SRoCS: Leveraging Stigmergy on a Multi-robot Construction Platform for Unknown Environments

Michael Allwright[1], Navneet Bhalla[2], Haitham El-faham[1], Anthony Antoun[3],
Carlo Pinciroli[3], and Marco Dorigo[1,3]

[1] Department of Computer Science, University of Paderborn, Paderborn, Germany
`michael.allwright@upb.de, helfaham@mail.upb.de`
[2] Sibley School of Mechanical and Aerospace Engineering, Cornell University,
Ithaca, New York, USA
`navneet.bhalla@cornell.edu`
[3] IRIDIA, Université Libre de Bruxelles, Brussels, Belgium
`{aantoun,cpinciro,mdorigo}@ulb.ac.be`

Abstract. Current implementations of decentralized multi-robot construction systems are limited to construction of rudimentary structures such as walls and clusters, or rely on the use of blueprints for regulation. Building processes that make use of blueprints are unattractive in unknown environments as they can not compensate for heterogeneities, such as irregular terrain. In nature, social insects coordinate the construction of their nests using stigmergy, a mechanism of indirect coordination that is robust and adaptive. In this paper, we propose the design of a multi-robot construction platform called the Swarm Robotics Construction System (SRoCS). The SRoCS platform is designed to leverage stigmergy in order to coordinate multi-robot construction in unknown environments.

1 Introduction

It is possible that a multi-robot construction system will be a practical solution in the future for building basic infrastructure, such as shelter, rail, and power distribution networks on extraterrestrial planets or moons, prior to the arrival of humans [12]. Due to the distances involved, real-time control of the robots or communication supporting the surveying of the remote environment prior to construction are typically not viable options. For this reason, a system that is robust and capable of performing construction in a variety of environments without specific programming is desirable.

Stigmergy is a form of indirect coordination that enables the self-organization observed in social insects such as ants, bees, termites, and wasps. Grassé [8] originally introduced the concept of stigmergy in the context of termite nest construction, where previous work by the termites became a stimulus to perform further work. Although this form of coordination that makes use of stigmergy has been shown to be less efficient than hierarchical coordination, it benefits

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from not having a single point of failure, is capable of operating in a variety of environments without specific programming, and requires simpler hardware [7].

A number of multi-robot systems that use exclusively stigmergy to coordinate the building process have been presented in the literature; however, they are only capable of constructing rudimentary structures such as clusters and walls [1, 10, 17, 23–25, 29]. While there are construction systems that make use of stigmergy and are capable of building more complex structures, these systems supplement the use of stigmergy with a blueprint or external infrastructure for positioning and communication [21, 30, 31, 33]. These approaches are not attractive in unknown environments, as the use of a blueprint is a form of specific programming that is unable to compensate for variations in the environment, such as irregular terrain. Furthermore, the use of external infrastructure for positioning and communication is not suitable for rapid deployment in unknown environments.

In order to demonstrate the potential of stigmergy for construction in unknown environments, we propose the design of a multi-robot construction platform called the Swarm Robotics Construction System (SRoCS). The SRoCS platform makes use of stigmergy to coordinate a flexible building process that is capable of adapting to the environment, without relying on external infrastructure for positioning and communication. This is achieved by encoding the construction process as simple rules that use previously completed work, as well as heterogeneities and templates in the environment, to guide the construction process. This approach is inspired by Theraulaz et al. [26, 27] who simulated the construction of wasp nests in a 3D lattice.

Following an overview of the background literature in Section 2, we present in Section 3 the design of our multi-robot construction platform, SRoCS. Experiments using SRoCS are described in Section 4 and the conclusions of this work are then provided in Section 5.

2 Background

In this section, we present some examples where stigmergy is used to coordinate the construction of termite and social wasp nests in nature. Following these examples, we provide an overview of the work done in multi-robot construction in simulation and using real hardware, focusing on the use of stigmergy where present.

