

Parallel Self-Assembly under Uniform Control Inputs

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Abstract—We present fundamental progress on parallel self-assembly using large swarms of micro-scale particles in complex environments, controlled not by individual navigation, but by a uniform global, external force with the same effect on each particle. Consider a 2D grid world, in which all obstacles and particles are unit squares, and for each actuation, robots move maximally until they collide with an obstacle or another robot. We present algorithms that, given an arbitrary 2D structure, designs an obstacle layout. When actuated, this layout generates copies of the input 2D structure. We analyze the spatial and time complexity of the factory layouts. We present hardware results on both a macro-scale, gravity-based system and a milli-scale, magnetically actuated system.

I. INTRODUCTION

One of the exciting new directions of robotics is the design and development of micro- and nanorobot systems, with the goal of letting a massive swarm of robots perform complex operations in a complicated environment. Due to scaling issues, individual control of the involved robots becomes physically impossible: while energy storage capacity drops with the third power of robot size, medium resistance decreases much slower. As a consequence, current micro- and nanorobot systems with many robots are steered and directed by an external force that acts as a common control signal [1]–[7]. These common control signals include global magnetic or electric fields, chemical gradients, and turning a light source on and off.

A. Selective Control with Global Inputs

Clearly, having only one global signal that uniformly affects all robots at once poses a strong restriction on the ability of the swarm to perform complex operations. This control symmetry can be broken using interactions between the robot swarm and obstacles in the environment. The key challenge is to establish if interactions with obstacles are sufficient to perform complex operations, ideally by analyzing the complexity of possible logical operations. In previous work [8]–[10], we were able to demonstrate how a subset of logical functions can be implemented; however, devising a fan-out gate (and thus the ability to replicate and copy information) appeared to be prohibitively challenging. In this paper, we resolve this crucial question by showing that only using unit-sized robots is insufficient for achieving

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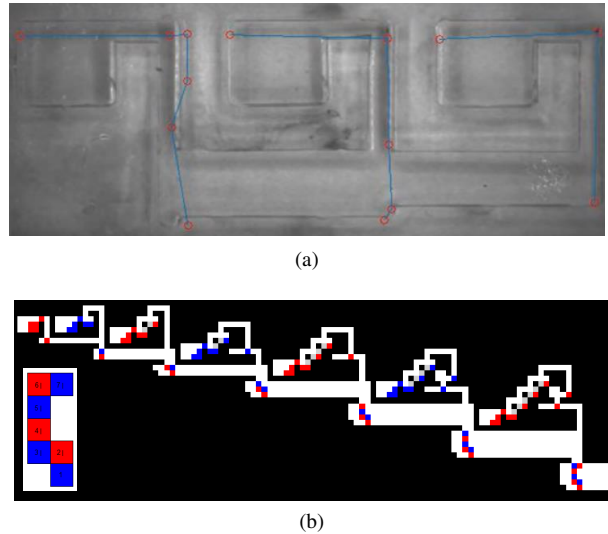


Fig. 1. (a) A milli-scale magnetic based prototype. (b) A seven tile factory. Each particle is actuated simultaneously by the same global field. The factory is designed so each clockwise control input assembles another component.

computational universality. Remarkably, adding a limited number of domino-shaped objects *is sufficient* to let a common control signal, mobile particles, and unit-sized obstacles simulate a computer. While this does not imply that large-scale computational tasks should be run on these particle computers instead of current electronic devices, it establishes that future nano-scale systems are able to perform arbitrarily complex operations *as part of the physical system*, instead of having to go through external computational devices.

B. Model

This paper builds on the techniques for controlling many simple robots with uniform control inputs presented in [8]–[10], using the following rules:

- 1) A planar grid *workspace* W is filled with a number of unit-square robots (each occupying one cell of the grid) and some fixed unit-square blocks. Each unit square in the workspace is either *free*, which a robot may occupy or *obstacle* which a robot may not occupy. Each square in the grid can be referenced by its Cartesian coordinates $x = (x, y)$.
- 2) All robots are commanded in unison: the valid commands are “Go Up” (u), “Go Right” (r), “Go Down” (d), or “Go Left” (l).
- 3) Robots all move in the commanded direction until they
 - a) hit an obstacle
 - b) hit a stationary robot.

