether or not stagnation, that is, high torque readings for the traction system or the turret, was observed in the past four control cycles; θ is the angular offset between the turret and the chassis. The neural network has two output nodes specifying the desired orientation α of the chassis (line 2), and the speed $M \in [0, M_{\text{max}}]$ of the traction system (line 3).

The parameters of the neural network, that is, the connection weights, have been determined in simulation by using an evolutionary algorithm (for details see [41]).

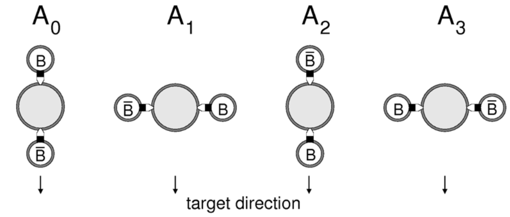

Fig. 2. Experimental setup. An object has to be transported towards a target. Two physical robot are manually attached to the object. They are labeled $\bar{B}$ and B, respectively. While robot $\bar{B}$ is fully operational, robot B is not capable of perceiving the target. The figure illustrates the four spatial arrangements used in the experiments.

IV. Transport by a Non-blind and a Blind Robot

A. Experimental Setup

We examine the transport of an object by a group of two s-bots. The object weighs $1000\,\text{g}$. It has to be transported towards a light source. Object and target are placed at the opposite sides of an arena of length $500\,\text{cm}$.[2] The two robots are labeled B and $\bar{B}$, respectively. While robot $\bar{B}$ is fully operational, robot B has a non-working vision system. Thus, it is *blind* and cannot perceive the target of transportation. Both robots are physically connected to the object from the beginning. They are put in one of the four distinct spatial arrangements (A_0, A_1, A_2, A_3) illustrated in Fig. 2.

We evaluate the performance of three distinct strategies: S_0, S_1, and S_2. In each case, robot $\bar{B}$ is controlled by the standard controller for non-blind robots (see Section III-B.1).

- S_0: The robot labeled B is manually replaced by a friction-less, passive caster. Note that in our experiments we manually remove the blind robot prior to experimentation as in our grasping based approach this is equivalent to having a friction-less passive caster.[3]
- S_1: The robot labeled B is controlled by the neural network based controller for blind robots (see Section III-B.2).
- S_2: The robot labeled B is manually replaced by a fully operational robot which in turn is controlled by the standard controller for non-blind robots (see Section III-B.1).

B. Results

For each pair $(S_i, A_j) \in \{S_0, S_1, S_2\} \times \{A_0, A_1, A_2, A_3\}$ ten trials lasting $25\,\text{s}$ are performed.

Fig. 3 plots the distance (in cm) by which the object approached the target. By looking at the dark gray boxes (strategy S_0) it can be seen that one s-bot alone was nearly incapable of moving the $1000\,\text{g}$ object when put in one of the spatial arrangements A_0, A_1, or A_3. However, when put in the spatial arrangement A_2 the s-bot moved the object for about $87\,\text{cm}$ (median value). It seems that the robot exerts a higher force while pushing the object than when pulling

[2] The initial distance between the object and the target is set to $437\,\text{cm}$.
[3] This is different from systems in which the robots lift the object, where a passive caster can facilitate the transport considerably.

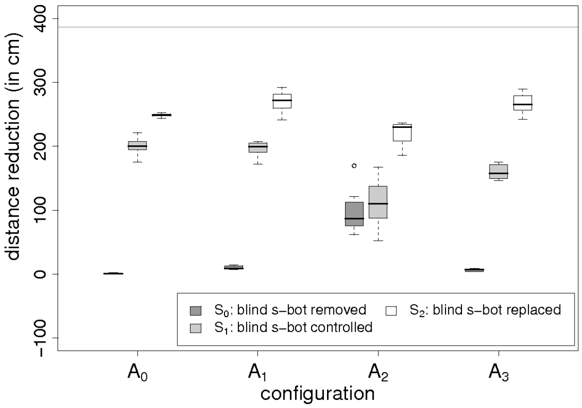

Fig. 3. Box-and-whisker plot [42] showing the observed distances (in cm) by which the object approached the target during the test period of 25 s. Observations are grouped according to the corresponding strategy and spatial arrangement (10 observations per box). The horizontal line on top indicates an upper bound for the transport performance assuming a weightless object (for details see text).

