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EM-Cube: Cube-Shaped, Self-reconfigurable Robots Sliding on Structure Surfaces

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***Abstract* — Many previous works simulate cube-shaped modular robots to explain their systems and algorithms. This paper explores a cube-shaped, self-reconfigurable system composed of EM-Cube robot modules. The paper describes the system's design, implementation, movement algorithms, and experimentation. It reports on the hardware and software, and presents the algorithms of linear walking, convex and concave transition, and locomotion. Finally, it discusses EM-Cube locomotion experiments.**

I. INTRODUCTION

To control 1000+ self-reconfigurable robots easily, a simple and generalized controller is required, which, in turn, requires simple and generalized hardware. An ideally designed simple robot comprises cube-shaped modules traveling on the structure's surface, which is used to describe a movement rule and algorithms in [1]-[2], [23], [26]. This paper describes a cube-shaped, self-reconfigurable robot sliding on a surface.

The long-term goal of this system is to build the simplest cube-shaped, self-reconfigurable robots. Because such robots are designed and built with components that can be manufactured by both micro- and macro-machining, they can be used in both the micro- and macro-realms. In the micro-world, the simplest structure enables the control of 1000+ micro-size robots with simple and light processors. Examples of 1000+ robots appear in movies, such as Transformers' Bumblebee or T-1000 in Terminator. In the macro-world, this system can take the form of a space structure such as a microscope [8] or explorer system that can be self-assembling, self-reconfigurable, and self-repairing [23]. When this system is sent into space via spacecraft, it can be packed as a large box composed of many small cubes. However, once this system arrives at its destination, it can assemble itself into a structure such as a parabolic antenna or explorer robot in [8]. Moreover, the simple structure will allow each cube of this system to perform a different role with various electronic systems, such as that performed by The Rock Abrasion Tool or Mossbauer Spectrometer.

The purpose of this work is to design a prototype robot as close as possible to the ideal robot described in previous works. When common algorithms or rules in self-reconfigurable robots are studied, cube-shaped robots traveling on the surface of a structure are used in [1]-[2], [8], and [26]. Cube-shaped, self-reconfigurable robots I named

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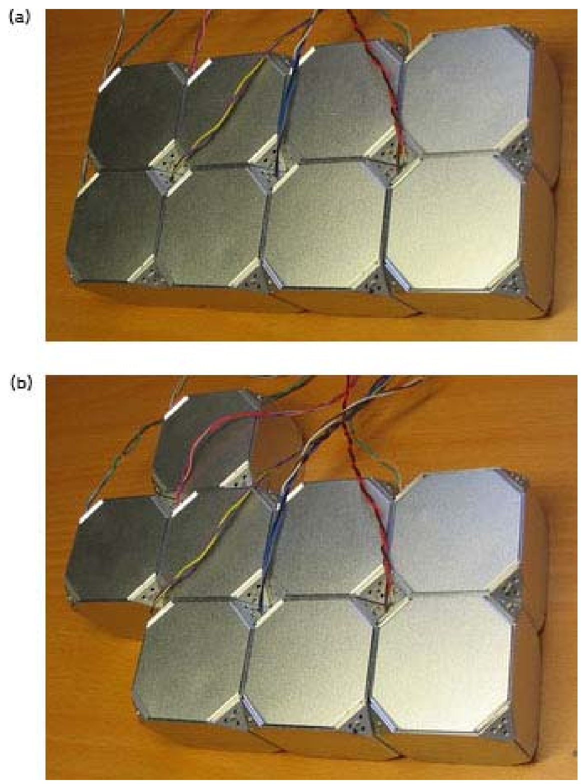

Fig. 1. (a) Initial formation of the cube-shaped self-reconfigurable modules. (b) Transforming modules by sliding on the surface

EM-Cube (Fig. 1.) and built for this purpose had three special features: a cube-shape, the capability of sliding along a surface, and electromagnets used as connecting and power-driven machinery. In this paper, I present EM-Cube's design, implementation, movement, and the experiments relating to it.

