Physical interactions in swarm robotics: the hand-bot case study

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Abstract This paper presents a case-study on the performance achieved by the mechanical interactions of self-assembling mobile robots. This study is based on the hand-bot robot, designed to operate within heterogeneous swarms of robots. The hand-bot is specialized in object manipulation and can improve its performance by exploiting physical collaborations by self-assembling with other hand-bots or with foot-bots (ground robots). The paper analyzes the achieved performance and demonstrates the highly super-linear properties of the accessible volume in respect to the number of robots. These extremely interesting performances are strongly linked to the self-assembling mechanisms and the physical nature of the interaction, and do not scale to a large number of robots. Finally, this study suggests that such interesting properties are more accessible for heterogeneous systems or devices achieving complex tasks.

1 Introduction

Self-assembling is a feature in collective robotics which allows us to drastically improve the performances of single individuals by exploiting mechanical interactions [10, 5]. Applications can be found in space robotics [14], all-terrain mobility [13], underwater robotics [7], and simulation of living systems [4]. The main advantages of this approach to robotics are robustness to failure, because of the redundancy provided by multiple physical units, and flexibility. This last property is achieved by the large number of configurations these robots can form. They can, for

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instance, form structures to navigate in specific shapes [1], to pass obstacles [11], or to pull heavy objects [12, 11]. An extended overview of the field is given in [5].

Self-assembling is widely studied in homogeneous groups of robots forming 2D structures [6, 5]. Few studies address self-assembly in 3D and none, to our knowledge, perform manipulation tasks in this space. This paper presents the case-study of the hand-bot, a robot specialized in object manipulation and capable of self-assembling to access 3D space. This example shows how self-assembly can enhance performance by mechanical interaction between assembled units. This work is an extension into the third dimension and to heterogeneous swarms of the work presented in [10]. While some of the conclusions are similar, the application of the same principles into heterogeneous and 3D systems capable of complex tasks allows a much deeper understanding of the phenomena.

2 The hand-bot robot

The hand-bot is a small-size robot specialized in manipulation of small objects positioned much higher than its size (details are given in [3]). The robot is about 30 cm high, weights 2.8 Kg, and can manipulate an object placed in a vertical structure, for instance a shelf, between the floor and a ceiling located at 2.5 m above the floor. The ceiling above the robot has to be ferromagnetic, which is the case in many offices at the Ecole Polytechnique Fédérale de Lausanne. To perform this task, we equipped the hand-bot with three main groups of actuators, presented in Fig. 1:

1. A launcher allowing to shoot to the ceiling a switchable magnet pulling a rope. Once attached, the robot can lift itself. When the operation is finished, the robot can detach the magnet and wind the rope, making it ready for a new launch.
2. Two fans to stabilize and control the yaw of the robot when suspended. These actuators also allow the robot to move forward and backward.
3. Two arms equipped with grippers to allow the robot to attach to existing structures, to grasp object, and to self-assemble with other hand-bots.

Using the attachment to the ceiling, the fans and the arms, a single hand-bot can operate following two main strategies:

1. Lift up in an empty area. This approach uses the rope for the vertical displacement and the fans for stabilizing yaw and for making small forward and backward movements. This leaves both grippers available for manipulation but the positioning accuracy is poor.
2. Lift up by grabbing parts of a structure, like a shelf. In this type of operation (see Fig. 3 and the corresponding video on YouTube[1]), the stabilization of the movement is made using the grippers by attaching to the structure [3]. The hand-bot uses the two grippers in an alternate way to keep a contact with the structure. This improves stability, provides precise positioning, and provides access to a

