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Parallel Self-Assembly of Polyominoes under Uniform Control Inputs

Dear Professor Antonio Bicchi,

Please find attached the revised paper, **Parallel Self-Assembly of Polyominoes under Uniform Control Inputs** (submission ID 17-0266) along with the document containing response to the reviewers. We are grateful to the reviewers for helping us in improving our manuscript through their comments and questions, which lead to major revisions of the paper. Please let us know if further information is required.

Sincerely,



Aaron T Becker (on behalf of all the authors)

**Response to Reviewers**

In the following document, we’ve provided detailed responses to the comments and questions of the reviewers. Comments and questions by reviewers are in blue, our responses are in black.

**Comments by Reviewer 1**

[R1: 1] “This paper presents an interesting and rather original approach to distributed assembly of 2D structures

that makes joint use of a single global control signal and a specifically designed factory whose geometry

enforces the coordinated motion of the modules to assemble at the right time and sequentially. As the

authors mention, this approach goes in the direction of showing how a predictable assembly outcome

from a single global control signal can be engineered, with interesting possible applications in the control

of large ensembles of particles and small-scale “robots”. The text is overall clearly written. The authors

however, 1) should try to get a better demonstration of the implementation of their algorithm at

microscale, 2) should improve the presentation of the content, and finally 3) should clear out some

important issues.”

We have made several changes to the paper. As suggested,

1. The microscale demonstration has been improved. We’ve added new images and text for this section in addition to repeating the experiments.
2. We’ve worked on improving the presentation style of the paper.
3. Finally, we’ve made every effort to clear out the issues pointed out by the reviewer. Please see below

“In Particular,”

[R1: 2] “Figure 1 and its caption are hardly appropriate. A generic picture explaining the algorithm may serve

much better, and even (b) should anyway appear before (a).”

Figure 1 has been updated in the revised manuscript. The figure and the caption now provide more

detail of the assembly process. Figure 1.a has moved to the micro-scale section.

[R1: 3] “The motivation of the work is explicitly mentioned in the text only at the very end of section II. Those last

2 sentences would better serve in section I.A”

As suggested, the last two sentences of section II have been moved to section I.A

[R1: 4] “In section I.A, do the authors explicitly have homogeneous sets of robots in mind? The symmetry can be

Alternatively, and perhaps as easily be broken by having a heterogeneous population of robots, each

robot type reaction differently to the same global signal. Please clarify and specify.”

This was unclear, but is important since we seek solutions for large populations. Section I.A now states:

“Independent control is possible by designing heterogeneous particles that respond differently to the global input, but this approach requires precise differences in each particle and is best suited for small populations.”

[R1: 5] “In the section on related work, all attention is on the microscale applications; however, the authors

present a (successful) macroscopic demo of their algorithm as well. They should consider adding a small

section on related macroscopic assembly approaches, citing for instance the work of Martinoli's group at

EPFL on fluidic assembly of polyominoes (Mermoud et al, ICRA 2012; Mastrangeli et al, ICRA 2014), also

using a single global signal. More generally, component sorting and palletizing at macroscopic scale is still

hugely relevant in manufacturing, so that an application of the authors' approach in that sense may be

conceived.”

These papers are highly related to this work. We added related work in the macro-scale to section I.B.

[R1: 6] “Until much later, in the text it is not mentioned why one needs Lemma 1, and in fact why the authors need

Two species of components. Indeed, one can in principle assemble all proposed polyominoes with a

single component type (the authors do mention that the condition is only sufficient), which in fact happens

to be the case in the microscale implementation proposed by the authors. And so, one may be puzzled to

read in section III.C that tiles should not slide past an opposite species of tile. Please amend and clarify.”

Section II-C now explains the main reason for using two species of tiles:

“Large populations of these two species can then be stored, like two-part epoxy, in separate hoppers, and

only assemble when dissimilar particles come in contact.”

We’ve also repeated the micro scale experiments with two different types of particles. Please see the revised manuscript.

[R1: 7] “Section III.B and caption of Fig. 3: the construction difficulty/impossibility is only referred to the proposed

algorithm, and eventually only to some assembly approaches that cannot access the third dimension, but

this is not explicated. Please amend.”

