Proceedings 2003 IEEE International Symposium on
Computational Intelligence in Robotics and Automation
July 16-20, 2003, Kobe, Japan

Group Robots Forming a Mechanical Structure
- Development of slide motion mechanism and estimation of energy consumption of the structural formation -

Norio INOU, Kengo MINAMI and Michihiko KOSEKI
Department of Mechanical and Control Engineering, Tokyo Institute of Technology
O-okayama, Meguro-ku, Tokyo, 152-8552 Japan
E-mail: inou@mech.titech.ac.jp

Abstract
This study deals with group robots forming a mechanical structure. The group robots consist of identical cellular robots with same mechanical structure and information processing. To realize the group robots in hardware, we propose a slide motion mechanism that supports a large mechanical loading. We report the performance test, and energy consumption required for transformation of the cellular robot under various configurations. This paper also discusses the shortest route with minimum energy in transformation when an initial configuration and a final one are given.
Key words: group robots, cellular robot, structural formation, procedure of structural transformation

1. Introduction

Autonomous distributed robots have potential to accomplish various missions which conventional robots have not ever done such as cooperative transportation, collection and construction [1]. According to the missions, various types of group robots were so far examined.

Reconfigurable modular robots are one of the types and have a feature of cooperative construction connecting with each other. With respect to research studies on group robots forming a structure in hardware, many studies have been proposed [2-7]. However, few robots are designed to support large outer forces. The reason why is that almost studies focused on a mobile function rather than a supporting function as a mechanical structure.

Our study focuses on group robots forming a mechanical structure. The group robots consist of modular robots called cellular robots. Each cellular robot has same mechanical and electric functions.

Figure 1 shows an example of missions of the group robots. They form a mechanical structure by themselves for variable mechanical environments such as a moving load. In this case, strength of structure is one of the most important factor to realize the structural formation by group robots because they must support the structure for the moving load.

In the previous paper [8], we proposed a concrete mechanism for structural formation using pneumatic actuators assuming application in the space where gravitational force is very small. In this study, we aim to develop reconfigurable modular robots which are available on earth. For this purpose, we propose a rigid motion mechanism as follows.

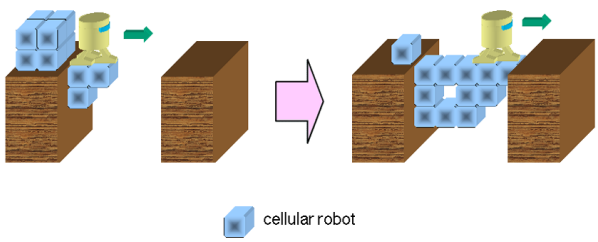


Fig. 1 Idea of cellular robots forming a bridge structure

2. Structure of cellular robot

To construct a rigid structure which is enough to support a load, cellular robots should have rigid motion mechanisms. As a cellular robot is assumed to be cubic, even small discrepancy of displacement or angle between cellular robots may cause failure of structural formation.

Hardware requirements of mechanism should minimize the discrepancy. The more complex the mechanism becomes, the more the discrepancy may increase because production errors cause in many mechanical parts. For this reason, we developed a simple motion mechanism as much as possible.

2.1 Slide motion mechanism

Figure 2 illustrates basic structural transformation of three 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.

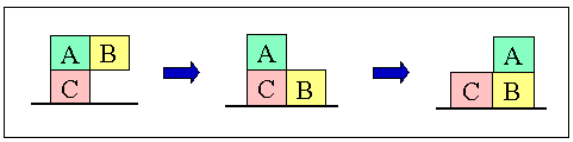


Fig. 2 Transformation of cellular robots by the proposed slide motion mechanism

The concrete slide motion mechanism is shown in Fig. 3. It consists of three plastic boards, that is, two lateral boards and a central board. They are formed by machined processing. The central board is sandwiched by the two lateral boards and all the boards are tightly connected. The each lateral board has 4 wheels for two directional sliding motions. The central board has grooves as sliding guides, which maintain high rigidity even in transformation. For this motion mechanism, cellular robots successfully connect to other robots.

