Self-Assembly Printer

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Abstract

In this paper, We demonstrate the application of self-assembly system for human manufacturing processes at meso- and macro-scale in order to pursue and expand the engineering applicability of self-assembly. First, we implemented a prototype referred to as "self-assembly printer" which can generate a dynamic, transformable, two-dimensional moulding and reuse the units that compose the printed objects. Secondly, noteworthy technological components to explain our prototype system is introduced in this paper. Lastly, some potential application based on the system such as "Self-Assembly Electronic Circuit (SAEC)" is implemented and proposed. As a result of these researches, our system attains scalability and alleviates the need for complex and accurate movements of assembler in traditional manufacturing system.

Introduction

Human manufacturing systems typically require high complexity that can be achieved only by top-down or laborious manual assembly. As technologists pursue smaller and more complex structures, traditional manufacturing schemes will not be able to meet such demands, because they are limited in their scalability, robustness, and complexity. As a solution to this problem, applying "Self-Assembly", which is the autonomous organization of components into pattern or structures without human invention, to human manufacturing process has been a long sought goal in many fields of both academia and industry [1]. Self-assembly has been used to create structures at the nano- and micro-scales using techniques such as chemical bounding, geometric interactions, and magnetic field. Even at the meso- and macro-scales, many techniques and basic theories to design self-assembling and self-reconfigurable systems has been proposed and implemented in the field of robotics [2][3]. Although these robotic systems are impressive and are approaching functionality, they offer little hope in terms of scalability for large applications or complex structures, because of its high application cost, failure of electronics and miscommunication between machines. Therefore, this paper focuses on physical properties and geometric forms of units and implements "Self-Assembly Printer" which applies self-assembly system to manufacturing processes. In detail, we implemented simple designed units and an assembler. And then we constructed a mathematical model based on this designed units. Consequently, self-assembly printer system was proposed and implemented. Moreover, some potential applications based on the system such as "SAEC (Self-Assembly Electronic Circuit)" will be proposed here.

Self-assembling processes are ubiquitous throughout nature and technology. They involve components from the molecular to the planetary scale and many different variations of interactions and the concept of self-assembly is used in many disciplines, with a different meaning and emphasis in each. Therefore, the term "Self-assembly" used in this paper have to be defined clearly here. There are two kinds of self-assembly: static and dynamic [4]. Static self-assembly involves systems that are at global or local equilibrium and do not dissipate energy. In static self-assembly, formation of ordered structure may require energy, but once it is formed, it is stable. On the other hand, in dynamic self-assembly, the interactions responsible for the formation of structures or patterns between components only occur if the system is dissipating energy. As the definition above, we are applying static self-assembling processes to a printer system, namely, we will propose and implement the hybrid system with static self-assembly system and traditional manufacturing system. And moreover, we will step into dynamic self-assembly based on our hybrid system. For example, Self-Assembly Electronic Circuit as a potential application can be defined as dynamic self-assembly system.

Self-Assembly Printer

Self-assembly printer system consists of 22 types of minimum units, a mathematical model, and a simple designed assembler (Figure 1). First, an objective shape at seven-segment display is determined through a graphical user interface. Second, a programmed software analyses the given shape in order to find or create the most appropriate Euler path and inform the assembler of the accurate order of units. Third, the assembler rotates to bring the units to the front of the extruder and pushes them out through it (Figure 1 (D)). By completing these steps, the self-assemble printer system can print some character or number at seven-segment display.

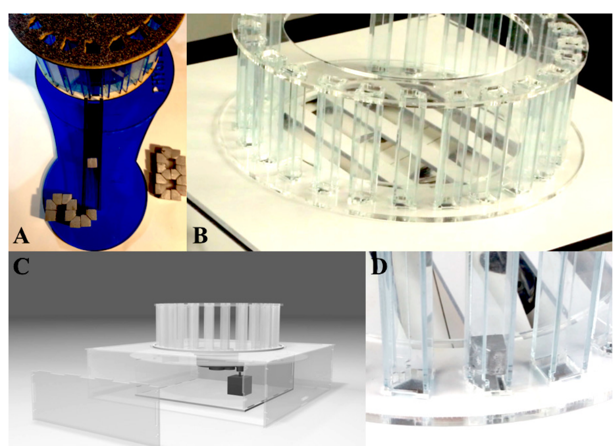

Figure 1. *"(A): First prototypes of the assembler which rotates and allocates units. (B): Second prototype of the assembler. (C): Inside-structure of second prototype. (D): The assembler rotates and slides to detach a unit from a storage of units".*