[1] http://www.youtube.com/watch?v=92bLgE6DO2g

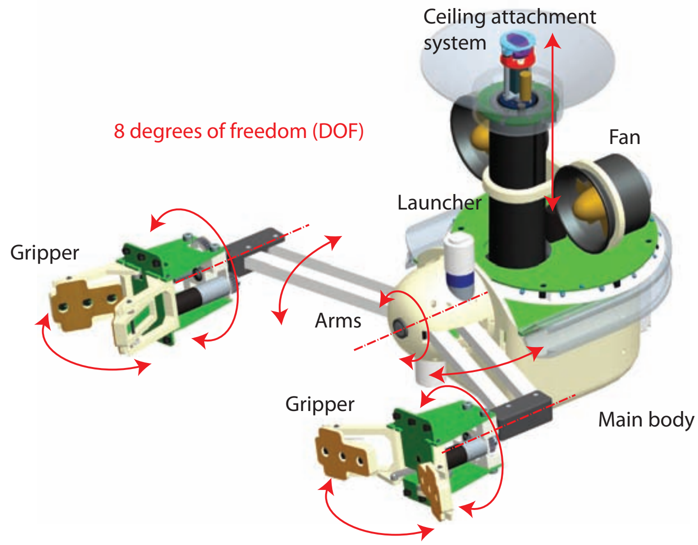

Fig. 1 Structure of the hand-bot and its degrees of freedom

large area because of lateral movements; but this limits the manipulation to one free gripper. Thus, the robot cannot climb and transport an object concurrently.

In both cases, the lifting principle is to use the attachment to the ceiling to generate most of the vertical force (F_w in Fig. 2). In addition, in strategy 1, the hand-bot can move a little on the horizontal axis, thanks to the fans which provide an horizontal force (F_f in Fig. 2). In strategy 2, the robot can push or pull on the structure using its attached gripper. The resultant (F_r in Fig. 2) is aligned with the arm.

As Fig. 2 shows, the maximal attachment force F_w depends on the orientation of the rope, given by the angle α. Indeed, as the attachment point of the rope on the magnetic device is located at six centimeters of distance from the ceiling (see real device on top right of Fig. 2), the force F_w generates a peeling moment which tends to detach the magnet when the rope is not vertical ($\alpha \neq 0$). Because the peeling moment is extremely hard to compute analytically, we measured the maximal value of F_w as function of the angle α on the real device, obtaining the values illustrated in Fig. 2.

It appears clearly that the main limitation of the first strategy (based on the fan) is the weak propulsion force of the fans, resulting in a limited accessible volume. When blowing at full power, we measured that the fans can only generate an angle α of 0.026 rad.

The main limitation of the second approach is in the use of one arm and one gripper for lateral displacement, which renders them unavailable for manipulation. The accessible area is much larger than in the first approach and is limited by the morphology. Moreover, near to the ceiling the angle of the rope increases and the

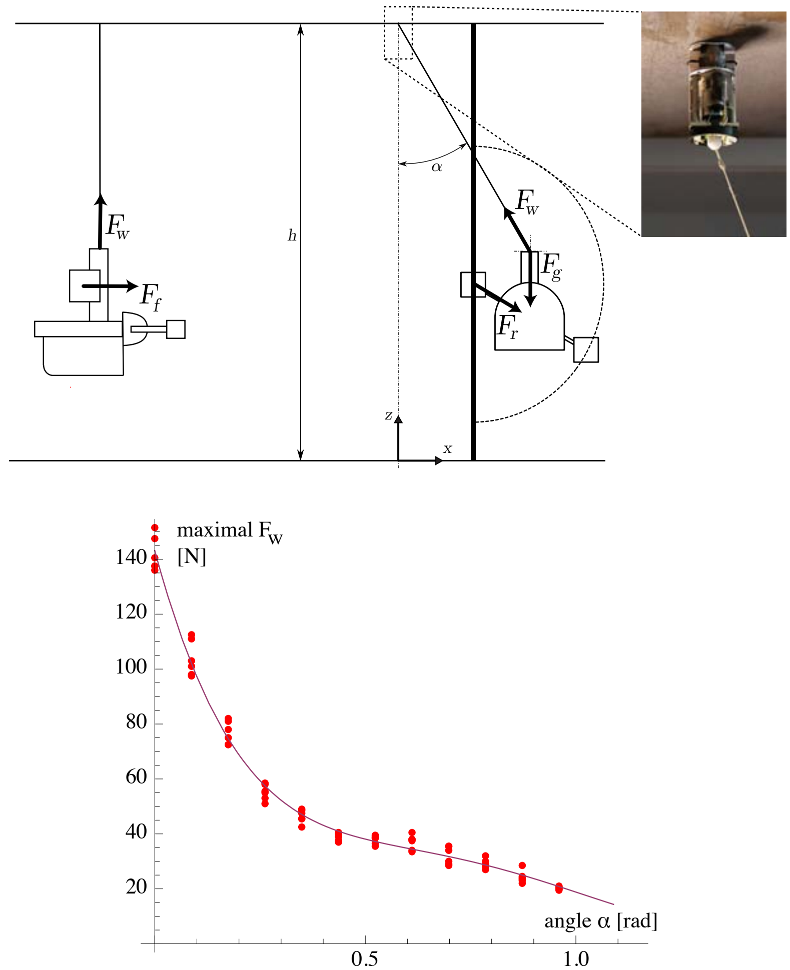

Fig. 2 Top: Scheme of forces and the detail of the magnetic attachment system. Bottom: Maximal attachment force of the magnetic system as function of the angle α of the rope; the measurements are represented as red dots, the line shows a possible interpolation.

magnetic system cannot support anymore the robot. Fig. 3 (right) compares the access zones of these two approaches.

