Cellular Robots Forming a Mechanical Structure

(Evaluation of structural formation and hardware design of "CHOBIE II")

Michihiko KOSEKI[1], Kengo MINAMI[1], and Norio INOU[1]

Department of Mechanical and Control Engineering, Tokyo Institute of Technology, 2-12-1, O-okayama, Meguro-ku, Tokyo, 152-8552 JAPAN
koseki@mech.titech.ac.jp

Summary. This paper deals with group robots called CHOBIE that cooperatively transform a mechanical structure. The CHOBIE have slide motion mechanisms with some mechanical constraints for large stiffness even in movement. First of all, a way of structural transformation including the mechanical constraints is discussed. Second, dissipative energy in the structural transformation based on experimental data of the CHOBIE is estimated. Third, for autonomy of the robots, CHOBIE II is developed and the performance test is demonstrated.
Key words: Modular robotic system, Self-reconfiguration, Mechanical structure, Slide motion mechanism

1 Introduction

Reconfigurable group robots have potential to fulfill various missions such as cooperative transportation, collection and construction [1]. To realize the group robots, variety of mechanisms have been developed [2]–[7]. However, there are few robots designed for supporting large outer forces. The reason why is that the almost developed robots are putting more emphasis on a mobile function than a supporting function.

Our study focuses on group robots forming a mechanical structure. The group robots consist of cellular robots. Each cellular robot communicates with adjacent robots and determines the behavior where it should be positioned. They form the structure by successive cooperative movements. We call the cellular robot "CHOBIE" (Cooperative Hexahedral Objects for Building with Intelligent Enhancement).

Figure 1 shows a concept of our study that CHOBIE cooperatively construct a mechanical structure. There are many cellular robots in the working space where the robots provide arrangements for constructing a structure. The construction of a structure is performed within the constructing area.

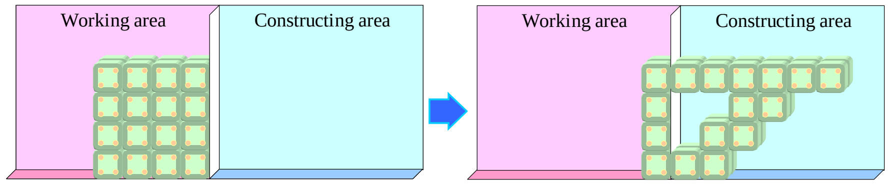

Fig. 1. Idea of cellular robots “CHOBIE” forming a mechanical structure

In our previous studies, we proposed a motion mechanism that cellular robots move in the rectangular directions keeping large stiffness. The cellular robots (we call them “CHOBIE I”) demonstrated that they adaptively changed the structure to support a large outer force [8].

This paper discusses three subjects to improve performance of the robots. The first subject is to discuss a way of structural formation of the proposed cellular robots because they some constraints in the structural formation. The second one is to estimate energy dissipation of the cellular robots for the structural formation. The third one is to develop revised robots CHOBIE II with autonomous functions since the previous robots CHOBIE I were demonstrated by a preprogrammed control without local communication between the neighboring robots.

2 Structure of a cellular robot

Figure 2(a) shows the proposed slide motion mechanism in our previous paper [8]. It consists of two lateral boards and a central board. The central board is sandwiched by the two lateral boards and all the boards are tightly connected.

The two lateral boards include symmetrical motion mechanisms that consist of two sets of wheels as shown in Fig. 2(b). They are allocated in vertical and horizontal directions, which enable the two directional motions of cellular robots. The only one DC motor is embedded in each lateral board, and jointly drives 4 wheels that are placed on the same plane through a drive shaft in the central board.

The central board has grooves as sliding guides, which maintain high rigidity even in transformation as shown in Fig. 2(c). For this motion mechanism, cellular robots successfully connect to other robots. The central board can change the depth and to embed controller, sensors and batteries for autonomic functions of cellular robots as described later.