2.1 Construction in Nature

Bruinsma [6] used stigmergy to explain the formation of various structural elements in termite nests. For example, Bruinsma described three uses of pheromones by termites that regulate the construction of the royal chamber. First, pheromones are used to form a trail that causes workers to be recruited towards the construction site. Second, a pheromone emitted by the queen termite is used to create a template for the chamber. Third, worker termites add pheromone to the soil pellets during construction. This pheromone attracts workers to place more soil pellets nearby those that have been recently placed.

Karsai et al. [11] demonstrated that social wasps coordinate the construction of brood combs by sensing the local environment using their antennae. Wasps use local information, such as the number of walls in a partially completed comb, to select from various actions such as lengthening a comb or starting a new comb.

2.2 Simulation

Deneubourg et al. [7] presented the first work using stigmergy in simulation using ant-like robots to implement decentralized clustering and sorting algorithms in a 2D lattice. In this system, the robots move around randomly, picking up and putting down objects with probabilities that are a function of the density of similar objects nearby. These actions are coordinated through stigmergy as the previous placement of objects indirectly coordinates further actions taken by other robots. Melhuish et al. [18] showed that this approach was scalable by demonstrating the sorting of up to 20 types of objects in a simulation based on hardware experiments with Holland et al. [10].

Based on a mathematical model developed to explain the emergence of structures observed in termite nests [5], Ladley and Bullock [13, 14] created an agent-based 3D simulation for the formation of chambers and walls, adding in physical and logistical constraints. This work was extended by Linardou [15] who demonstrated the impact of using realistic pheromone dispersion rules. This work showed that stigmergic coordination through interactions of the agents with pheromone gradients and previously completed work was capable of regulating the construction of various termite nest-like structures.

Theraulaz et al. [26, 27] demonstrated the construction of several wasp nest-like structures using algorithms that caused an agent to deposit a brick in a 3D lattice when a condition based on the local configuration was satisfied. These conditions would be in terms of patterns of existing bricks perceived by an agent. This coordination is an example of stigmergy as the patterns of existing bricks are the result of previous actions by other agents. In further work by Bonabeau et al. [4] genetic algorithms were used to search for sets of rules that lead to the construction of structured patterns.

2.3 Multi-robot Construction

Implementations of multi-robot systems have been used to demonstrate construction tasks. In this section, we discuss implementations of decentralized multi-robot construction systems with respect to how and if they use stigmergy in the construction algorithm. Implementations of centralized multi-robot construction systems often depend on external infrastructure for positioning and communication [2, 16, 32–34], which makes them unsuitable for rapid deployment in unknown environments.

Implementations of decentralized multi-robot construction systems are organized with respect to the type of stigmergy used. Stigmergy is classified as being quantitative or qualitative [3]. Quantitative stigmergy is where the likelihood of a response to a stimulus is proportional to the intensity of that stimulus. An example of this type of stigmergy was shown in the work of Bruinsma [6], where the termites would respond to the concentration of pheromones and soil pellets in their immediate environment. Qualitative stigmergy is where the probability of performing a given action is a function of a perceived environmental configuration. For instance in the nest of social wasps, an individual could decide whether or not to add a wall to the brood comb depending on the number of walls already built [11].

Construction Based on Quantitative Stigmergy. Beckers et al. [1] were the first to demonstrate the use of stigmergy in a multi-robot system for distributed clustering. They maintained that the use of stigmergy has a significant advantage over coordination using direct communication, as direct communication would have required the abstraction of the information regarding the type of task, as well as its spatial and temporal locality. Holland and Melhuish [10] extended the work in [1] to the task of clustering and sorting two kinds of Frisbees. In related work, Song et al. [24] used iRobot Creates to cluster square shaped objects using two developed behaviors, *twisting* and *digging* which exploited the geometry of the square tiles to be clustered.

