Robotics for Self-Organised Construction

Victor Gerling and Sebastian von Mammen
Organic Computing, University of Augsburg, Augsburg, Germany
victor-gerling@online.de, sebastian.von.mammen@informatik.uni-augsburg.de

Abstract—**Recent advances in material sciences and robotics promise a potential paradigm shift in the design and construction of human architecture. Inspired by nest constructions of social insects, architectural designs and constructions could arise from locally coordinated interactions of large numbers of robots. In order to achieve this goal, the algorithmic foundations of such processes need to be researched, these investigations' results need to be translated to productive systems, possibly first in the context of multi-physics simulations, and finally to actual, deployment-ready hardware systems. Important research steps are taken at all these levels of abstraction. In this paper, we present a brief survey of works that promote the deployment of self-organising robotic systems for the purpose of building construction. It focusses on the aspects of building materials (rigid and amorphous), deployed hardware (grounded and airborne) and the organisational realisation of the robots' coordination by means of stigmergic communication.**

I. Introduction

Originally inspired by nest construction in social insects [1], the concept of self-organising construction relies on a large number of agents that coordinate their building efforts by prompting and reacting to local stimuli. Very recently, with the wake of robotic swarms, seminal preceding works on automation of construction processes [2] and novel material processing approaches [3], including for instance 3D printing techniques [4] and innovative deployment of carbon fibres [5], self-organising construction is quickly gaining tremendous transformative significance in the context of various design and construction processes. These include also the construction, extension and renovation of architectural buildings [6], engineering design [7], industrial assembly and manufacture [8], and landscape architecture [9]. Automation of otherwise human-performed tasks is just a first step towards robotic deployment. Certain application niches emphasise the versatility, flexibility, human-safety and reaching otherwise unreachable targets. An according, popular illustrative example would be the vision of swarms of robot bulldozers building a lunar base [10]. Yet, the realisation of self-organised construction faces numerous challenges. These include engineering aspects as broad as finding construction materials, transporting them, identifying apt targets for deployment, path finding, path planning, actually deploying the building blocks, etc. It also greatly depends on finding solutions to challenges such as the translation of globally specified design requirements [11] or even specific architectural morphologies [12], [13] into locally executable construction behaviours. While great efforts are made to finding according solutions, for instance with respect to coordination in heterogeneous self-organising systems [14], this paper focusses on the very foundational aspects that prepare robotic technologies for self-organised construction processes. Different from self-assembling robotic systems, see e.g. [15], we hereby consider robots that deploy a construction material other than their own embodiments. As such, the focus of our survey lies in the materials utilised (Section II), the robotic hardware that makes the construction processes possible (Section III) and the approaches of self-organisation of constructing robot collectives (Section IV). We conclude this survey with an outlook on possible next steps towards production of self-organised robotic construction (Section V).

II. Materials

An adequate choice of construction materials is crucial to implement a specific construction process and to realise an envisioned artefact. After all, it determines the requirements and, indirectly, the capabilities of the deployed robotics hardware. It also shapes the form and structural capabilities of the target construction. In this section, we distinguish between solid and amorphous materials that have been investigated in this context.

A. Rigid Materials

In [16] cubic bricks were used to overcome ravines and to build towers. Magnets ensured a firm connection between the bricks, and they also helped to improve the deployed construction robot's ability to grab, transport and deploy the bricks. In [17] prefabricated building materials were used, as well. However, they were designed with greater structural integrity in mind: They have bulges and dents to tightly engage with each other and also to facilitate their transport. A beam-shaped aluminium block was used in [18]. Because of its dimensions, it had to be carried by two robots at once, which shows that the transport of heavy and bulky resources can still be managed using multiple robots. Less massive were the polyurethane foam blocks, which were used in [19]. They were picked up and deployed by aerial robots, which only had limited load capacities. In order to firmly grip the foam blocks were lubricated with a water-soluble adhesive. The adhesive had to be applied shortly before the installation. In [20], [21] building materials were augmented with electronic components - we will review this more in detail in Section IV-B.

B. Amorphous Materials

Different from the use of rigid materials, amorphous, i.e. non-crystalline, materials were investigated as well. In [22] amorphous foam was used to build ramps in uneven terrains.

