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Hardware Design of Modular Robotic System

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Abstract

In this paper we describe detail of hardware design of novel self-reconfigurable robotic system. We have classified previous studies on self-reconfigurable robotic systems into "lattice type" composed of spatially symmetric modules and "string type" like snake robots. The proposed system has both the advantages of simple operation of self-reconfiguration of the former and motion generation ability of the latter. Its simple structure and reliable operation allows us to construct large 3-D self-reconfigurable structure which functions as a robotic system such as a legged walking machine. We have examined its basic mechanical functions and verified its reliable operation of self-reconfiguration.

1. Introduction

Recently, considerable amount of work has been made on self-reconfigurable robots. It is a modular robotic system made of many autonomous modules and has an ability to change configuration without any external help. This functionality of self-reconfiguration makes it possible to realize new type of operation such as self-assembly and self-repair which are difficult for conventional methodology of robotics. The self-reconfigurable system is expected to have various uses in space robotics or deep-sea structure because of its ability to change its shape and functionality according to the surrounding environment.

Self-reconfigurable systems proposed so far can be classified into two categories; lattice type and string type. Self-reconfiguration is easer in the former, but the motion generation is difficult by them. By contrast the latter is suitable to generate various robotic motions, although self-reconfiguration is difficult. The proposing module design has advantages of both types. In this paper we describe its detailed hardware design and some experimental results which indicate a possibility to make a large system by these modules.

1.1 Related Work

The concept of self-reconfigurable robot was proposed almost a decade ago [11][12]. Since then hardware realization of such systems is the central issue, and still remains a difficult problem. Table 1 shows a list of existing self-reconfigurable systems including some semi-automatic ones. There are mainly two approaches to realize the self-reconfigurable modules.

The first category is lattice type system. In this type of system, a group of the modules are designed to fill some crystal structure. The lattice module possesses the spatial symmetry according to its crystal structure. The self-reconfiguration can be realized by a series of simple operations in which a module moves to the adjacent position in the lattice. However, the resultant structure is used as only a static structure because of difficulty of generating group motion on the lattice system.

It is relatively easy to design such modules in 2-D space, and some successful designs have been made. For instance, our 2-D module called "fractum" realized a cooperative operation such as self-assembly (automatic formation to a predetermined shape) and self-repair (automatic replacement of a faulty module) of more than 10 modules. The hardware module includes almost all functions necessary for self-reconfiguration such as an electro-magnetic actuation system, an onboard microprocessor and inter-unit communication device. The only exception is the power supply, which was given by tethers.

In 3-D space, the design of lattice module becomes very difficult because of the constraints of 3-D spatial symmetry and many degrees of motion freedom. All of the existing 3-D lattice modules need to have many actuators which makes these modules much complicated compared with 2-D modules. So far, primitive self-reconfiguration using only a few modules was examined by several research groups including us, but it seems to be difficult to construct a large system with many modules.

The second approach is a string type system. It is basically a serial link robot made of many joint modules. If the automatic connection and relative positioning between modules were possible, this kind of system could also have self-reconfigurability. However, it is more difficult than the lattice type system, because precise position control of many related joints is required.

Table 1. Existing reconfigurable systems

Developer [Ref.]	actuator for motion	actuator for connection
< 2D lattice >		
[1] MEL fractum	3 solenoids	---
[2] MEL micro unit	2 SMAs*	2 SMAs
[3] JHU hexagonal	3 servos	3 servos
[4] RIKEN vertical	2 servos	2 servos
[5] Dartmouth (Crystalline)	2 servos	2 solenoids
< 3D lattice >		
[6] Dartmouth (Molecule)	5 servos	10 solenoids
[7] MEL 3D unit	6 e-clutch s** (1 motor)	6 e-clutchs
[8] CMU ICES-cube	3 servos (arm)	6 servos (box)
< 3D string >		
[9] USC CONRO	2 servos	1 SMA
[10] Xerox PARC	2 servos	manual
< 3D hybrid >		
Proposed	2 servos	3 SMAs

*SMA: shape memory alloy actuator, **e-: electro-

In order to make a robot configuration other than a linear snake configuration, we need to add other types of modules with more than two connecting surface.