- c) share an edge with a compatible robot

If a robot shares an edge with a compatible robot the two robots bond and from then on move as a unit. A *move sequence* m consists of an ordered sequence of moves m_k , where each $m_k \in \{u, d, r, l\}$. A representative move sequence is $\langle u, r, d, l, d, r, u, \dots \rangle$. We assume the area of W is finite and issue each command long enough for the robots to reach their maximum extent.

II. RELATED WORK

A. Microscale Biomanufacturing

Naturally derived biomaterials as building blocks for functional materials and devices are increasingly desired because they are environmentally and biologically safer than purely synthetic materials. One such class of materials, polysaccharide based hydrogels, are intriguing because they can reversibly encapsulate a variety of smaller components. Many groups have termed these loaded-alginate particles as artificial cells, in that they mimic the basic structure of living cells (membrane, cytoplasm, organelles, etc.) [11] [1-3]. Construction with these micron-sized gels has numerous applications in industry, including cell manipulation, tissue engineering, and micro-particle assembly [4-8], but requires fundamental research in biology, medicine, and colloidal science. While there are several methods to efficiently fabricate these particulate systems, it is still challenging to construct larger composite materials out of these units [9]. Traditional methods of assembling larger macroscale systems are unemployable due to the change of dominant forces at small length scales. In particular, forces due to electromagnetic interactions dominate gravitational forces at the microscale resulting in strong adhesion and sudden shifts in the position of microparts under atmospheric conditions. Furthermore, analogs of basic macroscale robotic elements have not been suitably designed and commercialized. To form constructs out of microgels, groups have traditionally turned to non-robotic microfluidic systems that utilize a variety of actuation methods, including mechanical, optical, dielectrophoretic, acoustophoretic, and thermophoretic [10-14]. While each of these methods has proven to be capable of manipulating biological cells, each method has significant drawbacks that limit their widespread application. For example, microscale mechanical, acoustophoretic, and thermophoretic manipulation methods use stimuli that can be potentially lethal to live cells [15]. Furthermore, most, if not all, of these techniques require expensive equipment and lack control schemes necessary to precisely manipulate large numbers of cells autonomously.

B. Control of Microrobotic Swarms Using Only Global Signals

Today one of the most exciting new frontiers in robotics is the development of micro- and nanorobotic systems, which hold the potential to revolutionize the fields of manufacturing and medicine. Chemist, biologist, and roboticist have shown the ability to produce very large populations (10³-10¹⁴) of

small scale (10⁻⁹-10⁻⁶ m) robots using a diverse array of materials and techniques [16-18]. Untethered swarms of these tiny robots may be ideal for on-site construction of high-resolution macroscale materials and devices. While these new types of large-population, small-sized, robotic systems have many advantages over their larger-scale counterparts, they also present a set of unique challenges in terms of their control. Due to

current limitations in fabrication, micro- and nanorobots have little-to-no onboard computation, along with limited computation and communication ability [18-20]. These limitations make controlling swarms of these robots individually impractical. Thus, these robotic systems are often controlled by a uniform global external signal (e.g. chemical gradients, electric and magnetic fields), which makes motion planning for large robotic populations in tortuous environments difficult. However, it was recently demonstrated that obstacles present in the workspace can break the symmetry of approximately identical robotic swarms, enabling positional configuration of robots [21]. Using this novel method, it was shown that, given a large-enough free space, a single obstacle is sufficient for positional control over N particles. This method can be used to form complex assemblies out of large swarms of mobile microrobotic building blocks, using only a single global input signal.

