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***Abstract*— We study the cooperative transport of a heavy object by a group of mobile robots. The system is fully decentralized and the information flow between the robots is limited to physical interactions. The robots have no explicit or implicit knowledge about their relative positions.**

Ours is the first physical multi-robot system in which some robots that have no knowledge about the position of the transport target exploit physical interactions with other robots that have such knowledge, to achieve a performance superior to that of a passive caster. A comprehensive experimental study with up to six physical robots confirms the effectiveness, reliability and robustness of the system. Finally, the performance of 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 last 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. However, they can also connect to each other to form versatile structures that can self-reconfigure their 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]. 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].

In this paper we address the problem of controlling a group of *s-bots* that are physically connected to an object so that they transport it towards a target location. 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 have no knowledge about the position of the target. Such heterogeneity can either be designed into the system, or might arise during task execution if, for instance, a subset of the robots have hardware failures in their sensing system. Or, it might be due to the nature of the environment: for example, the presence of obstacles can make it impossible for some of the robots to perceive the target.

The paper is organized as follows. Section II overviews the related work on group transport by mobile robots. Section III details 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 including the use of tools such as a robe [8], [9], that are not considered here.

1) Transport by Pushing or Caging: Pushing behaviors have the advantage that they make possible 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 and is decentralized.

Most studies consider two robots pushing a wide box simultaneously from a single side [4], [11]–[14]. To coordinate the robots actions, robots are specifically arranged [4], [11], [13], [14], control is synchronized [11], relative positions are known [4], [13], explicit communication is used [11], [13], or individuals tasks are generated by a specific leader agent [12], [14]. Only few systems considered more than two robots pushing simultaneously a wide box [15]–[18]. In these cases,

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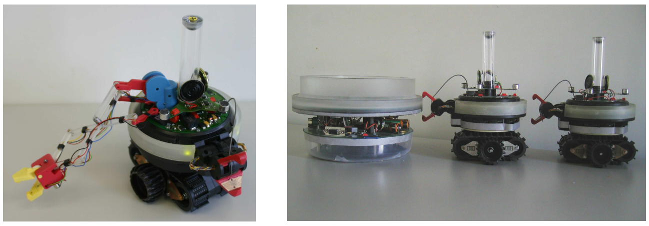
[1] For a theory on the mechanics of pushing see Mason [10].



(a) (b)

Fig. 1. The swarm-bot concept: (a) a single s-bot robot, (b) an s-bot connecting with an object, a second s-bot connecting with the first one.

the control is homogeneous and decentralized. In addition, the robots make no use of explicit communication.

Kube *et al.* [17], [18] reported that if the object is small compared to the size of the pushing robots the performance decreases drastically with group size as the objects provides only limited contact surface. Some other works on multi-robot systems consider objects of about the size of a single robot or less [19], [20]. However, in these cases the object was light enough so that a single robot could move it 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* [21]–[24]. In current systems, typically the object is light so that it can be moved by a single robot alone. It is worth noting that a single robot can constrain the object in several directions using multiple contact points [22], [23]. To test and maintain the condition of object closure, decentralized control algorithms have been proposed [24], [25].

2) Transport by Grasping or Lifting: Many works considered the transport of an object by multiple, mobile robots grasping and/or lifting it [26]–[38]. In some systems the desired trajectories are given prior to experimentation to all the robots of the group. The object is transported as each robot follows the given trajectory by making use of dead-reckoning [26]. In other systems, the manipulation is planned in real-time by an external workstation which communicates with the robots [32], [34], [36]. 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* [31], [33]. However, in many leader-follower systems explicit communication is not required [28]–[30], [35], [37], [38]. Typically, this is realized in system in which the object is lifted by the robots. The followers simulate the behavior of a virtual caster.

None of the works listed in this section considered the transport of an object by groups of more than four physical robots. To the best of our knowledge, group transport on rough terrain has only been reported for teams of two object-lifting robots in the works by Huntsberger *et al.* and Takeda *et al.* [37], [39], [40].

III. SYSTEM DESIGN

A. Hardware Design

Fig. 1(a) 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 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 is equipped with eight RGB LEDs distributed around the robot, 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 a VGA omni-directional camera and a 2 DOF force sensor between the turret and the chassis. Furthermore, proprioceptive sensors provide internal motor information such as the torque acting on each side of the tracks.