it (notwithstanding the fact that the magnitude of the force applied to the traction system is identical in both cases).[4]

As shown by the white boxes in Fig. 3, a group of two fully operational robots always achieved better performance than a single robot (for each spatial arrangement). An upper bound for the performance is given by the distance a single robot without any load can cover in the same time period (25 s) by moving straight.[5] The upper bound is $387\,\mathrm{cm}$ (indicated by the horizontal line in the figure). During transport this performance cannot be achieved because the robots are slowed down by the load they pull and push. The median performance of a group of two robots is 64%, 70%, 59%, and 69% of this theoretical value for the spatial arrangements A_0, A_1, A_2, and A_3, respectively.

The performance of strategy S_1 is significantly better than that of strategy S_0. This shows that the blind robot contributes to the performance of the group. To assess the quality of this contribution we introduce the following performance measures.

Let the environment of the transport task (i.e., the object and its initial location, the target and its location, the ground, etc.) be fixed. Let $\mathrm{P}^K(i, j) \in [0, \infty)$ be the performance of a group of i robots of which j are blind and whose task is to transport a specific object (the higher the value, the better). The robots are put in a specific spatial arrangement $K = (K^{(1)}, K^{(2)}, \ldots, K^{(i)})$, where $\{K^{(1)}, K^{(2)}, \ldots, K^{(i-j)}\}$ is the set of locations (and orientations) of the non-blind robots, while $\{K^{(i-j+1)}, K^{(i-j+2)}, \ldots, K^{(i)}\}$ is the set of locations (and orientations) of the blind ones.

Given a group size N, a number of blind robots N_B, a spatial arrangement $A = (A^{(1)}, A^{(2)}, \ldots, A^{(N)})$, and a performance $\mathrm{P}^A(N, 0) \neq 0$, we can define the relative system performance as

$$\mathrm{RSP}^A(N, N_\mathrm{B}) = \frac{\mathrm{P}^A(N, N_\mathrm{B})}{\mathrm{P}^A(N, 0)}. \qquad (1)$$

In other words, $\mathrm{RSP}^A(N, N_\mathrm{B})$ is the ratio between the performance of N robots of which N_B are blind and the performance of N non-blind robots given the spatial arrangement A.

Furthermore, we define the contribution factor of blind robots as

$$\mathrm{CF}^A(N, N_\mathrm{B}) = \frac{\mathrm{P}^A(N, N_\mathrm{B}) - \mathrm{P}^{A^*}(N - N_\mathrm{B}, 0)}{\mathrm{P}^A(N, 0) - \mathrm{P}^{A^*}(N - N_\mathrm{B}, 0)}, \qquad (2)$$

for $\mathrm{P}^A(N, 0) > \mathrm{P}^{A^*}(N - N_\mathrm{B}, 0)$, where A^* is obtained from the spatial arrangement A by removing the locations (and orientations) that correspond to the N_B blind robots.

$\mathrm{CF}^A(N, N_\mathrm{B})$ is the ratio between the contribution of N_B blind robots and the contribution that N_B non-blind robots would provide when put in spatial arrangement A. Note that if $N - N_B$ non-blind robots exhibit a higher performance that N non-blind robots, the contribution factor is undefined. This situation typically occurs if the object is light enough for being transported with high speed by $N - N_B$ robots.

In our study, the performance measure is the distance (in cm; averaged over multiple trials) by which the object approached the target during the test period of 25 s. For the relative system performance, we obtained $\mathrm{RSP}^{A_0}(2, 1) = 0.81$, $\mathrm{RSP}^{A_1}(2, 1) = 0.73$, $\mathrm{RSP}^{A_2}(2, 1) = 0.48$, and $\mathrm{RSP}^{A_3}(2, 1) = 0.59$. The contribution factors are $\mathrm{CF}^{A_0}(2, 1) = 0.80$, $\mathrm{CF}^{A_1}(2, 1) = 0.72$, $\mathrm{CF}^{A_2}(2, 1) = 0.16$, and $\mathrm{CF}^{A_3}(2, 1) = 0.58$. The lowest contribution was observed for the spatial arrangement A_2. Although the pushing robot alone achieves only 37% of the performance of two fully operational robots, paired with a blind robot there is no clear benefit in this particular arrangement.