C. Microrobot Based Microassembly

The ability to create microrobots, and control algorithms capable of autonomous manipulation and assembly of small scale components into functional materials is currently a major manufacturing challenge [1]. To address this challenge, teams of microrobotic systems must work together intelligently to coordinate manipulation tasks in novel environments. While several microrobots capable of performing simple manipulation and assembly tasks have been reported [2-7], few have shown the ability to pattern intricate designs or assemble complex multi-component parts. Recently, some groups have begun to develop cell-safe magnetically actuated microrobotic systems for cell patterning, yet their method is limited in that these systems are manually controlled, not automated, and suffer from low spatial resolution [22, 23]. In this project, we seek to combine the use of microscale hybrid organic/inorganic actuators along with novel swarm control algorithms for object manipulation, mask free programmable patterning, and micro-assembly. Specifically, we will apply swarm control and particle logic computations to magnetically actuate artificial cells, so as to use them as micro-scale robotic swarms, to create complex, high resolution, 2D and 3D patterns and assemblies.

III. THEORY

Two design factories that build arbitrary 2D shaped polyominoes, we first assign species to individual tiles of the polyomino, next discover a build path, then iteratively build factory components that add each tile to partially assembled polyomino.

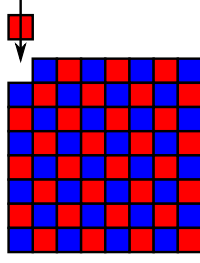


Fig. 2. Any polyomino can be constructed with two compatible robot species.

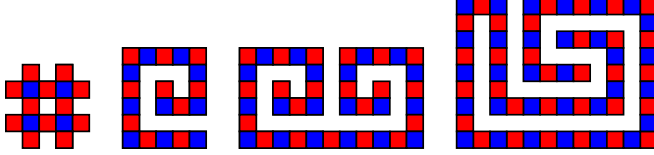


Fig. 3. Polyomino parts. Difficulty increases from left to right. The rightmost part cannot be built by additive construction.

A. Arbitrary 2D shapes require two particle species

A *polyomino* is a 2D geometric figure formed by joining one or more equal squares edge to edge. Polyominoes have four-point connectivity.

Lemma 1: Any polyomino can be constructed using just two species

Proof: Label a grid with an alternating pattern like a checkerboard. Any desired polyomino can be constructed on this checkerboard, and all joints are between dissimilar species. An example shape is shown in Fig. 2. ■

The sufficiency of two species to construct any shape gives many options for implementation. The two species could correspond to any gendered connection, including electric charge, ionic charge, magnetic polarity, or hook-and-loop type fasteners.

B. Complexity Handled in This Paper

Different 2D part geometries are more difficult to construct than others. Fig. 3 shows three parts of varying complexity. The part of the left is shaped as a '#' symbol. Though it has an interior hole, any of the 16 particles could serve as the seed particle, and the shape could be constructed around it. The second shape is a spiral, and must be constructed from the inside-out. If the outer spiral was completed first, there would be no path to add particles to finish the interior because added particles would have to slide past compatible particles. Increasing the number of species would not solve this problem, because there is a narrow passage through the spiral that forces incoming parts to slide past the edges of all the bonded particles.

The third shape on the right is two mirrored spirals that are connected. This part cannot be assembled by adding one particle at a time, because each spiral must be constructed from the inside-out. Instead, this part must be divided into sub-assemblies that are each constructed, and then combined.

A polyomino is said to be *column convex* if each column has no holes. Similarly, a polyomino is said to be *row convex* if each row has no holes. A polyomino is said to be *convex* if it is row and column convex.

Lemma 2: Any convex polyomino can be constructed by adding one particle at a time

Proof: Select any pixel as the *seed block*, or root node. Perform a breadth-first search starting at the seed block, labelling each block in the order they are expanded. Constructing the shape according to the ordering ensures that the polyomino is convex at every step of construction. ■

The proof of 2 assumes the existence of fixtures for assembly.

Some non-convex polynomios cannot be constructed one particle at a time, as illustrated in Fig. 3. For instance, a polyomino consisting of a clockwise and a counterclockwise square spiral, joined at the ends with a gap of one unit between the spirals must be constructed by first assembling each spiral, and then combining the sub assemblies.