The omni-directional camera can be used to detect the angular position of a light source in the environment (e.g., the target of transport). The traction 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 objects that are physically linked to the s-bot. 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 $400\,\mathrm{MHz}$. The s-bot is equipped with a $10\,\mathrm{Wh}$ Lithium-Ion battery which provides for 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 no explicit or 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 angular position of the

Algorithm 1 Transport module for non-blind robots

```
1:  repeat
2:      $\alpha \leftarrow$ computeTargetDirection(camera)
3:      $M \leftarrow M_{\text{max}}$
4:      if (stagnation) then
5:          execute recovery move
6:      else
7:          if (risk of stagnation) then
8:              turn on the spot towards $\alpha$
9:          else
10:             move with speed $M$, softly re-aligning towards $\alpha$
11:         end if
12:     end if
13: until timeout reached
```

target (i.e., a light beacon), while others (called the *blind* ones) are not. In the following the corresponding controllers are detailed.

1) Controller for Non-Blind Robots: Algorithm 1 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 the camera vision system 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 robot 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 1, line 8). The soft alignment makes the s-bot turn while moving forward (line 10). 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 treshold. The parameter M_{max} limits the speed of the robot's wheels.

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, a recovery move is performed to prevent stagnation and the hardware from being damaged. The recovery move lasts about $160\,\text{ms}$. During this time the s-bot's wheels move forward and backward.

2) Controller for Blind Robots: The controller for those robots that have no knowledge about the target position can be derived from Algorithm 1. The only difference is in the lines 2–3: an Elman neural network [41] with four hidden nodes is executed in each iteration of the control loop. This network takes the input vector $(f_N, f_W, f_S, f_E, s, \theta)$. f_N, f_W, f_S and $f_E \in [0, 1]$ correspond to the sensor reading values of the force sensor (with respect to four preferential directions). $s \in \{0, 1\}$ indicates whether or not stagnation was present during the last four iterations. θ is the angular offset between the turret and the chassis. The neural network has two output nodes specifying the desired angular position α of the chassis (line 2), and the speed $M \in [0, M_{\text{max}}]$ of the wheels (line 3).

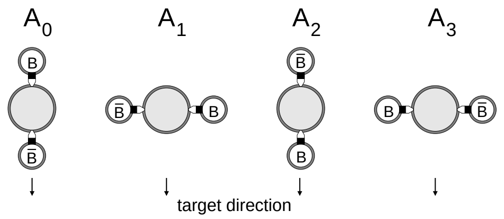


Fig. 2. Experimental setup. An object has to be transported towards a target. Two robot are manually attached to the object. They are labeled B and $\bar{B}$, respectively. While robot $\bar{B}$ is fully operational, robot B is not capable of perceiving the target. The figure shows the four spatial arrangements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

The parameters of the neural network—i.e., the connection weights—have been determined in simulation by using evolutionary algorithms. A detailed illustration of the simulation and the evolutionary algorithm used to design the artificial neural network can be found in [42].

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 $W_0 = 1000\,\text{g}$. It has to be transported towards a light beacon. 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 four distinct spatial arrangements $\{A_0, A_1, A_2, A_3\}$ as 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).

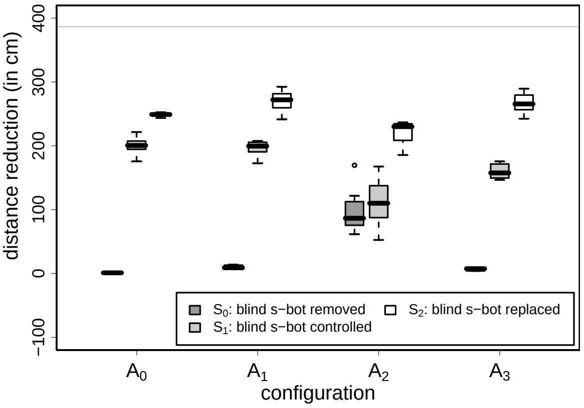


Fig. 3. Box-and-whisker plot [43] showing the observed distances (in cm) by which the object approached the target during the test period of $25\,\mathrm{s}$. Observations are grouped according to the corresponding strategy and spatial arrangement (10 observations per box). The horizontal line on top indicates an upper bound for the transport performance assuming a weightless object (for details see text).

B. Results

The test period is $25\,\mathrm{s}$. For each pair $(S_i, A_j) \in \{S_0, S_1, S_2\} \times \{A_0, A_1, A_2, A_3\}$ ten repetitions 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 $1000\,\mathrm{g}$ 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 $87\,\mathrm{cm}$ (median value). It seems that the robot exerts a higher force while pushing the object than when pulling it (notwithstanding the fact that the magnitude of the force applied to the tracks 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 covers in the same period ($25\,\mathrm{s}$) 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.

When controlled by strategy S_1, the performance is significantly better than when compared to 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 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 the group size N, the 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

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

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.