II. RELATED WORK

My work is related to prior and ongoing efforts in the field of lattice self-reconfigurable robots [3]-[22] and related algorithms [1]-[7]; for example: Kotay and Rus' "Molecule" [8], [26]; Rus and Vona's "Crystalline" [11]; and Murata, Kuokawa, et al.'s "3D Fracta" [19]. Other prototypes of lattice reconfiguration include [12]-[18].

Cube-shaped, self-reconfigurable robots are one type of lattice self-reconfigurable robots. Cube-shaped modules exist to simulate or explain various algorithms for self-reconfiguration in [1], [2], [8], [23], [26]; because one of the simplest closed structures can be built by cube-shaped

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modules, they are one of the most ideal shapes [1], [8]. Prior or ongoing works that use cube-shaped modules include Gilpin, Kotay et al.'s "Miche" [24], Koseki, Minami, et al.'s "CHOBIE" [9], White, Zykov, et al's self-assembly system [22], and Unsal, Kiliccote et al.'s "I-Cube" [5].

My proposed algorithm is related to the previous algorithms reported in [1]-[3], [8], [26]. The previous algorithms are simulated by ideal cube-shaped robots traveling on a surface generated by 3D simulation and experimented with "L"-shaped modules, "Molecule" [8], [26].

I propose the Surface Locomotion Algorithm, Caterpillar Algorithm, and Unconscious Traveling Algorithm, and experiment with cube-shaped modules sliding on the surface of a structure as in previous 3D simulations [1]-[2], [8], [26].

III. EM-Cube description

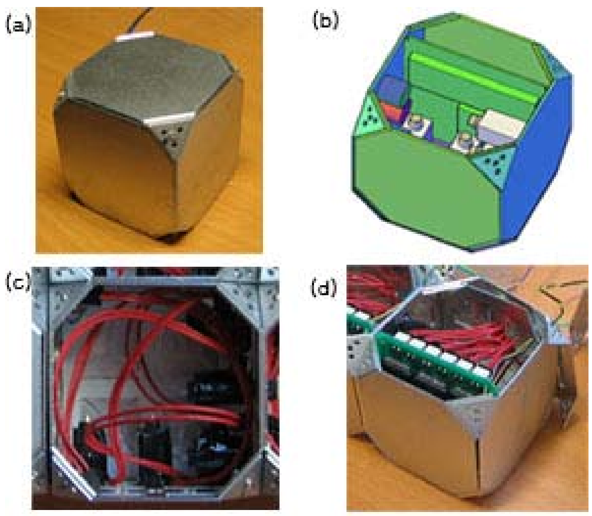

Fig. 2. A module of the EM-Cube system. (a) External. (b) CAD. (c) Internal. Left- and up-sides contain permanent magnets. Right- and down-sides contain electromagnets (d) Internal.

The outward appearance of the EM-Cube robot prototype is just a cube composed of six boards, as in Fig. 2 (a). The cube measures 60 mm on each side and weights 120 g. The six sides are connected with eight bolts on the edges.

The interior of the module contains electronic and mechanical components, such as the Zigbee chip, a microprocessor, electromagnets, and a permanentmagnets. The interior is really simple; about 75% of the entire volume is empty space sufficient to contain various components such as other microprocessors for special calculations, measuring instruments, or batteries, though these modules are supported by wired electronic power. For connection and locomotive power, each module contains eight permanent magnets and six electromagnets with a soft iron core. I built the eight identical modules for straight movement and two modules for spinning motion.

A. Connection and Movement Mechanism

Individual robots bind to each other only by permanent magnets and electromagnets and slide on the surface of the structure. This simple structure makes it possible to reduce the space required for a complex mechanical system. Individual modules have three kinds of faces: empty, electromagnetic, and permanent magnet. Permanent magnets generate the magnetic power required to connect each other so the system can keep its structural formation without electronic power.

The electromagnets and permanent magnets are designed and placed to enable them to slide along the surface of the modules. Electromagnets and permanent magnets stand in a line on the electromagnet and permanent magnet faces (Fig. 2 (b)). This mechanism basically allows regular, solid-shaped robots to spin and move in a straight direction. The principles of motion are described in section IV-A and B.