2. Design of Robotic Module

This section presents the novel modular robotic system suitable for 3-D shape reconfiguration and motion generation.

There are several peculiar problems for 3-D module design. The first is the gravity. The module must be able to lift other module that requires high power weight ratio. Second, sufficient structural stiffness to keep geometrical relationships especially in stacked situations must be guaranteed. Third, energy supply and communication by tethers are not feasible because complicated reconfiguration motion easily entangles them. Our design model basically solves these problems.

Figure 1 shows the prototype model of the module. It consists of three parts: two semi-cylindrical boxes and a link between them. In the link part, two servomotors (ordinary servomotors for radio-controlled planes) are embedded as the main actuation system for the module. One of the boxes is a passive part, which has passive connectors (permanent magnets on its three surfaces). It contains all the electric circuits including an onboard microprocessor. The other box is an active part, which has active connectors, consists of permanent magnets with opposite polarity to connect automatically to the passive part of another module. Disconnection is actively done by some special mechanisms explained later.

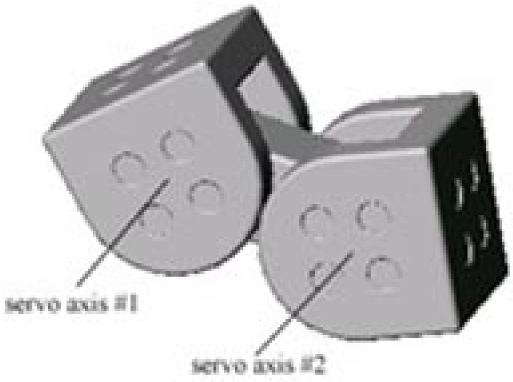


Figure1 CAD model of robotic module

In the following sections, we describe features of this module.

2.1 Module shape

The shape of the module has some peculiar advantages for the self-reconfigurable system. The semi-cylindrical shape of the box part allows it to play both roles of stiff structural building blocks and actuated robotic joints. It can be stacked without any mechanical problem and has a rotational degree of freedom of 180 degree.

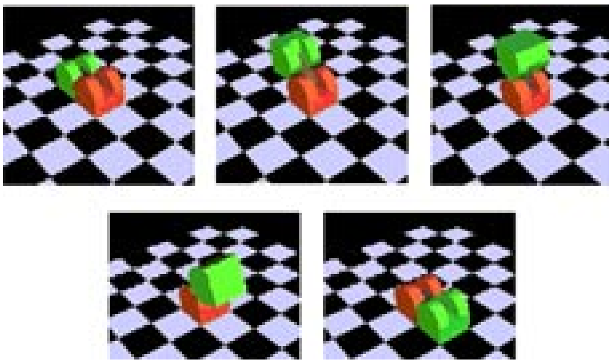
2.2 Reconfiguration method

There exist several basic reconfiguration methods for the module. To help understanding, assume a floor tiled by the module. There are two types of connection surfaces, active (N pole/black) and passive (S pole/white). These types must be placed in a checkerboard pattern. A module on this floor can move in several different manners. (a) forward roll mode by vertical rotation (Figure 2a), (b) pivot translation mode by switching horizontal rotation on both axes (Figure 2b), (c) mode conversion by using additional module to lift the converted module up which place it in the other mode (Figure 2c). Combination of these basic motions composes variety of operations of self-reconfiguration. Note that any combination of these motions conserves the checkerboard pattern of the active and passive connection surfaces.

