Proceedings of 2001 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS2001), 606-612.

# Self-Reconfigurable Modular Robot

## - Experiments on Reconfiguration and Locomotion -

Akiya KAMIMURA[*1], Satoshi MURATA[*2], Eiichi YOSHIDA[*1],
Haruhisa KUROKAWA[*1], Kohji TOMITA[*1] and Shigeru KOKAJI[*1]

[*1] Distributed System Design Research Group, Intelligent Systems Institute, AIST
1-2-1 Namiki, Tsukuba, 305-8564 Japan
{kamimura.a, e.yoshida, kurokawa-h, k.tomita, s.kokaji}@aist.go.jp
[*2] Department of Computational Intelligence and Systems Science, Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology
4259 Nagatsuta-cho, Midori-ku, Yokohama, 226-8502 Japan
murata@dis.titech.ac.jp

## Abstract

*We have proposed a self-reconfigurable robotic module, which has a very simple structure. The system is capable of not only building static structure but generating dynamic robotic motion. We also developed a simulator for motion planning. In this paper, we present details of the mechanical / electrical design of the developed module and its control system architecture. Experiments using ten modules demonstrate robotic configuration change, crawling locomotion and three types of quadruped locomotion.*

## 1 Introduction

Recently, a large amount of work has been made on self-reconfigurable robots. Self-reconfigurable robot sytems composed of homogeneous or heterogeneous modules have an ability to configure their shapes and repair them 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 are expected to have various advantages for operations such as rescue, search, transportation and maintenance in 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.

Most of the self-reconfigurable robot systems can be classified by following features (summarized in Table 1).

1. Homogeneity / heterogeneity of module composition
2. Dimension
3. Connection method
4. Communication and power supply method
5. Local processor
6. Centralized / distributed control
7. Motion generation

In the Table1, most of the modules are homogeneous except for CEBOT[1], ICES-Cube[8] and Polypod[12]. The latter two modules are semi-homogeneous because they have only two kinds of units.

There are two types of connection method between modules, manual and automatic. Obviously automatic inter-module connection is necessary for the self-reconfiguration. Most of the proposed modules[1-13] aim at the automatic connection and disconnection. 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 on the modules is also required. Modules proposed in [1,6,9-13] 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 [1,3] a completely distributed control algorithm is proposed for two-dimensional

Table 1: Various type of reconfigurable robot

| | Module composition (Hetero: heterogeneous, Homo: homogeneous) | Dimension | Self-contained | Local processor | Centralized (C) or distributed(D) control | Dynamic motion |
|---|---|---|---|---|---|---|
| [1] Nagoya Univ. CEBOT | Hetero | 2D | Yes | N/A | D | Yes |
| [2] JHU Hexagonal | Homo | 2D | No | Not embedded | C | No |
| [3] MEL Fructum | Homo | 2D | No | Z80 | D | No |
| [4] MEL Micro unit | Homo | 2D | No | BASIC STAMP II | C | No |
| [5] MEL 3D unit | Homo | 3D | No | Not embedded | C | No |
| [6] MEL proposed unit | Homo | 3D | Yes | BASIC STAMP II | C | Yes |
| [7] RIKEN Vertical | Homo | 2D | Yes | Not embedded | C | No |
| [8] Dartmouth Crystalline | Homo | 2D /3D | No | AT89C2051 | C | No |
| [9] Dartmouth Molecule | Homo | 3D | Yes | N/A | C | Yes |
| [10] CMU ICES-cube | Hetero | 3D | Yes | N/A | C | Yes |
| [11] USC CONRO | Homo | 3D | Yes | BASIC STAMP II | C | Yes |
| [12] Stanford Univ. Polypod | Hetero | 3D | Yes | Motorola XC68HC11E2 | C | Yes |
| [13] Xerox PARK PolyBot | Homo | 3D | Yes | PowerPC 555 | C | Yes |

self-reconfiguration of desired shape. In [5] 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 processing because there are various geometrical and physical constraints. A few papers discussed with the motion planning for 3-D systems [14,15]. 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 the previous paper [6], we presented the concept and the basic design of the module. It consists of two semi-cylindrical parts and a link, and this particular shape enables self-reconfiguration of robotic structure. In this paper, we present details of the mechanical / electrical design of the module, and the centralized control system architecture for cooperative motion generation. Reconfiguration experiments using several modules are also shown to demonstrate reliable operations of the 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. Each semi-cylindrical part can be rotated about its axis by 180 degrees by a servomotor embedded in the link. Each semi-cylindrical part has three connecting surfaces with four permanent magnets. The polarity of the magnets embedded on the surfaces of two