3 Collective strategies based on self-assembling

To overcome the limitations described in section 2, the hand-bot can self-assemble with other hand-bots or with foot-bots, a type of robots which we designed for dis-

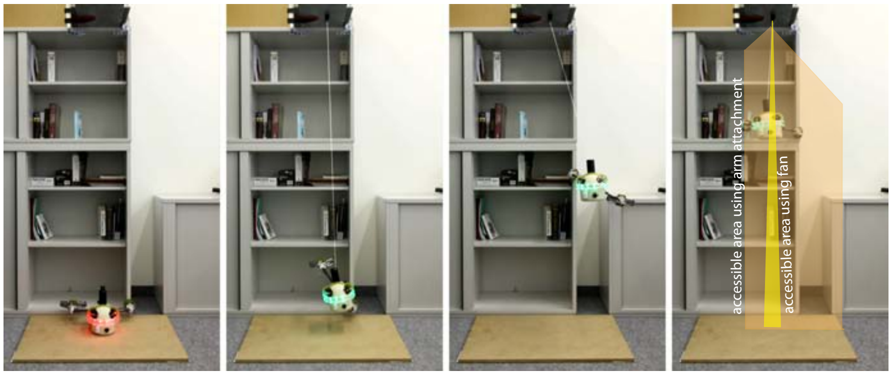

Fig. 3 Sequence of climbing and grasping: positioning, climbing and grasping of a book.

placement and navigation on the ground. The goal is to increase the accessible volume by a self-assembling collective approach.

3.1 Self-assembling with foot-bots

The hand-bot is strictly specialized in climbing and manipulation. This means for instance that the hand-bot is not equipped with wheels or any other actuator to move on the ground. The hand-bot achieves displacement on the ground by self-assembling with another type of robot, the foot-bot.

The foot-bot is a modified version of the marXbot, a robot designed for research in collective robotics [2, 8] (see Fig. 4, left). The foot-bot has tracks and wheels (called together ”treels”) and can move in all-terrain conditions. For this experiment, the foot-bot is specifically equipped with a self-assembling module allowing it to physically connect to the hand-bot and to form a common rigid body. Details on the marXbot robot and on the self-assembling mechanism are described in [2]. The main characteristics of this self-assembling mechanism of the foot-bot is that it can rotate all around the robot body. This allows a connected robot to move in any direction. Foot-bots can attach to the sides and to the back of the hand-bot (see Fig. 4, right).

This assembly of robots can provide the hand-bot with the necessary mobility on the ground. Its performance in displacement depends strongly on the number of foot-bots involved. One foot-bot alone can displace a hand-bot but can hardly position it correctly. A foot-bot connected to a hand-bot can only pull or push the hand-bot. It cannot move in other directions than those two, because this would make the hand-bot nearly rotate on the spot. If the foot-bot pulls the hand-bot, this makes it very hard to position, for instance, the hand-bot facing a shelf. If the foot-bot pushes the hand-bot, the control is highly unstable and requires very complex maneuvers. If foot-bots are available, they can achieve a much better configuration by attaching laterally to the hand-bot. This allows the foot-bots to move in any

Fig. 4 Left: Foot-bot robot. Right: Possible positioning of foot-bot robots around the hand-bot to provide movement on the ground.

direction. While this two-points system does not control all degrees of freedom, the positioning in the horizontal plane is much more precise and easier to control. The ideal situation occurs when the hand-bot is connected to three foot-bots, two placed laterally and one behind the hand-bot. This configuration allows to control all degrees of freedom. The hand-bot is therefore well stabilized and can be positioned in the best way. Self-assembly with more than three robots does not make sense from a stability and mobility point of view, and is difficult because of the limited area of attachment.

3.2 Self-assembling with hand-bots

In the previous sections we have seen the ability of one hand-bot to move vertically and the possibility to use self-assembly to position it on the ground. Probably the most interesting possibility is to self-assemble several hand-bots to extend the volume accessible by the robots. The hand-bot can self-assemble with other hand-bots using its gripper, as illustrated in Fig. 5.