Figure 4 shows the inner mechanism of the cellular robot. Two lateral boards include symmetrical motion mechanisms which consist of two set of wheels. 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 which are placed on the same plane through a drive shaft in the central board. The central board includes only drive shafts at this time. This part has enough space to embed controller, sensors and batteries for autonomic functions of cellular robots though the present model does not have them.

For generation of constant stable frictional force in sliding motion of cellular robots, we used plastic wheels and stamped low elastic rubbers on the bottom faces of grooves.

Table 1 shows specifications of the cellular robot. We made seven cellular robots and examined the performance.

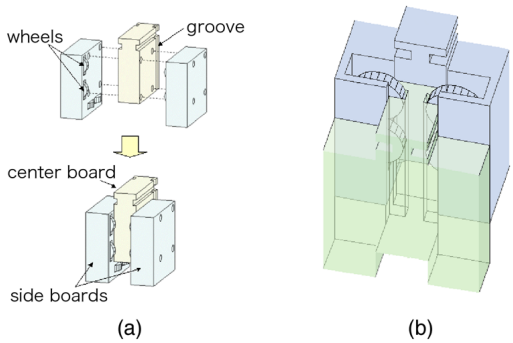


Fig. 3 Assembly of the proposed cellular robot (a) and connecting face driven by wheels (b)

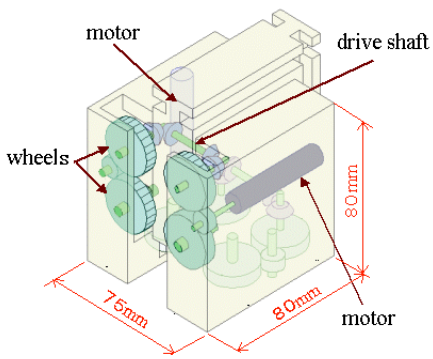


Fig. 4 Inner mechanism of the proposed cellular robot

Table 1: Specifications of the cellular robot

Size (mm)	80x80x75	Maximum driving power (N)	20
Weight (kg)	0.5	Driving velocity (mm/s)	7.6
Material	ABS	Number of parts	101
Actuators	DC motor x 2	Varieties of parts	23

2.2 Force sensor of cellular robot

It is necessary to sense stresses created on cellular robots to change the configuration according to the mechanical environment. We tried to implement the sensing function. It is expected that a large strain occurs at the place near the corner compared with other portions when a load is applied. For this reason, we put a strain gauge on the corner of a lateral board as shown in Fig. 5.

A loading test was performed by measuring voltage produced from the strain gauge. The load was applied in the vertical direction to a neighbor cellular robot under a loading and unloading cycles. Figure 6 shows the experimental results. There are some hysteresis loops during loading and unloading, but the maximum loadings show almost same output voltage values.