B. Processor and Communication

Each module has one microprocessor and one Zigbee chip. The microprocessor is Freescale's 8-bit MC9S08GT60 and the Zigbee chip is Freescale's MC13193. These chips are composed in Maxstream's XBee Module. The system can simultaneously communicate with many channels. Wire antennas are used to receive and transmit. The interior of each face is cut to a special shape, which increases the receiving rate without losing the face's strength (Fig 2(c)).

C. Fabricant for Body

Each robot's body is composed of six faces joined by eight bolts and built by CNC machine. Each face is processed from 1mm aluminum board which is unaffected by magnetic power. The sides of the aluminum boards are anodized to reduce frictional force and improve strength.

D. Control and Simulation Software

This software is used to control and simulate cube-shaped robots (Fig 3(a)). Both control and simulation language are used by Cube-shaped Robots Modeling Language (Fig 3(b)). 3D images are used in this paper to explain locomotion, and algorithms are also captured from this software.

To communicate with each other, protocol 802.15.4 is used; 802.15.4 is the layer below the Zigbee protocol. The wireless spot for communication connected on a computer contains Zigbee chips.

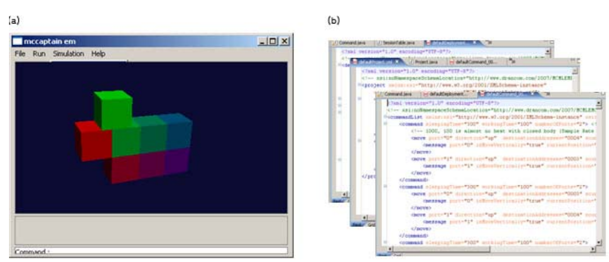

Fig. 3. (a) A snapshot of the Controller and Simulator for EM-Cube. Control and simulation are monitored on the 3D main window. (b) EM-Cubes are controlled and simulated by Cube-shaped Robots Modeling Language.

IV. MOVEMENT

Cube-shaped robots moving along the surface of a structure are commonly used to describe the movements of modular robots in [1]-[2], [8], [26]. In this work, permanent magnets and electromagnets are applied to enable modules to slide on the surfaces of the others modules and to consume electronic energy only when the module moves; electronic consumption occurs as a pulse. This mechanism keeps their structure by magnetic force without electronic power.

As seen in Fig. 4 and Fig. 5, repulsive or attractive magnetic forces from the electromagnets empower the EM-Cube to slide linearly or spin. By this simple movement, EM-Cubes are able to do convex and concave transition, surface locomotion, caterpillar locomotion, and unconscious surface traveling algorithm.

A. Linear walking

Energy for EM-Cube linear working is generated by attractive and repulsive magnetic forces from electromagnets. The modules slide straight with three electromagnetic states (see Fig. 4)

Through the attractive force between electromagnets with a soft iron core and faced permanent magnets, when electromagnets have no electronic power, they keep the structure seen in Fig 4 (a) and (e); Electromagnetic cores are magnetized by faced permanent magnets. Straight-standing electromagnets and permanent magnets reduce twisting when working.

Fig. 4 shows how modules do linear working. There are modules with no electronic power such as (a). To move, electromagnets are supplied with electronic power, and electromagnets generate magnetic power as in (b). Attractive

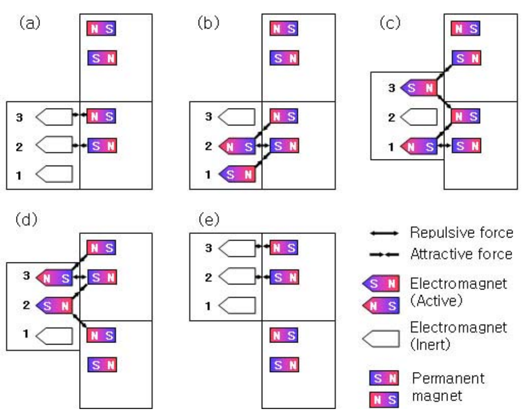

Fig. 4. This picture shows the changing status of the electromagnets during EM-Cube's linear walking. The structure keeps its formation with inert electromagnets (a), (e).

and repulsive forces between electromagnets and permanent magnets change position as the modules do in (c). Figs. (c), (d), and (e) describe the status of electromagnets for the next steps. For more steps, this sequence is repeated.