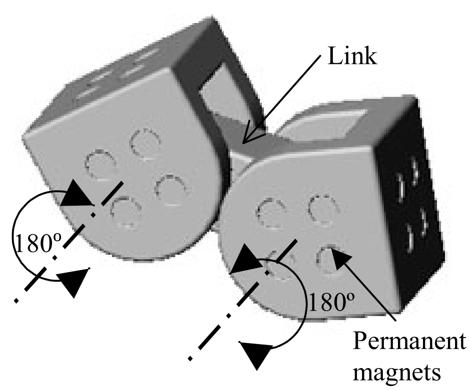

Figure 1: Schematic of the proposed module

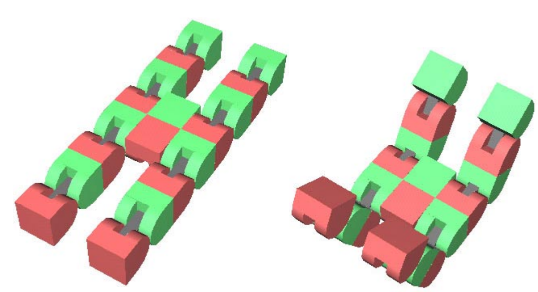
Figure 2: Static structure (left) and its motion (right)

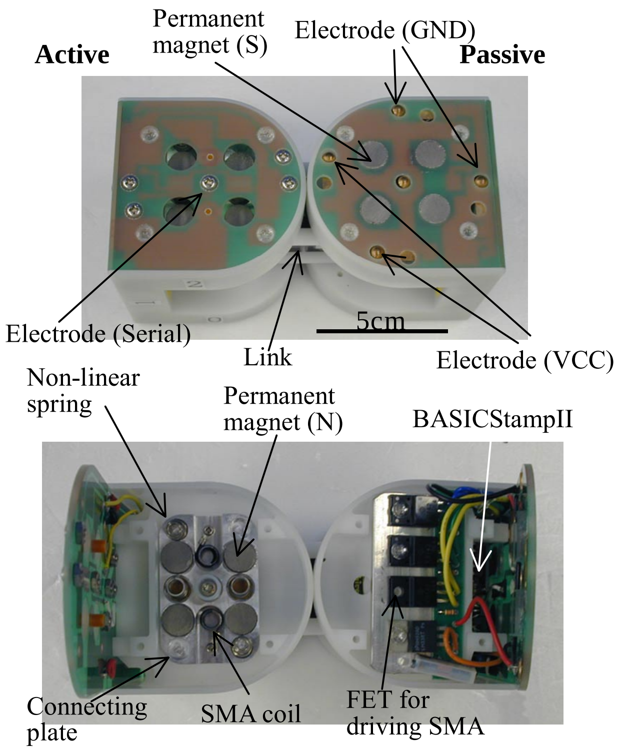

Figure 3: Photos of appearance and inner structure of the developed module

| 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 |
| Electrical resistance of module | 1.3 Ω |

Table 2: Specification of the module

semi-cylindrical parts is different. This polarity difference makes checkerboard-like parity as shown in Figure 2 and the parity is always maintained as long as the modules' rotational angles are restricted to multiples of a right angle. 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 motions by changing rotational angles of the links as shown in Figure 2.

### 2.2 Mechanical Design

Figure 3 shows the appearance and the inner structure of the module. The specifications are summarized in Table 2.

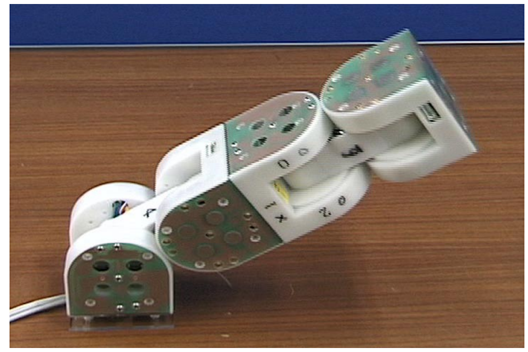
Figure 4: Lifting up motion with two modules