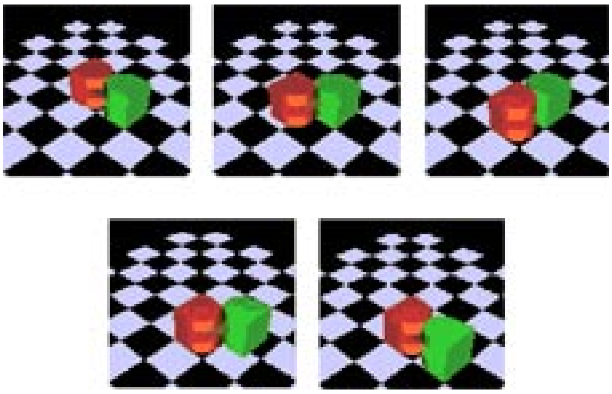
3. Hardware

3.1 Actuation system

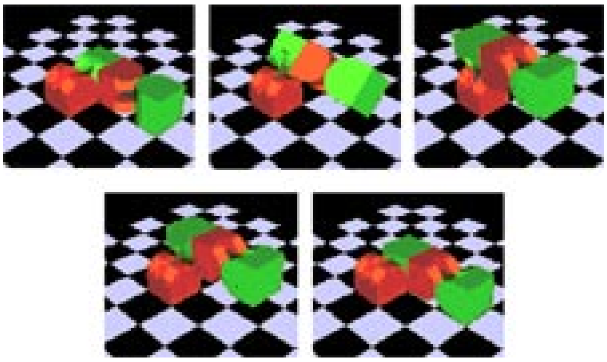
The main feature of this module is simplicity of the actuation system. Since the output axis of an ordinary servomotor is directly connected to the semi-cylindrical part, no additional gear system is necessary. We adopt a type of servomotor specially designed for retraction of landing gears of radio-controlled plane, which has high torque output.



a) forward roll mode



b) pivot translation mode



c) mode conversion

Figure 2 Basic operations

3.2 Connection system

Simple and reliable connection system is a key issue in self-reconfigurable system. One should remind that in conventional models many actuators were installed just for connection and they were burdens for the system in terms of weight and mechanical complexity. We adopt a novel method based on the idea of “the internally balanced magnetic unit (IBMU)” by Hirose et al. [13].

Connection between the passive and active boxes of the module are realized by the permanent magnets embedded on each surface. We adopt a rare

