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Design of the Octabot Self-Reconfigurable Robot

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Abstract: Self-reconfigurable robots are for the ability to change the shape of multiple cooperated robot modules that can be easily reconfigurable in the different working environment. Related work on two-dimensional robots is presented. A novel design for a self-reconfigurable robot, called "Octabot", is described. The Octabot robot is a two-dimensional self-reconfigurable robot with modules composed of eight e-type electromagnets. After the magnetic force characteristics based on FEM analyses, mechanical design and system properties are described. The current designs only use single type actuator. The group of Octabots can be easily expanded to a large scale if needed in any case. Via examining the basic mechanical functions, the Octabot in self-reconfiguration shows its satisfactory performance.

1. INTRODUCTION

Self-reconfigurable systems are formed by a set of robotic modules. The modular feature is for the ability to change the shape of multiple cooperated robot modules that can be easily reconfigurable in the different working environment (Østergaard et al., 2006) (Akiya et al., 2005). Typical applications of a self-reconfigurable robot could be working and maintaining in dodging barriers and rescuing after the earthquake etc.. However development of such robots including building and controlling is still a significant challenge. Development of self-reconfigurable robot is our subject to research. In this paper, we present a development of a novel two-dimensional self-reconfigurable robot by designing, testing and producing it forming the basic module.

In this paper, design of a novel self-reconfigurable robot is described. It is equipped with one on-board processing unit, eight drivers and eight e-type electromagnets, called the Octabot. Three Octabots have already been set up and used for facing autonomous reconfiguration in 2D. A term of modular robots should work cooperatively to be able to self-reconfigure and operate autonomously. Furthermore, related control software algorithm has been designed for coordinating the term of modules to change the shape in a distributed fashion.

2. RELATED WORK

The following pioneering works in 2D self-reconfigurable robot inspire the research discussed in this section. Several types of 2D modular robotic systems that can support self-reconfiguration have been proposed (Murata et al., 1994-Hosokawa et al., 1998). These robots usually comprise on constructing a large number of independent modules and on controlling them. This paper only concern about the hardware and shape aspects of self-reconfigurable robots, not on the control aspects.

The research of self-reconfigurable robots is opened from Fukuda system on the CEBOT (Fukuda et al., 1989a,b-1990a,b). According to the 2D self-reconfigurable robotic system, there have seven physical prototypes. All the 2D systems use one or two kinds of modules. To design 2D or 3D system, gravity is the most important factor that must be overcome. For most of the 2D systems, gravity is only helpful when the self-reconfigurable robot and ground rub. But in Hosokawa's (Hosokawa et al., 1998) and in Inou's (Inou et al., 2003) robot, the system runs in the vertical plane, and thus gravity must be considered.

Most of existing 2D systems have been built like lattice in order to reach the mould characteristic and reduce the complexity reconfiguration. All previously reported of 2D systems, including Murata system (Murata et al. 1994), Gear-Type Unit of Tokashiki et al. (Tokashiki et al., 2003), Chirikjian system (Chirikjian 1994), Crystalline (Rus et al., 2001), Yoshida system (Yoshida et al., 2000), Inou's robot (Inou et al., 2003) and Hosokawa system (Hosokawa et al., 1998). Each of these 2D self-reconfigurable robots has only one kind of mechanical module design. How to design the connector is an important and difficult challenge of the mechanical design. From the existing 2D self-reconfigurable systems, different design concepts of the connector have been used. In Yoshida system (Yoshida et al., 2000), the pin/hold structure is used. Permanent magnets are found in Murata system (Murata et al. 1994) and Hosokawa system (Hosokawa et al., 1998).

Tables 1-2 compare the existing 2D self-reconfigurable robots. Some geometrical properties are presented in Table 1. Table 2 summarizes some physical properties.

In this paper the mechanical design of the modular robot, the Octabot, a lattice homogeneous reconfigurable robot is described. The Octabot has some similarities with the Murata system (Murata et al. 1994). All are homogeneous and can separate their locomotion and reconfiguration stages.

Table 1. Geometrical properties. The Octabot is included for comparison.

Developer	Actuat. DOF	Connectors	Actuated
Fracta	0	6	3
Gear-Type Unit	1	6	0
Chirikjian	3	6	3
Crystalline	1	4	2
Yoshida	2	4	2
Inou	2	4	2
Hosokawa	2	4	2
Octabot	1	8	8

Table 2. Physical properties. The Octabot is included for comparison.

Developer	Weight (g)	Dimensions(cm)	Connector type
Fracta	1200	Ø12.5	Electro Magnets
Gear-Type Unit		Ø6	Perm. Magnets
Chirikjian			Mech. Hooks
Crystalline	375	5×5×18	Mech. Lock
Yoshida	80	4×4×8	Mech. Hooks
Inou	500	8×8×7.5	Mech. Grooves
Hosokawa			Perm. Mag. and Mech. Arms
Octabot	1500	Ø13.5	Electro Magnets

The contents of this paper are as follows. Related works are discussed in Section 2. Magnetic force analysis is presented in Section 3. In Section 4, magnetic modelling and simulation results are described. We describe the design principlein Section 5. Experimental tests are discussed in Section 6, and conclusion is provided in Section 7.