In Fig. 4, we can intuitively think of the left module as moving upward, but this is not the only way to describe it. We can describe the two right modules as moving downward relatively if the reference mark is the left module. The relative idea will help to describe the unconscious surface traveling algorithm in section VI.

B. Spinning

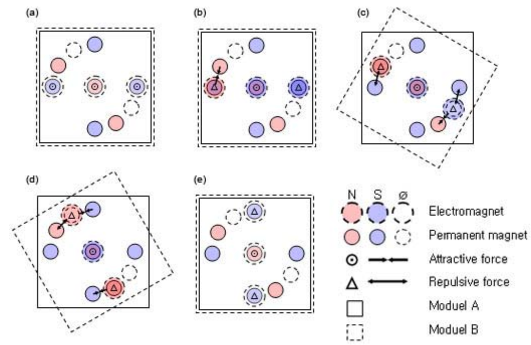

Fig. 5. Sequence of cube-shaped self-reconfigurable robots' spinning. A line square is the electromagnet face of Module A and a dotted-line square is the permanent magnet face of Module B.

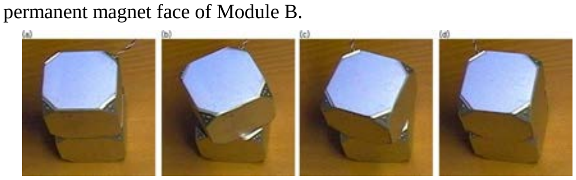

Fig. 6. Sequence of EM-Cube Spinning

When the modules change direction or act as a joint or a wrist, spinning is necessary. Spinning is also accomplished by forces that attract and repulse (Fig. 5). Every module has electromagnets on the inside of one face and permanent magnets on the inside of opposite faces. Fig. 5 depicts the interior of two module faces, a permanent magnet and an electromagnet. Modules maintain their structure with attractive forces (a). By electromagnets supplying electronic power, attractive and repulsive forces are generated (b) and force Module B to spin around to position (c). At this point, the central electromagnet and magnet form an axis. This principle allows Module B to spin as in (d) and (e).

C. Convex and Concave transition

For convex transition, two or more robots are required. Two modules on the left side in Fig. 7 present an example. First, two modules walk linearly (b). The upper module moves right and offers space for the other module, (c), to move up (d). When the two modules are aligned, together they move right (e).

Fig. 8 shows the performance of concave transition. A module starts in an initial position (a). It moves to the corner (b) and moves up to finish performing a convex transition (c).

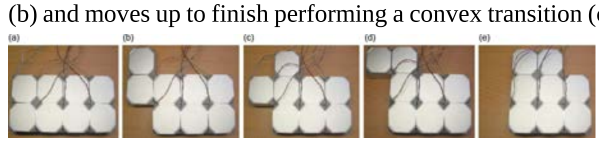

Fig. 7. Sequence of EM-Cube convex transition.

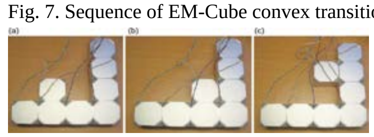

Fig. 8. Sequence of EM-Cube concave transition.

V. Locomotion Algorithm

A. Surface Locomotion Algorithm

Fig. 9 shows the sequence of surface locomotion, one of the standard locomotions of the EM-Cube. This locomotion has the potential to work well in unstructured environments [1]. The locomotion algorithm resembles the “water-flow”-like locomotion algorithm in [1], but the locomotion’s rules moving to NE and SE in [1], [26] substitute the convex transition described.