We repeated the same experiment with two other robot groups consisting of two robots each, to study the differences among the robotic hardware. Again 120 trials were performed per group. Fig. 4 plots the distance (in cm) by which the object approached the target. In each robot group, blind robots significantly contribute to the performance of the group. The lowest performance was observed for robot group 2; in a few cases even two fully operational robots were not strong enough for moving the object (see white box).

V. Transport by Groups of Non-blind and Blind Robots

A. Experimental Setup

We examine the transport of an object by a group of six s-bots. The arena is identical to the one used previously. The weight of the object is changed to either $W_1 = 2000\,\mathrm{g}$ or $W_2 = 3000\,\mathrm{g}$. Thus, it is either two or three times heavier than in the 2 s-bot experiment. The six robots are physically

[4] It is worth noting that the controller does not implement a stable pushing strategy. In fact, the robot is controlled so that it moves in the direction of the target. Even if the object could be placed exactly between the robot and the target, imprecision in the robot's sensors and actuators would cause the robot to turn around the object and eventually to pull it. This controller might not be the most effective solution for the transport of an object by a single robot. However, it is a general solution applicable to a wide range of scenarios including different group sizes, arbitrary spatial arrangements of robots in the group, and terrains with non-uniform friction.

[5] The speed M_max is applied to both wheels.

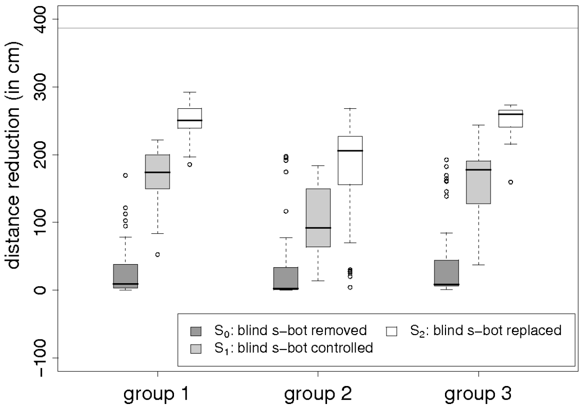

Fig. 4. Box-and-whisker plot showing the observed distances (in cm) grouped according to the corresponding strategy and the tested robot group (40 observations per box, 10 for each configuration). Each group consists of two robots. The three groups differ only in the particular robots used. The performance of group 1 is further analyzed in Fig. 3.

Fig. 5. Experimental setup. An object has to be transported towards a target (on the bottom; not shown). Six robot are manually attached to the object. While some robots are fully operational, others are not capable of perceiving the target.

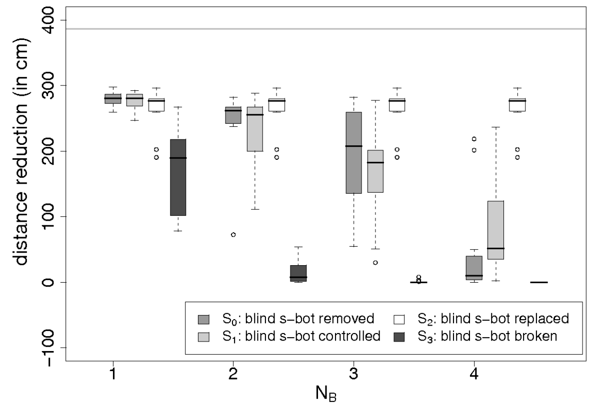

Fig. 6. Box-and-whisker plot showing the observed distances (in cm) by which an object of $W_1 = 2000\,\text{g}$ approached the target during the test period of $25\,\text{s}$. Observations are grouped according to N_B (the number of blind robots) and the employed strategy. Each box represents 15 observations. The horizontal line on top indicates an upper bound for the transport performance assuming a weightless object. For details see text.