Design of minimum units

In this part, we will introduce a prototyped unit and a way to infuse binary codes into them as a genetic code. First, we focused on the geometric forms and the direction of magnetic flux embedded within the units, and associated the physical properties with binary codes as seen the below Figure 2. Second, we prototyped each units which have only four relative patterns (with Objet260: 3D Printer) although we had to fabricate 22 types without considering their geometric symmetry. The surface of each units is designed based on a 13-millimeter cube and the units are embedded with one neodymium magnet (ϕ10mm$\times$2mm). Third, we introduced "catalyst unit" a unit that comes off the printed object after the printing in order to achieve the required shape and to assemble units more efficiently.

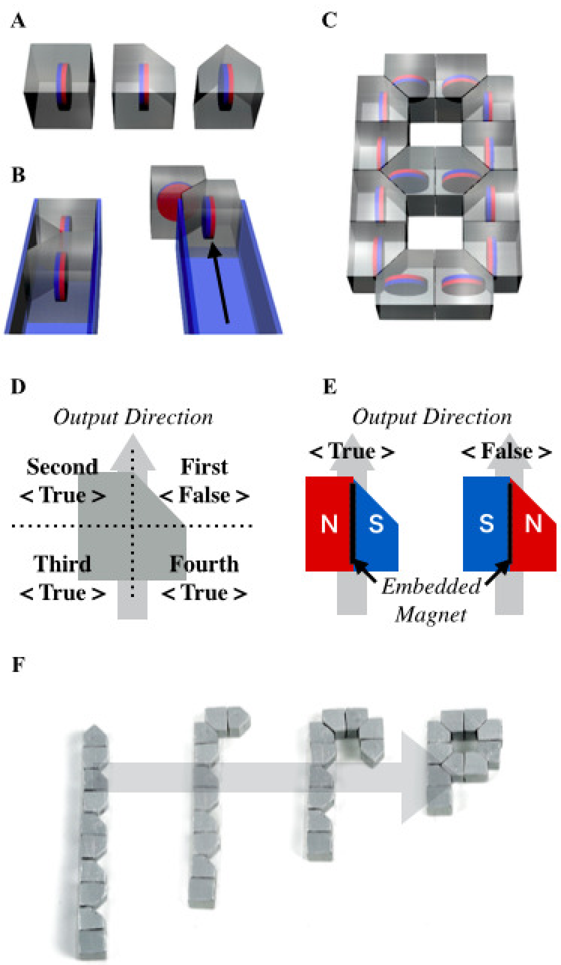

Figure 2. *"(A): Three absolute patterns of units (B): Basic interaction between units. Left side shows a unstable condition, right side shows a stable condition. (C): Example of a transparent object model which shows dispositions and directions of magnet embedded within them. (D),(E): How to map a binary code with geometric pattern and direction of magnetic flux. (F): As an example of print processing. Character "p" is printed as a seven-segment display on self-assemble printer system".*

Bridge-Method

Automatic formation of arbitrary three-dimension objects is difficult in practice. On the other hand, biological systems achieve this by folding sets of chained parts into geometric patterns dictated by mutual components interaction. This approach is impressive and can be expected to be one of a reliable method to construct any arbitrary shapes. Our system also takes the folding approach to print any arbitrary shapes. As we understand how any shape is printed with only single path by the folding approach, we confront Hamiltonian path problem. There is an effective mathematical method proposed [5] to find a Hamiltonian path in any two- or three-dimensional shape. However, in the method, the number of vertices of given the graph are forced to be quadrupled in the case of two-dimensional figures and thus the scale of the object becomes bigger. Namely, this method is difficult to apply for a practical manufacturing process because the form of object determines the scale and number of the components. Therefore, we developed new method called Bridge-Method to create an Euler path without changing the scale and number of components.