The caption of Fig.3 was shortened to avoid this inaccuracy. This paper focuses on challenges for 2D assembly processes, leaving 3D work for the future. Section II-C now explains:

“Shape 4 is the combination of a left-handed and a right-handed spiral. Adding one particle at a time in 2D cannot assemble this part, 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. Shape 5 contains compound overhangs, and may be impossible to construct with additive 2D manufacturing using only two species. The algorithms in this paper detect if the desired shape can be constructed one particle at a time. If so, a build order is provided, and a factory layout is designed.”

[R1: 8] “In section V.B: should the section not be titled "microscale"?”

Yes! We’ve changed the section title to “Micro-scale Magnetic-Based Prototype

[R1: 9] “In section V.B: Second paragraph: how are the alginate microrobots loaded in the hoppers”

The manuscript now explains that each alginate microrobot was loaded in the hoppers by way of pipette transportation (0.5 μl). Each hopper was filled with alginate by several times of transportation.

[R1: 10] “In section V.B: And, how does the return of the permanent magnet to its home position

after each instruction not reverse the effect of the action itself”

The return of the magnetic to its’ “home” location did not affect the locomotion significantly. As these

particles are attracted to the trailing dipole of the magnet square, when the magnet is moving in the

opposite direction suddenly, the alginate microrobot does not move.

[R1: 11] “In section V: Third paragraph: does "typical movement ... was hindered" imply that typically the process

did not work?”

Smooth movement was hindered by the roughness of the PDMS environment, as the surface produced

was rough due to the 3D printer and slicer of the CAD design. Additional attempts to create a more

smooth surface for better movement was done by using the PDMS environment created from the 3D

printed mold and plasma treated onto a glass slide. When we did this, and added a surfactant solution of

10% Tween 20, instead of a solution of PEG as used, movement was significantly improved. In the new

experiments the substrate was silicon, which provided a better substrate than the former PDMS.

[R1: 12] “As mentioned earlier, it would really help that the authors could show in fig. 11 a result of the process in

(c) that matches the expectation in (a).”

New experimental results have replaced the older images.

[R1: 13] “Several typos are scattered in the text. Starting from page 3, oftentimes "polyominoes" is replaced by

"polynomials" (bad autocorrection?).”

Thank you for pointing this out. We’ve made many typo corrections to the paper.

[R1: 16] “On page 4, reference to fig. 9 is wrong (should be fig. 6). Please check and amend.”

The reference to the figure has been corrected.

**Comments by Reviewer 2**

[R2: 1] “The major contribution to this paper are new algorithms for planar assembly of parts using uniform control

inputs. The paper presents lots of good work but is confusing to read due to its presentations style. For

example, Section 1.B. should be moved to the beginning of the "Theory" section to help define the

problem. Section II on related work can be combined into Section I. Section IV.C is just one sentence

long and does not deserve its own section.”

Thank you for your positive assessment. As suggested.

1. Section I-B has been moved to the beginning of “Theory” section
2. Section II has been combined with Section I
3. Section IV-C has been combined with Section IV-B

[R2: 2] “There is a large body of work in automated sequence planning that is not referenced here. Some of it is

very relevant and could be leveraged. See the following refs for some examples:

Su, Q., 2007. “Computer aided geometric feasible assembly sequence planning and optimizing”. The

International Journal of Advanced Manufacturing Technology, 33(1-2), pp. 48–57.

Rashid, M., and Akella, S., 2012. “A review on assembly sequence planning and assembly line balancing

Optimization using soft computing approaches”. The International Journal of Advanced Manufacturing

Technology, PP(99), pp. 1–13.

Ghandi, S., and Masehian, E., 2015. “A breakout local search (BLS) method for solving the assembly

sequence planning problem”. Engineering Applications of Artificial Intelligence, 39, pp. 245–266.

Seymour J, Cappelleri DJ., 2016. "Automated Microassembly Sequence Planning With Sub-Assemblies".

ASME International Design Engineering Technical Conferences and Computers and Information in

Engineering Conference, doi:10.1115/DETC2016-59736.”

These references highlight important work in the research literature and so additional related work has now been cited in the appropriate “Related Work” section. Please see the revised version of the manuscript.

We were not able to include “Ghandi, S., and Masehian, E., 2015” due to space constraints.

