Space Ants: Constructing and Reconfiguring Large-Scale Structures with Finite Automata

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Abstract

In this video, we consider recognition and reconfiguration of lattice-based cellular structures by very simple robots with only basic functionality. The underlying motivation is the construction and modification of space facilities of enormous dimensions, where the combination of new materials with extremely simple robots promises structures of previously unthinkable size and flexibility. We present algorithmic methods that are able to detect and reconfigure arbitrary polyominoes, based on finite-state robots, while also preserving connectivity of a structure during reconfiguration. Specific results include methods for determining a bounding box, scaling a given arrangement, and adapting more general algorithms for transforming polyominoes.

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1 Introduction

Building and modifying large-scale structures is an important and natural objective in a vast array of applications. In many cases, the use of autonomous robots promises significant advantages, but also a number of additional difficulties. This is particularly true in space, where the difficulties of expensive supply chains, scarcity of building materials, dramatic costs and consequences of even small errors, and the limitations of outside intervention in case of malfunctions pose a vast array of extreme challenges.

In recent years, a number of significant advances have been made to facilitate overall breakthroughs. One important step has been the development of ultra-light and scalable composite lattice materials [29] that allow the construction of modular, reconfigurable, lattice-based structures [35]; see Figure 1. A second step has been the design of simple autonomous robots [32, 34] that are able to move on the resulting lattice structures and move their cell components, allowing the reconfiguration of the overall edifice; see Figure 2.

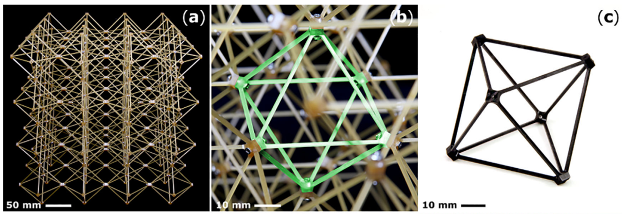

Figure 1 (a) An assembled cuboctahedral lattice specimen, made from octahedral unit cells (highlighted), termed *voxels*. (c) A single injection molded voxel. (See [29].)

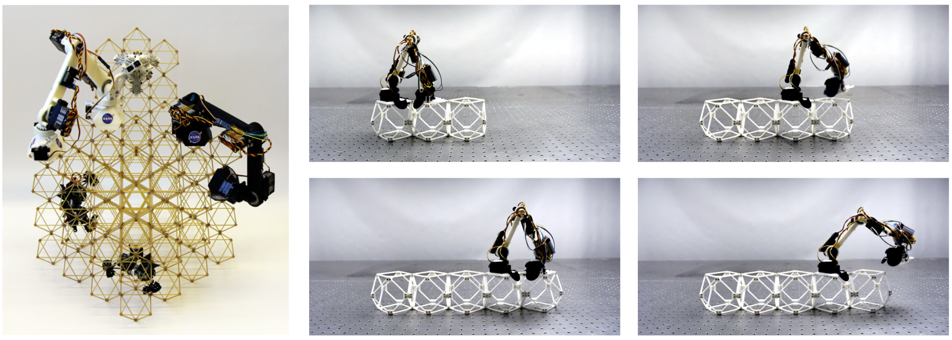

Figure 2 (Left) Modular reconfigurable 3D lattice structure and mobile robots; note how robots are similar in size to lattice cells, and the parallel use of multiple robots. (See [7].) (Right) A sequence of images from the video: a BILL-E robot moving on an expanding row of voxels. (See [31].)

We address the next step in this hierarchy: Can we enable extremely simple robots to perform a more complex spectrum of construction tasks for cellular structures in space, such as patrolling and marking the perimeter, scaling up a given seed construction, and a number of other design operations? As we demonstrate, finite automata can achieve these tasks.

2 Related Work

The structures considered in this work are based on *ultra-light material*, as described by Cheung and Gershenfeld [6] and Gregg et al. [29]. Modular two-dimensional elements mechanically link in 3D to form reversibly assembled composite lattices. This process is not limited by scale, and it enables disassembly and reconfiguration. As shown by Cramer et al. [8] and Jenett et al. [33], large but light-weight structures can be built from these components. Jenett et al. have developed autonomous robots that move on the surface [32, 31] or within the cellular structure [34]. With the help of these robots, individual cells can be attached to an existing assembly, or moved to a different location [31]. An approach for global optimization of a corresponding motion plan has been described by Costa et al. [7], while the design of hierarchical structures was addressed by Jenett et al. [36].