This would not have been directly possible by means of rigid materials as the flexibility and thereby the adaptability of the amorphous material vastly facilitates this task. Nagpal and Napp continued their work in [23], in which bulky constructions were built with the help of foam material and the previous ramps. In [24] robots also set out to building ramps. But this time the focus lied in the used materials rather than algorithmic concepts and analyses: Here, three rather different amorphous materials were chosen and examined. Firstly, toothpicks and glue were used to build a structure, which reminds of beaver dams and birds' nests. To this end, the two tips of the toothpicks were covered in glue and superimposed on each other. Secondly, sandbags were aligned to build the ramp. In order to fill possible crannies or gaps, fine grains of rice or corn were used. Sand was chosen because of its compressive strength. This rationale was also followed in [25], where sandbags were used for building a wall, not unlike embankments commonly seen along water streams to prevent flooding. Thirdly, as in [22], [23], foam material was tested to building ramps. All three approaches were examined for characteristics like pressure sensitivity, effort and costs. In comparison, it was obvious that there is no universally favourable material approach. Foam, for instance, offers a high degree of expansion, which is advantageous considering its simpler storage and transport but it comes at a higher cost. Sandbags, on the other hand, do not expand at all but do not need to cure either, which can save a lot of time and simplify synchronisation in a multi-unit system. In the end, the preference for a specific material greatly depends on any given project requirements. And these material requirements can be rather specific, other projects such as the one presented in [26] attempt to increase the versatility. Here, two-component polyurethane was mixed and "printed" by an aerial robot in-situ. The use of a mobile, airworthy robots overcomes the limitations of 3D printers that are static to begin with or tied to motion on the ground, like the limitation of size. Another piece of work considered the precision of the printing result due to the dynamics that need to be balanced out during the flight of a quadcopter [27]. Similarly to the utilisation of amorphous materials, there have been efforts to let quadcopters build tensile structures unrolling threads or ropes, e.g. [28], [29], [30].

C. Comparing Rigid and Amorphous Materials

Rigid, well-specified, prefabricated building materials guarantee for stable and precise constructions. Consequently, the manufacturing process is relatively high. It must be ensured that the building blocks are designed to facilitate the transport by the construction robots (or by some kind of interwoven infrastructure). These materials also need the capability to adhere to each other or be mechanically joined. When there is no such mechanism, the robots have to work with a secondary material such as cement or mortar, which not only increases the complexity of the robots' hardware but also of the construction processes. Furthermore, weight and volume of the materials and the characteristics of the given terrain are significant for the construction process. Rigid blocks are usually not adaptable and their use in unsteady terrain can be problematic. Complementary to this are amorphous materials, which can potentially handle any terrain. One disadvantage of nonrigid materials lies in the degree of imprecision introduced by their (temporary) viscosity and their expansion. However, they lend themselves well for evening out rough surfaces, filling gaps or patching holes. Like in traditional processes of building construction (think of concrete foundations and brick walls), a several phase construction process to blend and thereby harness both material types should be considered. In this way, an uneven terrain can be prepared by using amorphous materials whereas rigid materials can provide for precise and swift construction.

III. Robotic Hardware

Continuing our bottom-up approach to surveyed technologies for self-organising construction, we now focus on the robotic hardware platforms. Again, there are two categories that we look at more in-depth: Grounded and aerial robots.

A. Grounded Hardware Platforms

The so-called marXbot [16], [31] may be considered a representative for the majority of the other ground robots. It is a small, lightweight and manoeuvrable robot, which is equipped with a set of basic sensors. It comes with one rotating distance sensor, 24 ultrasonic sensors and 8 ground sensors. It has a built-in battery which provides a runtime of up to seven hours. Two magnetic grabbing arms enable the marXbot to interact with the environment and to deploy building materials. However, there are also several possible complications. As an example, to guarantee a maximally constant work flow, recharging the battery should be possible. There are two possible solutions to this challenge: (1) Setting up a charging station that can be visited by the robot. The advantage lies in quick recharge cycles, potential disadvantages are: The need for an infrastructure to orientate itself, to calculate shortest paths and to adjust the route in when facing unforeseen obstacles. (2) The robot might pause its construction work (for a typically considerably longer period of time) and recharge through harvesting naturally available energy sources like solar energy. Also considerable would be the use of inductive charging, which is becoming popular in automated guided vehicles in industrial automation. Another challenge is posed by the mechanisms for grabbing and deploying construction materials, as for instance stressed in [32]. In [33], robots are directed to the construction material through a truss-like infrastructure. Complementary to lab-tests and functional prototypes, conceptual deliberations such as [34] can support the design of hardware platforms capable of climbing the built artefact and to manipulate it. It stresses the need to finely tune the hardware platform and the deployed construction material in order to ensure the required flexibility in movement. The Swarm Robotics Construction System (SRoCS) deploys a construction robot that handles cubic construction blocks similarly to a fork-lift [35]. Futuristic visions such as [36] introduce concepts such as self-reconfigurable robots capable of changing their own shape and therefore able to navigate through any terrains. Adjusting these to the task of self-organising construction holds a great number of additional challenges but might also provide efficient solutions to switching from efficient transport to high precision material deployment.

