Research on Self-Reconfigurable Modular Robot System*

(Experiments on Reconfiguration and Locomotion with Several Modules)

Akiya KAMIMURA**, Satoshi MURATA***, Eiichi YOSHIDA**, Haruhisa KUROKAWA**, Kohji TOMITA** and Shigeru KOKAJI**

Growing complexity of artificial systems arises reliability and flexibility issues of large system design. Robots are not exception of this, and many attempts have been made to realize reliable and flexible robot systems. Distributed modular composition of robot is one of the most effective approaches to attain such abilities and has a potential to adapt to its surroundings by changing its configuration autonomously according to information of surroundings. In this paper, we propose a novel three-dimensional self-reconfigurable robotic module. Each module has a very simple structure that consists of two semi-cylindrical parts connected by a link. The modular system is capable of not only building static structure but also generating dynamic robotic motion. We present details of the mechanical/electrical design of the developed module and its control system architecture. Experiments using ten modules with centralized control demonstrate robotic configuration change, crawling locomotion and three types of quadruped locomotion.

Key Words: Mechatronics and Robotics, Modular Robot, Distributed Autonomous System, Self-Reconfiguration, Self-Repair, Robotic Motion Generation

1. Introduction

Recently, a large amount of work has been made on self-reconfigurable modular robots. Self-reconfigurable modular robot is composed of homogeneous or heterogeneous modules and has an ability to configure its shape or repair itself by changing connecting relations between modules. When the robot is

able to assemble its own body structure, it has "self-assembly" function, and when it fixes itself by replacing defective part, it has "self-repair" function. These kinds of novel functions for robots are expected to have various advantages for operations such as rescue, search, transportation and maintenance in unexpected and unstructured environments.

Various types of modular systems have been proposed for self-reconfigurable robots⁽¹⁾⁻⁽¹³⁾. In these researches, the hardware design of the module and the software design of the control algorithms are the central issues. The self-reconfigurable robot systems can be classified by following features.

1. Homogeneity/heterogeneity of module composition
2. Dimension of the configurable structure by modules (2-D or 3-D)
3. Connection method
4. Communication and power supply method
5. Local processor

* Received 14th May, 2003 (No. 01-0540). Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 68, No. 667, C (2002), pp. 886-892 (Received 1st May, 2001)

** Distributed System Design Research Group, Intelligent Systems Institute, AIST, 1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, Japan. E-mail: kamimura.a, e.yoshida, kurokawa-h, k.tomita, s.kokaji@aist.go.jp

*** Department of Computational Intelligence and Systems Science, Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226-8502, Japan. E-mail: murata@dis.titech.ac.jp

6. Centralized/distributed control
7. Motion generation

Most of the proposed modular systems⁽¹⁾⁻⁽¹⁰⁾ are a homogeneous system and the other⁽¹¹⁾⁻⁽¹³⁾ is a heterogeneous system. The main reason for adopting a homogeneous system is for changeability between modules in case of a failure of a module, and for simplicity of self-reconfiguration by many modules. As for connection method, there are two types of connection method between modules, manual and automatic. Obviously automatic inter-module connection is necessary for the self-reconfiguration. However, there are problems such that some mechanisms need precise alignment and some need large volume.

Wiring is also an important issue. Self-contained module or power/communication supply through the connection interface is required to avoid wiring troublesome. In order to use the system as a robot, an ability to generate dynamic group motion by modules is also required. Modules proposed in Refs.(5), (8) - (10), (11) - (13) can generate robotic motion.

Development of distributed control algorithms for self-reconfigurable robot systems is a challenging issue. Only a few distributed algorithms for two or three-dimensional systems have been reported so far. (Here, we do not count pure algorithms such as A-Life simulations.) In Refs.(2) and (11), a completely distributed control algorithm is proposed for two-dimensional self-reconfiguration of a desired shape. In Ref.(4), a distributed algorithm for three-dimensional self-reconfiguration is proposed, but the hardware control is centralized.

For reconfiguration of 3-D systems, motion planning is very difficult in general even by centralized method because there are various geometrical and physical constraints. A few papers^{(14),(15)} discussed with the motion planning for 3-D systems. They only adhere to their own specific module design. Establishing a general methodology for 3-D reconfiguration and distributed algorithm is a future subject.

In this paper, we present details of the mechanical/electrical design of our module hardware, and the centralized control system architecture for cooperative motion generation. Reconfiguration and locomotion experiments using several modules are also shown to demonstrate reliable operations of the proposed modular system.

2. Development of Self-Reconfigurable Robotic Module

This chapter describes the mechanical/electrical design of the developed module and its control system architecture.