Assembly by simple robots has also been considered at the micro scale, where global control is used for supplying the necessary force for moving agents, e.g., see Becker et al. [2] for the corresponding problem of motion planning, Schmidt et al. [39] for using this model for assembling structures, and Balanza-Martinez et al. [1] for theoretical characterizations. On the algorithmic side, work dealing with *robots or agents on graphs* includes Blum and Kozen [4], who showed that two finite automata can jointly search any unknown maze. Other work has focused on exploring general graphs (e.g.,[38, 23, 20]), as a distributed or collaborative problem using multiple agents (e.g. [3, 21, 9, 5]) or with space limitations (e.g. [22, 23, 17, 24, 25]).

From an algorithmic view, we are interested in *different models representing programmable matter* and further recent results. Inspired by the single-celled amoeba, Derakhshandeh et al. introduced the Amoebot model [11] and later a generalized variant, the general Amoebot model [15]; see [13, 10, 16, 14, 12] for various results in this model. Other models with active particles were introduced in [40] as the Nubot model and in [30] with modular robots. In [26], Gmyr et al. introduced a model with two types of particles: active robots acting like a deterministic finite automaton and passive tile particles. Furthermore, they presented algorithms for shape formation [28] and shape recognition [27] using robots on tiles.

3 Results for Finite Automata

We consider a set of N two-dimensional orthogonal *tiles* that form a *polyomino* P of total width w and height h. We use *robots* as active particles, which work like *finite deterministic automata* that can move between adjacent grid positions, where they can place or remove a tile. We assume that different robots cannot occupy the same position at the same time, and communication between robots is limited to adjacent positions. A basic step for recognizing and possibly reconfiguring P is based on constructing its bounding box $bb(P)$, which is the boundary of the smallest axis-aligned rectangle enclosing but not touching P; this implies that there is a gap of one tile between the two, so we use a robot to keep the two parts connected.

The first result demonstrated in the video deals with constructing the bounding box, and thus recognizing the extent of a shape. See [19, 18, 37] for technical details.

▶ **Theorem 1.** *Given a polyomino P of width w and height h, we can build a bounding box surrounding P with the boundary and P always being connected, with two finite-state robots in $O(\max(w, h) \cdot (wh + k \cdot |\partial P|))$ steps, where k is the number of convex corners in P.*

The second result demonstrated in the video achieves *scaling* of a given shape.

▶ **Theorem 2.** *After building $bb(P)$, scaling a polyomino P of width w and height h by a constant scaling factor c without loss of connectivity can be done with one finite-state robot in $O(wh \cdot (c^2 + cw + ch))$ steps.*

Further reconfiguration results mentioned in the video are as follows.

▶ **Theorem 3.** *Copying a polyomino P columnwise can be done within $\mathcal{O}(wh^2)$ steps using $\mathcal{O}(N)$ of auxiliary particles and $\mathcal{O}(wh)$ additional space in $O(h)$ extra rows and columns.*

▶ **Theorem 4.** *Reflecting a polyomino P horizontally can be done in $\mathcal{O}(w^2h)$ steps, using $\mathcal{O}(w)$ of additional space and $\mathcal{O}(w)$ auxiliary particles.*

▶ **Theorem 5.** *There is a strategy to rotate a polyomino P by $\pm\frac{\pi}{2}$ within $\mathcal{O}((w+h)wh)$ steps, using $\mathcal{O}(w+h+|w-h|h)$ of additional space in $\mathcal{O}(|w-h|+1)$ extra rows and columns and $\mathcal{O}(w+h)$ auxiliary particles.*

Finally, the video demonstrates how we can carry out any geometric transformation by finite-state robots, if and only if there is a corresponding Turing machine for transforming the corresponding one-dimensional string $S(P_1)$ (arising from a row-wise scan of P_1) into $S(P_2)$.