B. Airborne Hardware Platforms

In contrast to grounded robots, aerial robots have another spatial dimension at their disposal. This gives them more freedom to navigate but, of course, also imposes the threat of crashes with the ground and the need to tightly integrate accurate battery life predictions in the robot controller's decisions. Works like [19], [26], [37], [27], [28], [29], [30] are examples for approaches to airborne robotic construction. The flexibility and precise controls of quadcopters render them the ideal platform for construction purposes. However, the transport of construction material, and even more so, its deployment pose great challenges. In [37] approaches for handling construction materials were investigated. The work emphasises the need to carefully determine the relative position for the transported construction material as it greatly impacts the flight and the robotic unit's ability to deploy it.

C. Grounded vs. Airborne Units

Ground units have some indisputable advantages over airborne units and vice versa. For instance, ground units can generally carry greater loads and their risk of a total breakdown is lower. They mostly simply stop working, if the battery runs out or another problem disrupts its functionality, whereas airborne units often fall victim to unrecoverable crashes. Due to their load capacity, ground units can generally also be equipped with larger batteries ensuring a longer activation phase to begin with. Especially in terms of construction, the benefit of airborne units to easily build upwards trumps the ground units' capabilities. As seen in numerous of the presented works, temporary infrastructures in form of ramps have to be built in order to facilitate ground units' construction efforts at higher altitudes. A useful division of labour strategy between grounded and airborne units might deploy units on the ground to carry heavy packets of construction material to central and accessible locations. There, airborne units might pick them up to construct elevated building modules. Also, the ground units might alleviate the airborne units' task by establishing guiding templates or beacons on the floor. Taking into account the two-phase strategy suggested in Section II-C, grounded units could take on the task to build foundations utilising levelling amorphous materials that airborne units can build on top.

IV. Means of Self-organisation

Further pursuing our approach to surveying self-organised construction techniques and technologies bottom-up, the next higher level of design considers the individual units' capacity to coordinate their work. To this end, the robots should be capable of making right decisions in different situations. Unfortunately, this behavioural challenge is multi-facetted including common tasks in robotics such as path finding, path planning, collision avoidance, material transport, communication, deployment of construction material, and self-maintenance (including battery recharge). For an overview of common challenges in robotics and according solutions, see, for example, [7]. Even more, these primitives have to be combined into higher level strategies that greatly depend, for instance, on the material processing steps and the targeted buildings' overall designs. Based on empirical research that investigates self-organised construction in nature, most prominently nest construction by social insect colonies, there are two key aspects that can be considered the foundation of all of these behavioural aspects: (1) The concept of a collective of entities collaborating and (2) the means to coordinate via the environment, i.e. stigmergy. In this section, we briefly review these two foundational aspects of self-organised construction.

A. From Weak to Strong Self-Organisation

A single robot solves certain problems considerably slower than a collective of robots. An according study was conducted in [38]. Here, a two-staged process was conducted to measure the effect of the number of robots on the speed of construction. To this end, the robots had to first find building blocks and then deploy them. Each building block assumed one of two colours to coordinate the construction process. A robot picking up the wrong block would drop it again and resume its search for the correct block. Throughout the according simulation experiments, the number of simultaneously working robots was steadily increased and the completion time was logged. The completion times first improved with an increasing number of robots, came to a halt and dropped again, whereas the ideal number of robots was directly dependent on the size of the work area.