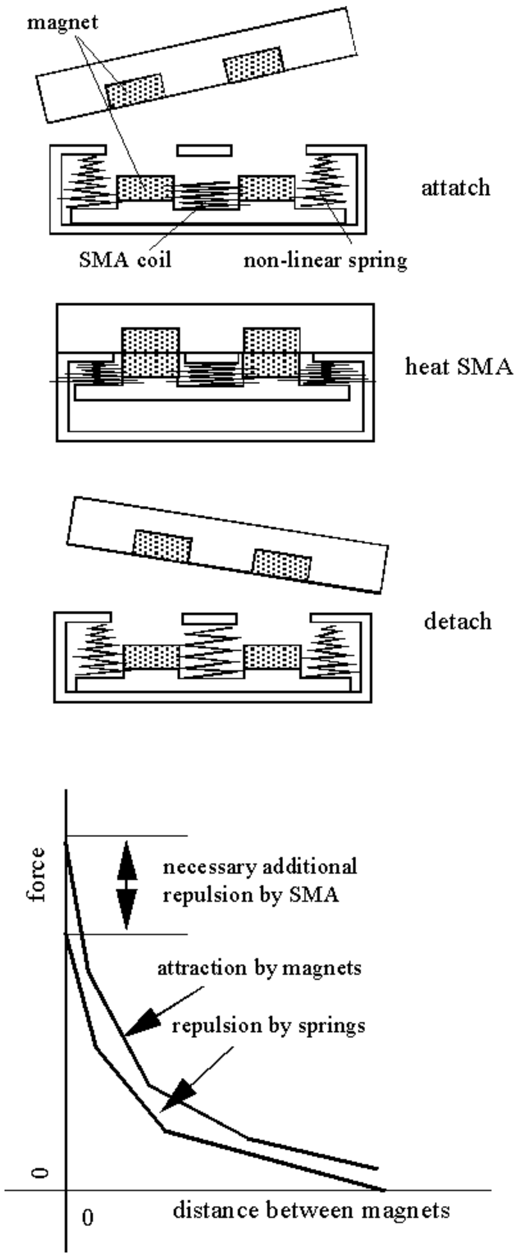


Figure 3 Connection mechanisms

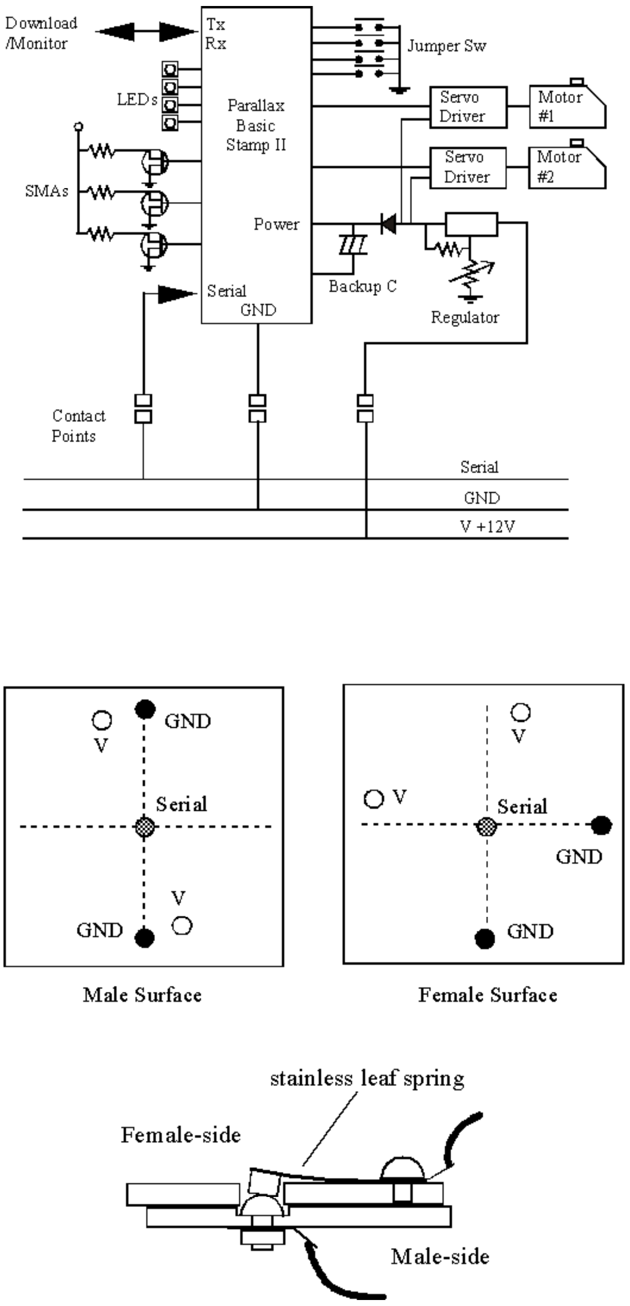


Figure 4 Control circuits and bus connection

earth metal (Sm-Co) permanent magnet, which is one of the strongest magnet commercially available. Although the force by the permanent magnet is enough to align and hold the module, it requires the same force to detach them. The IBMU solves this problem by using non-linear springs that conserve the magnetic potential energy (Figure 3). The springs are designed to have slightly lower force than the magnets when they are compressed. Thus the detachment is possible with relatively small additional force. We combined three kinds of springs to obtain such characteristics and added two SMA coil springs to reverse the balance between the magnets and the springs. When electric current heats the SMA, it extends to memorized length and pushes down the magnets.

3.3 Control circuits

Simplicity is also required in circuit design. Figure 4 (top) shows the block diagram of the overall circuits. An onboard microprocessor, servomotor drivers, switching circuits for SMA coils must be packed in a limited space in the box part. We adopt a PIC processor Basic Stamp II for this purpose. The program for the PIC is downloaded through a serial cable which can be removed after downloading. The PIC generates control signal for servomotors (high width control) and PWM output for SMA (SMA coil has almost no resistance, thus simple DC drive is not feasible. We use FET with large current capacity and drive them by PWM.) For identification of the modules, we have four-bit input to the PIC.

In this first prototype, we adopt centralized control method. Each module is controlled by a host PC through a serial bus line. The PIC decodes a command from the PC and generates necessary control signals for servomotors and SMA coils. The bus line also provides power supply.

The operation command includes module ID, SMA control and reference angles for two servomotors (total 5 bytes including header and footer byte).

Currently we are working on the next version to realize decentralized control. In the decentralized control system, communication through the bus line is not available, instead, local module-to-module communication channel is necessary. It requires six independent serial I/O for each module.