Some specific comments/questions on the paper are listed below:

[R2: 3] “You use both milli-scale and micro-scale to describe the same experiment. These are not the same

thing. Since your feature sizes are mostly on the micro-scale, you can probably just use that description.”

Yes! To be consistent, we’ve now used “micro-scale” throughout the revised manuscript.

[R2: 4] “Fig.1a needs some labels and some better explanation. It may be better to save this for later in the paper

since the reader will not be able to understand it where it is in the paper.”

As suggested, Fig 1a has been moved from the first page to the micro-scale section of the paper

[R2: 5] “Fig.1b: the assembly in the inset is not labeled or described anywhere. In fact, I cannot find any

references to Figure 1 in the paper. The numbers inside the colored boxes and arrows are not described

anywhere either.”

We’ve added a proper reference for Figure 1 and provided details regarding numbers and arrows inside the polyomino shown. The numbers are the build order and the arrows show the insertion direction of each tile.

[R2: 6] “There are few instances where "polyomino" is spelled as "polynomial".”

Thank you. We’ve amended the misspelling in the revised manuscript.

[R2: 7] “To be consistent with the explanation of the problem, I think you should assign "species types" instead

of a color to each block or mention somewhere that the colors correspond to different species of

blocks.”

We now describe in Section II that the two colors correspond to two different species of the particles.

[R2: 8] “When describing "for loops" in the paper, italicize the text so it is easier to understand that you are

talking about parts of an algorithm.”

Thank you. ‘For loops” has been italicized wherever it refers to an algorithm.

[R2: 9] “Fig.5: make images bigger”

We’ve improved the images by making them vector graphics and labeling the tiles in them.

[R2: 10] “Fig.6: This is not helpful to the reader at all. Can you zoom in at some particular region in more detail?

Also, the numbers and arrows in the actual assembly are not described.”

Our goal for Figure 6 is to show two complete, non-trivial factories. We’ve made Figure 6 a vector

graphic which can be zoomed into arbitrarily. The numbers and arrows in the polyominoes have been

enlarged.

[R2: 11] “Do you need a hopper for each tile of the assembly? This seems a bit inefficient. Since there are only

two types of robots, ideally there would just be 2 hoppers. Please discuss.”

You make an excellent point. Section II-E now explains:

“For ease of exposition, this paper has a unique hopper for each tile position. This enables precise

positioning of different materials, but a particle logic system could use just two hoppers, similar to the

systems in [9].

[R2: 12] “Section 3.E: Fig.9 --> Fig.6

Eq.1 to 3 are confusing. Maybe showing some values for these entities

for a simple example will help clarify things.”

We’ve improved the presentation of the equations in the revised manuscript to help clarify the math.

[R2: 13] “Why would the row parts and column parts of the same size give you different cycle times? If you are

just making a straight-line part in either direction it should take the same amount of time.”

This was a non-intuitive result. Fig 10 shows required factory sizes changes for 3-tile parts, and Equations 1—3 explain more.

[R2: 14] “Section 5.A.c: Fig.1b(b) --> should this be Fig.3(5)?”

We’ve renumbered the figures and removed Figure 1 a

[R2: 15] “Do the "stop blocks" prevent you from making any assemblies?”

“stop blocks” are obstacles and are necessary for making assemblies.

[R2: 16] “The results from the macro-scale prototype are not clear. Do you have any quantitative data from the

experiments? How many experiments did you do? what types of assemblies did you try?

success/failure rates?”

In the revised manuscript, the macro-scale prototype section has been changed. We’ve added

quantitative data for the experiments in the paper. We did 10 trials for each experiment and we

tried row and column and tetromino assemblies.

Milli-scale --> Micro-scale

This change has been made throughout.

[R2: 17] “For 5.B: It seems like all these robots are of the same species here. Is this correct? It seems to

contradict what is done with your algorithms.”

These alginate microrobots are all the same size. For the manufacturing methods, the alginate microrobots can appear slightly different sizes as the centrifugal methods produces an average size of 300 μm diameter, with a small variance. Ferromagnetic 10 μm diameter beads, as shown in the supplemental documentation, were used to show how the alginate particles can connect by the attraction of the opposing charges. It also shows they do not attract to the same charge. Large concentrations of these microbeads need to be charged separately. Still, as experimentation with the ferromagnetic microbeads encapsulated within the alginate microrobots proved to be difficult to manipulate through the channels on the silicon wafer. Paramagnetic nanoparticles proved to be the optimal material to encapsulate, as their manipulation was more manageable. For this specific reason, these particles are the same species.