Next to the potential speed-up, collectives are able solve certain problems that an individual cannot. In particular, the interactions of two or more robots may yield properties of the collective that the individual robots do not have by themselves [39]. Additional benefits of working with larger numbers of robots are the increased system robustness [40]. But with larger numbers of units, the task of programming such systems becomes increasingly difficult. In [41] two approaches of achieving this goal are presented: One centralised approach and one distributed approach. In the first, a single agent controls the behaviour of the group. Possible advantages of such an approach of weak self-organisation [42] may lie in the fact that the controlling agent manages and maintains global knowledge about the system, that it may precisely locate and inspect agents and resources, maintain a clear picture of the system's state of construction and efficiently concert their interactions. However, in this case, the overall system suffers from a single point of failure, from excessive computing costs burdening the controlling robot and large communication overhead. Generally speaking, it is not scalable.

Instead, it has been suggested to translate the coordination mechanisms found in social insects. In [43], for instance, ants were filmed while foraging, whereas the specific collectively performed task under investigation was the collective transport of heavy objects. The first ant to locate an object of interest attracts its peers by making special sounds. Together, the small group of ants then transports the object along a previously laid out pheromone trail back to their nest. In [44] this behavioural pattern was adapted for autonomous robots. First, the robots start their search for resources. Once a robot is successful, it searches for the shortest path between the resource and the targeted construction site. It then shares this information with its peers via bluetooth and the resources can be picked up and transported together. The link between the biological system and its technological realisation brings not only basic functionality to the robotic system but also flexibility and robustness. Similar to [43], several robots transport an object together in [18]: Two robots pick up a steel beam, carry it to its destination and add it to the construction. The engineering challenge lied in programming one of the bots in such a way that it would correctly interpret the torque forces and infer an appropriate adjustment of its driving speed. In another actual real-world robotic experiment inspired by ants, a collective of self-organised bulldozers carved out a circular hole reminiscent of an ants' nest by pushing building material outwards [45]. The robots hardly influenced each other, if it was not for collisions that triggered a re-alignment of the involved bulldozers' heading. The experiments were conducted deploying one, two and four such "blind" bulldozers. With increasing numbers, greater radii were achieved faster. In [21], robots were devised able to build two-dimensional structures, which could adapt their shape to immovable obstacles. During the building process, it could occur that a root got locked inside the construction. This is because the robots either enclosed an obstacle or they just built enclosing fences. The latter required the robots to also be able to tunnel through the built boundaries to ensure the capability to transport materials to the inside and fill the circumference. At the end, the tunnel also needed to be filled to complete the target construction. If a robot remained inside of the constructed artefact, it got trapped, effectively keeping it from contributing to the remaining building efforts. To avoid such a situation, special cooperative behaviour patterns were implemented. For example, in case of two robots navigating through a tunnel in opposite direction, the robots would hand over construction material and not pass each other. Also they would function as gatekeepers preventing robots from entering the construction and waiting for robots inside to decrease the odds of entrapments. In [41] this kind of behaviour is referred to as caring, which can be considered a more intelligent, reflective behaviour than implemented by simple reactive agents. In addition, the termination of subtasks is hard to determine, if dealing with reactive agents only. As a result, more complex objectives might often not be fulfilled. Napp and Klavins were dealing with this issue in [46]. The goal was to reach an even distribution of building blocks across a construction site areal. As a solution, a stochastic algorithm was proposed. Considering experiments with flying robotic units, a fleet of quadcopters was, for instance, deployed in [19]. They were programmed to build a tower from foam bricks. The a priori computation of intertwined trajectories ensured a conflict-free construction process. Different from these investigations, [25] presents a successful implementation of quadcopters improving their behaviours of path planning and collision avoidance by means of offline learning and heuristic search. The only drawback of this approach is the need for a large set of training data. The authors present an approach to generate the respective training set based on fusing data from several real-world quadrotors. In [47] both grounded robots as well as aerial robots were used in combination. It follows earlier concepts of heterogeneous swarms such as swarmoid [48]. For an extensive review of swarm robotics approaches, consider, for instance [49], [40]. In the considered work [47], aerial robots optimally position themselves to accomplish wide-ranged transmissions to support the grounded robots. A current perspective on the challenges and research directions for the realisation of heterogeneous self-organising systems is presented in [14].