In this paper, we will introduce an optimised part of this method for our system, however, this method has potential to apply some manufacturing process where an object is assembled with discrete components serially. Our system gives a graph into an objective shape for finding or creating an Euler path in order to understand how any shape is printed with only single path. For example, when an objective shape is character "A" our system gives a graph as seen Figure 3.

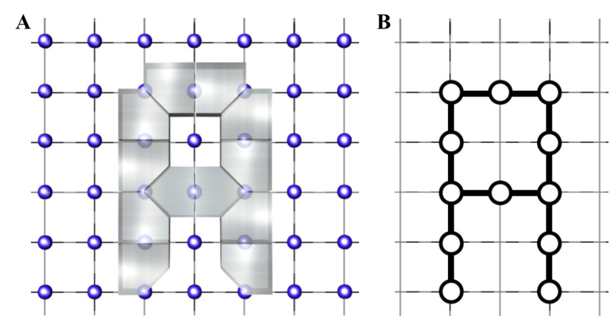

Figure 3. *"Example of a given graph of character "A" in our mathematical model. (A) Our system gives a graph whose vertices and edges allocated on a grid into an objective shape. (B) The system maps a contact point with a vertex in a graph".*

There are three-regulation in this model: only one vertex can exist on an intersection of the grid, only one edge can exist on a line of grid and the distance of each edges is limited within adjacent vertices, and each edges are not allowed to intersect. Following the regulations above, our method analyses a given graph and re-charts it to find or create an Euler path. Theorem 1: An undirected graph has an Eulerian path if and only if it is connected and the number of vertices with odd-degree is two or zero. First, Bridge-Method analyses a given graph to get a number of degrees of each vertices with an efficient parallel algorithm for finding an Eulerian path in an undirected graph [6]. If a given graph has zero odd point or two odd points, this system would print this shape. And if a graph has more than two odd points, this method would take following stages to create an Euler path (Figure 4).

- Stage (A): Comprehend the position and number of one-degree vertices and three-degrees vertices.
- Stage (B): Branch a new edge from all of three-degrees vertices and create a new vertex on the end of the new edge.
- Stage (C): Branch new three-edges from all of one-degree vertices and bridge a vertex with an adjacent vertex without adding new vertices.
- Stage (D): Add new vertices to bridge odd vertices until a number of odd vertices become less than two. Evaluate the cost of adding new vertices because there are several possibility of path created by new vertices.
- Stage (E): Finish to re-chart a given graph which has an Euler path and this system print this shape with normal units and Catalyst Units which will give off an object.
- Stage (F): Catalyst units will separate from a printed object autonomously.

Finally, our system can construct an object through one extruder more efficiently with Bridge-method.