Stewart and Russell [25] constructed a loose wall along a template using a team of robots. The template was formed by a leader robot moving a lamp in a straight line once the current point in the wall had enough material. Soleymani et al. [23] also demonstrated the construction of a wall along a template using soft materials. Napp et al. [19] reasoned that soft materials have advantages over rigid materials, as they conform to the shape of the surface on which they are placed.

Construction Based on Qualitative Stigmergy. Wawerla et al. [29] provided the first application of qualitative stigmergy, demonstrating the construction of a wall from two alternating types of velcro blocks. The wall was built along a laser generated template and the robots would exchange information about the next type of block to be placed.

The TERMES multi-robot construction system by Werfel et al. [21, 31], represents the current state of the art in decentralized multi-robot construction. This system is capable of building staircase-like structures using tiles that the robot can climb on. The system uses an offline compiler to flatten a user-specified cellular 3D structure onto a directed graph whose nodes constitute a height map. The edges of this directed graph specify how the robots can move across the structure. The robots execute an algorithm that selects a subset of these directed edges to traverse the structure. This directed graph is a blueprint containing all the required information to build the structure. In order to avoid deadlock conditions during construction, fixed stigmergic rules are used to regulate the construction order.

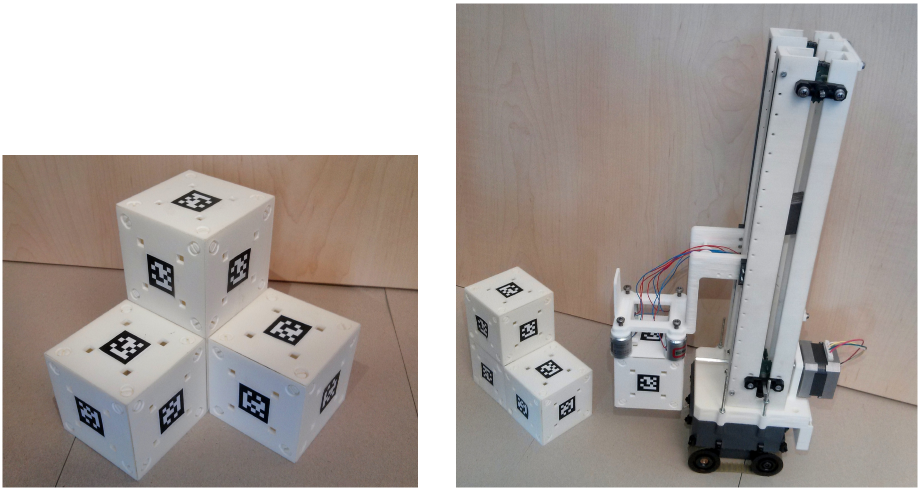
2.4 Summary

Decentralized multi-robot construction systems have been shown to be capable of building rudimentary structures like clusters and walls. While more sophisticated structures have been demonstrated using the TERMES system, this system is limited to performing construction in known environments where a blueprint of the structure to be built, is provided by an architect who has prior knowledge of the environment.

In order to enable decentralized construction in unknown environments, we present the design of a multi-robot construction platform called SRoCS. SRoCS aims at leveraging stigmergy to coordinate a flexible building process in a variety of environments.

3 Overview of the Proposed Platform

The design of the SRoCS platform consists of mobile robots and stigmergic building blocks whose prototypes are shown in Fig. 1. The robots are equipped with a specialized manipulator, which has been optimized for assembling the blocks. While disassembly of blocks would support experiments involving the use of temporary scaffolding-like structures, it is not supported in the initial prototype of the SRoCS platform. In addition, the use of a multi-robot simulator is discussed as an alternative to running experiments using real hardware.



(a) (b)

Fig. 1. Prototypes of (a) the stigmergic building block and (b) the mobile robot

3.1 The Stigmergic Building Blocks

In order to leverage stigmergy in SRoCS, we propose the design of stigmergic building blocks. These blocks aim at emulating the use of pheromones by termites in construction. The blocks contain four multi-color LEDs on each face. The colors of these LEDs can be sensed by the cameras on the robots and updated using the NFC (Near Field Communication) interface between the manipulator and the block.