▶ **Theorem 6.** *Let P_1 and P_2 be two polyominos with $|P_1| = |P_2| = N$. There is a strategy transforming P_1 into P_2 if there is a Turing machine transforming the corresponding one-dimensional string $S(P_1)$ into $S(P_2)$. The finite-state robot needs $\mathcal{O}(\partial P_1 + \partial P_2 + S_{TM})$ auxiliary particles, $\mathcal{O}(N^4 + T_{TM})$ steps, and $\Theta(N^2 + S_{TM})$ of additional space, where T_{TM} and S_{TM} are the number of steps and additional space needed by the Turing machine.*

4 The Video

The video starts with a discussion of the problems faced when building large-scale structures in space, and an introduction of digital, ultra light-weight materials and simple robots currently developed at MIT and NASA. This is followed by a description of finite automata corresponding to finite-state robots. As a first algorithmic demonstration, the connected construction of the bounding box of a given polyomino shape is shown, followed by producing a scaled copy of a shape. Then we show how general constructions can be built based on methods of Turing machines. The video concludes with a 3D simulation.

References

1 Jose Balanza-Martinez, Austin Luchsinger, David Caballero, Rene Reyes, Angel A Cantu, Robert Schweller, Luis Angel Garcia, and Tim Wylie. Full tilt: universal constructors for general shapes with uniform external forces. In *ACM-SIAM Symposium on Discrete Algorithms (SODA)*, pages 2689–2708, 2019.

2 Aaron T Becker, Sándor P Fekete, Phillip Keldenich, Dominik Krupke, Christian Rieck, Christian Scheffer, and Arne Schmidt. Tilt assembly: Algorithms for micro-factories that build objects with uniform external forces. *Algorithmica*, 82:165–187, 2020.

3 M. A. Bender and D. K. Slonim. The power of team exploration: two robots can learn unlabeled directed graphs. In *Symposium on Foundations of Computer Science (FOCS*, pages 75–85, 1994. `doi:10.1109/SFCS.1994.365703`.

4 M. Blum and D. Kozen. On the power of the compass (or, why mazes are easier to search than graphs). In *Symposium on Foundations of Computer Science (FOCS)*, pages 132–142, 1978. `doi:10.1109/SFCS.1978.30`.

5 P. Brass, F. Cabrera-Mora, A. Gasparri, and J. Xiao. Multirobot tree and graph exploration. *IEEE Transactions on Robotics*, 27(4):707–717, 2011. `doi:10.1109/TRO.2011.2121170`.

6 Kenneth C Cheung and Neil Gershenfeld. Reversibly assembled cellular composite materials. *Science*, 341(6151):1219–1221, 2013.

7 Allan Costa, Amira Abdel-Rahman, Benjamin Jenett, Neil Gershenfeld, Irina Kostitsyna, and Kenneth Cheung. Algorithmic approaches to reconfigurable assembly systems. In *IEEE Aerospace Conference*, pages 1–8, 2019.

8 Nicholas B Cramer, Daniel W Cellucci, Olivia B Formoso, Christine E Gregg, Benjamin E Jenett, Joseph H Kim, Martynas Lendraitis, Sean S Swei, Greenfield T Trinh, Khanh V Trinh, and Kenneth C. Cheung. Elastic shape morphing of ultralight structures by programmable assembly. *Smart Materials and Structures*, 28(5):055006, 2019.

9 Shantanu Das, Paola Flocchini, Shay Kutten, Amiya Nayak, and Nicola Santoro. Map construction of unknown graphs by multiple agents. *Theoretical Computer Science*, 385(1):34–48, 2007. doi:10.1016/j.tcs.2007.05.011.

10 Joshua J. Daymude, Robert Gmyr, Andréa W. Richa, Christian Scheideler, and Thim Strothmann. Improved leader election for self-organizing programmable matter. In *Algorithms for Sensor Systems (ALGOSENSORS)*, pages 127–140, 2017. doi:10.1007/978-3-319-72751-6_10.