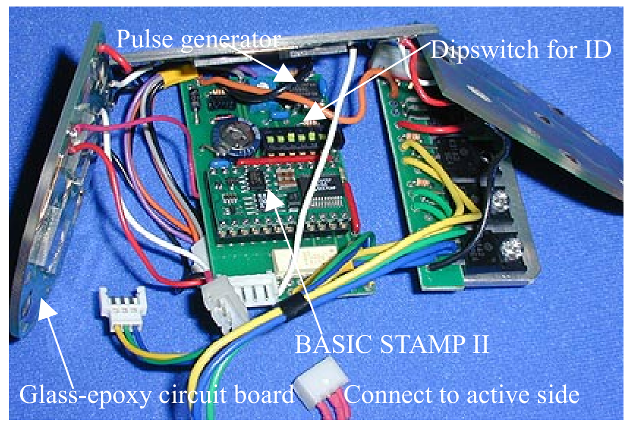

Figure 5: Control circuits in the passive side

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.

The link part includes two set of precision-geared motor, reduction gear and servo circuit. The maximum torque of each servo is about 23kg·cm, which is enough to lift up one module as shown in Figure 4.

On the surface of the passive part, there are four Samarium-Cobalt permanent magnets (S poles on the surface), two pair of electrodes (anode and cathode), and one electrode for a serial communication. The connecting force between modules achieved by the magnets is about 25N. The passive part contains all the control circuits. The details of the control circuits are described in 2.3.

The active part includes the connecting mechanism. The connecting mechanism is composed of non-linear springs, SMA (Shape Memory Alloy) coils and four permanent magnets (N poles on the surface), which are fixed on the connecting plate. The connecting plate is balanced by the spring force and the magnetic force, in order to reduce force for detachment. Detachment is achieved by heating SMA coils by electric current.

## 2.3 Electrical Design

Figure 5 shows the control circuits contained in the passive part. They 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 pulsated current in the detaching operation. The elapsed time for detachment is 5 seconds. The power consumption needed for detachment is about 180J. The microprocessor also verifies the status of connection surfaces (connected or detached).

Control commands corresponding to these operations are issued by the host computer. There are five commands as summarized in Table 3. The total length of the control command is three bytes.

The power supply and the serial communication between modules and host PC are achieved by connecting a base plate to one of the module surface. The base plate shown in Figure 6 is actually a passive connection surface.

## 2.3 Control System Architecture

Figure 7 shows the control system architecture. The system consists of host PC, relay PIC (BASIC STAMP II, the same one to the onboard microprocessor) and modules, and they are connected as the diagram shown in the figure. The communication between host PC and relay PIC, relay PIC and modules are all achieved by 4800bps asynchronous serial communication. There are two communication wires for sending and receiving between host PC and relay PIC. However, there is only one wire between relay PIC and modules.

Between relay PIC and the modules, the communication is achieved by the token passing. The host PC issues a control command with module’s ID number. And the relay PIC broadcasts this command to the modules on the serial line. Only