We define a help function. For $l \in \{0, 1, \ldots, N\}$, let be

$$\Gamma(A, l) = (A^{(1)}, A^{(2)}, \ldots, A^{(l)}). \tag{2}$$

For $\mathrm{P}^A(N,0) > \mathrm{P}^{\Gamma(A,N-N_B)}(N - N_\mathrm{B}, 0)$, we define the contribution factor of blind robots as

$$\mathrm{CF}^A(N, N_\mathrm{B}) = \frac{\mathrm{P}^A(N, N_\mathrm{B}) - \mathrm{P}^{\Gamma(A,N-N_B)}(N - N_\mathrm{B}, 0)}{\mathrm{P}^A(N,0) - \mathrm{P}^{\Gamma(A,N-N_B)}(N - N_\mathrm{B}, 0)}. \tag{3}$$

$\mathrm{CF}^A(N, N_\mathrm{B})$ is the ratio between the contribution of N_B blind robots and the contribution that N_B non-blind robots would provide when in spatial arrangement A.

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 $25\,\mathrm{s}$. For the relative system performance, we obtained $\mathrm{RSP}^{A_0}(2,1) = 81\%$, $\mathrm{RSP}^{A_1}(2,1) = 73\%$, $\mathrm{RSP}^{A_2}(2,1) = 48\%$ and $\mathrm{RSP}^{A_3}(2,1) = 59\%$. The contribution factors are $\mathrm{CF}^{A_0}(2,1) = 80\%$, $\mathrm{CF}^{A_1}(2,1) = 72\%$, $\mathrm{CF}^{A_2}(2,1) = 16\%$, and $\mathrm{CF}^{A_3}(2,1) = 58\%$. 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 to study the differences among the robotic hardware. Again 120 trials have been 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 performance of the group. The lowest performance was observed for robot group 2; in a few cases two fully operational robots were not strong enough to move the object.

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[2] The initial distance between the object and the target is kept constant ($437\,\mathrm{cm}$).

[3] This is different from systems in which the robots lift the object, where a passive caster can facilitate the transport considerably.

[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 maximum speed of our controllers is applied to both wheels.

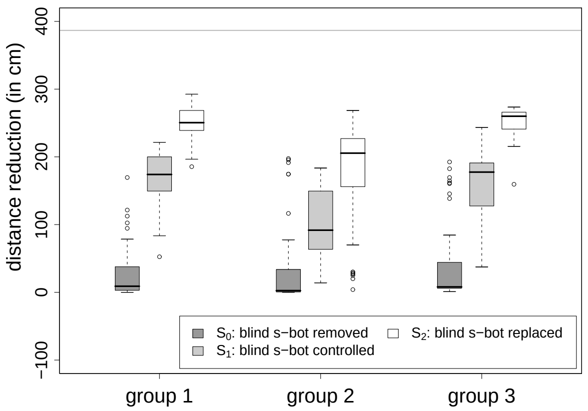

Fig. 4. Box-and-whisker plot showing the observed distances (in cm) grouped according to the corresponding strategy and the tested robot group (40 observations per box, 10 for each configuration). Observations belonging to group 1 are further analyzed in Fig. 3.

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.

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 object weighs either $W_1 = 2000\,\text{g}$ or $W_2 = 3000\,\text{g}$. The six robots are physically connected to the object at six specific points from the beginning as shown in Fig. 5. The positions of the blind robots are assigned randomly by uniformly sampling without replacement from the set of six possible positions.

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)

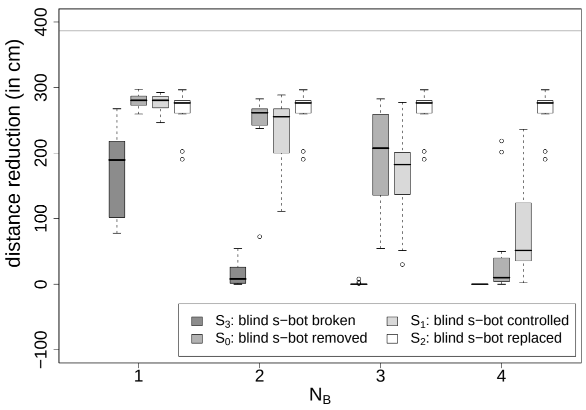

Fig. 6. Box-and-whisker plot showing the observed distances (in cm) by which an object of $W_1 = 2000\,\text{g}$ approached the target during the test period of $25\,\text{s}$. Observations are grouped according to N_B (the number of blind robots) and the employed strategy. Each box represents 15 observations.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

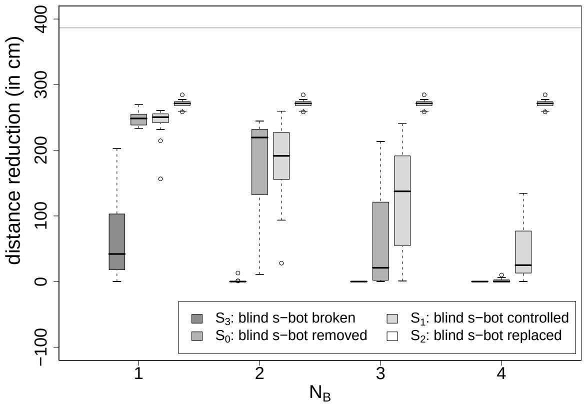

Fig. 7. Box-and-whisker plot showing the observed distances (in cm) by which an object of $W_2 = 3000\,\text{g}$ approached the target during the test period of $25\,\text{s}$. For details see Fig. 6.