11 Zahra Derakhshandeh, Shlomi Dolev, Robert Gmyr, Andréa W. Richa, Christian Scheideler, and Thim Strothmann. Brief announcement: Amoebot – a new model for programmable matter. In *ACM Symposium on Parallelism in Algorithms and Architectures (SPAA)*, pages 220–222, 2014. doi:10.1145/2612669.2612712.

12 Zahra Derakhshandeh, Robert Gmyr, Alexandra Porter, Andréa W. Richa, Christian Scheideler, and Thim Strothmann. On the runtime of universal coating for programmable matter. In Yannick Rondelez and Damien Woods, editors, *DNA Computing and Molecular Programming*, pages 148–164, 2016. doi:10.1007/978-3-319-43994-5_10.

13 Zahra Derakhshandeh, Robert Gmyr, Andréa W. Richa, Christian Scheideler, and Thim Strothmann. An algorithmic framework for shape formation problems in self-organizing particle systems. In *International Conference on Nanoscale Computing and Communication (NANOCOM)*, pages 21:1–21:2, 2015. doi:10.1145/2800795.2800829.

14 Zahra Derakhshandeh, Robert Gmyr, Andréa W. Richa, Christian Scheideler, and Thim Strothmann. Universal coating for programmable matter. *CoRR*, abs/1601.01008, 2016. arXiv:1601.01008.

15 Zahra Derakhshandeh, Robert Gmyr, Thim Strothmann, Rida Bazzi, Andréa W. Richa, and Christian Scheideler. Leader election and shape formation with self-organizing programmable matter. In Andrew Phillips and Peng Yin, editors, *DNA Computing and Molecular Programming*, pages 117–132, 2015. doi:10.1007/978-3-319-21999-8_8.

16 Giuseppe Antonio Di Luna, Paola Flocchini, Nicola Santoro, Giovanni Viglietta, and Yukiko Yamauchi. Shape formation by programmable particles. *CoRR*, abs/1705.03538, 2017. arXiv:1705.03538.

17 Krzysztof Diks, Pierre Fraigniaud, Evangelos Kranakis, and Andrzej Pelc. Tree exploration with little memory. *Journal of Algorithms*, 51(1):38–63, 2004. doi:10.1016/j.jalgor.2003.10.002.

18 Sándor P. Fekete, Robert Gmyr, Sabrina Hugo, Phillip Keldenich, Christian Scheffer, and Arne Schmidt. CADbots: Algorithmic aspects of manipulating programmable matter with finite automata. *CoRR*, abs/1810.06360, 2018. To appear in: Proceedings of Workshop of Algorithmic Foundations of Robotics (WAFR 2018). arXiv:1810.06360.

19 Sándor P. Fekete, Eike Niehs, Christian Scheffer, and Arne Schmidt. Connected assembly and reconfiguration by finite automata. *CoRR*, abs/1909.03880, 2019. arXiv:1909.03880.

20 Rudolf Fleischer and Gerhard Trippen. Exploring an unknown graph efficiently. In *European Symposium on Algorithms (ESA)*, pages 11–22, 2005.

21 Pierre Fraigniaud, Leszek Gasieniec, Dariusz R. Kowalski, and Andrzej Pelc. Collective tree exploration. *Networks*, 48(3):166–177, 2006. doi:10.1002/net.20127.

22 Pierre Fraigniaud and David Ilcinkas. Digraphs exploration with little memory. In *Symposium on Theoretical Aspects of Computer Science (STACS)*, pages 246–257, 2004.

23 Pierre Fraigniaud, David Ilcinkas, Guy Peer, Andrzej Pelc, and David Peleg. Graph Exploration by a Finite Automaton. *Theoretical Computer Science*, 345(2-3):331–344, 2005. doi:10.1016/j.tcs.2005.07.014.

24 Leszek Gasieniec, Andrzej Pelc, Tomasz Radzik, and Xiaohui Zhang. Tree exploration with logarithmic memory. In *ACM-SIAM Symposium on Discrete Algorithms (SODA)*, pages 585–594, 2007. URL: http://dl.acm.org/citation.cfm?id=1283383.1283446.

25 Leszek Gasieniec and Tomasz Radzik. Memory efficient anonymous graph exploration. In *Graph-Theoretic Concepts in Computer Science (WG)*, pages 14–29, 2008.