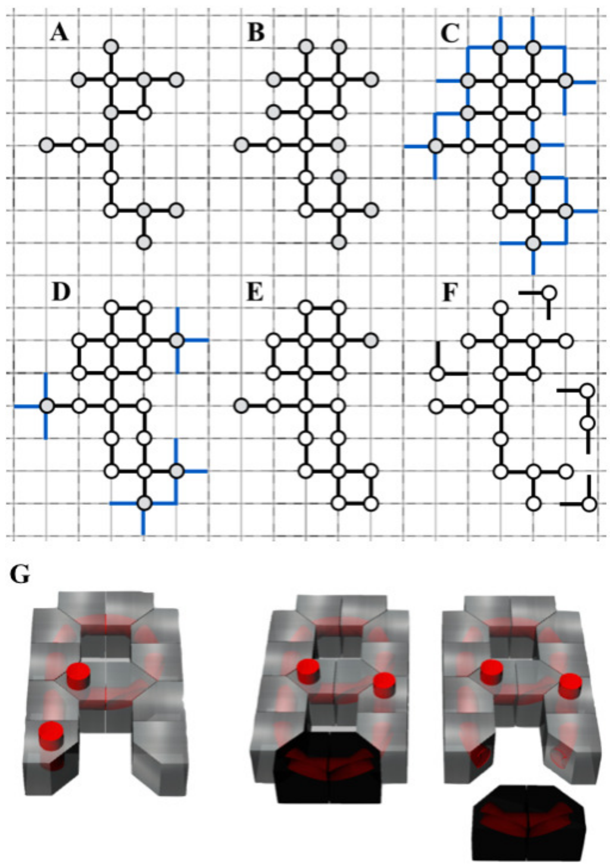

Figure 4. *"From(A)to(F): When a given graph has more than two odd vertices, these stages mentioned above have to be taken. (G): After re-charting a graph which has an Euler path, catalyst units will give off the printed object physically".*

Experimental Result and Discussion

We have implemented self-assembly printer system and have demonstrated how it prints various shapes. Our system was able to print all characters and numbers at seven-segment display as seen the below Figure 5. From here, we will compare "Self-assembly Printer system" and "Fused Deposition Modeling (FDM) 3D Printer system" based on the results of our system and outputs, and will mention what is difference between them and how our system can solve the problem (Table 1).

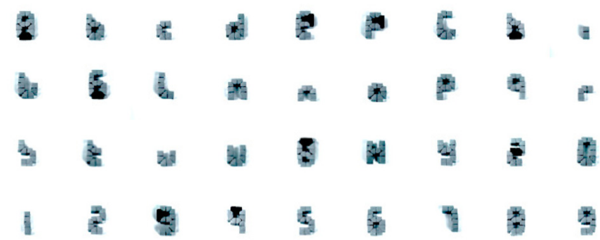

Figure 5. *"All characters and numbers printed by self-assembly printer".*

Table1: Noteworthy difference between self-assembly printer system and FDM 3D printer system

	Self-Assembly Printer	FDM 3D Printer
material	made by casting and moulding, magnet embedded within them, material is reusable.	thermal processing from ABS and PLA, material is disposable.
printable object	any two dimensional shape so far	any three dimensional shape
software and algorithm	compile an objective shape into an order information	compile an objective shape into the path information such as g-code
assembler function	select, order, rotate	adjust position, heat extruder, operate high-precisely, push out material
output range	unlimited	limited within the table range

We listed the noteworthy difference points between them in the table above. First, it is difficult to reuse the materials of a FDM 3D printer because of its high-cost and laborious procedures: shatter a printed object into fragments and melt them to manufacture a filament. On the other hand, our system can reuse the materials without laborious steps because each units are designed discretely and universally. Second, FDM 3D printer should be a high-precise machine because the machine requires many functions: adjust an adequate temperature of extruder, adjust the position of the extruder, and operate the extruder high-precisely and intricately. In contrast, the assembler at our system is required just to order and rotate accordingly to the order to bring units in front of the extruder and push them out. As the result, even simple designed assembler can print a complex structured object. Finally, although FDM 3D printer is limited to print within the table range, theoretically our system can print an object without a print range. As a mater of fact, our system sometimes fails to print the required shape because of influence of friction force and is unable to print infinite numbers of units on the gravity. However, the system would print an infinite numbers of units on zero gravity environment such as space or in the water (Figure 6).

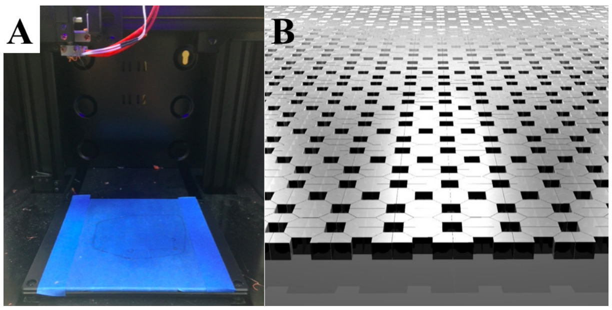

Figure 6. "(A) SCOOVO which is FDM 3D printer can print within the limited range. (B) Self-assembly printer can print an object without a limited range".