B. *Stigmergy*

Social insects like certain species of ants and termites make use of so-called stigmergy. Stigmergy does not provide a direct way to communicate between individual members of a swarm, but rather an indirect approach of communication by modification and interpretation of the environment [50], [51]. Experiments in [52], [20] were inspired by this behavioural mechanism. In the first work, the impact of four different building materials on finishing times and error rates were examined. In what Nagpal and Werfel considered the most common stigmergic communciation example, scenarios with inactive and indistinguishable, i.e. normal, blocks were tested. Here, the only information obtained is the presence of the blocks. Next, the blocks were modified by means of RFID tags (Radio-Frequency IDentification). These are circuits capable of saving information without the need of an external energy source. In this way, every block can obtain a unique identifier, which can, in turn, be read by robots. This information can be used to improve navigation by using the blocks as unique features of a mapped environment. In the next test, the RFID tags were not only readable but also writeable. Hence, the robots were enabled to store their internally measured, current position in the blocks. This extension improved the ability to navigate even further. In the fourth and last test, the blocks were given the ability to communicate. To this end, the blocks were equipped with a microprocessor to empower them to locally process information. In addition, they were equipped with transceivers to exchange information with other blocks relying on wired connections. In this way, the activation of different wires can provide valuable information about blocks in the environment. The first three approaches are complementary in that the machines had to figure out the correct positions by themselves. The authors referred to the last three experiment scenarios as extended stigmergy tests as they augmented the abilities of the materials. And indeed, they yielded considerable performance gains (tests one to four steadily increased in speed). To our knowledge, extended stigmergy offers a truly unique approach to overcoming common issues in navigation tasks. It was also realised in hardware by the SRoCS platform where cubic building blocks emit different colours which can be sensed (through video) and changed (through Near Field Communication) by nearby robots [35]. Less biologically but rather mathematically inspired concepts were presented in [53]. It is based on the idea that the assembly process of a target construction should be completed much faster relying on a Hamiltonian cycle. A Hamiltonian cycle is a closed path in a graph that passes every node exactly once Applying the Hamiltonian on an arbitrary shape and minimising its distance would yield the ideal position for the deployment of the next construction element. In order to facilitate the creation of such a path, an arrow is drawn on each side of a block. When combining the blocks, the robots have to make sure, that the emerging trajectories shown by the arrows result in a correct Hamiltonian cycle. When a correct cycle was created, the robots just have to follow the given trajectories. Another take on stigmergy was shown in [17]. The machines were capable of resuming work at a construction site just by means of already given structures. In this context the terms bottom-up and top-down should be mentioned. Stigmergic approaches are designed bottom-up. Therefore we firstly define concrete and simple actions for reaching a higher level goal. In the prior works, robots were capable of simple actions, which can be implemented relatively easily. It is more problematic to work top-down from the desired outcome, as the basic interactions needed have to be inferred.

Considering the diverse examples we presented, we conclude that stigmergy has not only been shown to effectively drive biological mechanisms but it was successfully retraced in simulation and hardware-based experiments. They also showed that the extension of building materials should be considered when designing a autonomous robotic system, as it can increase stability and performance of the system. Various inspirations to take this path can be looked up in [54]. The alternative, i.e. an exclusively sensor-based navigation approach like in [55], [56], [57], [58] is still possible, but given the considerable successes, we advise the pursuit of (extended) stigmergic approaches.

V. Future Work

Ease of transport, versatility and accuracy of deployment are primary criteria for the choice of construction materials in the context of self-organised construction. Amorphous materials stand out due to their expansion property and rigid materials due to their load-bearing capacities. Grounded construction units are typically more robust and stronger (comparing the relative power intake) than airborne units which, in turn, afford greater mobility. Based on the surveyed work, we suggest several different directions for future research towards self-organising robotic construction.

First, the advantages of different materials and types of hardware platforms could be combined. Robots could, for instance, locally roast bricks to achieve great construction accuracy and to directly release the amorphous base material to level uneven grounds. Considering hardware, as in previously presented visions of heterogeneous swarms, flying and grounded robots could enhance and support each other. In this way, a grounded robot might be lifted quickly by several airborne units to build at higher levels. If the building unit dragged along a flexible tube, a steady flow of construction material could be ensured and the costs for lifting the builder would be alleviated.

Second, in terms of stigmergic communication, we want to motivate a rigorous algorithmic analysis of the relationship between number of robotic units, number of extended stigmergic signals, their configuration spaces and the complexity of the given task. The results of such a work would provide an important foundation for the versatile design of sustainable and effective extended stigmergy hardware components.