26 R. Gmyr, I. Kostitsyna, F. Kuhn, C. Scheideler, and T. Strothmann. Forming tile shapes with a single robot. In *European Workshop on Computational Geometry (EuroCG 2017)*, pages 9–12, 2017. URL: https://research.tue.nl/en/publications/forming-tile-shapes-with-a-single-robot.

27 Robert Gmyr, Kristian Hinnenthal, Irina Kostitsyna, Fabian Kuhn, Dorian Rudolph, and Christian Scheideler. Shape Recognition by a Finite Automaton Robot. In *Mathematical Foundations of Computer Science (MFCS)*, pages 52:1–52:15, 2018. doi:10.4230/LIPIcs.MFCS.2018.52.

28 Robert Gmyr, Kristian Hinnenthal, Irina Kostitsyna, Fabian Kuhn, Dorian Rudolph, Christian Scheideler, and Thim Strothmann. Forming tile shapes with simple robots. In *DNA Computing and Molecular Programming*, pages 122–138, 2018. doi:10.1007/978-3-030-00030-1_8.

29 Christine E Gregg, Joseph H Kim, and Kenneth C Cheung. Ultra-light and scalable composite lattice materials. *Advanced Engineering Materials*, 20(9):1800213, 2018.

30 Ferran Hurtado, Enrique Molina, Suneeta Ramaswami, and Vera Sacristán. Distributed reconfiguration of 2d lattice-based modular robotic systems. *Autonomous Robots*, 38(4):383–413, 2015. doi:10.1007/s10514-015-9421-8.

31 B. Jenett, A. Abdel-Rahman, K. Cheung, and N. Gershenfeld. Material–robot system for assembly of discrete cellular structures. *IEEE Robotics and Automation Letters*, 4:4019–4026, 2019.

32 Ben Jenett and Kenneth Cheung. BILL-E: Robotic platform for locomotion and manipulation of lightweight space structures. In *AIAA/AHS Adaptive Structures Conference*, pages 1876–ff., 2017.

33 Benjamin Jenett, Sam Calisch, Daniel Cellucci, Nick Cramer, Neil Gershenfeld, Sean Swei, and Kenneth C Cheung. Digital morphing wing: active wing shaping concept using composite lattice-based cellular structures. *Soft Robotics*, 4(1):33–48, 2017.

34 Benjamin Jenett and Daniel Cellucci. A mobile robot for locomotion through a 3D periodic lattice environment. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 5474–5479, 2017.

35 Benjamin Jenett, Daniel Cellucci, Christine Gregg, and Kenneth Cheung. Meso-scale digital materials: modular, reconfigurable, lattice-based structures. In *International Manufacturing Science and Engineering Conference*. American Society of Mechanical Engineers Digital Collection, 2016.

36 Benjamin Jenett, Christine Gregg, Daniel Cellucci, and Kenneth Cheung. Design of multifunctional hierarchical space structures. In *IEEE Aerospace Conference*, pages 1–10, 2017.

37 Eike Niehs, Arne Schmidt, Christian Scheffer, Daniel E. Biediger, Michael Yanuzzi, Benjamin Jenett, Amira Abdel-Rahman, Kenneth C. Cheung, Aaron T. Becker, and Sándor P. Fekete. Recognition and reconfiguration of lattice-based cellular structures by simple robots. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2020. To appear.

38 Petrişor Panaite and Andrzej Pelc. Exploring unknown undirected graphs. *Journal of Algorithms*, 33(2):281–295, 1999. doi:10.1006/jagm.1999.1043.

39 Arne Schmidt, Sheryl Manzoor, Li Huang, Aaron T Becker, and Sándor P Fekete. Efficient parallel self-assembly under uniform control inputs. *IEEE Robotics and Automation Letters*, 3(4):3521–3528, 2018.

40 Damien Woods, Ho-Lin Chen, Scott Goodfriend, Nadine Dabby, Erik Winfree, and Peng Yin. Active self-assembly of algorithmic shapes and patterns in polylogarithmic time. In *Innovations in Theoretical Computer Science (ITCS)*, pages 353–354, 2013. doi:10.1145/2422436.2422476.