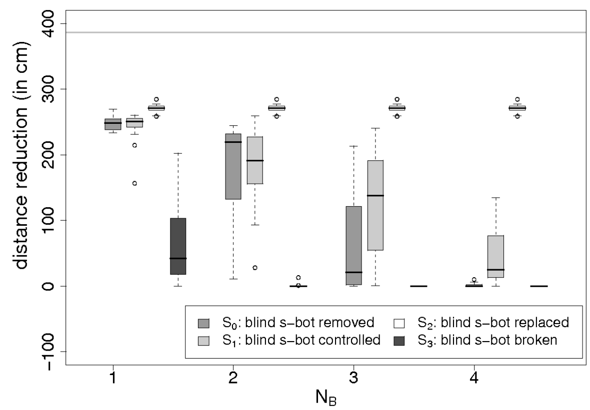

Fig. 7. Box-and-whisker plot showing the observed distances (in cm) by which an object of $W_2 = 3000\,\text{g}$ approached the target during the test period of $25\,\text{s}$. For details see Fig. 6.

connected to the object at six specific points as shown in Fig. 5. The non-blind and blind robots are randomly assigned to these points.

Let N be the number of robots. N_B denotes the number of *blind* robots (all labeled B), while the other $N - N_B$ robots are fully operational (and all labeled $\bar{B}$).

We evaluate the performance of the three strategies S_0, S_1, and S_2 introduced in Section IV-A. In addition, we evaluate the performance of strategy S_3:

- S_3: Robots labeled B are broken down. Thus, their actuators do not move, but they remain connected to the object. Robots labeled $\bar{B}$ are controlled by the standard controller for non-blind robots (see Section III-B.1)

B. Results

For each situation (W_i, S_j, N_B), $i \in \{1, 2\}$, $j \in \{0, 1, 2, 3\}$, $N_B \in \{1, 2, 3, 4\}$, 15 randomly generated arrangements are tested. The situations for strategy S_2 (i.e., to replace all blind robots by non-blind ones) are essentially the same, regardless of the number of blind robots N_B. Therefore, strategy S_2 is evaluated only 15 times per object weight. In total $2 \cdot 3 \cdot 4 \cdot 15 + 2 \cdot 15 = 390$ trials are performed. Each trial lasts $25\,\text{s}$.

Fig. 6 plots the distance (in cm) by which the object of $W_1 = 2000\,\text{g}$ approached the target. Averaged over all 15 spatial arrangements, the relative system performances are $\text{RSP}(6, 1) = 1.01$, $\text{RSP}(6, 2) = 0.92$, $\text{RSP}(6, 3) = 0.66$, and $\text{RSP}(6, 4) = 0.19$. The contribution factor $\text{CF}(6, 1)$ is not well defined.[6] For the other cases, we obtain $\text{CF}(6, 2) = -0.40$, $\text{CF}(6, 3) = -0.36$, and $\text{CF}(6, 4) = 0.16$.

Fig. 7 plots the distance (in cm) by which the object of $W_2 = 3000\,\text{g}$ approached the target. Averaged over all 15 spatial arrangements, the relative system performances are $\text{RSP}(6, 1) = 0.92$, $\text{RSP}(6, 2) = 0.71$, $\text{RSP}(6, 3) = 0.51$, and $\text{RSP}(6, 4) = 0.09$. The contribution factors are $\text{CF}(6, 1) = 0.09$, $\text{CF}(6, 2) = -0.54$, $\text{CF}(6, 3) = 0.46$, and $\text{CF}(6, 4) = 0.09$.

It is worth noting, that the $2000\,\text{g}$ and $3000\,\text{g}$ objects can be moved efficiently by 3 and 4 robots, respectively. In case, 1 or 2 robots of the group are blind and controlled by the neural network, there is no major difference in performance

[6] The performance of both the dynamic caster and the neural network strategies are slightly better than the performance of a fully operational group.