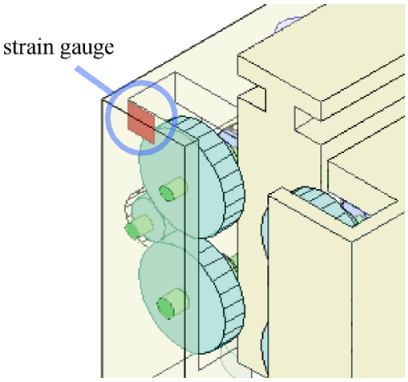


Fig. 5 Force sensor of cellular robot

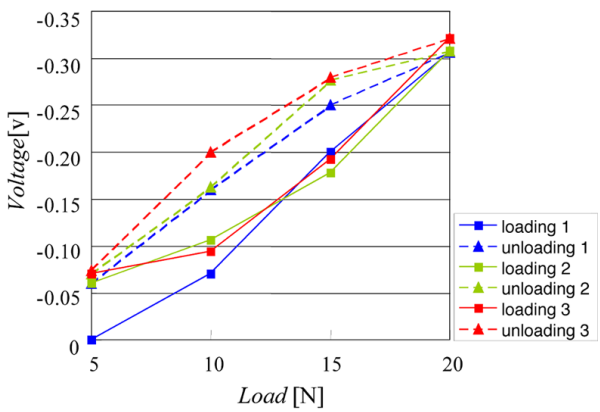


Fig. 6 Results of the load sensing experiment

2.3 A demonstration of structural formation

Structural formation was examined by seven cellular robots. Figure 7 shows the sequential transformation from No. 1 to No. 9. At No. 6, a loading force was applied at the tip of the right cellular robot. As the cellular robot colored in pink created high stress in the body, the configuration of the robots changed calling other robot to a neighbor place of the stressed robot. Three photos (a), (b) and (c) as shown in Fig. 8 correspond to No. 2, 6 and 8 in Fig. 7.

The motions of the seven robots were controlled by a PC (personal computer) using I/O ports. The structural change of the robots was performed by a sequential program while the robots took positional signals from limit switches embedded in them. When the pink cellular robot senses the force at No. 6, the robot transmitted the signal to the PC. Then the PC gave a command of reinforcement of structure to some robots. This adaptive mechanism for the outer force resulted in the final structure depicted by No. 9.

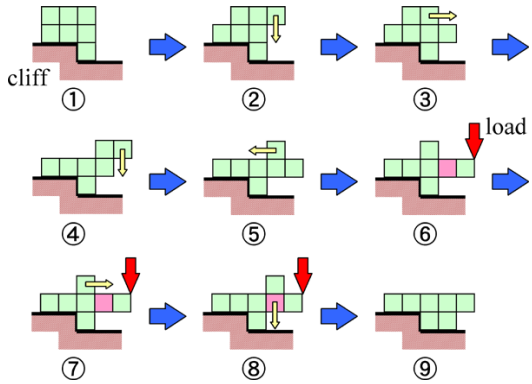


Fig. 7 Demonstration of structural formation

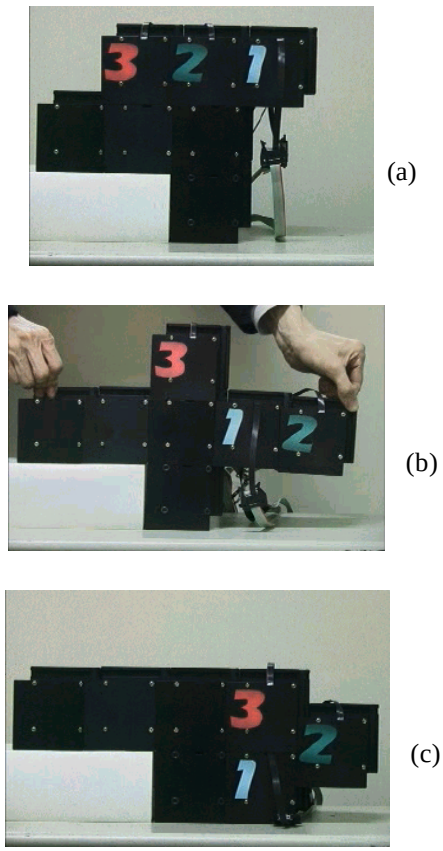


Fig. 8 Photos of robots for corresponding to Fig. 7

3. Routes in structural formation

In this chapter we discuss the way to find the shortest routes in structural transformation when an initial and final configurations of robots are given. We will further discuss a preferable route among them by comparing necessary energy cost in the transformation.

3.1 Procedure of structural formation

The proposed mechanism of the cellular robot has a constraint in structural transformation. Figure 9 shows the constraint in structural transformation. The cellular robot does not have a separation function for each face of the robot. The robots must transform to an objective structure taking into consideration of this constraint.