Third, a systematic exploration of required steps, conceptual components and behaviours is important for establishing a functional toolkit for self-organising robot construction (not unike the strategic and ongoing efforts by Allwrigth, Werfel, Nagpal, and Napp) and others but considering the multidimensional challenges, a broadly concerted effort would be helpful to quickly establish the cornerstones of this new field. Subjects of necessary investigation range from individual hardware components such as printing nozzles, over the dynamic realisation of required support infrastructures such as ramps, to the exploration of new construction materials.

Fourth, algorithms and optimisation approaches for generating coordinated local behaviours still pose a major challenge.

References

[1] G. Theraulaz, E. Bonabeau, and J.-L. Deneubourg, "The origin of nest complexity in social insects," *Complexity*, vol. 3, no. 6, pp. 15–25, 1998.

[2] K. S. Saidi, J. B. OBrien, and A. M. Lytle, "Robotics in construction," in *Springer handbook of robotics*. Springer, 2008, pp. 1079–1099.

[3] Y. W. Tay, B. Panda, S. C. Paul, M. J. Tan, S. Qian, K. F. Leong, and C. K. Chua, "Processing and properties of construction materials for 3d printing." in *Materials Science Forum*, vol. 861, 2016.

[4] R. A. Buswell, R. Soar, A. G. Gibb, and A. Thorpe, "Freeform construction: mega-scale rapid manufacturing for construction," *Automation in construction*, vol. 16, no. 2, pp. 224–231, 2007.

[5] C. Bakis, L. C. Bank, V. Brown, E. Cosenza, J. Davalos, J. Lesko, A. Machida, S. Rizkalla, and T. Triantafillou, "Fiber-reinforced polymer composites for construction-state-of-the-art review," *Journal of composites for construction*, vol. 6, no. 2, pp. 73–87, 2002.

[6] S. Daftry, C. Hoppe, and H. Bischof, "Building with drones: Accurate 3d facade reconstruction using mavs," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2015, pp. 3487–3494.

[7] B. Siciliano and O. Khatib, *Springer handbook of robotics*. Springer Science & Business Media, 2008.

[8] G. Michalos, S. Makris, N. Papakostas, D. Mourtzis, and G. Chryssolouris, "Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach," *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 2, pp. 81–91, 2010.

[9] D. Schmidt, M. Proetzsch, and K. Berns, "Simulation and control of an autonomous bucket excavator for landscaping tasks," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, 2010, pp. 5108–5113.

[10] R. A. Brooks, P. Maes, M. J. Mataric, and G. More, "Lunar base construction robots," in *Intelligent Robots and Systems' 90.'Towards a New Frontier of Applications', Proceedings. IROS'90. IEEE International Workshop on*. IEEE, 1990, pp. 389–392.

[11] S. von Mammen and C. Jacob, "Evolutionary swarm design of architectural idea models," in *Genetic and Evolutionary Computation Conference (GECCO) 2008*. Atlanta, USA: ACM Press, 2008, pp. 143–150.

[12] S. von Mammen, C. Jacob, and G. Kókai, "Evolving swarms that build 3d structures," in *CEC 2005, IEEE Congress on Evolutionary Computation*. Edinburgh, UK: IEEE Press, 2005, pp. 1434–1441.

[13] J. Werfel, K. Petersen, and R. Nagpal, "Designing collective behavior in a termite-inspired robot construction team," *Science*, vol. 343, no. 6172, pp. 754–758, 2014.

[14] H. Hamann, L. Khaluf, J. Bote, M. D. Soorati, E. Ferrante, O. Kosak, J.-M. Montanier, S. Mostaghim, R. Redpath, J. Timmis, F. Veenstra, M. Wahby, and A. Zamuda, "Hybrid societies: Challenges and perspectives in the design of collective behavior in self-organizing systems," *Robotics and AI*, vol. 3, no. 14, 2016.

[15] R. Groß, M. Bonani, F. Mondada, and M. Dorigo, "Autonomous self-assembly in swarm-bots," *IEEE transactions on robotics*, vol. 22, no. 6, pp. 1115–1130, 2006.

[16] S. Magnenat, R. Philippsen, and F. Mondada, "Autonomous construction using scarce resources in unknown environments," *Autonomous Robots*, vol. 33, 2012.