(a) (b)

Fig. 8. Types of terrain: (a) moderately rough terrain, (b) rough terrain.

(in absolute terms) with respect to a fully operational group as indicated by the RSP measure. The group can compensate for a single robot break-down (see the dark gray boxes for $N_B = 1$ in Figs. 6 and 7). However, if two or more robots break down or do not operate properly, the object can no longer be moved. In cases in which removing N_B robots would cause a decrease in performance of more than 50%, these N_B robots, when controlled by the neural network based controller instead, contribute to the performance of the group, as indicated by the CF measure.

VI. Transport by A Group on Rough Terrain

In the literature, group transport has been extensively studied on flat terrain. Recently, group transport on rough terrain has been investigated with teams of two object-lifting robots in the works by Huntsberger *et al.* [43], [44] and Takeda *et al.* [38]. In this section, we report some initial results obtained with six s-bots transporting an object on two types of rough terrain. Both types are unnavigable for most standard wheeled robots of a similar size.

A. Experimental Setup

We examine the transport of an object by a group of six s-bots on a moderately rough terrain (see Fig. 8a). The object weighs either $W_1 = 2000\,\text{g}$ or $W_2 = 3000\,\text{g}$. Apart from the terrain, the setup is identical to the one detailed in Section V-A. In this study, there are no blind robots ($N_B = 0$).

B. Experimental Results

Fig. 9 plots the performance exhibited on the flat and the moderately rough terrain. We also tried a more difficult, rough terrain (see Fig. 8b), and observed that the object can easily get stuck during transport. However, six s-bots could transport a relatively light object (700 g, that is, the weight of an s-bot) reliably by lifting it with their elevation arms.

VII. Conclusions

This paper addressed the cooperative transport of a heavy object by a group of mobile robots. We presented the first system in which group members lacking knowledge about the position of the transport target exploit physical interactions with other members of the group that have such knowledge to achieve a performance superior to that of a passive caster. Quantitative results based on 750 trials with up to six physical

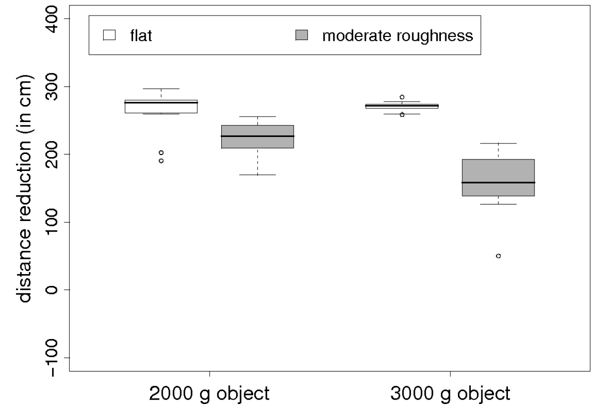

Fig. 9. Experiments with six physical robots on flat and moderately rough terrain: box-and-whisker plot showing the observed distances (in cm) by which the object approached the target during the test period of 25 s. Observations are grouped according to the object's weight and the terrain roughness.

robots confirm the effectiveness, reliability, and robustness of the system.

The role of being a leader or a follower is assigned prior to experimentation and does not change thereafter. In our ongoing work, the control modules for blind and non-blind robots have been integrated in a common framework which allows to cope also with more complex retrieval tasks in which the roles of robots change dynamically.

We believe this study to represent a sensible step towards object transportation systems of some practical use in unstructured environments. The proposed system, which is fully autonomous in perception, control, action, and power, could cope, to some extent, with partial and complete robot failure, and performed robustly on a moderately rough terrain.

Acknowledgment

This work was supported by the "ANTS" project, an "Action de Recherche Concertée" funded by the Scientific Research Directorate of the French Community of Belgium, and by the "SWARM-BOTS Project", funded by the Future and Emerging Technologies program of the European Commission, grant IST-2000-31010. The Swiss participants of the project were supported under grant 01.0012 by the Swiss Government. 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. Roderich Groß acknowledges additional support from the Japan Society for the Promotion of Science (JSPS). Marco Dorigo acknowledges support from the Belgian FNRS, of which he is a Research Director.