3 Structural formation of cellular robots

The proposed motion mechanism has some constraints in the transformation of the structure. Figure 3 illustrates basic structural transformation of three

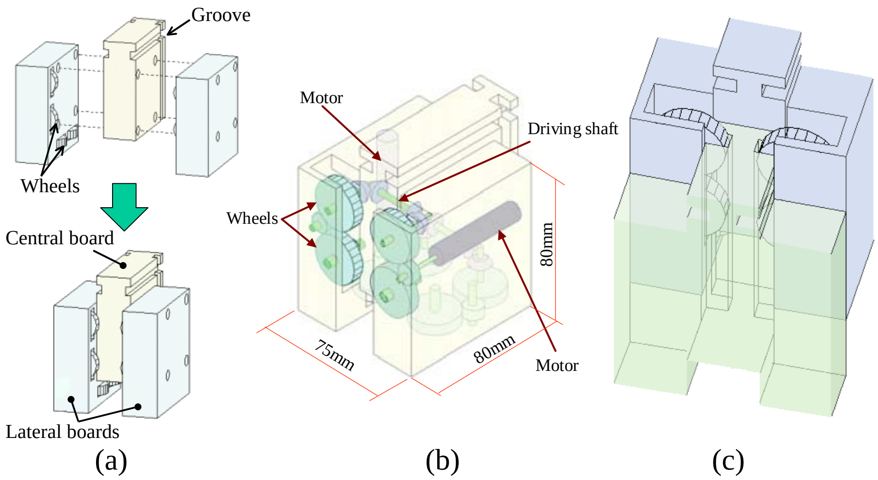

Fig. 2. Slide motion mechanism of the cellular robot

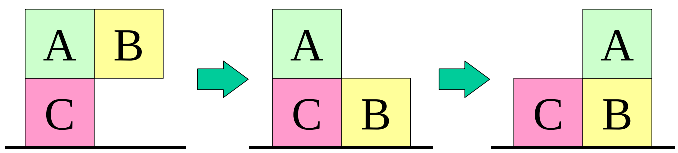

Fig. 3. Transformation of cellular robots by the proposed slide motion mechanism

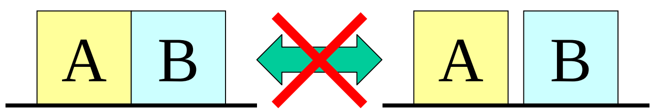

Fig. 4. Mechanical constraints of cellular robots

group robots with the proposed motion mechanism. First, the robot B slides down the faces of robots A and C. After the robot B reached the bottom, the robot A horizontally slides on the faces of the robots C and B. Since the robot has slide motion mechanisms, it can neither separate nor connect each other as in Fig. 4. In spite of the mechanical constraints, it is possible to build up various structures. We will show the way of the transformation as follows.

We start from an initial structure with a long straight arrangement as shown in Fig. 5. If the initial structure is plainly straight, it cannot change to other structure. The initial structure has a cellular robot called "seed" at the right angle to the trunk in the working area. The seed robot plays an important role in the structural transformation as it breeds another seed called “sub-seed” in the working area. Figure 6 shows a breeding way of the sub-seed. Plural sub-seeds are easily bred in the same manner.

The sub-seed makes a structure in the constructing area by moving them to the constructing area. Figure 7 shows the way of the construction that sliding movement of a sub-seed robot produces a cellular robot called “sprout” in the constructing area. The continuous production of sprout extends the structure like a trunk as in Figure 8. Using the ways of transformation, various structures can be built up because it is possible to transform a two dimensional structure by recurrent productions of the trunk structure. A topological structure including holes is also produced in the same manner. When the robots in the working area start from a rectangular arrangement as shown in Fig. 1, they can also form a various structure in the constructing area because the straight arrangement with a seed is possible to transform the rectangular arrangement.