2.1 Concept of module design

Figure 1 shows a schematic view of the module. The module is composed of two semi-cylindrical parts and a link part. Each semi-cylindrical part can be rotated about its axis by 180 degrees independently by a servomotor embedded in the link. Each semi-cylindrical part has three connecting surfaces with four permanent magnets. The polarity of the magnets between two semi-cylindrical parts is different. This polarity difference makes a checkerboard-like parity structure as shown in Fig. 2 and the parity is always maintained as long as the modules are placed in the lattice grid. Not only 2-D structures but also 3-D structures can be constructed by connecting several modules. Reconfiguration is achieved by repeating basic operations such as detaching a surface, rotating the links and reconnecting the surface. After the construction of static structures, it is also possible to make robotic motions such as walking and crawling by using internal degrees of freedom of module structures as shown in Fig. 2.

2.2 Mechanical design

Figure 3 shows the appearance and the inner structure of the module. The frame of the module is made of engineering plastic (delrin). Connection surfaces are directly made of glass-epoxy fiber circuit boards to decrease the number of electric wiring and total weight. There are three parts, called 'Active', 'Passive' and 'Link' part. The active and passive parts

Fig. 1 Schematic of the proposed module

Fig. 2 Static structure (left) and its motion (right)

are connected by the link part mechanically and electrically.

The link part includes two set of precision-g geared motor, reduction gear and servo circuit. The maximum torque of each servo is about $23 \text{ kg}\cdot\text{cm}$, which is enough to lift up one module as shown in Fig. 4.

On the surface of the passive part, there are four Samarium-Cobalt permanent magnets (S pole outside), two pair of electrodes (anode and cathode), and one electrode for a serial communication. They are placed symmetrically around the rotation axis in order that the surface connection between modules can be achieved in every 90 degrees. The connecting force between modules achieved by the magnets is about 25 N. The passive part contains all the control circuits. The details of the control circuits are described in section 2. 3.

The active part includes the connection mechanism, which is composed of non-linear springs, SMA

Fig. 3 Photos of appearance and inner structure of the developed module

Fig. 4 Lifting up motion with two modules

(Shape Memory Alloy) coils and four permanent magnets (N pole outside). They are fixed on a moving part called the connecting plate (Figs. 3 and 5). This mechanism is based on Internally Balanced Magnetic Unit (IBMU) method⁽¹⁶⁾. In this mechanism, the magnetic potential energy is not dispersed but changed into internal elastic energy of springs. The nonlinear spring is designed so that the repulsion by the springs is slightly weaker than the attraction by the magnets and the difference between these two forces is designed to be constant for any position of the connecting plate (Fig. 5). Note that when two surfaces, passive and active, are attached, the repulsive force by nonlinear springs is internally balanced inside the active box and does not affect the connecting force between two surfaces. Connection is easily released when the SMA coils generate a larger force than the difference between magnetic attraction and spring repulsion. The SMA coils are directly heated by electric pulse current. In the detachment process, the SMA coils are needed to be driven for about 5 s (180 J) for detachment.

The specifications of the module are summarized in Table 1.

Fig. 5 Diagram of connection mechanism using IBMU method

2.3 Electrical design

Figure 6 shows the control circuits contained in the passive part. There are an onboard microprocessor (BASIC STAMP II, Parallax, Inc.), a power supply circuit and a pulse generator circuit for driving SMA coils. The microprocessor has dipswitch inputs to set ID number of the module. Electrodes on passive and active surfaces are connected through wirings run inside the link.

The rotational angles of the two servomotors are changed by Pulse Width Modulated (PWM) signals from the microprocessor. The microprocessor drives the SMA coils by pulsed current in the detaching operation. The microprocessor also verifies the status of connection (connected or detached).

Control commands corresponding to these operations are issued by the host computer through the serial communication line. The total length of the control command is three bytes, which include the module ID, the command number (shown in Table 2) and the data.

Both of the power supply and the serial communication between modules and the host PC are achieved by connecting a base plate (Fig. 7) to one of the active connection surfaces of the constructed module structure.

2.4 Control system architecture

Figure 8 shows the control system architecture. The system consists of a host PC, a relay BS II

(BASIC STAMP II, the same one used as the onboard microprocessor) and connected modules. When the modules are connected mechanically, they are also connected electrically through a serial communication line as shown in the figure. The communication between the host PC and the relay BS II, the relay BS II and the modules are all achieved by 4 800 bps asynchronous serial communication.