Fig. 9 (top left) represents one of the examples of the initial state. Following the procedure – convex transition, linear walking, and convex transition – one movement is completed. Though Fig. 9 represents one movement with two modules, more than two modules are able to move simultaneously by following two modules.

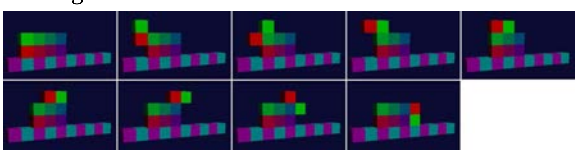

Fig. 9. Nine snapshots taken from EM-Cube surface locomotion simulation.

B. Caterpillar Locomotion Algorithm

The Caterpillar Locomotion Algorithm is simpler and consumes less electronic power then the surface locomotion algorithm though the algorithm can be used in environments where the obstacles’ height is lower than the modules; surface locomotion can be used in unstructured environments regardless of obstacle height.

Fig. 10 shows the sequence of the Caterpillar Locomotion Algorithm. Fig. 10 (left) is an example of the initial state. Modules on the second flower move right; while the left module goes up and the right module goes down. In this way, robots go straight. The algorithm is demonstrated by the second flower movement, but the other flower can also be applied. The algorithm can be used to carry other loads such as other robots or humans.

Fig. 10. Five snapshots taken from the EM-Cube Caterpillar locomotion simulation.

VI. Unconscious surface traveling algorithm

There was previous robots working in the environment of random movement as in [27], [28]. The unconscious traveling algorithm allows self-reconfigurable robots to eclipse process and electronics for sensing or computing to walk and to perform linear locomotion, convex transition, and concave transition by identical motion. In the algorithm, four modules, or four groups of modules, work together as an elementary unit.

A. Basic Motion

Fig. 11 shows the basic motion of the unconscious traveling algorithm. The algorithm employs four steps, and the initial position is (a). To move clockwise, first A and B move right (b). C moves up as in (c), and B moves down as in (d). Lastly, C and A move right, and the four modules move a step clockwise (e). For the next step, this sequence is repeated. I explained the basic motion when the reference point is Module D (Fig. 11 (first line)).

The basic motion can be explained with other reference points. For example, if Module B is the reference point as in Fig. 11 (last line), the first motion is that C and D move left (b). C moves up as in (c), and C, A, and D move up as in (d). Lastly, C and A move right, and the four modules return to the initial position (e). As a result, they move clockwise automatically only by repeating the basic motion. I introduce more detail with linear movement.

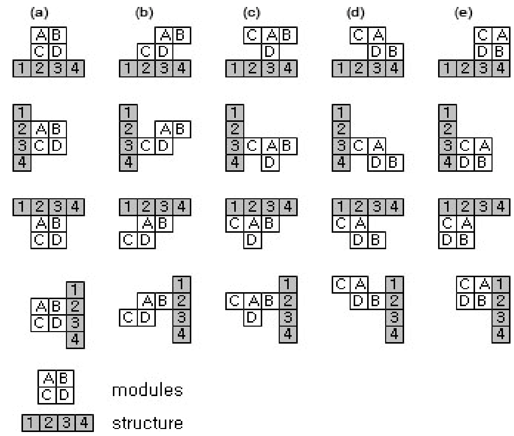

Fig. 11. Basic motion and linear walking using the unconscious traveling algorithm. Modules move clockwise with identical motions.

B. Linear Walking

Fig. 11 illustrates linear movement too. As in Fig. 11 (first line), when modules are on the up side of a structure, A and B move right because they are free (a). C moves up (b) and D moves down (c). C and A then move right (d) and accomplish a step.

Fig. 11 (second line) shows the initial position of the modules on the right of the structure for clockwise linear walking. This time, A and B move to the right because they are free (b). For the basic motion, C should move up; however, because A, B, and D are free, they move down as in (c) of Fig. 11 (second line). B moves down (d), and D and B move left because they are free (e).