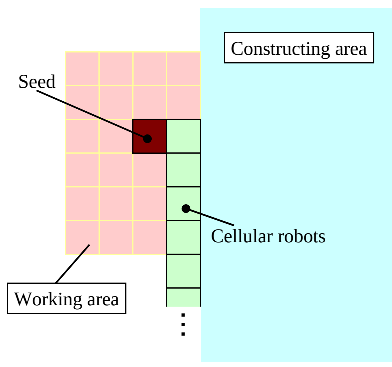

Fig. 5. Initial straight structure with a “seed”

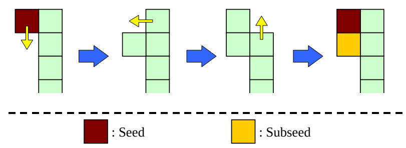

Fig. 6. Breeding way of a “sub-seed”

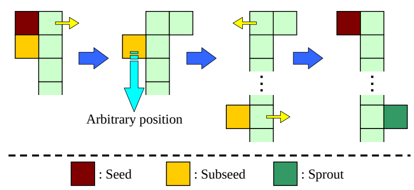

Fig. 7. Construction of a structure called “sprout”

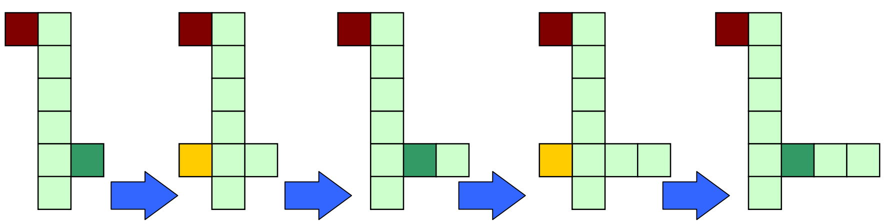

Fig. 8. Extension of a structure like a trunk

4 Estimation of dissipative energy

For effective structural formation, estimation of dissipative energy to require the formation is important. In the previous study, we reported a method to find the shortest routes in structural transformation when an initial configuration of robots and a final one are given. This paper describes a way to find a preferable route considering energy consumption in each step.

To evaluate the dissipative energy for each transformation step, we made formulation of energy consumption based on the experimental results for typical movements. The formulation is classified into three equations considering the gravitational effect as follows:

$$\begin{aligned} &\text{movement} \\ \text{Horizontal} &: E = 0.45(F_1 + F_2)L + 0.5 \\ \text{Upward} &: E = 0.45(F_1 + F_2)L + 2.0G \\ \text{Downward} &: E = 0.45(F_1 + F_2)L + 0.5 - 0.3G \end{aligned} \tag{1}$$

where F_1, F_2 = reaction forces produced at the moving face as a foundation [N], L = side length of the robot [m], G = the number of robots whose gravitational position is changed

The above equations were formulated on the assumption that dissipated energy was basically represented by multiplication of reaction forces produced at the sliding part and the moving distance of the robots. The reaction forces F_1, F_2 were derived using the cantilever model as shown in Fig. 10.

The simulator calculates the dissipated energy along structural formation using the above equations considering driving power of the robots. That is, the simulator judges possibility of transformation of the robots comparing the required energy for the movement with the maximum possible power of the robots. If E_{max} is greater than the required power, the simulator passes the calculation of the movement because the transformation is impossible. E_{max} is calculated as follows:

$$\begin{aligned} E_{max} &= U \times I_p \times T \times R_s \times n \\ &= 6.0 \times 0.17 \times 10 \times 0.5 \times n \\ &= 5.1n \end{aligned} \tag{2}$$

where U = nominal voltage [V], I_p = maximum continuous current [A], T = required time to move unit length [sec], R_s = safety ratio and n = the number of driving motors.

Figure 11 shows the energy consumption for each step computed by the above method when an initial and a final configuration are given. There are six possible transformations. We easily find the most effective transformation that needs the minimum dissipated energy. This transformation includes a transformation step that six robots are moving at the same time. The simulation result shows that we should consider not only the number of steps of transformation but also the amount of the energy consumption.