The complete scenario using self-assembling of foot-bots and hand-bots is the following: Foot-bots place the hand-bots in several locations at the limits of the working area. In the following examples we will consider two or three hand-bots placed at distance d to each other. When the hand-bots are placed, they attach to the ceiling, shooting their attachment system. Then foot-bots bring all hand-bots together in the center of the working area. This allows them to self-assemble using their grippers. When assembled, the hand-bots can move within the 3D space by concurrently using their attachments to the ceiling.

As illustrated in section 2, the hand-bot can use two main actuators for lateral displacement: fans and arms. By self-assembling we can add a third actuator, which is the ceiling attachment system of another hand-bot. If we consider the situation of elevating the hand-bot in the air keeping both gripper available for manipulation, we can distinguish three main situations:

1. When the hand-bot is alone, it can control its lateral movements and yaw (three degrees of freedom ”DOF”) using only the fans. The accessible volume is limited, as we discussed in section 2.
2. When two hand-bots are assembled, two DOF are controlled by this additional connection and only one DOF needs to be controlled by the fans. The volume is bigger and follows a vertical plane crossing the two attachment points.
3. When three hand-bots are assembled, all DOF are controlled by the ropes connected to the ceiling. The volume becomes more important and is enclosed within the three vertical planes crossing the attachment points.

In the second and third situations, the upper limitation of the volume is given by the attachment force with respect to the angle as illustrated in Fig. 2. The resulting volumes for a distance between robots d of 100 cm are illustrated in Fig. 6.

In this self-assembling collaboration, it is interesting to observe the effect of cooperation on normalized system performances. An interesting measurement of collective performance is the collective speedup factor [9] of a group of n robots, given by equation 1.

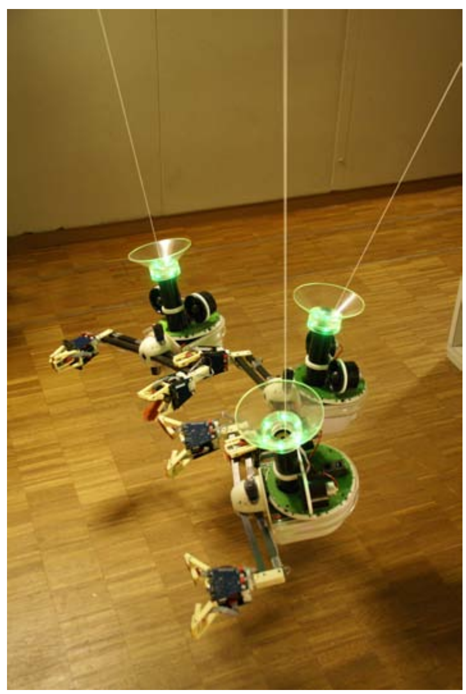

Fig. 5 Three hand-bots self-assembled and suspended by the ropes.

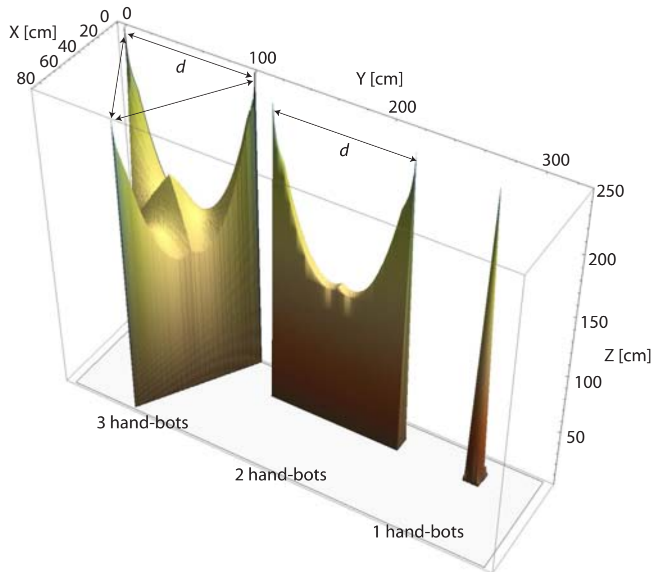

Fig. 6 Accessible volume for one, two and three hand-bots cooperating by self-assembly. This situation considers a distance between robots of $d = 100$cm.

$$CS(n) = \frac{mP(n)}{nP(m)} \tag{1}$$

where $P(n)$ is the performance of a group of n robots and m is the minimal number of robots needed to perform the task. We can distinguish between superlinear performances when $CS(n) > 1$, linear performances when $CS(n) = 1$ and sublinear performances when $CS(n) < 1$. A simple combination of n robots having no influence on each-other should generate a linear performance by performing the task n times better or faster than one robot or module.