A prototype of this block is shown in Fig. 1a. We have chosen the geometry to be cubic as it allows the block to be placed into the structure without the need for rotation. Eight spherical magnets in the corners allow the blocks to self-align with each other and allow the blocks to be picked up by a robot. In order to simplify the computer vision required by the robots to see the blocks, localizable 2D barcodes called AprilTags [20] are added to the faces of the block.

Inside the block, a main circuit board hosts a micro-controller, an accelerometer and a Zigbee radio for collecting experimental data and debugging. Depending on the software running on the blocks, additional functionality such as block-to-block communication is also possible.

3.2 The Mobile Robots

The BeBot [9] is selected as the mobile robot in the SRoCS platform due to its small size, modularity, and availability. In the SRoCS platform, the robots move around the environment randomly searching for building blocks that can be used for construction. Proximity sensors around the base of the robots allow for obstacle avoidance with other robots and the structure being built. The camera on the robot allows for the detection of the AprilTag barcodes on the block. The detection of these barcodes allows the robot to localize itself with respect to the building blocks in the environment or to the structure being built.

To pick up and place the building blocks into a structure, the robot is equipped with a specialized manipulator that is shown in Fig. 1b. The manipulator design bears similarities with a fork-lift, with the exception that the block is picked up from the top and held in place using electro-permanent magnets. To detach the block from the manipulator the electro-permanent magnets are activated causing the magnetic field that held the block in place to drop to near zero. We have optimized the manipulator for creating structures of a height of up to three blocks; this provides a good trade-off between flexibility and stability.

The robots are able to communicate indirectly with each other by positioning the building blocks and updating the colors of the LEDs on the blocks. These colors can be assigned various meanings depending on the algorithm in use. For instance, a particular color can be used to indicate a seed block or a block that has already been placed into the structure.

3.3 Simulation Tool

Running experiments with real hardware is time consuming and can be expensive when experimenting with large numbers of robots. It is therefore desirable to use a simulation tool to evaluate the performance of the construction algorithm, before running experiments using the real hardware.

The ARGoS simulator [22] is used as the simulator for this construction platform as it achieves both flexibility and efficiency. Flexibility is necessary as our system requires the simulation of technologies, such as magnetism, that are not commonly found in robot simulation packages. Efficiency is also important as SRoCS is a multi-robot construction platform, and it is desirable that it be possible to run simulations with tens or hundreds of robots.

To simulate the hardware described above, several extensions have been developed for ARGoS. These extensions include a magnetism plugin based on [28] and a new 3D physics plugin based on the open-source physics engine Bullet. These extensions have been shown to simulate the self-alignment behavior of the blocks, as well as the attachment/detachment dynamics of the manipulator.

A prototyping plugin was also developed for the ARGoS simulator that allows for a quick evaluation of designs. This plugin also enables the sensors and actuators required to implement the manipulator, the computer vision, and the communication between the blocks and the robots.

4 Swarm Construction Examples

SRoCS is designed to leverage stigmergy to coordinate construction. Examples are provided to demonstrate the different ways in which stigmergy can be used to coordinate various construction tasks. Figs. 2-4 are visualizations from the ARGoS simulator and are based on the described hardware. These visualizations aim to give examples of the types of experiments that the SRoCS platform has been designed to run.

4.1 Substructure Formation

Blueprints of overall structures to be built are avoided as they are not adaptive to heterogeneities in the environment, such as irregular terrain. It is however useful to encode some substructures as sets of simple rules that use previously completed work to precisely regulate part of the construction.

In the example shown in Fig. 2, the robots are coordinated through the positions of the stigmergic building blocks and the colors of the LEDs on the faces of the blocks, in order to regulate the following construction steps. This approach to leveraging stigmergy is inspired by the work of Theraulaz et al. [26, 27] and is an example of using qualitative stigmergy in the SRoCS platform.