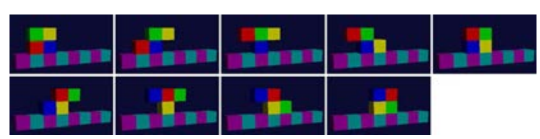

Fig. 12. Snapshots taken from a linear walking simulation using the unconscious traveling algorithm.

There are modules on the downside of the structure in Fig. 11 (third line). This time, C and D are free (b). So, when A and D are forced right, C and D move left (c). C moves up (d) and B moves down. Because D and B are free, they move left when C and A are forced right (e).

When modules are on the left side of the structure, as in Fig. 11 (fourth line), C and D move right because the modules are blocked by the structure on the right side (b). C moves up (c) and A, C and D move up (d). Lastly, A and C move right (e).

Modules in any position do clockwise linear walking with only the basic motion. If the modules move in opposite directions, they perform counterclockwise linear walking.

C. *Convex transition*

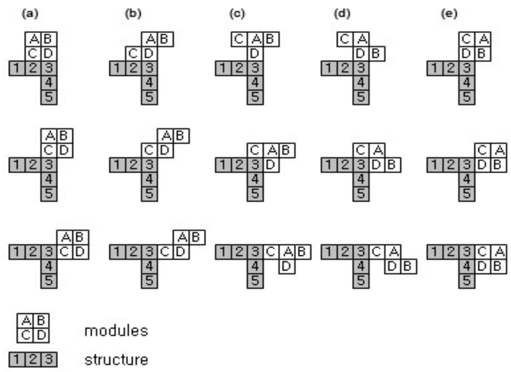

Fig. 13. Convex transition using the unconscious traveling algorithm. Modules move clockwise with identical motions.

Convex transition is also accomplished by the repetition of basic motion as in Fig. 13. To accomplish the convex transition as Fig. 13 (top line), they do linear walking to the right. After they arrive on the edge (Fig 13 middle line (a)), A and B move right (b). C moves up; however, because A, B, and D are free, they move down (c). B moves down (d), and C and A move right (e). After that as in Fig 13. (bottom line), A and B move right (b). A, B, and D move down (c), and B moves down (d). D and B move right and the modules accomplish convex transition (e). Convex transition on this and the other corners are simulated in Fig. 14.

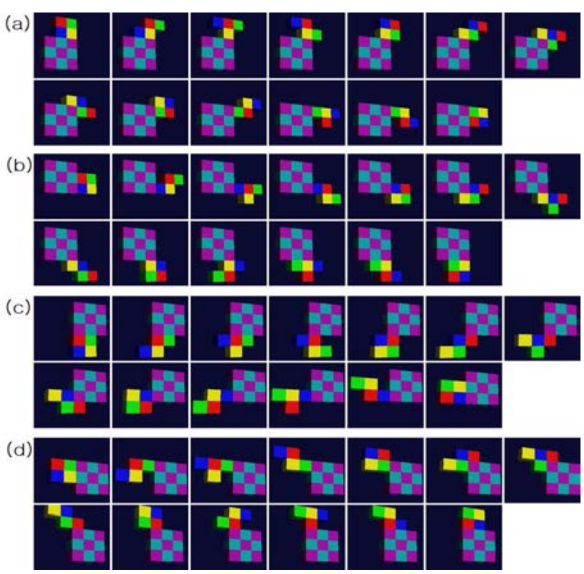

Fig. 14. Snapshots taken from a convex transition using unconscious traveling algorithm simulation. (a) Top-right convex transition. (b) Right-bottom convex transition. (c) Bottom-left convex transition. (d) Left-top convex transition.

D. *Concave transition*

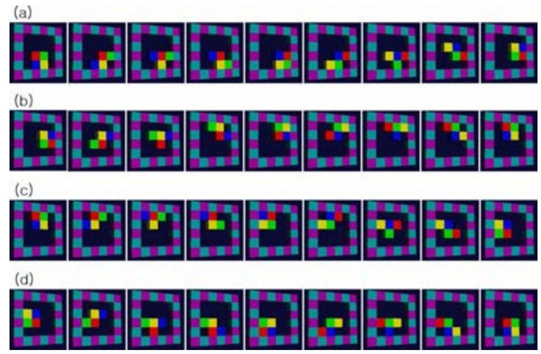

Fig. 15. Snapshots taken from a concave transition using unconscious traveling algorithm simulation on right-down corner (a), right-up corner (b), and left-up corner (c), and left-down corner (d).