3.4 Bus connection

Each module has six connection surfaces, three passive and three active. To make the modules always connected to the bus line, we need at the least of five contact points on each surface. Their arrangement is shown in Figure 4 (bottom). This arrangement of the electrode connects three lines even if the surface is rotated by 90 degrees. The electrode is a combination of a bolt (male) and a leaf spring (female) for structural simplicity.

4. Experiments

We have made two modules (four more in process) based on the design explained above. The specification is given below:

Size: 66 mm (size of semi-cylindrical box)
Weight: 400g
2 Servomotor: Hitec 6.6 kg-cm
3 SMA for disconnection driven by PWM
Processor: Parallax, Basic Stamp II, 20MHz
Power supply: DC 12V
Connection strength (to attach): 3.6 Kg
Reduced connection strength (to detach): 0.3 Kg
Communication rate: 9600 bps

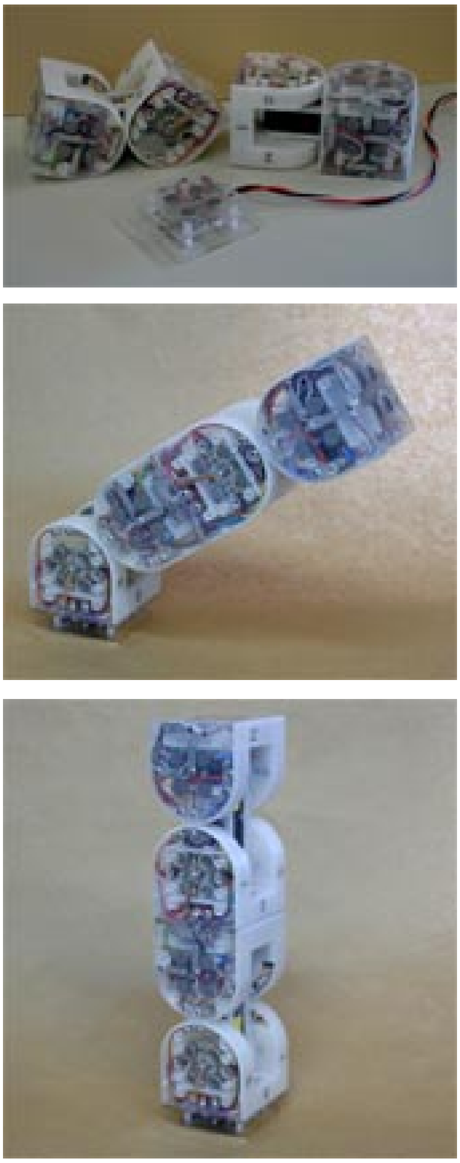


Figure 6 Lift up test

1

2

3

4

5

Figure 7 Self-reconfiguration process

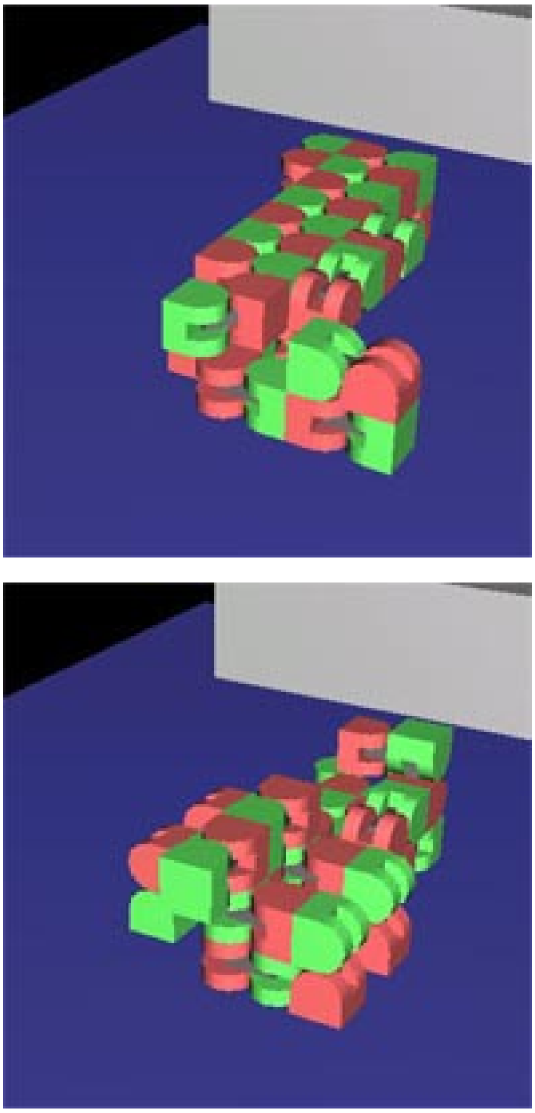
Figure 6 is a test to verify its capacity to lift another module in the severest situation. The bottom module is attached to a fixed base plate (which has passive connection surface) connected to the bus line. From this test we can conclude that the module has enough torque and connection force.