References

[1] M. Dorigo, V. Trianni, E. Şahin, R. Groß, T. H. Labella, G. Baldassarre, S. Nolfi, J.-L. Deneubourg, F. Mondada, D. Floreano, and L. M. Gambardella, "Evolving self-organizing behaviors for a *Swarm-Bot*," *Auton. Robots*, vol. 17, no. 2–3, pp. 223–245, 2004.

[2] W. Burgard, M. Moors, C. Stachniss, and F. Schneider, "Coordinated multi-robot exploration," *IEEE Trans. Robot.*, vol. 21, no. 3, pp. 376–386, 2005.

[3] T. Fukuda, H. Mizoguchi, K. Sekiyama, and F. Arai, "Group behavior control for MARS (micro autonomous robotic system)," in *Proc. of the 1999 IEEE Int. Conf. on Robotics and Automation*, vol. 2. IEEE Computer Society Press, Los Alamitos, CA, 1999, pp. 1550–1555.

[4] B. R. Donald, J. Jennings, and D. Rus, "Information invariants for distributed manipulation," *Int. J. Robot. Res.*, vol. 16, no. 5, pp. 673–702, 1997.

[5] M. Dorigo, "SWARM-BOT: An experiment in swarm robotics," in *Proc. of the 2005 IEEE Swarm Intelligence Symposium*. IEEE Computer Society Press, Los Alamitos, CA, 2005, pp. 192–200.

[6] F. Mondada, L. M. Gambardella, D. Floreano, S. Nolfi, J.-L. Deneubourg, and M. Dorigo, "The cooperation of swarm-bots: Physical interactions in collective robotics," *IEEE Robot. Automat. Mag.*, vol. 12, no. 2, pp. 21–28, 2005.

[7] R. Groß, M. Bonani, F. Mondada, and M. Dorigo, "Autonomous self-assembly in a swarm-bot," in *Proc. of the 3rd Int. Symp. on Autonomous Minirobots for Research and Edutainment (AMiRE 2005)*. Springer Verlag, Berlin, Germany, 2006, pp. 314–322.

[8] ——, "Autonomous self-assembly in mobile robotics," IRIDIA - Université Libre de Bruxelles, Tech. Rep. IRIDIA/2005-2, 2005.

[9] B. Donald, L. Gariepy, and D. Rus, "Distributed manipulation of multiple objects using ropes," in *Proc. of the 2000 IEEE Int. Conf. on Robotics and Automation*, vol. 1. IEEE Computer Society Press, Los Alamitos, CA, 2000, pp. 450–457.

[10] N. Inou, M. Koseki, and T. Suzuki, "Cooperative conveyance of an object with tethers by two mobile robots," in *Proc. of the* 11^{th} *World Congress in Mechanism and Machine Science*, vol. 4, China Machine Press, Beijing, China, 2004, pp. 1552–1557.

[11] M. T. Mason, "Mechanics and planning of manipulator pushing operations," *Int. J. Rob. Res.*, vol. 5, no. 3, pp. 53–71, 1986.

[12] M. J. Matarić, M. Nilsson, and K. T. Simsarian, "Cooperative multi-robot box-pushing," in *Proc. of the 1995 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, vol. 3. IEEE Computer Society Press, Los Alamitos, CA, 1995, pp. 556–561.

[13] H. Sugie, Y. Inagaki, S. Ono, H. Aisu, and T. Unemi, "Placing objects with multiple mobile robots—mutual help using intention inference," in *Proc. of the 1995 IEEE Int. Conf. on Robotics and Automation*, vol. 2. IEEE Computer Society Press, Los Alamitos, CA, 1995, pp. 2181–2186.

[14] L. E. Parker, "Adaptive heterogeneous multi-robot teams," *Neurocomputing*, vol. 28, no. 1-3, pp. 75–92, 1999.

[15] B. P. Gerkey and M. J. Matarić, "Sold!: Auction methods for multirobot coordination," *IEEE Trans. Robot. Automat.*, vol. 18, no. 5, pp. 758–768, 2002.