Table 3: Module control command

| 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 |

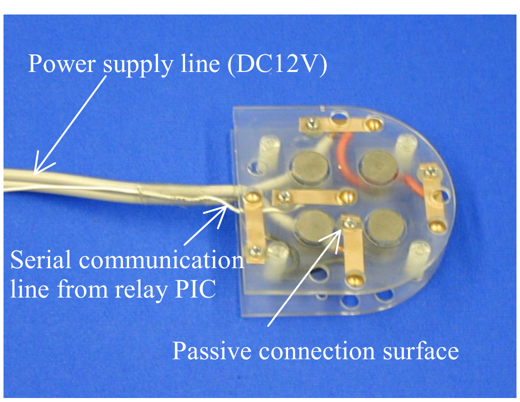


Figure 6: Photo of the base plate

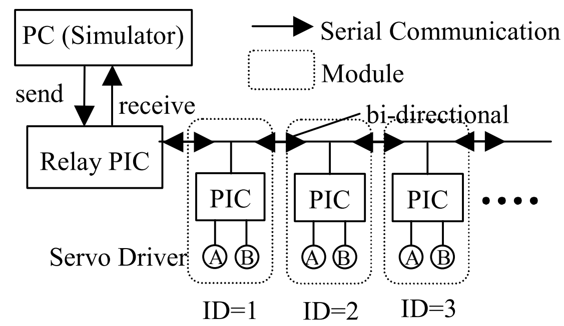


Figure 7: Schematic of the control system architecture

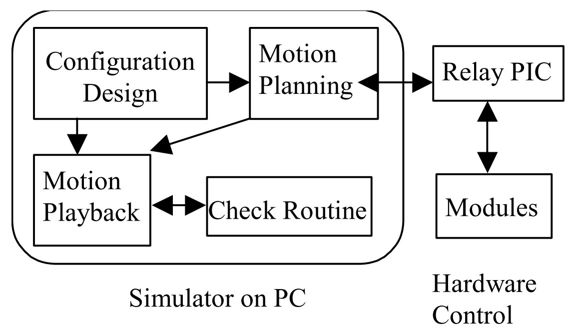


Figure 8: Diagram of simulator to hardware

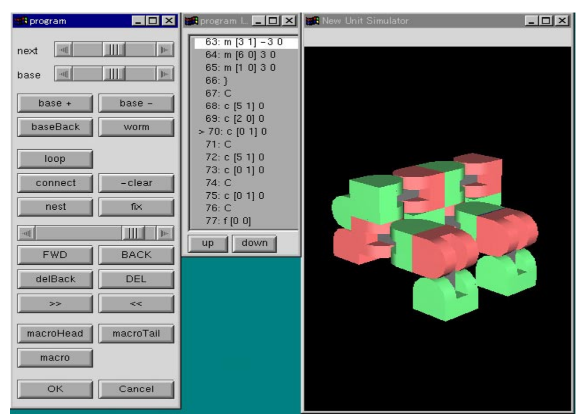

Figure 9: Screen capture of the developed simulator

the module with the same ID executes the task and then sends back a validation signal to host PC through relay PIC. In case of no validation are returned from the module or the signal is not correct, the host PC sends the commands again for recovery.

## 3 Simulator for Motion Planning

We developed a simulator for motion planning (Figure 8 and 9). The process of motion planning is as follows[16]: First, initial configuration of modules is created by using the configuration editor control panel (not shown). Next, the module motion sequence is programmed by using the motion control panel in the left most pane in Figure 9. The generated motions are recorded and displayed as motion language in the middle pane. Then, collisions between modules and connectivity of the whole configuration are automatically checked before execution of the sequence. Static feature such as center of gravity is calculated by the simulator but the dynamics is not taken into account in the current version. 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 Experiments

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

### 4.1 Self-Reconfiguration

The first experiment is a self-reconfiguration with three modules (Figure 10). In this experiment, automatic self-reconfiguration has been successfully realized. Small displacement between the connection surfaces are absorbed by magnetic attraction, thus no additional position control is necessary.

### 4.2 Locomotion and Transformation

We examined various types of locomotion modes such as three kinds of quadruped locomotion, crawling and transformation between them.

**Quadruped robot (type 1)**

This robot is composed of nine modules and walks by using four leg parts as shown in Figure 11. However, the walking speed is quite slow because of the friction of the floor is not sufficient.

**Quadruped robot (type 2)**

Another quadruped robot composed of eight modules is examined (Figure 12). This robot can walk 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. Arrows in photo indicates robot's moving direction.

**Crawler**

This robot is composed of six modules. Transformation from a straight chain to the crawler (loop) is shown in Figure 13. Closing the loop has been successfully done without precise position control. The rolling motion of the crawler has been successfully achieved as well.

**Crawler to quadruped robot (type 3)**

Initial configuration composed of nine modules is first transformed into a crawler and then to a quadruped robot. The resultant quadruped robot walks in a statically stable gait called the intermittent crawler gait (Figure 14).

## 5 Future Work

As no sensors are embedded in current module hardware, the modules have no ability to sense the surrounding environments. We plan to install sensors (e.g. an angle sensor, a torque sensor, an inclination sensor, a proximity sensor and a vision sensor) in the next prototype.