C. Discovering a Build Path

Algorithm 1 FINDBUILDPATH(P)

P is the x, y coordinates of a 4-connected polyomino. Returns **C**, **c** and **m** where **C** contains sequence of polyomino coordinates, **c** is a vector of color labels and **m** is a vector of directions.

```

1: C  $\leftarrow \{\}$ , c  $\leftarrow \{\}$ , m  $\leftarrow \{\}$ 
2: c  $\leftarrow$  LABELCOLOR(P)
3: for  $m \leftarrow 1, m \leq |\mathbf{P}|$  do
4:   C  $\leftarrow$  DEPTHFIRSTSEARCH(Pm, P)
5:   m  $\leftarrow$  CHECKPATHTILE(C, c)
6:   if  $\{\}$   $\neq$  m then
7:     break
8:   end if
9: end for
10: return {C, c, m}

```

D. Assembling Tiles

1) *Hopper Construction:* Two-part adhesives react when the components mix. Placing the components in separate containers prevents mixing. Similarly, storing many particles of a single species in separate containers allows controlled mixing.

We can design *part hoppers*, containers that store similarly labelled particles. These particles will not bond with each other. The hopper shown in Fig. 4 releases one particle every cycle.

E. Part Assembly Jigs

IV. ANALYSIS

A. Running Time

B. Space Required

C. Simulation Results

Algorithms 1, 2, and 3 were coded in MATLAB and are available at [12].

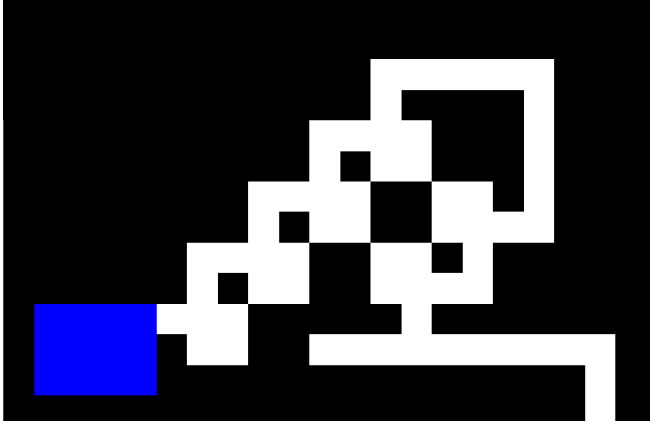


Fig. 4. Hopper with delays. The hopper is filled with similarly-labelled robots that will not combine. Every clockwise command sequence $\langle u, r, d, l \rangle$ releases one robot from the hopper.

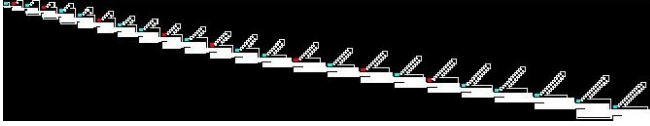


Fig. 5. A twenty-four tile factory

Algorithm 2 BUILDFACTORY(\mathbf{P}, n)

\mathbf{P} is the x, y coordinates of a 4-connected polyomino. n is the number of parts desired. Returns a two dimensional array \mathbf{F} containing the factory obstacles and filled hoppers.

```

1:  $\mathbf{F} \leftarrow \{\}$  ▷ the factory obstacle array
2:  $\mathbf{b} \leftarrow \{\}$  ▷ the part being built
3:  $\{\mathbf{C}, \mathbf{c}, \mathbf{m}\} \leftarrow \text{FINDBUILDPATH}(\mathbf{P})$ 
4: if  $\{\} \neq \mathbf{m}$  then
5:   for  $i \leftarrow 1, i \leq |\mathbf{m}|$  do
6:      $\{\mathbf{A}, \mathbf{b}\} \leftarrow \text{FACTORYADDTILE}(n, \mathbf{b}, \mathbf{m}_i, \mathbf{C}_i, \mathbf{c}_i, w)$ 
7:      $\mathbf{F} \leftarrow \text{CONCATFACTORIES}(\mathbf{F}, \mathbf{A})$ 
8:   end for
9: end if
10: return  $\mathbf{F}$ 