The communication between relay BS II and the modules is achieved by token passing. The host PC issues a control command with the target module's ID number, and then the relay BS II broadcasts this command to the modules on the serial line. Only the module which has the same ID executes the command and then sends back a validation signal to the host PC through the relay BS II. In case of no validation is returned from the module or the signal is not correct, the host PC sends the commands again for recovery.

Table 2 Module control commands

Number	Function
1	Set each angle parameters but not execute motion
2	Release fixation of angles
3	Detach surface
4	Check state of connection, connecting or not
5	Execute motion

Table 1 Specifications of the module

Item	Value
Dimension	66x132x66 mm
Weight	0.44 kg
CPU	BASIC STAMP II
Power supply	DC 12V
Maximum torque of each axis	23 kg·cm
Connecting force	25 N
Elapsed time for detachment	5 seconds
Power consumption for detachment	180 J

Fig. 6 Control circuits in the passive side

Fig. 7 Photo of the base plate

Fig. 8 Schematic of the centralized control system architecture

3. Simulator for Motion Planning

We developed a simulator for motion planning of the modular system (Figs. 9 and 10). The process of motion planning is as follows (details are described in Ref.(17)): First, initial configuration by modules is made by using the configuration editor control panel (not shown). Next, the module motion sequence is programmed by the motion control panel in the left most pane in Fig. 10. The generated motion is recorded and displayed as robotic motion language in the middle pane. Then, collisions between modules and connectivity of the whole configuration are automatically checked before hardware execution. Static physical feature such as center of gravity is calculated by the simulator but the dynamics is not taken into account in the current version. Here, stability of the

Fig. 9 Diagram of simulator to hardware control. The above number shows operation order.

Fig. 10 Screen capture of the developed simulator

module motion such as walking is confirmed by checking whether the center of gravity of the module configuration is always within the area enclosed by contact points between the legs and the ground. After editing the motion sequence, it is translated into a series of hardware control commands and they are sent to the module hardware via serial line.

4. Hardware Experiments

To confirm basic functions of the modular system such as self-reconfiguration and module motions, we carried out several experiments as follows.

4.1 Self-reconfiguration experiment

The first experiment is a self-reconfiguration with three modules (Fig.11). In this experiment, automatic self-reconfiguration has been successfully realized. It was confirmed that since small displacement between two surfaces are absorbed by magnetic attraction, no additional position control is necessary.

4.2 Locomotion and transformation experiments

We examined various types of following locomotion modes, e.g. quadrupedal motion and crawling, and transformation between them. All motions in the experiments are programmed in advance by using the simulator.

Quadruped robot (type 1)

This robot is composed of nine modules and walks by using four leg parts as shown in Fig.12. However, the walking speed was quite slow because the friction of the floor was not sufficient and the motion sequence was not optimized.

Quadruped robot (type 2)

Another quadruped robot composed of eight modules was examined (Fig.13). This robot can move by using two of the legs. The robot configuration has a radial symmetry so that it can move toward four directions with the same gait pattern. Furthermore, the robot can turn about its center axis by folding two legs in opposite directions. The arrows in photos indicate robot's moving direction.

Crawler

This robot is composed of six modules. Transform-

Fig. 11 Self-reconfiguration experiment (3 modules)

mation from a straight chain to the crawler (loop) is shown in Fig. 14. Closing the loop was successfully achieved without precise position control. The rolling motion of the crawler was smooth and successfully achieved as well.

Crawler to quadruped robot (type 3)

In this experiment, an initial configuration (H

shape configuration) composed of nine modules is first transformed into a crawler shape and then to a quadruped robot. The resultant quadruped robot walked successfully in a statically stable gait pattern called the intermittent crawler gait (Fig. 15).

From above hardware experiments, the feasibility of the proposed self-reconfigurable modular sys-

Fig. 12 Motion of the quadruped robot (Type 1) (9 modules)

Fig. 13 Motion of the quadruped robot (Type 2) (8 modules).
The arrows show moving directions of the robot at each step.

Fig. 14 Motion of the crawler (6 modules)

Fig. 15 Locomotion and transformation experiment.
The H shape configuration using 9 modules changes to the crawler shape, and then it rolls to move. After that it changes into the quadruped robot (Type 3) and walks.

tem was confirmed.

5. Concluding Remarks

In this paper, we presented a novel hardware design of a robotic module which can make various 3-D module structures and robotic motions. The centralized control system architecture used for the modular system and the simulator for motion planning were also shown. The hardware experiments using 9 modules proved that various kinds of robotic configurations, locomotion and transformations are possible by the proposed system.