[17] J. Werfel, K. Peterson, and R. Nagpal, "Designing collective behavior in a termite-inspired robot constructionteam," *Science*, 2014.

[18] A. Stroupe, T. Huntsberger, A. Okon, H. Aghazarian, and M. Robinson, "Behavior-based multi-robot collaboration for autonomous construction tasks," *IEEE International Conference on Intelligent Robots and Systems*, 2005.

[19] F. Augugliaro, S. Lupashin, M. Hamer, C. Male, M. Hehn, M. W. Mueller, J. S. Willman, F. Gramazio, M. Kohler, and R. D'Andrea, "The flight assembled architecture installatio: Cooperative construction with flying machines," *IEEE Control Systems*, 2014.

[20] J. Werfel, Y. Bar-Yam, D. Rus, and R. Nagpal, "Distributed construction by mobile robots with enhanced building blocks," *IEEE International Conference on Robotics and Automation*, 2006.

[21] J. Werfel, D. Ingber, and R. Nagpal, "Collective construction of environmentally-adaptive structures," *IEEE International Conference on Intelligent Robots and Systems*, 2007.

[22] N. Napp and R. Nagpal, "Distributed amorphous ramp construction in unstructured enviroments," *Robotica*, 2014.

[23] ——, "Robotic construction of arbitrary shapes with amorphous materials," *IEEE International Conference on Robotics and Automation*, 2014.

[24] N. Napp, O. R. Rappoli, J. M. Wu, and R. Nagpal, "Materials and mechanisms for amorphous robotic construction," *IEEE International Conference on Intelligent Robots and Systems*, 2012.

[25] S. R. B. dos Santos, C. L. N. Júnior, and S. N. Givigi, "Planning and learning for cooperative construction task with quadrotors," *Systems Conference (SysCon)*, 2014.

[26] G. Hunt, F. Mitzalis, T. Alhinai, P. A. Hooper, and M. Kovac, "3d printing with flying robots," *IEEE International Conference on Robotics and Automation (ICRA)*, 2014.

[27] X. Chen, J. Liu, T. Shi, H. Qian, K. Chen, and Q. Wei, "3d printing robot: model optimization and image compensation," *Journal of Control Theory and Applications*, vol. 10, no. 3, pp. 273–279, 2012.

[28] F. Augugliaro, A. Mirjan, F. Gramazio, M. Kohler, and R. D'Andrea, "Building tensile structures with flying machines," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2013, pp. 3487–3492.

[29] S. von Mammen, S. Tomforde, J. Höhner, P. Lehner, L. Förschner, A. Hiemer, M. Nicola, and P. Blickling, "Ocbotics: An organic computing approach to collaborative robotic swarms," in *Swarm Intelligence (SIS), 2014 IEEE Symposium on*. IEEE, 2014, pp. 1–8.

[30] F. Augugliaro, E. Zarfati, A. Mirjan, and R. D'Andrea, "Knot-tying with flying machines for aerial construction," in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*. IEEE, 2015, pp. 5917–5922.

[31] T. Soleymani, V. Trianni, M. Bonani, F. Mondada, and M. Dorigo, "Autonomous construction with compliant building material," *Advances in Intelligent Systems and Computing*, 2015.

[32] A. Karakerezis, M. Ippolito, Z. Doulgeri, C. Rizzi, C. Cugini, and v. Petridis, "Robotics handling for flat non-rigid materials," *IEEE*, 1994.

[33] F. Nigl, S. Li, J. Blum, and H. Lipson, "Structure-reconfiguring robots," *IEEE Robotics & Automation Magazine*, 2013.

[34] R. Saltaren, R. Aracil, J. M. Sabater, O. Reinoso, and L. M. Jimenez, "Simulation and conception of parallel climbing robots for construction and service," *Robotics*, 2005.

[35] M. Allwright, N. Bhalla, H. El-faham, A. Antoun, C. Pinciroli, and M. Dorigo, "Srocs: Leveraging stigmergy on a multi-robot construction platform for unknown environments," in *International Conference on Swarm Intelligence*. Springer, 2014, pp. 158–169.

[36] D. Rus, "Self-reconfiguring robots," *IEEE Intelligent Systems and their Applications*, 1998.