4.2 Construction Using Templates

As discussed in Section 2.1, the formation of the termite royal chamber is in part regulated by the dispersion of a pheromone by the queen. This pheromone stimulates the worker termites to build around her. A similar mechanism can be employed in SRoCS as shown in Fig. 3. In this scenario one or more seed blocks

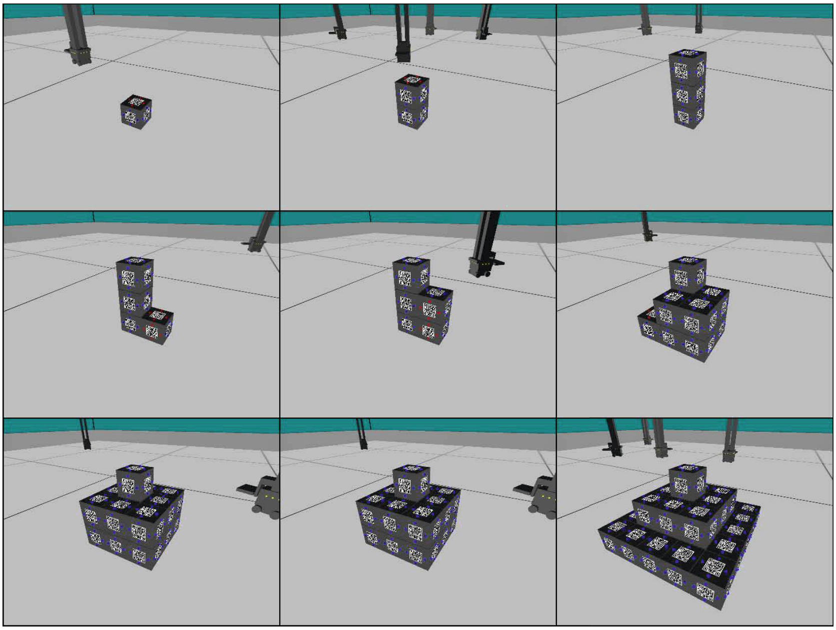


Fig. 2. Construction of a pyramid

are placed in the environment with the LEDs set to a designated color. These seed blocks can form a template in the environment that in conjunction with previously completed work, facilitates the construction of chambers or passage-like structures through stigmergy.

Depending on the implementation, this approach can lead to a stochastic building process. Stochasticity in the building process can be exploited to increase the adaptivity of the system to the environment. It is also possible that stochasticity is fundamental in some cases, such as when the system is required to dynamically explore multiple solutions and adapt the structure being built to the heterogeneities found in the environment.

4.3 Construction Exploiting Environmental Heterogeneities

When designing a system that must be able to build in an unknown environment, heterogeneities need to be taken into account. For example, geographical features in the terrain, such as the presence of a river, must be compensated for in the building process. An example of this is shown in Fig. 4, where the robots are using the previously placed blocks as well as the variations in the simulated terrain to regulate the construction of a wall. This indirect coordination that uses the previously placed blocks as well as variations in the terrain to regulate the construction process is an example of how the SRoCS platform can leverage stigmergy in unknown environments.

