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Parallel Self-Assembly of Polyominoes under Uniform Control Inputs

Dear Professor Antonio Bicchi,

Please find attached the final version of our 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. Please let us know if further information is required.

Sincerely,



Aaron T Becker (on behalf of all the authors)

**Response to AE and Reviewers**

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

**Comments by AE**

Two of the three reviewers agreed that the paper has been improved to fit with the standard of

IEEE-RAL. One of them said that there is still room of improvement for the paper before publication at

this journal.

I suggest that the authors consider the different remarks, particularly and carefully the comments of this

latter reviewer, for a revised and improved version of the paper.

In the revised manuscript, we’ve made several changes according to the comments of all three reviewers.

**Comments by Reviewer 1**

[R1: 1] “The authors thoroughly reworked the manuscript according to reviewers' comments and suggestions. The

revised paper is of better quality and deserves publication, as it is a significant contribution for

programmable manufacturing.”

We are grateful to you for your positive assessment.

**Comments by Reviewer 2**

[R2: 1] “The authors have done a good job of answering my previous comments along with the comments of the

other reviewers. However, many of the explanation in the rebuttal document did not make it into the final

version of the paper. Incorporating them into the final version of the paper will help clarify many points.

Some specific comments on this version are the following:”

Thank you. The individual comments are answered below.

[R2: 2] “Please define "polyomino" in the introduction where it is first mentioned.”

As suggested we have defined “polyomino” in the introduction:

” A polyomino is a 2D geometric figure formed by joining one or more equal squares edge to edge”

[R2: 3] “Fig.11 – Label the magnet in this figure”.

We have labelled the magnet in Figure 11

[R2: 4] “In the video for the micro-scale experiments, it seems like the particles move over the borders of the

factory walls. Can you explain this? Also, the attachments of the particles keep changing although

they are not designed to do so. It just so happens in the end that they end up in the desired

configuration. It would be helpful to show more than one experiment here to get some idea of the

robustness of the system.”

*The person doing the hardware experiment is performing an internship in Korea, so we’ll not be able*

*to provide more experimental results by the deadline of 10th June.*

*In our video, we added a red arrow showing where the particle overlaps the boundary and added annotation saying, “encapsulating the factory will prevent skips”.*

At the 2min mark in the video, it is apparent that one alginate particle moves over the boundary. This is

partly due to the buoyancy of the particle. As the microrobots move into the smaller channel, because of

additional permanent magnetic manipulation, the alginate particle behind the center particle is forced

underneath of the center particle and temporarily lifts the center particle above the boundary. In future work,

we will be using soft lithography to produce a PDMS structure that is fully encapsulated. This will prevent

any undesirable lift from occurring. These particles are encapsulated with paramagnetic nanoparticles and

are magnetized by the introduction of a magnetic field. If the permanent magnet moves too quickly

underneath the magnetic connection between the alginate particles tended to break. Moving the magnetic

back underneath of the particles allowed them to become magnetized once again. These particles are

moving through the motion of the algorithm until they reach the destination, the square shape polyomino.

As stiction and surface tension caused issues with the proper movement, this delayed the introduction of

new particles. At the 2:05 mark in the video, the particles create the proper shape.

Different shapes require different factory walls and factory designs to construct the final polyomino, as this

one is fabricated for a square polyomino the final product is a square polyomino.

[R2: 5] “Finally, for the assembly shown in Fig.1 - would something like this actually be possible at the microscale?

How can you get part 7 to stop precisely at the top and attach to part 6 instead of moving down and

attach to part 4 or 2?”

Our preliminary results show that it is possible. To improve the robustness, we’re looking at soft robotics

this summer. With soft microrobots, it is possible to change the shape and type of robots used. Here we

used spherical microrobots, but with this using a square shape would be more optimal. As for the connection between microrobots, there are several different applications that have been used with photoresponsivity of caged Ca reagent. We have begun experimentation with encapsulating these caged Ca reagents inside of alginate, introducing to UV light to see the interactions between microrobots. The square microrobot would also allow for greater interaction with other microrobots, but will increase surface tension as contact area will also increase.

**Comments by Reviewer 3**

[R3: 1] “When you say, "We assume all tiles move unit distance in unit time." this may not be a valid assumption

in the micro-scale because of the surface forces and stiction. As also evident from the micro-assembly

video, the typical stiction phenomena of the micro-particles to the obstacles is observed and the motion of

the particles is jerky. That is, the particles generally either get stuck or snap across the maximal distance

in almost no time. It may be argued that under a certain global force field, the time it takes to move a

particle a certain distance is statistically linearly related to the distance. Alternatively, it may be argued that

this time is a function of how fast the global force can be applied (turned on, changed direction etc.). The

former argument may hold in the case with weaker force fields whereas the latter may hold in the case

with stronger force fields that overcome stiction more easily. Therefore, the difference between the cycle

time of different shapes in Figure 7 can be attributed to the former case. Otherwise, the difference would

diminish and cycle time (“the time required during production cycles to advance all partial assemblies one

cycle”) would not be a function of distance but rather a function of how fast the global force field can be

applied. Even another alternative is as mentioned in IV-B where “Each input was applied sufficiently long

to ensure all alginate microrobots touched a wall.” which means the cycle time was fixed in this particular

experiment. So, the future work of reducing the assembly time partly requires investigating what the cycle

time is dependent on.”

In the revised manuscript, we’ve changed cycle time and construction time to maximum cycle distance and construction distance respectively. The ‘ANALYSIS’ section now analyzes distance travelled in and space required for a factory. The conclusion now says, “techniques to improve particle speed should be investigated”.

[R3: 2] “Although the concept of "cycle" was not defined formally, it is understood that every clockwise command

sequence is a cycle. Then, the time it takes to do that is the cycle time, assuming all tiles move unit

distance in unit time. The definition of cycle time (“the time required during production cycles to advance

all partial assemblies one cycle") indicates that the cycle time is the sum distance traveled by a tile in

each cycle (which is greater than the distance the sub-assembly travels). Also, “Maximum Cycle Time” in

Figure 7 means that it is the time taken by the last hopper cycle in an assembly which has the longest

path for a tile. With this understanding, Figure 7 makes sense as to why the maximum cycle time is a

linear function of the number of tiles in an assembly. Therefore, it would make Figure 7 clearer if the

axes titles were “Cycle Time” versus “Hopper/Tile No” which would indicate that the next tile had a longer

cycle time than the previous tile.”

This was unclear. The worst-case cycle distance for a given polyomino is being plotted. The Figure 7 caption now explains this is the “Worst case cycle distance plotted as a function of polyomino size n”. The y-axis label was changed to: Maximum Cycle Distance (Unit Distance Moves)

[R3: 3] “In II-A, particle and robot were used interchangeably in the same sentence. It would be better to stick

with one term, at least in a single sentence.”

Thank you for pointing this out! In the revised manuscript, we’ve used ‘particle’ throughout II-A.

[R3: 4] “You may want to revise this sentence to clarify it: "Different 2D part geometries are more difficult to construct than others."

We’ve revised the sentence to:

“2D part geometries vary in difficulty”

[R3: 5] “Just an idea: Instead of using delay blocks, MEMS actuators could potentially be used in Silicon based

factories to block the motion of tiles. Trade-offs might be saving real estate on the wafer by getting rid of

delay blocks in return for creating a more complex electromechanical design.”

That is an interesting suggestion. This summer we’re exploring soft lithography to implement a pneumatic valve system to better the control of the microrobots through the system. With this system, we can choose specific locations to close off. In these closed regions, additional operations can be performed and in turn can without disturbing the other channels.