In our case we can look to the accessible volume, for a task feasible with one robot:

$$CS_v(n,d) = \frac{V(n,d)}{nV(1)} \tag{2}$$

where $V(n,d)$ is the volume accessed by n hand-bots with attachments placed at a distance d to each other, and $V(1)$ the volume accessed by one hand-bot using the fans for lateral displacement. Fig. 7 shows on the left the plot of the accessible volume $V(n,d)$ as function of d for n =1,2 and 3. On the right of the same figure, the resulting $CS_v(n,d)$ shows that the system exhibits highly superlinear performances.

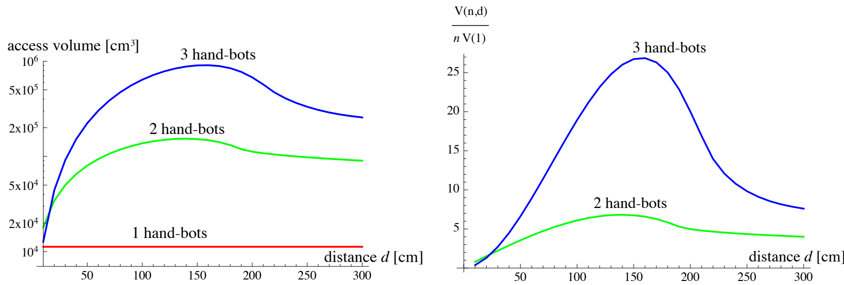

Fig. 7 Left: Volume accessible by one, two and three hand-bots exploiting self-assembling. Right: Ratio between access volume using n hand-bots and volume using one hand-bot, normalized per number of robots.

4 Discussion

The system presented in this paper shows a case study of physical collaboration among robots based on self-assembling. The example shows clearly that physical collaboration can generate a very strong multiplication of performance. This was already observed in [10] but the performance factor was much smaller than the one observed here. In the positioning task, the absolute performance is hard to define and measure — we should measure the involved engineering work — but the improvement in performance is clear when moving from one to two foot-bots. Three foot-bots can generate the best performance, even if the performance factor between two and three could be sublinear. Indeed the gain in performance between two and three robots appears to be minor considering that the number of robots has been increased by fifty percent. Additional foot-bots can improve the robustness, the payload and the speed of the system, but do not improve quality in positioning or in control efficiency.

Our system shows superlinear performance when considering 3D access. Self-assembling two hand-bots increases the collective-volume access by a factor of 6.8 in the best case (d =140 cm). Adding another hand-bot allows us to achieve a collective factor of 26.8, which represents an additional increase of a factor four with respect to a combination of two robots. These performances are achieved through the geometry of the system, where adding a robot means adding dimensionality to the system. This is very specific to physical systems. Also very specific to physical systems is the fact that those systems do not scale. For more that three robots (both foot-bots and hand-bots) the evolution of the volume depends on the shape of its base, evolving from a equilateral triangle of side d, to a n-sided polygon inscribed in a circle of diameter d, n being the number of hand-bots. This area saturates (at $d^2\pi/4$) and the corresponding volume too. Therefore the system performance stay stable with n increasing and therefore CS_v drops.

The collective-performance factors listed above do not consider the total number of robots, which should include both the foot-bots and the hand-bots involved in the task. When taking into consideration both types of robots, the ratio m/n would increase and the performance factor as well. This shows a very interesting effect of heterogeneity. Having different robots for ground mobility and for vertical operations allows us to optimize each subsystem independently and to combine functionalities in an orthogonal manner. For instance, in this case-study, once three foot-bots are available, the number of hand-bots can be chosen freely, the foot-bots being capable to position each hand-bots in a sequential way. This would increase the *CS*.

Finally, we can make an observation about the hardware requirements for self-assembling. Foot-bots, which are simple mobile robots that have to move around — a trivial task — require a specific hardware module to ensure the self-assembling capability. The added hardware is even one of the most complex hardware component in the foot-bot. On the contrary, the hand-bot embeds grippers in its basic configuration because its basic task is more complex (manipulation). Using the same grippers for self-assembling, the hand-bot does not require additional hardware to perform physical cooperation. This suggests that in more complex tasks, requiring more complex robots, cooperation based on self-assembling could be more accessible and require less extra specific hardware than for simple robots.