Fig. 15 shows concave transition. Concave transition on each corner is composed of two kinds of linear walks on each corner. To pass the right-down corner as in Fig. 15 (a), modules perform the basic motion twice for linear walking to the right and up. On the other corners, they also do the basic motion twice for linear walking as in Fig. 15 (b), (c), (d).

VII. EM-Cube Experiments

Figs. 16 and 17 show the EM-Cube surface locomotion experiment. I have performed a number of experiments on sheet Polyvinylchloride (PVC) (Fig. 16) and plate glass (Fig. 17). Given differences in the friction coefficient, there is a gap between their results.

When EM-Cubes slide, one step is 10 mm because the gap between the centers of the permanent magnets is 10 mm. So, to cover the distance of a module’s side, six steps are required because the cube measures 60 mm per side. Normally, each step is completed in 100 ms. One or more modules can simultaneously make their own steps.

Surface locomotion is completed by top-left convex transition, linear walking, and top-right convex transition. In Figs. 16 and 17, the first four pictures, (a)-(d), are top-left convex transition, the next two pictures, (e) and (f), are linear walking, and the last four pictures, (g)-(j), are top-right convex transition.

A. *On Sheet Polyvinylchloride (PVC)*

Table 1 shows the results for 36 EM-Cube surface locomotion experiments on sheet PVC coating a desk (Fig. 16). On sheet Polyvinylchloride, the success rate for top-left convex transition is 91.7% and linear walking is 100.0%; however, top-right convex transition is 24.2%. Top-right convex translation errors occurred while EM-Cubes transform from Fig. 16 (h) to (i). While EM-Cubes transform from Fig. 16 (g) to (h), a moving module is twisted by frictional force and pushes the following module back. As a result, the following module's alignment is broken, and it frequently fails the next transformation from Fig. (h) to (i).

B. Plate Glass

To reduce frictional force, I laid a plate glass whose friction coefficient is less than that of sheet PVC (Fig. 17). Table 2 shows the results of 64 EM-Cube surface locomotion experiments on plate glass. The success rate for top-left convex transition is 78.1%, while linear walking is 98.0% and top-right convex transition is 95.9%.

By reducing frictional force on plate glass, the success rate of top-right convex transition increased steeply. However, top-left convex transition failed while EM-Cubes transformed from Fig 17 (a) to (b). When the modules took the first step, they fell apart because frictional force decreased and was insufficient to cancel the repulsive force between electromagnets and permanent magnets in facing modules.

C. Discussion

Because movement power is not enough to overcome frictional force, there is a difference between the results of the two experiments on the surfaces of different materials. The center of balance of the EM-Cube is slightly on the right and bottom. For top-left convex transition, which uses the heavier right face, sheet PVC gives better results. However, for top-right convex transition, which uses the lighter left face, plate glass gives better results. The gap between the results may be closed by changing electromagnets that have enough capacity to cancel frictional force; the module's electromagnets are too small. The electromagnets' core diameter is 4 mm, although the diameter of the permanent magnet and the distance between the electromagnets are 10 mm each.

TABLE I
EM-CUBE LOCOMOTION EXPERIMENTAL RESULTS ON SHEET PVC

	Top-left convex transition	Linear walking	Top-right convex transition	Total
Success	33	33	8	8
Failure	3	0	25	28
% Success	91.7	100.0	24.2	22.2

TABLE II
EM-CUBE LOCOMOTION EXPERIMENTAL RESULTS ON PLATE GLASS

	Top-left convex transition	Linear walking	Top-right convex transition	Total
Success	50	49	47	47
Failure	14	1	2	17
% Success	78.1	98.0	95.9	73.4

EM-Cube movements were demonstrated in eight EM-Cube experiments, which illustrated that the methods are robust. There is room for improvement, particularly on the hardware front, which can be accomplished by replacing the electromagnets.