```

Algorithm 3 FACTORYADDTILE($n, \mathbf{b}, m, \mathbf{C}, c, w$)

```

1:  $\{\text{hopper}\} \leftarrow \text{HOPPER}(c, n, w)$ 
2: if  $m = d$  and  $(C_y \leq \max \mathbf{b}_y \text{ or } C_y > \min \mathbf{b}_x)$  then
3:    $\{\mathbf{A}, \mathbf{b}\} \leftarrow \text{DOWNDIR}(\text{hopper}, \mathbf{b}, \mathbf{C})$ 
4: else if  $m = l$  and  $(C_x \leq \max \mathbf{b}_x \text{ or } C_y > \min \mathbf{b}_y)$  then
5:    $\{\mathbf{A}, \mathbf{b}\} \leftarrow \text{LEFTDIR}(\text{hopper}, \mathbf{b}, \mathbf{C})$ 
6: else if  $m = u$  and  $(C_y \leq \min \mathbf{b}_y \text{ or } C_x > \min \mathbf{b}_x)$  then
7:    $\{\mathbf{A}, \mathbf{b}\} \leftarrow \text{UPDIR}(\text{hopper}, \mathbf{b}, \mathbf{C})$ 
8: else if  $m = r$  and  $(C_y \leq \min \mathbf{b}_x \text{ or } C_y > \min \mathbf{b}_y)$  then
9:    $\{\mathbf{A}, \mathbf{b}\} \leftarrow \text{RIGHTDIR}(\text{hopper}, \mathbf{b}, \mathbf{C})$ 
10: end if
11: return  $\{\mathbf{A}, \mathbf{b}\}$ 

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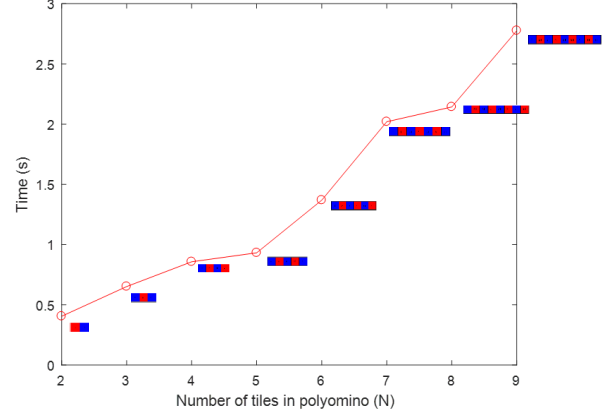


Fig. 6. Running time plotted against number of tiles (N). add max and min bounds, show results for column and row parts and arbitrary parts

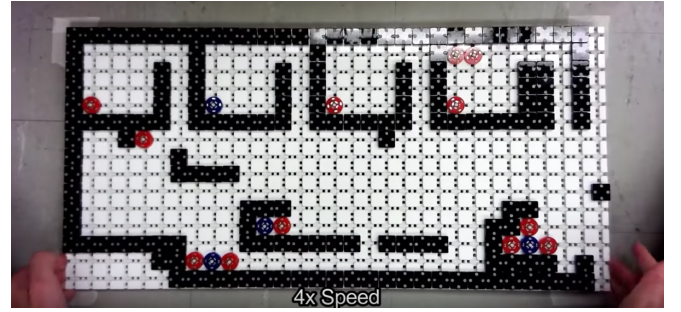


Fig. 7. A large-scale demonstration of particle assembly using gravity as the external force and magnetic attraction between red and blue particles for assembly.

This section examines experiments that generate actual running time and space required for different parts.

FIG: xy plot that shows number of tiles on the x-axis, and running time on y-axis.

FIG: xy plot that shows number of tiles on the x-axis, and space required on y-axis. (two lines: vertical space and horizontal space and a line for the best and the worst case bounds from your previous section)

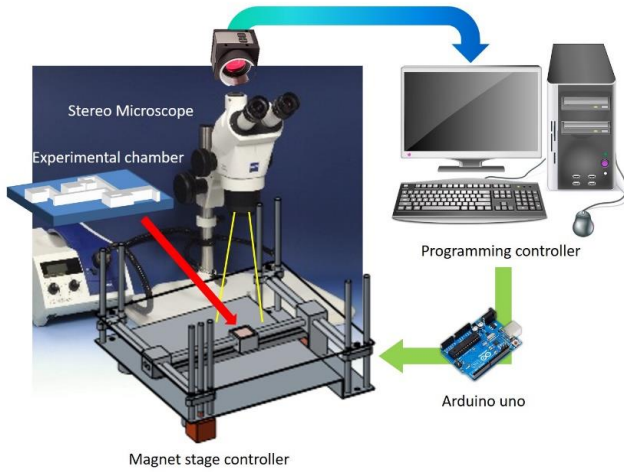


Fig. 8. Experiment

V. EXPERIMENT

A. Macro-scale, Gravity-Based Prototype

B. Milli-scale, Magnetic-Based Prototype

To demonstrate the algorithm, we developed a magnetic control stage and alginate micro-particles.

a) Experimental setup: This stage generates a magnetic drag force by moving a permanent magnet. The permanent magnet is able to move x, y direction as following two rail shafts. The permanent magnet has T and the dimension is cm^2 . The main channel is made up PDMS and it was filled with motility buffer. The alginate microrobot was fabricated using . After the alginate microrobots were located at each chamber in the channel, the experimental channel was located on the center of the stage where a magnet was positioned initially. The stage controller was manipulated by a C++ programming through an Arduino UNO. The channel was observed by a stereo microscope and the installed camera captured all sequent images (fps). The scheme of system is shown in Fig. 8.