[16] C. R. Kube and H. Zhang, "Collective robotics: From social insects to robots," *Adapt. Behav.*, vol. 2, no. 2, pp. 189–218, 1993.

[17] S. Yamada and J. Saito, "Adaptive action selection without explicit communication for multirobot box-pushing," *IEEE Trans. Syst., Man, Cybern. C*, vol. 31, no. 3, pp. 398–404, 2001.

[18] C. R. Kube and H. Zhang, "Task modelling in collective robotics," *Auton. Robots*, vol. 4, no. 1, pp. 53–72, 1997.

[19] C. R. Kube and E. Bonabeau, "Cooperative transport by ants and robots," *Robot. Auton. Syst.*, vol. 30, no. 1–2, pp. 85–101, 2000.

[20] F. R. Noreils, "Toward a robot architecture integrating cooperation between mobile robots: Application to indoor environment," *Int. J. Robot. Res.*, vol. 12, no. 1, pp. 79–98, 1993.

[21] T. Fukuda, H. Mizoguchi, F. Arai, and K. Sekiyama, "Micro autonomous robot systems (MARS): Coordination and control of multiple micro robots," *Journal of Micromechatronics*, vol. 1, no. 3, pp. 239–251, 2002.

[22] R. Fierro, A. Das, J. Spletzer, J. Esposito, V. Kumar, J. P. Ostrowski, G. Pappas, C. J. Taylor, Y. Hur, R. Alur, I. Lee, G. Grudic, and B. Southall, "A framework and architecture for multi-robot coordination," *Int. J. Rob. Res.*, vol. 21, no. 10–11, pp. 977–995, 2002.

[23] Z.-D. Wang, V. Kumar, Y. Hirata, and K. Kosuge, "A strategy and a fast testing algorithm for object caging by multiple cooperative robots," in *Proc. of the 2003 IEEE Int. Conf. on Robotics and Automation*, vol. 2. IEEE Computer Society Press, Los Alamitos, CA, 2003, pp. 2275–2280.

[24] Z.-D. Wang, Y. Hirata, and K. Kosuge, "Control multiple mobile robots for object caging and manipulation," in *Proc. of the 2003 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, vol. 2. IEEE Computer Society Press, Los Alamitos, CA, 2003, pp. 1751–1756.

[25] G. A. S. Pereira, M. F. M. Campos, and V. Kumar, "Decentralized algorithms for multi-robot manipulation via caging," *Int. J. Robot. Res.*, vol. 23, no. 7–8, pp. 783–795, 2004.

[26] Z.-D. Wang, Y. Hirata, and K. Kosuge, "An algorithm for testing object caging condition by multiple mobile robots," in *Proc. of the 2005 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*. IEEE Computer Society Press, Los Alamitos, CA, 2005, pp. 2664–2669.

[27] J. Desai, C.-C. Wang, M. Žefran, and V. Kumar, "Motion planning for multiple mobile manipulators," in *Proc. of the 1996 IEEE Int. Conf. on Robotics and Automation*, vol. 3. IEEE Computer Society Press, Los Alamitos, CA, 1996, pp. 2073–2078.

[28] O. Khatib, K. Yokoi, K. Chang, D. Ruspini, R. Holmberg, and A. Casal, "Vehicle/arm coordination and multiple mobile manipulator decentralized cooperation," in *Proc. of the 1996 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, vol. 2. IEEE Computer Society Press, Los Alamitos, CA, 1996, pp. 546–553.

[29] K. Kosuge and T. Oosumi, "Decentralized control of multiple robots handling an object," in *Proc. of the 1996 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, vol. 1. IEEE Computer Society Press, Los Alamitos, CA, 1996, pp. 318–323.

[30] K. Kosuge, T. Oosumi, and K. Chiba, "Load sharing of decentralized-controlled multiple mobile robots handling a single object," in *Proc. of the 1997 IEEE Int. Conf. on Robotics and Automation*, vol. 4. IEEE Computer Society Press, Los Alamitos, CA, 1997, pp. 3373–3378.

