Self-Reconfigurable Robot
~ Module Design and Simulation~

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A novel concept of self-reconfigurable robotic system is presented. The system is made of autonomous robotic modules that can change local connective configuration without external help. A group of such modules can metamorphose into desired configuration which functions as a robotic system. In this paper, we show the first prototype model of the robotic module and simulation results of configuration change.

1. Introduction

Self-reconfigurability is an ability to change robot configuration without external help. Such ability is useful to realize flexible and reliable robotic systems. For instance, the self-reconfigurable robot is able to repair itself by replacing faulty part by spare part. Note that "self" means this operation of replacement can be done by the system alone. The self-reconfigurable system is also able to change its functionality by changing its structure. It can be used as a primary structure in space or deep sea which is able to change its shape according to the environmental change. It also can be used as a flexible robotic manipulator which can change its configuration according to required workspace, or various walking machine for unknown terrain. Ordinary mechanical systems with fixed configuration cannot achieve such versatility.

To achieve such self-reconfiguration capability, we need particular design of the system. First, the system structure must possess modularity to some extent. Various systems can be built by combination of these modules. Second, each module must have ability to change connection among the modules. Thus each module must have some inter-module connection mechanism and some actuated mobility. Third, information processing and communication ability for each module is necessary. This means the total system works as a distributed computer network that dynamically changes its topology. And last, distributed algorithm for such computer network to realize global functionality must be developed.

Based on the above concept, several robotic systems have been built. There are two different approaches. The first approach is to build a system by homogeneous modules [1-4]. A cluster of the modules forms some spatial crystal pattern to pack desired shape. The module requires only limited mobility, namely it is enough to change its local position in adjacent lattice points. By repeating this rearrangement, the total system can metamorphose into a desired shape. For convenience, we call this type "lattice system." Self-assembly and self-repair is easy for the lattice system by its nature, however, lattice structure is not suitable to generate a group motion.

The second approach is to build a system by linear segments [5-7]. It can be regarded as a serial link robot system.
This type of system is suitable to make a robotic motion. But to build more complicated structure than a simple snake, we need to add fork modules. It breaks the homogeneity of the modules, and consequently self-assembly and self-repair is difficult for this type of system.

In this paper we present a novel approach that has advantages of both types. It is homogeneous system capable of self-assembly, self-repair, and also motion generation as a robotic system. As a lattice system, the modules can metamorphose into various configurations without outside help, then it functions as a robotic system to generate a group motion. In the following sections, we describe basic design of prototype modules, mechanical design of the inter-module connection mechanism, basic procedure of self-reconfiguration, and simulation system for reconfiguration and motion generation. As a demonstration, we show a metamorphosis from a planar structure to a legged walking machine.

2. Mechanical Design

The robotic module consists of two semicylindrical boxes and a link between them (Fig. 1). The boxes are connected to the link by rotational bearings and they can rotate by 180 degrees owing to its semicylindrical shape. Two high-torque servomotors are embedded in the link to control the rotational angles. The output axis of the servomotor is directly connected to the box, thus no additional gear system is necessary. In the next section, we will show that these two rotational axes are enough to self-reconfiguration and to build various robotic systems.

Three surfaces of each semicylindrical box are used for the connection mechanism. By this mechanism the adjacent boxes can connect firmly, and at the same time, electricity supply and communication channel are connected. We adopt the basic idea from "Internally Balanced Magnetic Unit [8]." The connection is basically magnetic. Although very strong connection can be realized easily by using rare-earth metal magnet, it requires the same force to detach the connection. The internally balanced magnetic unit solves this problem by using non-linear springs to conserve the magnetic potential energy. The springs are designed to have slightly lower characteristic than the magnetic attraction force. Thus, relatively small force is necessary to detach the magnets, and we adopt SMA (shape memory alloy) to apply additional force. Figure 2 shows the mechanism and its principle.

![Robotic module](image-url)
3. Self-reconfiguration procedure

Self-reconfiguration among the modules is possible by using only the limited degree of freedom. Here we explain the self-reconfiguration process in three methods of basic reconfiguration. The first two methods are translations on a plane tilted by the same modules. The forward roll mode (Fig. 3) is a linear translation on a line, and the module cannot change the direction in this mode. But as is explained later, the module is able to move to another layer. The module can traverse the plane to any direction in the horizontal translation mode (Fig. 4). The third method is a mode conversion (Fig. 5). In this figure the left module acts as a converter. The right module in a horizontal translation mode is lifted by the converter, and placed in the forward roll mode. In order to construct a desired shape, we need to design a sequence of these basic procedures. Figure 6 shows one of method to move a box cluster of the module. Here, the main body consists of modules in the horizontal translation mode. This enables the cluster to move to any direction maintaining the box shape. We set two additional modules in the forward roll mode aside. This pair of modules is called "a manipulator" because this pair can do many types of operation such as mode conversion of main body module, stacking another layer, and making another manipulator pair. By using the manipulator we can build variety of structures.
Fig. 3  Forward roll mode

Fig. 4  Pivot translation mode

Fig. 5 Mode conversion

Fig. 6  Box cluster
4. Prototype module

We are now building the first prototype modules. The size of module is 66 mm (size of semicylindrical part) and it weighs about 350 g. We adopt two servomotors for radio-controlled airplane and its torque (6.6 kgcm) is enough to lift another module. The module is controlled by an onboard microprocessor (PARALLAX, Basic Stamp II, 20 MHz). Power supply (DC 12 V) is provided through electrodes embedded on the connecting surface, thus the module doesn’t have a battery inside other than a small capacitor for short-time backup. Figure 7 shows configuration operation of two modules. The lower module is placed on a base plate which is connected to power supply and host computer. Serial communication channel for inter-module information exchange is also realized through contact points on the connection surface. For the connection mechanism, we adopt
four pairs of rare-metal magnets (\( \phi 10 \text{ mm, } t 3 \text{ mm} \)). The attraction force between these magnets is 3.6 kgf (attached). When SMA is heated, it is reduced to 0.3 kgf.

5. Development of simulation system

Software system for self-reconfigurable robotic system is also under development. As the first step for this, we have built a simulation system of the modular system. This allows us to design a sequence of reconfiguration, and to verify the process of metamorphosis, and to give motion to the modules. At this moment, the reconfiguration sequence is hand-coded by human operator through a graphic user interface. We adopt OpenGL for real-time visualization of the motion sequence. The internal state of the module (position, direction, rotation angle, etc.) is also displayed to the operator.

As a demonstration, Fig.8 shows a designed process of metamorphosis from a planar structure to a legged walking machine. After the construction, it walks on the plane according to a given motion pattern for leg joints.

Fig.8 Self-reconfiguration process from a box cluster to a legged walker
6. Conclusion and future work

In this paper, we proposed a novel modular robotic system that can assemble itself. The prototype design of the hardware module, method of reconfiguration, software systems to develop the self-reconfiguration sequence are presented.

Our next target is to achieve a semi- or fully-automated self-reconfiguration considering environmental circumstances or desired specification. The algorithmic side of self-reconfiguration problem is still an open problem. We need to find out a method to describe a relationship between a geometric configuration and its functionality.

References