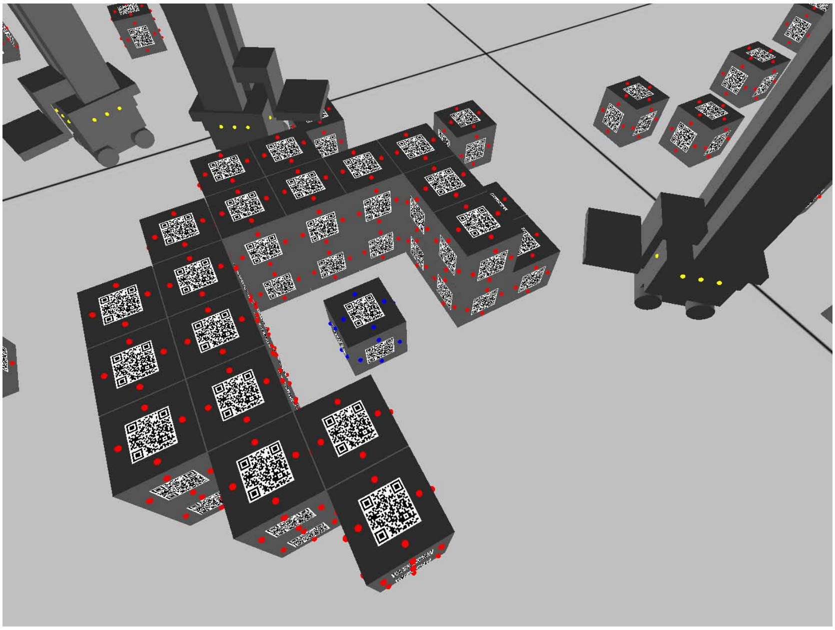


Fig. 3. Building a chamber-like structure using a template

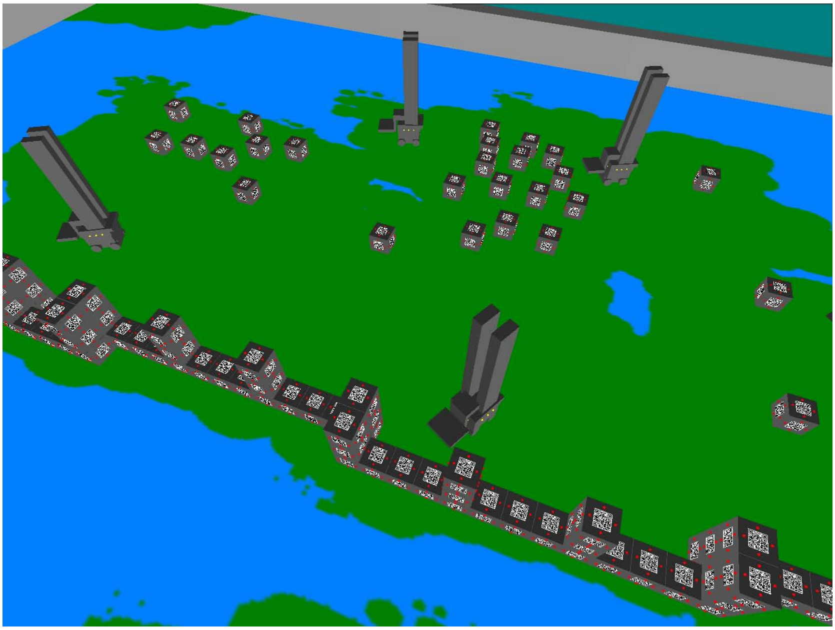


Fig. 4. Building a barrier along a heterogeneity in the environment

5 Conclusions

Current implementations of decentralized multi-robot construction systems are limited to the construction of rudimentary structures such as walls and clusters, or rely on the use of a blueprint or external infrastructure for positioning and communication. In unknown environments, the use of blueprints is unattractive as it cannot adapt to the heterogeneities in the environment, such as irregular terrain. Furthermore, the reliance on external infrastructure is also unattractive, as it is unsuitable for rapid deployment in unknown environments.

In this paper, we have proposed the design of a multi-robot construction platform called SRoCS. In contrast to other multi-robot construction systems, the aim of SRoCS is to provide a flexible building process that is adaptive to heterogeneities and variations in the environment. The coordination of the building process in SRoCS is facilitated through stigmergy, and based on the observations and models of the construction of social wasp and termite nests as described by Karsai et al. [11] and Bruinsma [6] respectively.