5 Conclusion

We presented a case study of physical interactions in a heterogeneous group of robots. This type of collaboration allows very high increase in performance, but is not scalable. The heterogeneity improves performances and allows to optimise different robots for different sub-tasks. The complexity of the tasks, requiring complex robotic hardware, improves accessibility to self-assembling operation. These conclusions shows very singular properties of heterogeneous self-assembling systems. Additional research work is necessary to increase the understanding and to develop the exploitation of this particular but promising type of systems.

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References

1. Baldassarre, G., Trianni, V., Bonani, M., Mondada, F., Dorigo, M., Nolfi, S.: Self-Organised Coordinated Motion in Groups of Physically Connected Robots. IEEE Transactions on Systems, Man and Cybernetics Part B : Cybernetics **37**(1), 224–239 (2007)
2. Bonani, M., Longchamp, V., Magnenat, S., Rétornaz, P., Burnier, D., Roulet, G., Bleuler, H., Mondada, F.: The marxbot, a miniature mobile robot opening new perspectives for the collective-robotic research. In: Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems IROS2010. IEEE Press, Piscataway, New Jersey, USA (2010)
3. Bonani, M., Magnenat, S., Rétornaz, P., Mondada, F.: The Hand-bot, a Robot Design for Simultaneous Climbing and Manipulation. In: M. Xie et al. (ed.) Proceedings of the Second International Conference on Intelligent Robotics and Applications, *Lecture Notes in Computer Science*, vol. 5928, pp. 11–22. Springer-Verlag, Berlin Heidelberg (2009)
4. Breivik, J.: Self-organization of template-replicating polymers and the spontaneous rise of genetic information. Entropy **3**(4), 273–279 (2001)
5. Gross, R., Dorigo, M.: Self-assembly at the macroscopic scale. Proceedings of the IEEE **96**(9), 1490 –1508 (2008)
6. Groß, R., Bonani, M., Mondada, F., Dorigo, M.: Autonomous Self-assembly in Swarm-Bots. IEEE Transactions on Robotics **22**(6), 1115–1130 (2006)
7. von Haller, B., Ijspeert, A., Floreano, D.: Co-evolution of structures and controllers for Neubot underwater modular robots. Advances in Artificial Life pp. 189–199 (2005)
8. Magnenat, S., Longchamp, V., Bonani, M., Rétornaz, P., Germano, P., Bleuler, Hannes,, Mondada, F.: Affordable SLAM through the Co-Design of Hardware and Methodology. In: Proceedings of the 2010 IEEE International Conference on Robotics and Automation. IEEE Press (2010)
9. Martinoli, A.: Swarm intelligence in autonomous collective robotics: From tools to the analysis and synthesis of distributed collective strategies. Ph.D. thesis, Swiss Federal Institute of Technology in Lausanne (EPFL), Lausanne, Switzerland (1999)
10. Mondada, F., Bonani, M., Guignard, A., Magnenat, S., Studer, C., Floreano, D.: Superlinear Physical Performances in a SWARM-BOT. In: Proceedings of the VIIIth European Conference on Artificial Life, Lecture Notes in Artificial Intelligence, pp. 282–291 (2005)
11. Mondada, F., Pettinaro, G.C., Guignard, A., Kwee, I., Floreano, D., Deneubourg, J.L., Nolfi, S., Gambardella, L., Dorigo, M.: SWARM-BOT: a New Distributed Robotic Concept. Autonomous Robots, special Issue on Swarm Robotics **17**(2-3), 193–221 (2004)
12. Nouyan, S., Groß, R., Bonani, M., Mondada, F., Dorigo, M.: Teamwork in Self-Organized Robot Colonies. IEEE Transactions on Evolutionary Computation **13**(4), 695–711 (2009)
13. O'Grady, R., Groß, R., Christensen, A., Dorigo, M.: Self-assembly strategies in a group of autonomous mobile robots. Autonomous Robots **28**(4), 439–455 (2010)
14. Toglia, C., Kettler, D., Kennedy, F., Dubowsky, S.: A study of cooperative control of self-assembling robots in space with experimental validation. In: ICRA'09: Proceedings of the 2009 IEEE international conference on Robotics and Automation, pp. 3847–3852. IEEE Press, Piscataway, NJ, USA (2009)