[R2: 18] “More details on these experiments are needed. How many robots did you have in each hopper?”

One microrobots per hopper was used for the new experiments.

[R2: 19] “How did you determine this number to put there?”

To better show the process of the overall algorithm, it was determined to show 1 alginate microrobot per hopper in the updated experimental results.

[R2: 20] “How are they not all sticking together all the time?”

The alginate particles are paramagnetic. As these microrobots are affected by outside magnetic fields and does not produce one of its own, these microrobots do not stick together. As shown in supplemental documentation, alginate microrobots were loaded with 10 μm diameter beads. Once created through a centrifugal method, alginate microrobots were charged both positive and negative. As supplemental documentation shows, these particles attract to the opposite charge microrobots and do not attract to the same charge.

[R2: 21] “How did you make different species of them?”

There are a number of ways to create different species, alginate microrobots are very versatile. The first is to change the size of the microrobot. This can be completed by changing the rcf or needle size during the fabrication process, as these alginate microrobots are produced by centrifugal methods. The slower the rcf will cause larger alginate microrobots, where larger rcf will cause smaller alginate particles. An additional way to change the species is to change the concentration of paramagnetic nanoparticles. And third, would be changing the rigidity of the alginate microrobots, by changing the concentrations of sodium alginate and calcium chloride.

[R2: 22] “What shape are the robots? How does this affect the assemblies? Can you control the robot shape?”

The robots are a spherical shape. Currently, the spherical alginate microrobots provide a good method to use; as the shape decreases surface friction, due to the minimized contact the alginate microrobot has with the surface. Further investigation is being done to develop more shapes in the future.

[R2: 23] “The biggest issue at this scale has to do with the surface force interactions. You state there were issues

with this and that's it. What do you proposed to do to overcome this? Are there experiments you can

design to help you figure this out? Much more discussion on this key topic area is needed to convince

the reader that this is feasible at the micro-scale.”

To overcome the surface interaction forces that are present, involves changing a number of different

parameters. One such parameter is to change the species of robots being used. The more spherical the shape, the less physical contact is being made with the surface and therefore less friction. This also involves increasing the concentrations of sodium alginate and calcium chloride being used during the crosslinking process, as a higher concentration provides a more rigid structure. Additionally, changing the physical properties of the liquid medium can decrease the interactions with surface forces. The use of a surfactant, can greatly reduce the surface interactions.

[R2: 24] “There is an extra sentence at the top of the last paragraph of the conclusion that should be deleted.”

The extra sentence from conclusion has been removed.

**Comments by Reviewer 3**

[R3: 1] “The authors present a part assembly method that uses a set of obstacle courses (i.e. factory) to guide the

constituent parts under the influence of a global force field. The method is suitable for 2D assembly of milli

and micro scale parts which can be controlled with a global force such as a magnetic field. The

contributions of the paper are the formalization of the factory design process through algorithms and

analysis of the complexity of these algorithms and the factory layout. Overall, the subject is very

interesting and covered to a satisfactory depth with a demonstration in the macro scale as well as an

example for the implementation of the method in the micro-scale. The significance of the paper lies in its

potential applicability to micro-assembly problems as an alternative to other methods such as multi-scale

robotic micro-assembly and cell manipulation.”

Thank you for your positive assessment.

[R3: 2] “The title of the paper suggests that the proposed method is a "parallel self-assembly" technique. It is

stated in the paper that the process adds one particle at a time to the assembly which is inherently a

serial process. However, the very nature of the factory layout allows construction of multiple assemblies

at the same time.

Therefore, the method is a combination of serial and parallel processes and it would be nice to identify

where the efficiency of this method stands with respect to a purely serial and purely parallel process.

Also, what aspect of this method qualifies it as a self-assembly process is left unmentioned. Therefore,

the authors should consider adding some discussion about it.”

To clarify matters we’ve remade figure 1 to illustrate how global commands can actuate many factories all at once. We’ve also rewritten the introduction.

We’ve placed a discussion of running time in Section III A.

The presentation of the material can be improved by:

[R3: 3] “Properly cross referencing each and every figure (e.g. Fig. 1) and algorithm, and providing sufficient

amount of explanation for each.”