Figure 7 is a demonstration of self-reconfiguration process. According to the command sequence from the host PC, two modules change their relative connections. At the steps 1 and 4, the SMA was heated to release the connection.

5. Development of Software System

In this paper, we have to focused on the hardware of the modular robotic system due to limited space. The detail of self-reconfiguration software will be given in the other paper [14]. In this section, we would like to briefly introduce current status of software development.

As the first step, we have built a simulator for the module system. It provides a graphic user interface (GUI) based on Open GL to assist the design process of the self-reconfiguration and motion generation. At this moment, the reconfiguration process is hand-coded by using this simulator.



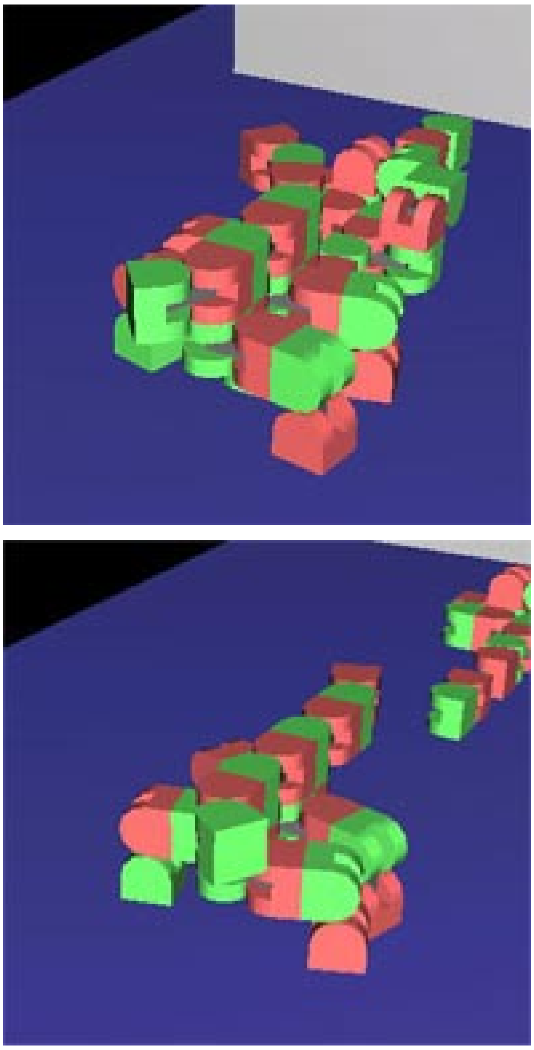


Figure 8 Simulated self-reconfiguration process

Figure 8 shows a designed sequence of metamorphosis from a block structure to a legged walking machine. After the construction, it walks on the plane according to a given motion pattern for leg joints also designed by the simulator.

As the next target, we are planning to introduce some evolutionary algorithm to find a feasible solution in semi-automatic way.

6. Conclusion

In this paper we described detailed hardware design of a new type of self-reconfigurable robotic system. The system has advantages of both lattice type system and string type of system owing to its semi-cylindrical shape of the part. Its simple structure and reliable operation enables us to construct 3-D self-reconfigurable system in large scale. We have examined its basic mechanical and electrical functions and verified its reliable operation of self-reconfiguration. We are now processing additional four modules, and more experimental results of larger self-reconfiguration will be reported.

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