3. MAGNETIC FORCE CALCULATION

A schematic diagram of proposed system is about this system, there are eight e-type electromagnets. To model this system, the magnet force analyzed becomes a very important issue. These reasons motivate us to calculate the magnetic force of the e-type electromagnet that used to achieve the objective of the Octabot with motion. Thus, we discuss with the analytic approach by utilizing several useful methods in electromagnetic force calculation in this section. Furthermore, design of such electromagnetic devices with e-type electromagnets as well as the design of any electromagnetic devices requires the calculation of magnetic force.

The force calculation can be classified into two methods. The first method contains Maxwell stress. The second is based on the virtual work principle. They are so-called Maxwell Forces and Virtual work force. They are universal and can be used to compute the total force on either ferromagnetic or current-carrying objects. In this paper, Maxwell forces and Virtual work are discussed.

Maxwell Forces

The Maxwell stress tensor is used to determine forces. It provides a convenient way of computing forces acting on bodies by evaluating a surface integral. This force calculation on surfaces of air material elements which have a nonzero face loading specified is performed (Moon 1984). In the following numerically integrated surface integral for the 2-D application, this method uses extrapolated field values and results:

$$\mathbf{F}_{\mathrm{MX}} = \frac{1}{\mu_0}\int_{\mathrm{S}} \begin{bmatrix} \mathrm{T}_{11} & \mathrm{T}_{12} \\ \mathrm{T}_{21} & \mathrm{T}_{22} \end{bmatrix} \begin{bmatrix} \mathrm{n}_1 \\ \mathrm{n}_2 \end{bmatrix} ds \tag{1}$$

where μ_0 is the permeability of free space, $\mathrm{T}_{11} = \mathbf{B}_x^2 - \frac{1}{2}|\mathbf{B}|^2$, $\mathrm{T}_{12} = \mathbf{B}_x\mathbf{B}_y$, $\mathrm{T}_{21} = \mathbf{B}_x\mathbf{B}_y$, $\mathrm{T}_{22} = \mathbf{B}_y^2 - \frac{1}{2}|\mathbf{B}|^2$, n_1 is a component of unit normal in x-direction and n_2 is a component of unit normal in y-direction. The 2-D case cans extension to 3-D application.

Virtual Work Forces

The virtual work principle is used to calculate Electromagnetic nodal forces. These are two formulations currently used to calculate force. One is the element shape method that is used to calculate magnetic forces. The other is the nodal perturbations method that is to calculate electromagnetic forces. First, the element shape method is been discussed. The virtual work method is used to calculate Magnetic forces that are obtained as the derivative of the energy versus the displacement of the movable part. This calculation is valid for a layer of air elements surrounding a movable part (Coulomb et al., 1984). To determine the total force acting on the body, the forces in the air layer surrounding it can be summed. The basic equation for an approximate force of an air material element in the s direction is:

$$\mathbf{F}_{\mathrm{s}} = \int_{\mathrm{V_e}} \mathbf{B}^{\mathrm{T}} \frac{\partial \mathbf{H}}{\partial \mathrm{s}} dv + \int_{\mathrm{V_e}} \left(\int_0^{\mathbf{H}} \mathbf{B}^{\mathrm{T}} d\mathbf{H} \right) \frac{\partial}{\partial \mathrm{s}} dv \tag{1}$$

where $\mathbf{F}_{\mathrm{s}}$ is force in element in the s direction, $\partial\mathbf{H}/\partial\mathrm{s}$ is derivative of the magnetic field intensity with respect to displacements, s measures the virtual translation of the movable part along a given direction and $\mathrm{V_e}$ is a volume of the element. Second, the nodal perturbation method is been discussed. Electromagnetic forces are calculated as the derivatives of the total element coenergy (sum of electrostatic and magnetic coenergies) with respect to the element nodal coordinates (Gyimesi et al. 2004):

$$\mathbf{F}_{x_i} = \frac{1}{2}\frac{\partial}{\partial x_i}\left[\int_{\mathrm{V_e}} \left(\mathrm{d}^{\mathrm{T}}\mathbf{E} + \mathbf{B}^{\mathrm{T}}\mathbf{H} \right) d\mathrm{v} \right] \tag{2}$$

where: $\mathbf{F}_{x_i}$ is the x-component (y- or z-) of electromagnetic force calculated in node i , x_i is the nodal coordinate (x-, y-, or z-coordinate of node i),v is the volume of the element and d is the nodal perturbation distance. Nodal electromagnetic forces are calculated for each node in each element. In an assembled model the nodal forces are added up from all adjacent to the node elements.