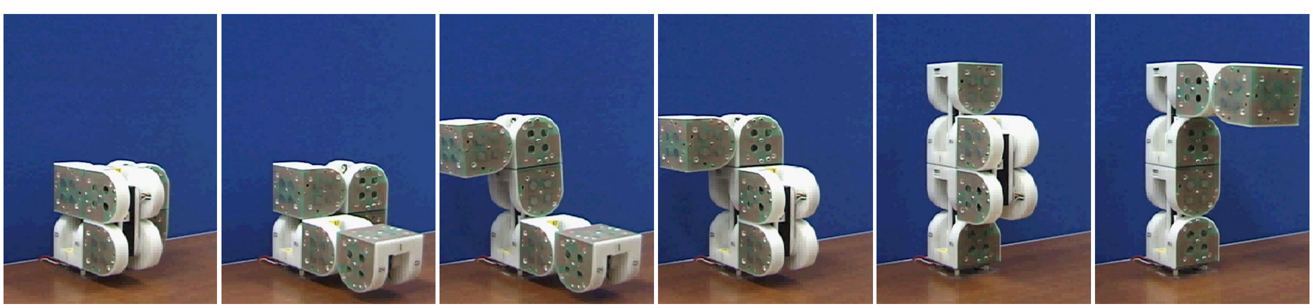

Figure 10: Self-reconfiguration experiment

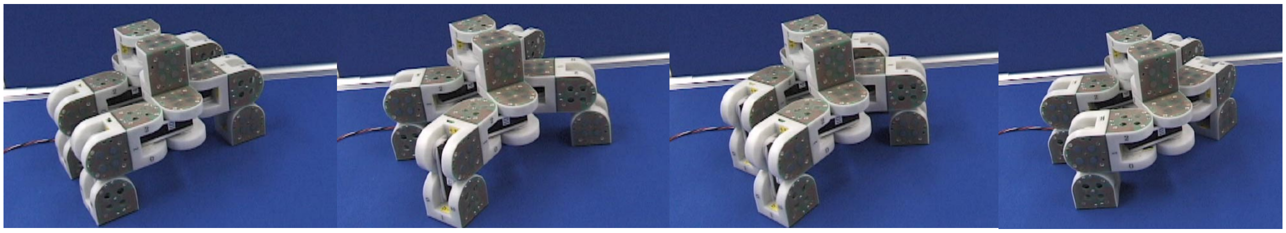

Figure 11: Motion of the quadruped robot (Type 1)

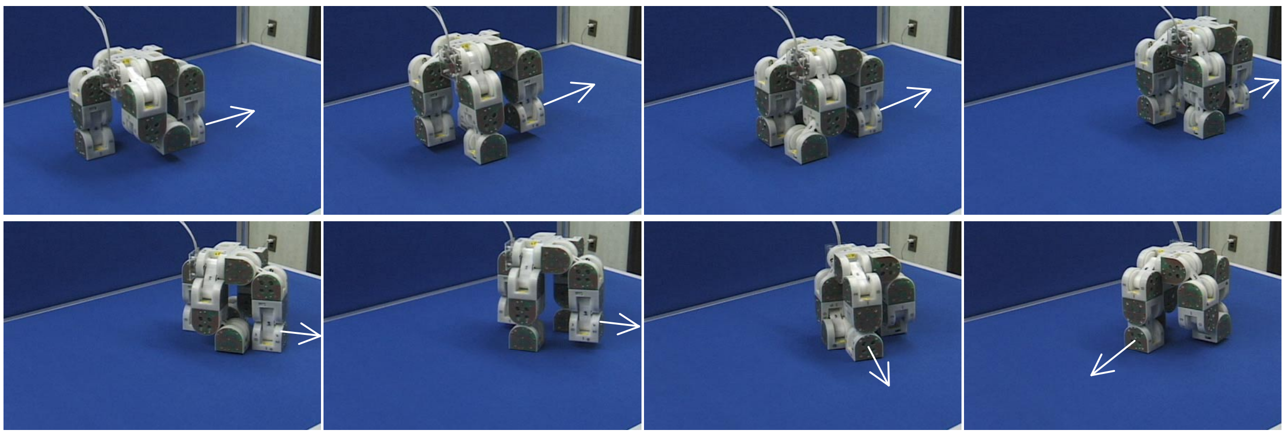

Figure 12: Motion of the quadruped robot (Type 2)