B. Results

The test period is kept constant $(25\,\text{s})$. For each pair (N_B, W_i), $N_B \in \{0, 1, 2, 3, 4\}$, $i \in \{1, 2\}$, the strategies S_0, S_1, S_2 and S_3 have been evaluated 15 times. In total 390 trials are performed.[6]

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 $\text{RSP}(6,1) = 101\%$, $\text{RSP}(6,2) = 92\%$, $\text{RSP}(6,3) = 66\%$, and $\text{RSP}(6,4) = 19\%$. The contribution factor $\text{CF}(6,1)$ is not well defined.[7] For the other cases, we obtain $\text{CF}(6,2) = -40$, $\text{CF}(6,3) = -36$ and $\text{CF}(6,4) = 16$.

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 $\text{RSP}(6,1) = 92\%$, $\text{RSP}(6,2) = 71\%$, $\text{RSP}(6,3) = 51\%$, and

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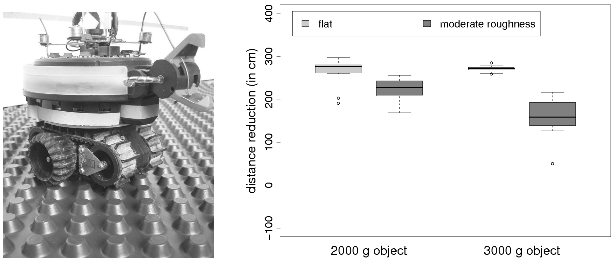
[6] Strategy S_0 (i.e., to repair broken robots and to use the standard controller) has been evaluated 15 times in total.

[7] 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. Experiments with six robots on moderately rough terrain: (a) the terrain with an s-bot, (b) box-and-whisker plot showing the observed distances (in cm) by which the object approached the target during the test period of $25\,\mathrm{s}$. Observations are grouped according to the weight of the object and the roughness of the terrain.

$\mathrm{RSP}(6,4) = 9\%$. The contribution factors are $\mathrm{CF}(6,1) = 9$, $\mathrm{CF}(6,1) = -54$, $\mathrm{CF}(6,1) = 46$ and $\mathrm{CF}(6,1) = 9$.

It is worth noting, that the $2000\,\mathrm{g}$ and $3000\,\mathrm{g}$ objects can already be moved efficiently by 3 and 4 robots, respectively. The group can compensate for a single robot break-down (see the dark gray boxes in Figs. 6 and 7). However, if two or more robots do not act properly or do not move, the object cannot be moved. Whether 1 or 2 robots are removed, replaced or controlled by the blind robots does not result in any major difference in the performance. However, in the cases in which removing the N_B robots results in a drop in the performance of more than 50%, these N_B robots, when controlled by the neural network based controller, exhibited a contribution to the performance of the group.

VI. TRANSPORT BY A GROUP ON ROUGH TERRAIN

A. Experimental Setup

We examine the transport of an object by a group of six s-bots on moderately rough terrain (see Fig. 8(a)). The object weighs either $W_1 = 2000\,\mathrm{g}$ or $W_2 = 3000\,\mathrm{g}$. 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. 8(b) shows the experimental results. Due to the roughness of the terrain, the performance of a group of six robots moderately decreases. When the rougness of the terrain is further increased, we observed that the object can easily get stuck. However, six s-bots could transport a light object ($700\,\mathrm{g}$) reliably if the robots lifted it by making use of their elevation arms.

VII. CONCLUSION

We studied the cooperative transport of a heavy object by a group of mobile robots. The system is fully decentralized and the information flow between the robots is limited to physical interactions. The robots have no explicit or implicit knowledge about their relative positions.

Ours is the first physical multi-robot system in which robots that have no knowledge about the position of the transport target exploit physical interactions to achieve a performance superior to that of a passive caster. A comprehensive experimental study with up to six physical robots confirmed the efficacy, reliability and robustness of the system.

Finally, we showed that our system can easily cope with moderately rough terrain. We believe that this is a sensible step towards potential real-world applications.

In this paper, 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 tasks in which the role changes dynamically.

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