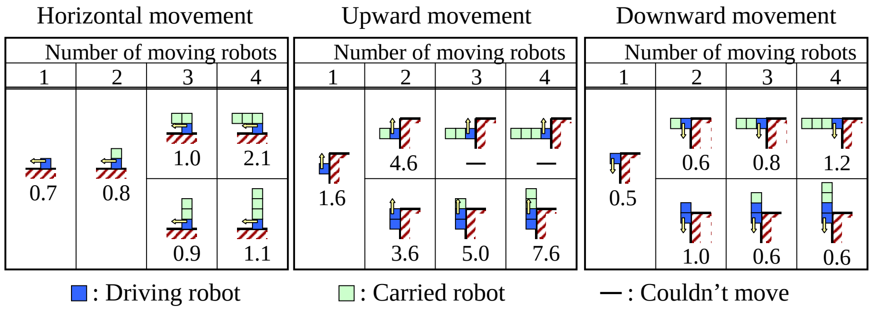

Fig. 9. Dissipative energy for the typical movements (unit of energy: joule)

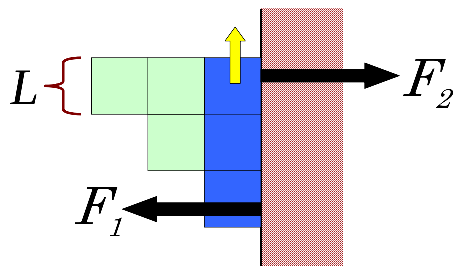

Fig. 10. Parameters to calculate energy consumption of the cellular robots

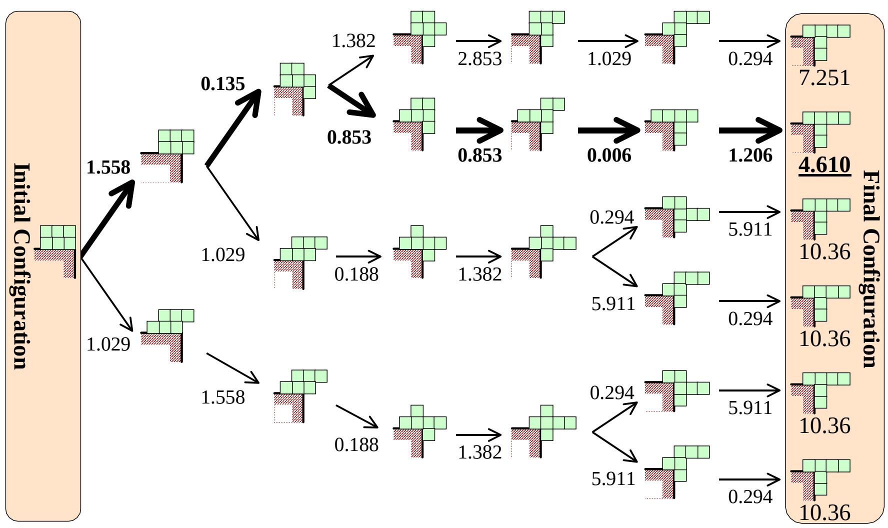

Fig. 11. Total energy for structural transformation (unit of energy: joule)

5 Development of devices for autonomous cellular robots

Our study aims to develop the autonomous cellular robots adaptively forming a mechanical structure. The robot needs the following functions: locomotive function, connecting and separating functions, sensing function for stressed states and information function.

The locomotive function using the slide motion mechanism is described in the above. However, the previous model does not complete connecting and separating functions because it cannot hold a specified position because lack of a lock mechanism. We examine the lock mechanism at this time. We also challenge to boost up autonomy of the robots adding required devices to them.

5.1 Connecting and separating functions

For realizing cellular robots forming a mechanical structure they must have a connecting function to endure outer forces and their own weight. The proposed cellular robots provide slide motion mechanism that enable to move the cellular robot maintaining a connecting state at any time. The mechanism smoothly has large stiffness for normal direction of the sliding direction. However, it is liable to be misaligned for sliding direction because of the speed reducing gear train mechanisms. We introduced a locking mechanism for CHOBIE II so that they hold a precise position with large stiffness in the sliding direction.