As future works, following respects should be considered. The first one is to improve the hardware system. Since the developed module hardware has no internal and external sensors, stable locomotion, obstacle avoidance and transformation using sensor feedbacks have not been realized. By installing sensors such as an infrared ray sensor, an acceleration sensor for gravity detection or a vision camera, it will be possible to work autonomously and to transform into a suitable configuration adaptively to its surroundings. The second issue is software algorithms. Automatic generation methods for a stable locomotion pattern of an arbitrary module configuration and for a transformation sequence from one structure to another are required for the self-reconfigurable modular robot system, because there are a wide variety of possible configurations. The last issue is control system architecture. In the current system, a centralized control method is used. To make the modular system more robust to failures, some kinds of distributed algorithms for generating motion and transformation should be proposed.

References

- (1) Chirikjian, G., Pamecha, A. and Ebert-Uphoff, I., Evaluating Efficiency of Self-Reconfiguration in a Class of Modular Robots, *J. Robotic Systems*, Vol. 13, No. 5 (1995), pp. 317-338.
- (2) Murata, S., Yoshida, E., Kurokawa, H., Tomita, K. and Kokaji, S., Self-Repairing Mechanical Systems, *Autonomous Robots*, Vol. 10 (2001), pp. 7-21.
- (3) Murata, S., Kurokawa, H., Yoshida, E., Tomita, K. and Kokaji, S., A 3-D Self-Reconfigurable Structure, *Proc. IEEE Int. Conf. Robotics and Automation (ICRA98)*, (1998), pp. 432-439.
- (4) Yoshida, E., Murata, S., Kokaji, S., Tomita, K. and Kurokawa, H., Micro Self-Reconfigurable Robotic System Using Shape Memory Alloy, *Distributed Autonomous Robotic Systems*, Vol. 4 (2000), pp. 145-154.
- (5) Murata, S., Yoshida, E., Tomita, K., Kurokawa, H., Kamimura, A. and Kokaji, S., Hardware Design of Modular Robotic System, *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2000)*, (2000), pp. 2210-2217.
- (6) Hosokawa, K., Tsujimori, T., Fujii, T., Kaetsu, H., Asama, H., Koruda, Y. and Endo, I., Self-Organizing Collective Robots with Morphogenesis in a Vertical Place, *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA1998)*, (1998), pp. 2858-2863.
- (7) Rus, D. and Vona, M., A Basis for Self-Reconfigurable Robots Using Crystal Modules, *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2000)*, (2000), pp. 2194-2202.
- (8) Kotay, K., Rus, D., Vona, M. and McGray, C., The Self-Reconfigurable Robotic Molecule, *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA1998)*, (1998), pp. 424-431.
- (9) Castano, A. and Will, P., Mechanical Design of a Module for Reconfigurable Robots, *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2000)*, (2000), pp. 2203-2209.
- (10) Casal, A. and Yim, M., Self-Reconfigurable Planning for a Class of Modular Robot, *Proc. SPIE*, Vol. 3839 (1999), pp. 246-257.
- (11) Kawauchi, Y., Inaba, M. and Fukuda, T., A Study on Cellular Robotic System (A Realization of Robotic System Capable of Adaption, Self-Organization, and Self-Evolution), *RSJ (in Japanese)*, Vol. 12 (1994), pp. 116-132.
- (12) Unsal, C., Kiliccote, H. and Kohsla, K., I (CES)-Cubes; A Modular Self-Reconfigurable Bipartite Robotic System, *Proc. SPIE*, Vol. 3839 (1999), pp. 258-269.
- (13) Yim, M., New Locomotion Gaits, *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA 1994)*, (1994), pp. 2508-2514.
- (14) Yim, M., Zhang, Y. and Mao, E., Distributed Control for 3D Shape Metamorphosis, *Autonomous Robots*, Vol. 10, No. 1 (2001), pp. 41-56.
- (15) Yoshida, E., Murata, S., Kurokawa, H., Tomita, K. and Kokaji, S., A Distributed Method for Reconfiguration of a Three-Dimensional Homogeneous Structure, *Advanced Robotics*, Vol. 13, No. 4 (1999), pp. 363-379.
- (16) Hirose, S., Imazato, M., Kudo, Y. and Umetani, Y., Internally-Balanced Magnet Unit, *Advanced Robotics*, Vol. 3, No. 1 (1986), pp. 225-242.
- (17) Kurokawa, H., Tomita, K., Yoshida, E., Murata, S. and Kokaji, S., Motion Simulation of a Modular Robotic System, *Proc. IEEE Int. Conf. Industrial Electronics, Control and Instrumentation (IECON-2000)*, (2000), pp. 2473-2478.