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References

1. Beckers, R., Holland, O.E., Deneubourg, J.L.: From local actions to global tasks: Stigmergy and collective robotics. In: Artificial life IV: Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems, pp. 181–189. MIT Press, Cambridge (1994)
2. Bolger, A., Faulkner, M., Stein, D., White, L., Rus, D.: Experiments in decentralized robot construction with tool delivery and assembly robots. In: 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2010), pp. 5085–5092. IEEE Press, Piscataway (2010)
3. Bonabeau, E., Dorigo, M., Theraulaz, G.: Swarm Intelligence: From Natural to Artificial Systems. Oxford University Press, New York (1999)
4. Bonabeau, E., Guérin, S., Snyers, D., Kuntz, P., Theraulaz, G.: Three-dimensional architectures grown by simple 'stigmergic' agents. BioSystems 56(1), 13–32 (2000)

5. Bonabeau, E., Theraulaz, G., Deneubourg, J.-L., Franks, N.R., Rafelsberger, O., Joly, J., Blanco, S.: A model for the emergence of pillars, walls and royal chambers in termite nests. Philosophical Transactions of the Royal Society of London B: Biological Sciences 353(1375), 1561–1576 (1998)
6. Bruinsma, O.H.: An Analysis of Building Behaviour of the Termite Macrotermes Subhyalinus (Rambur). Ph.D. thesis, Landbouwhoge School, Wageningen, The Netherlands (1979)
7. Deneubourg, J.-L., Goss, S., Franks, N., Sendova-Franks, A., Detrain, C., Chrétien, L.: The dynamics of collective sorting robot-like ants and ant-like robots. In: Meyer, J.A., Wilson, S. (eds.) Proceedings of the First International Conference on Simulation of Adaptive Behavior on From Animals to Animats, pp. 356–363. MIT Press, Cambridge (1991)
8. Grassé, P.P.: La reconstruction du nid et les coordinations inter-individuelles chez Bellicositermes Natalensis et Cubitermes sp. La théorie de la stigmergie: Essai d'interpretation du comportement de termites constructeurs. Insectes Sociaux 6(1), 41–80 (1959)
9. Herbrechtsmeier, S., Witkowski, U., Rückert, U.: Bebot: A modular mobile miniature robot platform supporting hardware reconfiguration and multi-standard communication. In: Kim, J.-H., et al. (eds.) Progress in Robotics. CCIS, vol. 44, pp. 346–356. Springer, Heidelberg (2009)
10. Holland, O., Melhuish, C.: Stigmergy, self-organization, and sorting in collective robotics. Artificial Life 5(2), 173–202 (1999)
11. Karsai, I., Pénzes, Z.: Comb building in social wasps: Self-organization and stigmergic script. Journal of Theoretical Biology 161(4), 505–525 (1993)
12. Khoshnevis, B.: Automated construction by contour crafting – related robotics and information technologies. Automation in Construction 13(1), 5–19 (2004)
13. Ladley, D., Bullock, S.: Logistic constraints on 3D termite construction. In: Dorigo, M., Birattari, M., Blum, C., Gambardella, L.M., Mondada, F., Stützle, T. (eds.) ANTS 2004. LNCS, vol. 3172, pp. 178–189. Springer, Heidelberg (2004)
14. Ladley, D., Bullock, S.: The role of logistic constraints in termite construction of chambers and tunnels. Journal of Theoretical Biology 234(4), 551–564 (2005)
15. Linardou, O.: Towards Homeostatic Architecture: Simulation of the Generative Process of a Termite Mound Construction. Master's thesis, University College London, London, United Kingdom (2008)
16. Lindsey, Q., Mellinger, D., Kumar, V.: Construction with quadrotor teams. Autonomous Robots 33(3), 323–336 (2012)
17. Martinoli, A., Mondada, F.: Probabilistic modelling of a bio-inspired collective experiment with real robots. In: Distributed Autonomous Robotic Systems, vol. 3, pp. 289–298. Springer, Heidelberg (1998)
18. Melhuish, C., Wilson, M., Sendova-Franks, A.: Patch sorting: Multi-object clustering using minimalist robots. In: Kelemen, J., Sosík, P. (eds.) ECAL 2001. LNCS (LNAI), vol. 2159, pp. 543–552. Springer, Heidelberg (2001)
19. Napp, N., Rappoli, O.R., Wu, J.M., Nagpal, R.: Materials and mechanisms for amorphous robotic construction. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012), pp. 4879–4885. IEEE Press, Piscataway (2012)
20. Olson, E.: AprilTag: A robust and flexible visual fiducial system. In: 2011 IEEE International Conference on Robotics and Automation (ICRA 2011), pp. 3400–3407. IEEE Computer Society Press, Los Alamitos (2011)