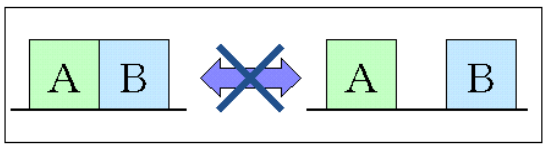


Fig. 9 Constraint in transformation

It is very difficult to find the shortest route by a heuristic approach when an initial and a final structures are given. This study adopted best-subset selection method. That is, every possible structure is checked by each transformation step. This method needs a lot of CPU time for searching the shortest routes. We devised the searching method to decrease the CPU time.

As best-subset selection method produces numerous patterns of cellular configuration, it needs a lot of CPU time to check whether each configuration is same. To speed up of the pattern recognition, we introduce a parameter which roughly characterizes a configuration of cellular robots using the next equation.

$$\boldsymbol{prm} = \sum (256\boldsymbol{x} + \boldsymbol{y})$$

Where, x is a coordinate in the horizontal axis for each cellular robot, and y is a coordinate in the vertical axis for the robot. The coordinates x and y are independently added up to the prm when absolute of y is less than 256. If a configuration of robots has a different prm from other ones, we can assure that the configuration is unique. Using the parameter, we can speedily identify a new configuration of the cellular robots. We examined performance of the algorithm in case of six cellular robots. Possible configurations at the present step were compared with previous ones generated until former steps. Required CPU time for the pattern recognition was significantly speeded up as shown in table 2.

Table 2 CPU time for solution

Number of steps	5	7	9
without prm	20	366	1128
with prm	11	90	153
Ratio of speed up	1.8	4.1	7.4

Figure 10 shows processes of structural formation of the six cellular robots with the proposed mechanism. The figures in the rectangular box are an initial and a final structures. There are several possible routes which are satisfied with the constraint in transformation. The routes are same configuration steps. In the following section, we will discuss a desirable route among them taking into consideration of energy consumption.

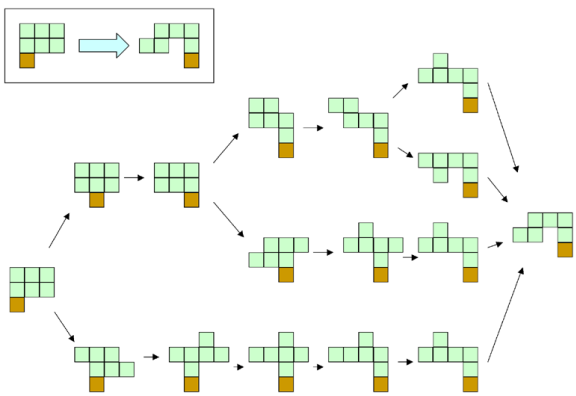


Fig. 10 Structural formation by group robots with slide type motion mechanism

3.2 Energy cost for movement

The proposed cellular robots with the slide motion mechanism has high rigidity and enable to construct a structure under a certain load. It is preferable to minimize energy consumption for construction because each cellular robot is supposed to mount a limited battery.

Figure 11 shows a performance test in the vertical movement. We estimated necessary electric power to move unit side length of the cellular robot by measuring

the electric current and voltage dissipated in DC motors. As the required electric power depends on configuration of robots, we measured them under various conditions as shown in Fig. 12. These data are available to estimate total energy that group robots transform a different configuration.

3.3 Total energy consumption of formation

As described in the previous section, energy required for partial transformation of group robots was measured under various conditions. Summing up these energy values along routes in structural formation as shown in Fig. 10, we can calculate the total energy cost. However, energies for some partial transformations along the routes are not known because we do not have adequate robots to measure the transformations at this time. In such the cases, we presumed the energies from the obtained data.

Figure 13 shows the total energy for structural transformations. The best route with minimum dissipative energy is found by this method.