The locking mechanism is composed of a rod and a hole as shown in Fig. 12. The rod passively protrudes with a spring force and also actively retreats with a wired tension. There are two rods on the sliding sides for each robot and they are placed at the bottom side and the left side of the robot. On the other hand, the hole is placed at the top and right side. When the rod comes to a hole that belongs to other cellular robot, it automatically protrudes to the hole with a spring force. The protrusion is detected by a photo interrupter and firmly fixes in the sliding direction. A tether is used for release of the lock. The rod is retreated by winding up the tether with DC motor.

5.2 Integration of Information functions

The cellular robots must communicate the information signals. We integrate the functions to the inner case of the robot. To endow the robot with autonomy, we must integrate several devices into each robot: sensors, an electric controller and electric battery. To put these devises into the robot we increased the width of the central board from 25mm to 50mm.

Photo sensors that communicate with neighboring robots are embedded on the surface of the frame and force sensors are attached at the corner of a portion that produces large strain by outer forces as shown in Fig. 13. We use PIC (Peripheral Interface Controller) as the electric controller. This devise (PIC16F84) is a microcomputer chip and has a programmable function with

I/O ports. Lithium batteries are also embedded in the central board. Figure 14 shows the control circuits embedded in the central board of CHOBIE II.

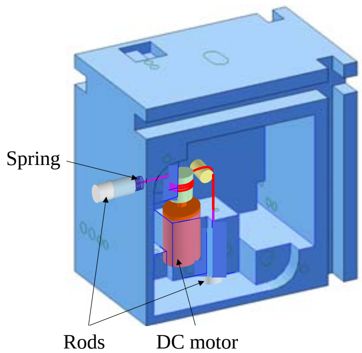

Fig. 12. Lock and unlock mechanism

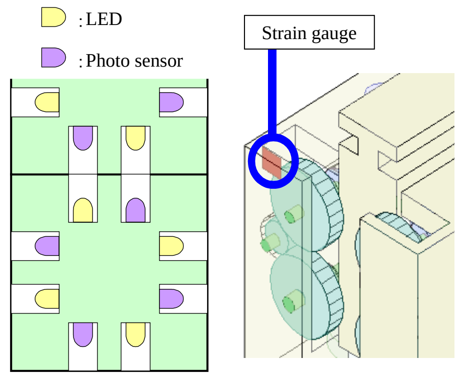

Fig. 13. Photo sensor and force sensor

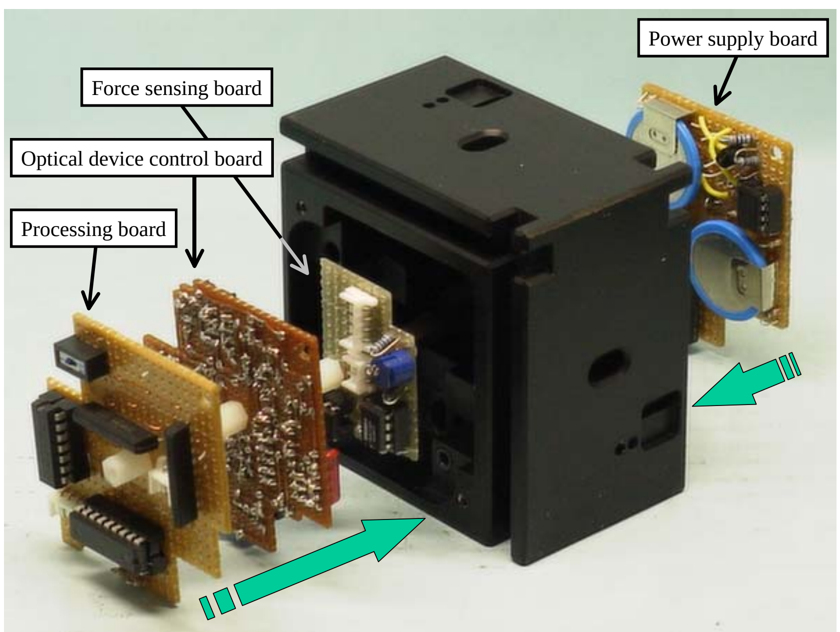

Fig. 14. Control circuits and central board of CHOBIE II

6 Demonstration of cellular robot

We fabricated three cellular robots including the autonomous informations function as stated above and made the performance test. Before the experiment, a program code was installed in the PIC of each robot. In this experiment, we used the most fundamental algorithm as shown in the below.