21. Petersen, K., Nagpal, R., Werfel, J.: TERMES: An autonomous robotic system for three-dimensional collective construction. In: Durrant-Whyte, H.F., et al. (eds.) Robotics: Science and Systems VII, pp. 257–264. MIT Press, Cambridge (2011)
22. Pinciroli, C., Trianni, V., O'Grady, R., Pini, G., Brutschy, A., Brambilla, M., Mathews, N., Ferrante, E., Di Caro, G., Ducatelle, F., Birattari, M., Gambardella, L.M., Dorigo, M.: ARGoS: a modular, parallel, multi-engine simulator for multi-robot systems. Swarm Intelligence 6(4), 271–295 (2012)
23. Soleymani, T., Trianni, V., Bonani, M., Mondada, F., Dorigo, M.: Autonomous construction with compliant building material. In: Intelligent Autonomous Systems (IAS 2014). AISC. Springer, Berlin (in press, 2014)
24. Song, Y., Kim, J.H., Shell, D.A.: Self-organized clustering of square objects by multiple robots. In: Dorigo, M., Birattari, M., Blum, C., Christensen, A.L., Engelbrecht, A.P., Groß, R., Stützle, T. (eds.) ANTS 2012. LNCS, vol. 7461, pp. 308–315. Springer, Heidelberg (2012)
25. Stewart, R.L., Russell, R.A.: A distributed feedback mechanism to regulate wall construction by a robotic swarm. Adaptive Behavior 14(1), 21–51 (2006)
26. Theraulaz, G., Bonabeau, E.: Coordination in distributed building. Science 269(5224), 686–688 (1995)
27. Theraulaz, G., Bonabeau, E.: Modelling the collective building of complex architectures in social insects with lattice swarms. Journal of Theoretical Biology 177(4), 381–400 (1995)
28. Thomaszewski, B., Gumann, A., Pabst, S., Straßer, W.: Magnets in motion. ACM Transactions on Graphics 27(5) 162, 162:1–162:9 (2008)
29. Wawerla, J., Sukhatme, G.S., Matarić, M.J.: Collective construction with multiple robots. In: 2002 IEEE/RSJ International Conference on Intelligent Robots and System (IROS 2002), vol. 3, pp. 2696–2701. IEEE Press, Piscataway (2002)
30. Werfel, J., Bar-Yam, Y., Rus, D., Nagpal, R.: Distributed construction by mobile robots with enhanced building blocks. In: 2006 IEEE International Conference on Robotics and Automation (ICRA 2006), pp. 2787–2794. IEEE Computer Society Press, Los Alamitos (2006)
31. Werfel, J., Petersen, K., Nagpal, R.: Designing collective behavior in a termite-inspired robot construction team. Science 343(6172), 754–758 (2014)
32. Willmann, J., Augugliaro, F., Cadalbert, T., D'Andrea, R., Gramazio, F., Kohler, M.: Aerial robotic construction towards a new field of architectural research. International Journal of Architectural Computing 10(3), 439–460 (2012)
33. Wismer, S., Hitz, G., Bonani, M., Gribovskiy, A., Magnenat, S.: Autonomous construction of a roofed structure: Synthesizing planning and stigmergy on a mobile robot. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012), pp. 5436–5437. IEEE Press, Piscataway (2012)
34. Worcester, J., Rogoff, J., Hsieh, M.A.: Constrained task partitioning for distributed assembly. In: 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011), pp. 4790–4796. IEEE Press, Piscataway (2011)