4. Conclusions

Cellular group robots adaptively forming a mechanical structure according to outer mechanical environments were discussed. The proposed slide motion mechanism showed enough rigidity to construct a structure stably. A sensing device with a strain gauge was successfully developed. The experimental demonstration showed the robots changed the structure for a loading condition. Procedure of routes for structural formation was also discussed. Energy consumption along the transformation route was estimated.

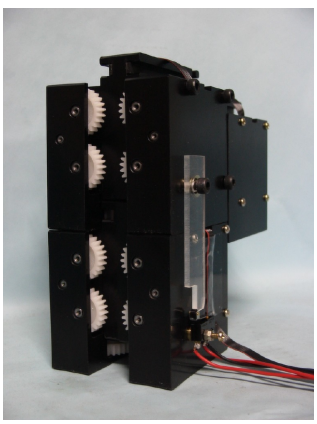
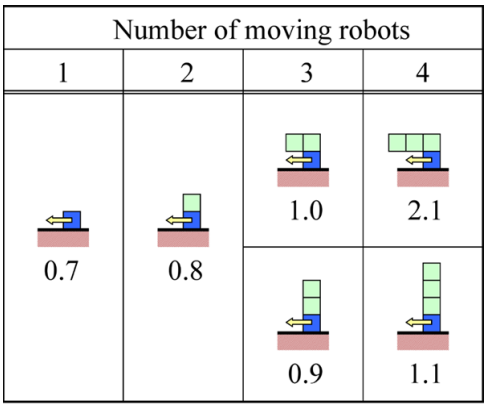
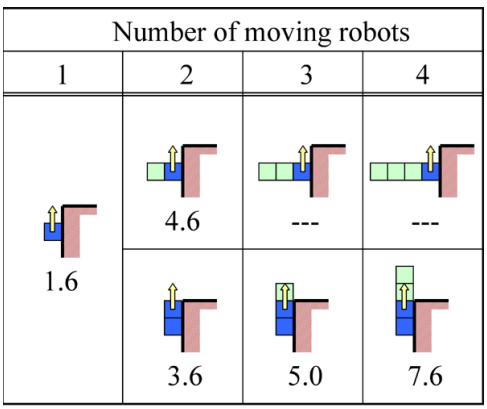


Fig. 11 Experiment of vertical movement

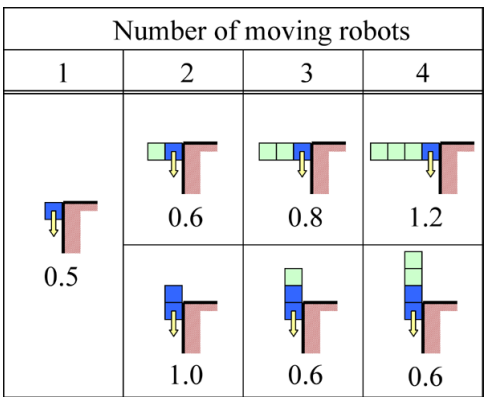


(a) horizontal movements



---: couldn't move

(b) upward movements



(c) downward movements

: driving robot
: carried robot

Fig. 12 Energy consumption of configurational change (unit of energy: joule)