I tried to get the robot to work against gravity by using stronger permanent magnets and electromagnets with more power. The module usually moved up the first step. However, it did not make it up the next step. It is easily twisted or moved down and quickly overheated.

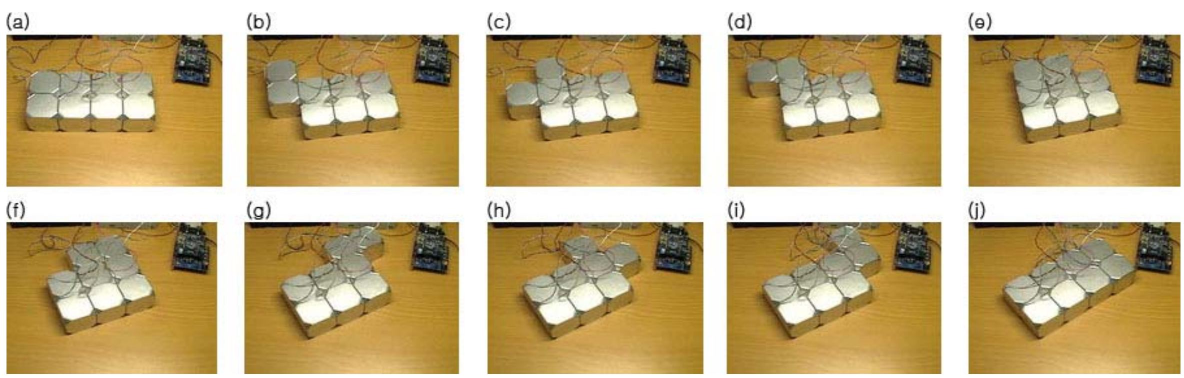

Fig. 16. EM-Cube surface locomotion experiment on sheet Polyvinylchloride

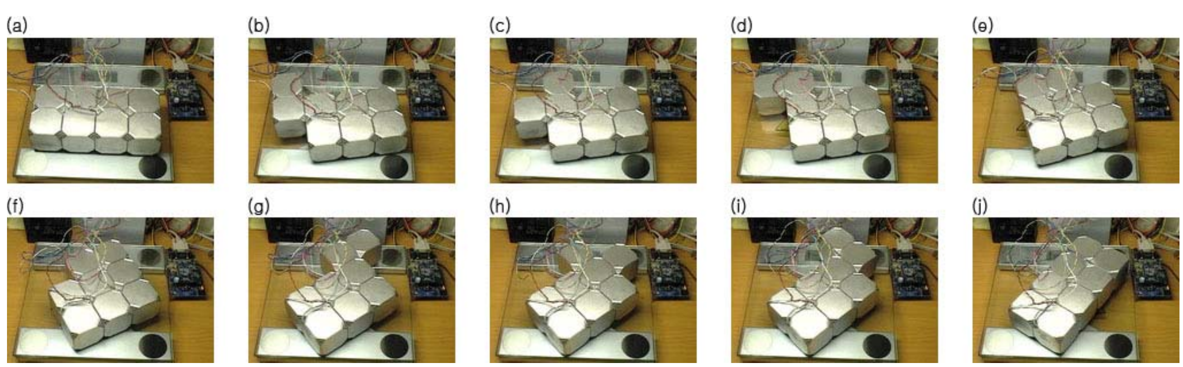

Fig. 17. EM-Cube surface locomotion experiment on plate glass

VIII. Conclusion

I have described EM-Cube cube-shaped, self-reconfigurable robots traveling on the surface of a structure. I reported the design, implementation, movement algorithms, and experiments, and explained the principle of the movement with electromagnets and permanent magnets that can be used for regular-shaped robots.

The experimental results demonstrate a surface locomotion algorithm with eight EM-Cube modules. Although the success rate on sheet PVC is 22.2%, the success rate on plate glass is 73.4%.

Acknowledgments

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