b) Experimental result: Using one of construction maps, it is available to demonstrate the map using multiple alginate microrobots. The initial scene is shown in Fig. 9a and the first assemble was manipulated moving the magnet in a clockwise direction as indicated in Fig. 9b. The alginate microrobots moved in the oriented direction until coming into contact with an object. The final completion of a square polyomino is shown in the lower right corner in Fig. 9c. In addition, other polyominoes were simultaneously being manufactured.

VI. CONCLUSION

This work introduces a new model for additive assembly that enables efficient parallel construction because it does not depend on individual control of each agent. Instead, the

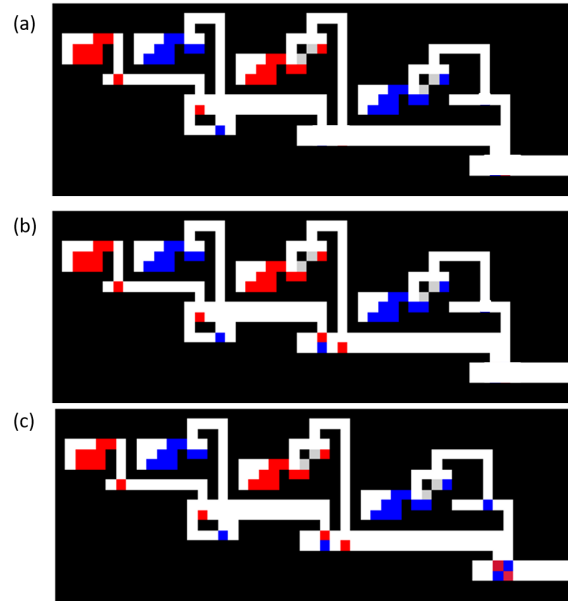


Fig. 9. Fig. Construction of a microrobotic polyomino from four alginate artificial cells. (a) Initial position of alginate microrobots at all chambers, (b) First assemble by two microrobots from two chambers, (c) Final result of construction.

workspace is designed to direct particles. This enables a simple global control input to produce a complex output.

Interesting applications will aim at microfluidics work.

Future work could extend Algorithms 1–3 to three dimensions. To build a robot, our current algorithm requires time that grows linearly with the number of tiles in a polyomino. Parts can be decomposed into subassemblies, which would enable more complex parts to be created and enable construction in logarithmic time.

REFERENCES

- [1] B. R. Donald, C. G. Levey, I. Paprotny, and D. Rus, "Planning and control for microassembly of structures composed of stress-engineered MEMS microrobots," *The International Journal of Robotics Research*, vol. 32, no. 2, pp. 218–246, 2013. [Online]. Available: <http://ijr.sagepub.com/content/32/2/218.abstract>
- [2] P.-T. Chiang, J. Mielke, J. Godoy, J. M. Guerrero, L. B. Alemany, C. J. Villagómez, A. Saywell, L. Grill, and J. M. Tour, "Toward a light-driven motorized nanocar: Synthesis and initial imaging of single molecules," *ACS Nano*, vol. 6, no. 1, pp. 592–597, Feb. 2011.