[37] D. Mellinger, Q. Lindsay, M. Shomin, and V. Kumar, "Design, modeling, estimation and control for aerial grasping and manipulation," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011.

[38] J. Wawerla, G. S. Sukhatme, and M. J. Mataric, "Collective construction with multiple robots," *Intelligent Robots and Systems*, 2002.

[39] C. Müller-Schloer and B. Sick, "Emergence in organic computing systems: Discussion of a controversial concept," in *International Conference on Autonomic and Trusted Computing*. Springer, 2006, pp. 1–16.

[40] M. Brambilla, E. Ferrante, M. Birattari, and M. Dorigo, "Swarm robotics: a review from the swarm engineering perspective," *Swarm Intelligence*, vol. 7, no. 1, pp. 1–41, 2013.

[41] Y. U. Cao, A. S. Fukunaga, and A. B. Kahng, "Cooperative mobile robotics: Antecedents and directions," *Autonomous Robots*, 1997.

[42] C. Müller-Schloer and H. Schmeck, "Organic Computing - Quo Vadis?" in *Organic Computing - A Paradigm Shift for Complex Systems*, C. Müller-Schloer, H. Schmeck, and T. Ungerer, Eds. Birkhäuser Verlag, 2011, ch. 6.2, pp. 615 – 625.

[43] S. Berman, Q. Lindsay, M. S. Sakar, V. Kumar, and S. C. Pratt, "Experimental study and modeling of group retrieval in ants as an approach to collective transport in swarm robotic systems," *Proceedings of the IEEE*, 2011.

[44] R. Cioarga, I. Nalatan, S. Tura-Bob, M. Micea, V. Cretu, M. Biriescu, and V. Groza, "Emergent exploration and resource gathering in collaborative robotic environments," *Robotics and Sensors Environments*, 2008.

[45] C. A. C. Parker, H. Zhang, and C. R. Kube, "Blind bulldozing: multiple robot nest construction," *Intelligent Robots and Systems*, 2003.

[46] N. Napp and E. Klavins, "Load balance for multi-robot construction," *IEEE International Conference on Robotics and Automation*, 2011.

[47] S. Gil, M. Schwager, B. J. Julian, and D. Rus, "Optimizing communication in air-ground robot networks using decentralized control," *IEEE International Conference on Robotics and Automation*, 2010.

[48] M. Dorigo, "Swarm-bots and swarmanoid: Two experiments in embodied swarm intelligence." in *Web intelligence*, 2009, pp. 2–3.

[49] Y. Mohan and S. Ponnambalam, "An extensive review of research in swarm robotics," in *Nature & Biologically Inspired Computing, 2009. NaBIC 2009. World Congress on*. IEEE, 2009, pp. 140–145.

[50] P.-P. Grassé, "La reconstruction du nid et les coordinations interindividuelles chezbellicositermes natalensis etcubitermes sp. la théorie de la stigmergie: Essai d'interprétation du comportement des termites constructeurs," *Insectes Sociaux*, vol. 6, no. 1, pp. 41—81, 1959.

[51] G. Theraulaz and E. Bonabeau, "A brief history of stigmergy," *Artificial Life*, vol. 5, pp. 97–116, 1999.

[52] J. Werfel and R. Nagpal, "Extended stigmergy in collective construction," *IEEE Intelligent Systems*, 2006.

[53] J. Werfel, "Robot search in 3d swarm construction," *First International Conference on Self-Adaptive and Self-Organizing Systems*, 2007.

[54] N. Correll and R. Groß, "From swarm robotics to smart materials," *Neural Computing & Applications*, vol. 19, no. 6, pp. 785–786, 2010.

[55] A. Walker, J. Hallam, and D. Willshaw, "Bee-havior in a mobile robot: the construction of a self-organized cognitive map and its use in robot navigation within a complex, natural environment," *Neural Networks*, 1993.

[56] J. L. Salagnac, "Development of positioning systems for autonomous robots on construction sites," *Intelligent Robots and Systems*, 1989.

[57] J. Kotzian, J. Konecny, H. Prokop, T. Lippa, and M. Kuruc, "Autonomous explorative mobile robot navigation and construction," *9th RoEduNet IEEE International Conference*, 2010.

[58] I. Ashokaraj, A. Tsourdos, P. M. G. Silson, and B. A. White, "A robust approach to multiple sensor based navigation for an aerial robot," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2006.