In the revised version, we’ve amended references of all the figures and algorithms and added detailed

explanation for each.

[R3: 4] “Defining terms like "4-connected polyomino" and "8-connected free space" before using them for those

readers who are not familiar with polyominos.”

Definitions for “4-connected polyomino” and “8-connected free space” have been added to the

manuscript.

[R3: 5] “Revising sections which do not connect with or relate to the rest of the discussion such as:

"In this paper, we seek to combine the use of microscale hybrid organic/inorganic actuators along with

novel swarm control algorithms for mask free programmable patterning and micro-assembly.”

We’ve revised many sections of the paper. In particular, this sentence has been shortened and moved

from section II to section I. A

[R3: 6] “Shortening the discussion in V-A on the details of the macro-scale prototype. That prototype illustrates

the idea very well but its construction details are not that interesting. The provided video is helpful and

mostly sufficient to explain that prototype.”

The section titled “Macro-scale gravity based prototype” has been revised. As suggested, it has

been shortened.

[R3: 7] “Allowing more space for the discussion of the milli-scale prototype. For instance, how was the micro-

fluidic factory fabricated and constructed? How can the stiction of particles to the factory walls be

handled?”

The microfluidic environment was constructed as a CAD model. After the design of the CAD model was completed, the model was converted into G-Code with the use of the slicer Simplify3D. The model was then printed using a Monoprice 3D printer. Once the 3D print was completed, PDMS was then cured at a 10:1 ratio and poured into the mold. After placing the mold on a hot plate for a couple of hours, the PDMS structure was complete and carefully removed. In the new experimentation, the microfluidic factory layout was microfabricated by traditional methods. SU-8 negative photoresist was used as the building structure of the channels. The channels have a thickness of 300 μm and a width of 500 μm. The substrate was proven to be much easier to break surface friction than the PDMS structure formally used. To overcome stiction to the walls some play was needed with the manipulation of the magnet, if stuck on the walls a quick movement in the opposite direction can dislodge the microrobot and allow it to follow the designated path.

[R3: 8] “Some of the strongest points of the paper are Fig. 8 where the size of the factory is bounded with respect

to the complexity of the assembly being made.

Analysis of the required factory space and assembly time in section IV.” Including some discussion on the following would improve the soundness of this paper:

Thank you

[R3: 9] “How fast can a tile factory operate? What are the challenges for increasing speed in milli/micro-scale?”

Challenges are related to the drag and frictional forces of the alginate microrobot. Surfactant needs to be

used to reduce the surface friction and drag of the fluid medium, as the alginate microrobot moves

through. The determining factor for how quickly the alginate micro robots can move is from the speed of

the physical magnet itself, as well as the microrobots ability to overcome friction.

[R3: 10] “How is precision controlled in milli/micro-scale? How does the proposed method compare with the

related methods existing in the literature in terms of cost and precision?”

The slower the system moves, the more precise the movement of the microrobots become. Currently,

the standard methods to control microrobots rely on the Helmholtz and Maxwell coil systems, which are

very expensive to setup and require large power supplies to produce strong magnetic fields. With the

permanent magnet stage, the method is significantly less expensive to set up and generate high

magnetic field without applying high power into the system.

[R3: 11] “How does the proposed method overlap with MEMS and how can they benefit from each other?”

The microfluidic environment is produced through photolithography methods which falls under the

realm of MEMS. As this system allows for the construction of multiple polyominoes continuously, a

traditional MEMS structure would only produce one at a time. This method would drastically reduce

potential costs related to continuous expensive MEMS manufacturing methods.

[R3: 12] “Loading the particles in the hoppers would be a significant part of a practical micro/milli-scale

application. What are the ways to load the particles and how can that process be accounted for in the

system complexity and overall assembly time analyses?”

In this instance, the alginate microrobots are loaded manually through a pipette method. Each are

individually placed in the hopper. For future work, the alginate will be introduced to the system, into the

hopper by way of a pneumatic valve. The pneumatic valve will control the input of the alginate microrobots

individually, which will assist the continual creation of polyominoes. The alginate microrobots are kept in a

syringe pump, producing the necessary pressure, that if the pneumatic valve opens to introduce new

microrobots, they are readily available.