(1) Each robot inspects the neighboring existance by use of the photo sensors.
(2) IF the left side of a robot is vacant and the robot is connected to neighboring robots both in the right side and the under side, THEN the heading direction of the robot is "left".
GOTO (5).
(3) ELSE,
IF the under side of a robot is vacant and the robot is connected to neighboring robots both in the right side and the upper side, THEN the heading direction of the robot is "downward".
GOTO (5).
(4) ELSE,
The robot will not move actively to any direction and waits for messages from other robots; EXIT.
(5) The robot send the heading direction to other robots.
(6) The robots slide with the other robots that are positioned in-line simultaneously.
(7) GOTO (1).

Figure 15 shows the sequential motions based on the above algorithm. As the embedded battery was not enough power to move DC motors smoothly, we added an additional battery at an external surface of the robot. An autonomy of CHOBIE II was successfully demonstrated by the addition. As the installed program code in the PIC is very simple and signals by force sensors are not used in this experiment, sophisticated transformation is not yet realized. However it is possible to construct a more complicated structure considering outer forces by revising the program code.

7 Conclusions

The cellular group robots "CHOBIE" forming a mechanical structure were discussed. It is possible to transform various structures although the proposed robots have mechanical constraints. We proposed a method to estimate energy consumption along the transformation route. This method is useful to perform effective structural transformation. To realize autonomy of the robots we developed CHOBIE II. Experimental demonstration showed the robots changed the structure communicating neighboring robots.

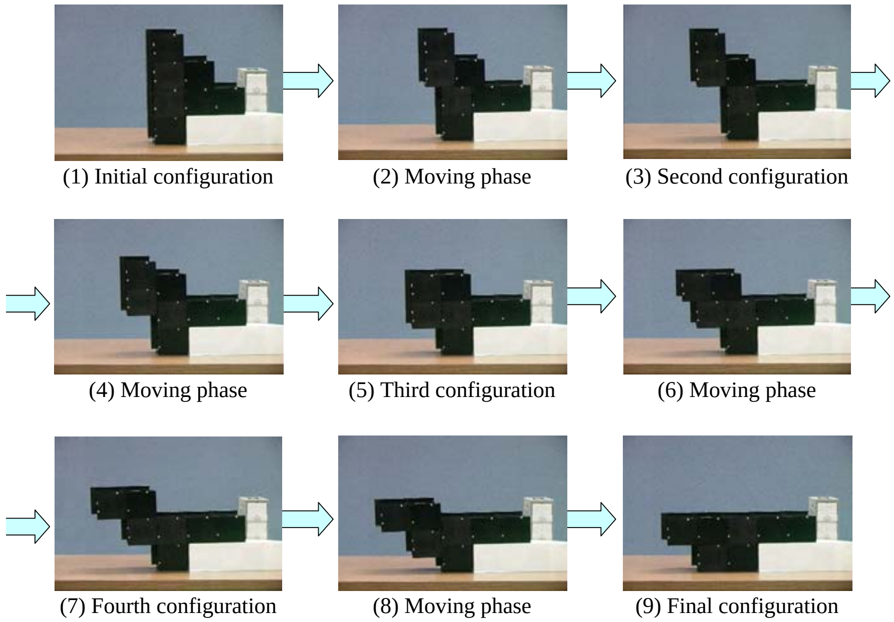

Fig. 15. Experimental demonstration of autonomous transformation

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