- [3] H.-W. Tung, D. R. Frutiger, S. Panè, and B. J. Nelson, "Polymer-based wireless resonant magnetic microrobots," in *IEEE International Conference on Robotics and Automation*, May 2012, pp. 715–720.
- [4] E. Diller, J. Giltinan, and M. Sitti, "Independent control of multiple magnetic microrobots in three dimensions," *The International Journal of Robotics Research*, vol. 32, no. 5, pp. 614–631, 2013. [Online]. Available: <http://ijr.sagepub.com/content/32/5/614.abstract>
- [5] W. Jing, N. Pagano, and D. Cappelleri, "A tumbling magnetic microrobot with flexible operating modes," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, May 2013, pp. 5514–5519.
- [6] Y. Ou, D. H. Kim, P. Kim, M. J. Kim, and A. A. Julius, "Motion control of magnetized tetrahymena pyriformis cells by magnetic field with model predictive control," *Int. J. Rob. Res.*, vol. 32, no. 1, pp. 129–139, Jan. 2013.

- [7] D. de Lanauze, O. Felfoul, J.-P. Turcot, M. Mohammadi, and S. Martel, "Three-dimensional remote aggregation and steering of magnetotactic bacteria microrobots for drug delivery applications," *The International Journal of Robotics Research*, 11 2013. [Online]. Available: <http://ijr.sagepub.com/content/early/2013/11/11/0278364913500543>
- [8] A. Becker, E. Demaine, S. Fekete, G. Habibi, and J. McLurkin, "Reconfiguring massive particle swarms with limited, global control," in *International Symposium on Algorithms and Experiments for Sensor Systems, Wireless Networks and Distributed Robotics (ALGOSEN-SORS)*, Sophia Antipolis, France, Sep. 2013, pp. 51–66.
- [9] A. Becker, E. Demaine, S. Fekete, and J. McLurkin, "Particle computation: Designing worlds to control robot swarms with only global signals," in *IEEE International Conference on Robotics and Automation (ICRA)*. Hong Kong: IEEE, May 2014, pp. 6751–6756.
- [10] A. Becker, E. D. Demaine, S. P. Fekete, G. Habibi, and J. McLurkin, "Reconfiguring massive particle swarms with limited, global control," in *Algorithms for Sensor Systems*, ser. Lecture Notes in Computer Science, P. Flocchini, J. Gao, E. Kranakis, and F. Meyer auf der Heide, Eds. Springer Berlin Heidelberg, 2014, vol. 8243, pp. 51–66. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-45346-5_5
- [11] T. M. S. Chang, "Therapeutic applications of polymeric artificial cells," *Nature Reviews Drug Discovery*, vol. 4, no. 3, pp. 221–235, 2005.
- [12] S. Manzoor and A. T. Becker, "Particle Assembly," <https://github.com/aabecker/particlecomputation/tree/master/assembly>, Feb. 2017.

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