Figure 13: Motion of the crawler

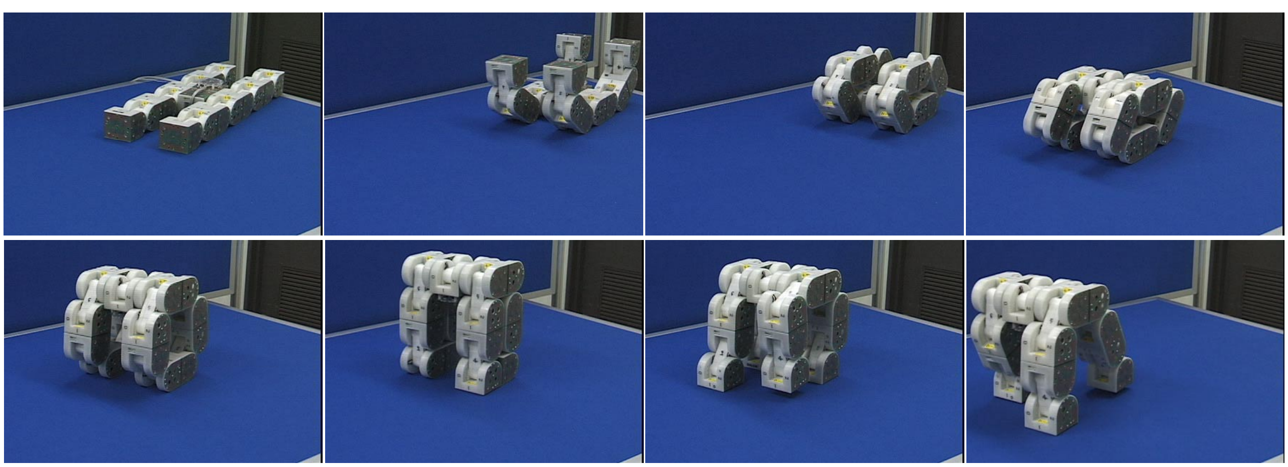

Figure 14: Transformation of the crawler to the quadruped robot (Type 3)

It is also needed to decrease the power consumption. Switching FETs for SMA consume the largest current, thus we plan to adopt another heating method to reduce the current.

The automatic generation of the transformation sequence from one structure to another has not been established. We proposed a two-layered approach that makes the module motion sequences with a global planner and a local motion scheme selector [17], when the configuration of the modules is of a particular lattice structure. More general algorithm for transformation is required to realize broad application field of the modular robots.

## 6 Conclusions

In this paper, we have described the hardware of the proposed module, the control system architecture, the simulator for motion planning and the experimental results using the developed modules. We have confirmed that various kinds of robotic configurations and transformations between them are possible by the proposed system. We are now working on the next prototype system with a larger number of modules.

## References


[1] Y.Kawauchi, M.Inaba and T.Fukuda, A study on cellular robotic system (A realization of robotic system capable of adaption, self-organization, and self-evolution), RSJ, vol.12, 116/132 (1994), in Japanese.

[2] G.S.Chirikjian, et al, Evaluating Efficiency of Self-Reconfiguration in a Class of Modular Robots, J.Robotic Systems, 12-5, 317/338 (1995).

[3] S.Murata, et al., Self-assembling machine, Proc. IEEE ICRA, 441/448 (1994).

[4] S.Murata, et al., A 3-D self-reconfigurable structure, Proc. IEEE ICRA, 432/439 (1998).

[5] E.Yoshida, et al., Micro self-reconfigurable robotic system using shape memory alloy, DARS2000, 145/154 (2000).

[6] S.Murata, et al., Hardware Design of Modular Robotic System, Proc. IEEE IROS, 2210/2217 (2000).

[7] K.Hosokawa, et al, Self-Organizing Collective Robots with Morphogenesis in a Vertical Place, Proc. IEEE ICRA, 2858/2863 (1998).

[8] D.Rus and M.Vona, A basis for self-reconfigurable robots using crystal modules, Proc. IEEE IROS, 2194/2202 (2000).

[9] K.Kotay, et al., The self-reconfigurable robotic molecule, Proc. IEEE ICRA, 424/431 (1998).

[10] C.Unsal, H.Kiliccote and K.Kohsla, I(CES)-cubes; a modular self-reconfigurable bipartite robotic system, Proc. SPIE, vol.3839, 258/269 (1999).

[11] A.Castano and P.Will, Mechanical design of a module for reconfigurable robots, Proc. IEEE IROS, 2203/2209 (2000).

[12] M.Yim, New Locomotion Gaits, Proc. IEEE ICRA, 2508/2514 (1994).

[13] A.Casal and M.Yim, Self-reconfigurable planning for a class of modular robot, Proc. SPIE, vol.3839, 246/257 (1999).

[14] M.Yim, Y.Zhang and E.Mao, Distributed Control for 3D Shape Metamorphosis, Autonomous Robots, Vol.10, No.1, 41/56 (2001).

[15] E.Yoshida, et al, A distributed method for reconfiguration of a three-dimensional homogeneous structure, Advanced Robotics, Vol.13, No.4, 363/379 (1999).

[16] H. Kurokawa, et al., Motion Simulation of a Modular Robotic System, Proc. IECON-2000, p.6, (2000) (in CD-ROM).

[17] E.Yoshida, et al., Motion planning for self-reconfigurable modular robot, accepted ISER (2000).