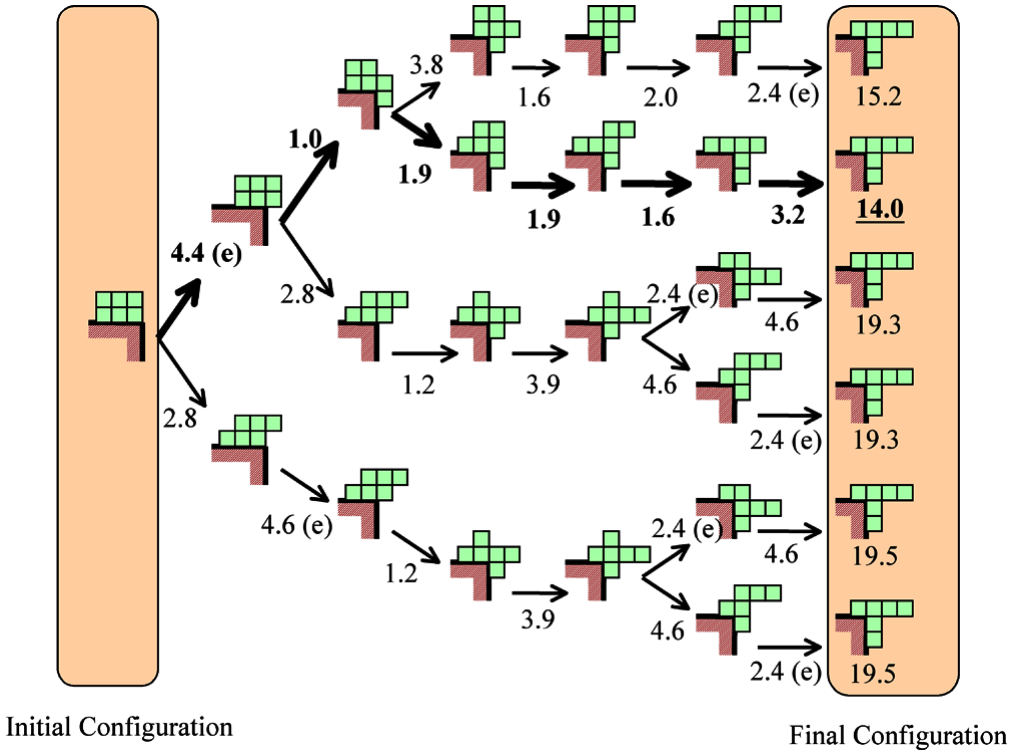


Fig. 13 Total energy for structural transformation
(e: estimated value)

Acknowledgement: This study was supported by a Japanese Grant-in-Aid for COE Research Project supported by the Ministry of Education, Culture, Sports, Science and Technology, "Super Mechano-Systems"(No. 09CE2004).

References

[1] Y.U.Cao, A.S.Fukunaga and A.B.Kahng: Cooperative Mobile Robotics: Antecedents and Directions, Autonomous Robots, Vol.4, 1997, pp.7-27

[2] T.Fukuda, S.Nagasawa, Y.Kawauchi and M.Buss: Structure Decision Method for Self Organizing Robots Based on Cell Structures-CEBOT, Proceedings of the 1989 IEEE International Conference on Robotics and Automation,1989, pp.698-700

[3] G.Chirikjian and A.Pamecha: Bounds for Self-Reconfiguration of Metamorphic Robots, Proceedings of the 1996 IEEE International Conference on Robotics and Automation, 1996, pp.1452-1457

[4] S.Murata, H.Kurokawa and S.Kokaji: Self-Assembling Machine, Proceedings of the 1994 IEEE International Conference on Robotics and Automation, 1994, pp.441-448

[5] S.Murata, E.Yoshida, K.Tomita, H.Kurokawa, A.Kamimura and S.Kokaji: Hardware Design of Modular Robotic System, Proceedings of 2000 IEEE/RSJ International Conference on Intelligent Robots and System (IROS2000), CD-ROM, F-AIII-5

[6] K.Hosokawa, T.Tsujimori, T.Fujii, H.Kaetsu, H.Asama, Y.Kuroda and I.Endo: Self-Organizing Collective Robots with Morphogenesis in a Vertical Plane, Proceedings of the IEEE International Conference on Robotics&Automation, 1998, pp.2858-2863

[7] M.Yim, D.Duff, K.Roufas and L.Kissner: Plybot: demonstrations of modular reconfigurable robot, Video Proceedings of the IEEE International Conference on Robotics and Automation, 2000

[8] N.Inou, H.Kobayashi and M.Koseki: Development of Pneumatic Cellular Robots Forming a Mechanical Structure, Seventh International Conference on Control, Automation, Robotics and Vision (ICARCV'02), 2002 , pp.63-68 (CD-ROM)