Self-Assembly Electronic Circuit

We implemented SAEC as a potential application with the self-assembly printer. In detail, SAEC units are designed with copper foils in the same pattern for each individual units, and an electronic circuit is accomplished just after constructing the object (Figure 7). Most fabrication of microelectronic devices is carried out by photolithography and is unable to reuse or replace its components [7]. SAEC offers a possibility to restore itself to its original condition or extend its function locally.

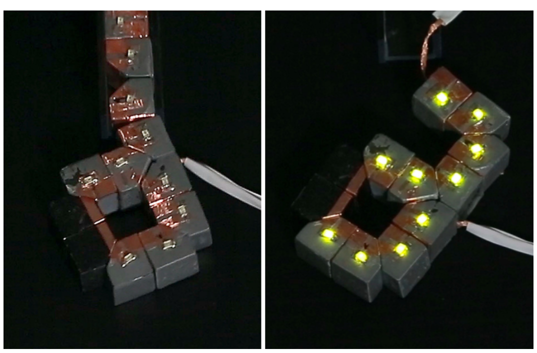

Figure 7. "Self-Assembly Electronic Circuit as a potential application of self-assembly printer. Each units are designed with copper foils in the same pattern".

As our second prototype, we propose "DSAEC: Dynamic SAEC" composed of more intelligent units than SAEC. Like the SAEC, DSAEC units are all designed in the same pattern, however, they are embedded with different electronic components such as LED, battery, and sensor (Figure 8). We will implement units that are constructed through static self-assembly in our system, and moreover, each units will become agents and interact with other agents dynamically. This is second-early-prototype of DSAEC unit and it has a potential to become a new type of a robot. We have already known "swarm robotics" where each robot agents work autonomously and the system accomplish their goal as a result of each agents work. Many researches demonstrate that swarm robotic system attains robustness because each agents follow a local program and even if a some of the agents crash, rest of the agents would work autonomously and cooperatively and the system can accomplish the goal. When we compare swarm robot's agents and the DSAEC agents constructed through static self-assembly process at our system, we can propose a novelty. DSAEC agents can reconstruct themselves, namely, they can replace components with components of another. In an extreme environment such as space, deep beneath the sea, or a disaster site, DSAEC agents can work more efficiently because if the system goes on a state of emergency and some agents crash, normal agents would deconstruct and reuse the components of crashed agents. If we can throw some components into this situation, DSAEC agent system would maintain the function level and work permanently. In our DSAEC agent system, we could show some possibility to attain a scalability for large applications or complex structures even in the field of robotics, because DSAEC agents can restore themselves autonomously and overcome failure of electronics or miscommunication between machines in the future.

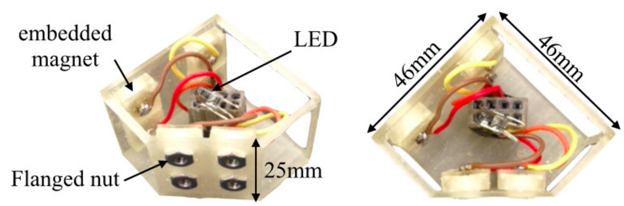

Figure 8. "An early prototype of Dynamic SAEC unit contains one LED, eight magnets, and eight flange nuts ".

Conclusion

The self-assembly printer system and an example of application was implemented and proposed here. The self-assembly printer system attains scalability to enable the assembler to print an object even if the scale is bigger than the size of the assembler. The system also alleviates the need for complex and accurate movements of assembler compared with top-down human manufacturing system. As our future work, we will develop the self-assembly system which can construct arbitrary three-dimensional forms. And also, we will apply this system for constructing small and complex structures of electronic circuit boards without highly-precise-assemblers and consider the engineering potentiality of Dynamic Self-Assembly Electronic Circuit system as a new type of robot.

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Author Biography

Masayoshi Mitsui received his Bachelor in applied physics from Keio University (2013). Since then he has worked in Government and Media department Keio University, Shonan Fujisawa. His work has focused on the development of Digital Fabrication through applying self-assembly system for human manufacturing processes.