[31] Y. Aiyama, M. Hara, T. Yabuki, J. Ota, and T. Arai, "Cooperative transportation by two four-legged robots with implicit communication," *Robot. Auton. Syst.*, vol. 29, no. 1, pp. 13–19, 1999.

[32] T. G. Sugar and V. Kumar, "Control of cooperating mobile manipulators," *IEEE Trans. Robot. Automat.*, vol. 18, no. 1, pp. 94–103, 2002.

[33] N. Miyata, J. Ota, T. Arai, and H. Asama, "Cooperative transport by multiple mobile robots in unknown static environments associated with real-time task assignment," *IEEE Trans. Robot. Automat.*, vol. 18, no. 5, pp. 769–780, 2002.

[34] Z.-D. Wang, E. Nakano, and T. Takahashi, "Solving function distribution and behavior design problem for cooperative object handling by multiple mobile robots," *IEEE Trans. Syst., Man, Cybern. A*, vol. 33, no. 5, pp. 537–549, 2003.

[35] M. Yamakita, Y. Taniguchi, and Y. Shukuya, "Analysis of formation control of cooperative transportation of mother ship by SMC," in *Proc. of the 2003 IEEE Int. Conf. on Robotics and Automation*, vol. 1. IEEE Computer Society Press, Los Alamitos, CA, 2003, pp. 951–956.

[36] Z.-D. Wang, Y. Takano, Y. Hirata, and K. Kosuge, "A pushing leader based decentralized control method for cooperative object transportation," in *Proc. of the 2004 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, vol. 1. IEEE Computer Society Press, Los Alamitos, CA, 2004, pp. 1035–1040.

[37] M. Yamakita and M. Saito, "Formation control of SMC with multiple coordinate systems," in *Proc. of the 2004 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, vol. 1. IEEE Computer Society Press, Los Alamitos, CA, 2004, pp. 1023–1028.

[38] H. Takeda, Z.-D. Wang, Y. Hirata, and K. Kosuge, "Load sharing algorithm for transporting an object by two mobile robots in coordination," in *Proc. of the 2004 Int. Conf. on Intelligent Mechatronics and Automation*. IEEE Computer Society Press, Los Alamitos, CA, 2004, pp. 374–378.

[39] P. E. Meyer, "Collective retrieval by autonomous robots," in *Proc. of the* 2^{nd} *Starting AI Researchers Symp.*, ser. Frontiers in Artificial Intelligence and Applications, vol. 109. IOS Press, Amsterdam, The Netherlands, 2004, pp. 199–204.

[40] J. L. Elman, "Finding structure in time," *Cognit. Sci.*, vol. 14, pp. 179–211, 1990.

[41] R. Groß and M. Dorigo, "Group transport of an object to a target that only some group members may sense," in *Proc. of the* 8^{th} *Int. Conf. on Parallel Problem Solving from Nature*, ser. LNCS, vol. 3242. Springer Verlag, Berlin, Germany, 2004, pp. 852–861.

[42] R. A. Becker, J. M. Chambers, and A. R. Wilks, *The New S Language. A Programming Environment for Data Analysis and Graphics*. Chapman & Hall, London, UK, 1988.

[43] T. Huntsberger, P. Pirjanian, A. Trebi-Ollennu, H. D. Nayar, H. Aghazarian, A. Ganino, M. Garret, S. S. Joshi, and P. S. Schenker, "CAMPOUT: A control architecture for tightly coupled coordination of multirobot systems for planetary surface exploration," *IEEE Trans. Syst., Man, Cybern. A*, vol. 33, no. 5, pp. 550–559, 2003.

[44] A. Trebi-Ollennu, H. D. Nayar, H. Aghazarian, A. Ganino, P. Pirjanian, B. Kennedy, T. Huntsberger, and P. Schenker, "Mars rover pair cooperatively transporting a long payload," in *Proc. of the 2002 IEEE Int. Conf. on Robotics and Automation*, vol. 3. IEEE Computer Society Press, Los Alamitos, CA, 2002, pp. 3136–3141.