4. MAGNET MODELING AND SIMULATION RESULTS

In this paper, 2D model was designed to investigate the accuracy and nature of the solutions for force prediction. The e-type electromagnet CAD model is shown in Fig. 1(a). The dimensions of the e-type electromagnet and a keeper are represented in Fig. 1(b). Because the e-type electromagnet and a keeper are axial symmetric, two regions surrounding the half e-type electromagnet are used to graduate the mesh and ensure that the meshing of the fringing flux is modelled well. For a 2D model, two simple and effective methods of calculating forces are the Virtual work and the Maxwell stress methods (Edwards et al. 1995) (Carpenter et al. 1960) (Edwards 1992) (ANSYS 9.OA1 1999). These methods have the advantage of only one solution for a given simulated excitation. The Virtual work and the Maxwell stress methods give the total force acting on a closed surface through an air region.

By using auxiliary software (ANSYS 9.OA1), simulated results are presented in Fig. 2. Table 3 is the parameters that were used in the simulation process. Fig. 2 shows the virtual work force and Maxwell stress tensor force. Their ordinates are magnetic force and cross axle are the distances. From the simulation results, the relationship between magnetic force and distance can be understood. Also, the force of the e-type electromagnet can attract each other.

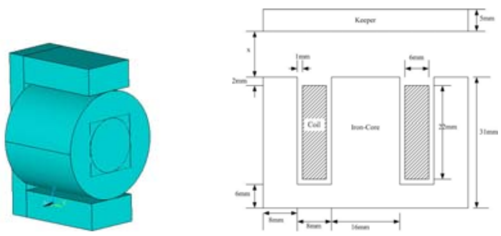


Fig. 1. (a) E-type electromagnet CAD (b) E-type electromagnet 2D section with a keeper

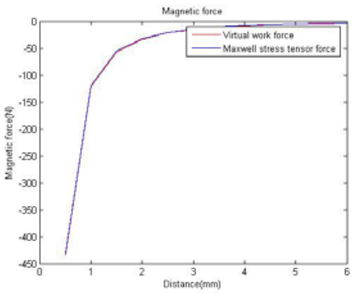


Fig. 2. Virtual work force and Maxwell stress tensor force of e-type electromagnet

Table 3. Simulation Parameters

E-type core	μ_r	1000
Keeper	μ_r	1000
Coil	μ_r	1
	Turns	727
Air	μ_r	1
Excitation	DC current applied to the coil	1.5 AMP
Model	Axial symmetric	

5. DESIGN PRINCIPLE

The Octabot have been proposed, the module has a chassis and eight connecting plane are mounted on it as shown in Fig. 3. The self-reconfiguring modular robot is a 2-D unit; it has a special actuation system to attach/detach other modular robot (Shiu et al., 2007). The modular robot can rotate via connection planes. By this connection between modular robots, an arbitrary modular robot can be realized.

The shape configuration of the modular robot system is changed by means of rotation and connection of them as shown in Fig. 4. The modular robots reach the firm connection through the attracting each other of the electromagnets. Every module has an octagonal shape and actuates by attraction of both modules as shown in Fig. 4. Each module has eight side formed by eight electromagnets and is fully self-contained; it has its own micro-controller, power supply, and actuators. From Fig. 3, eight electromagnets mounted on the Octabot module that produce two kinds of different polarity (N or S poles).Through the magnetic force of them between modules, attraction force allows the robot connection , disconnection, rotation to change shape and locomotion.

Each module has its own microprocessor to control the actuation, and the synchronization is performed through sensing an external beacon. Currently, there is no facility for global communications, so all operations must be performed in a distributed fashion.

The hardware structure of the Octabot module must support the control of the actuators and a power system. The objectives of the design of the system are to minimize the number of discrete components, their overall weight and their power consumption while preserving the self-sufficiency and autonomy of the module. Each module also has four steel ball rollers to reduce the friction. A functional diagram of the Octabot module is shown in Fig. 5.

6. SYSTEM MODELING

The motion planning and distributed formation problem of self-reconfigurable robots is defined to achieve the final configuration from an initial configuration as the

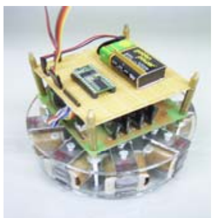


Fig. 3. The Octabot module

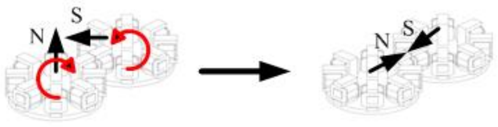


Fig. 4. Concept of rotation and connection

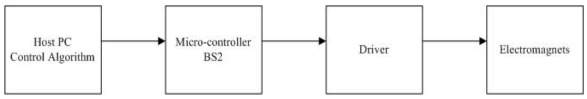


Fig. 5. Functional block diagram of a module

reconfiguration of a collection of modules based on certain constraints.

This problem can be formulated as the distributed formation control. Before treating self-reconfigurable robots, it is perhaps illuminating to give a result for the much simpler case of point masses. A modular robot can be represented as a vertex ($M_i \ (i=1,2,\cdots,n)$) and a connection between modular robots as an edge. Thus, we begin with the basic definitions and fundamental theorems in graph theory (Douglas 2001) and then state a topological graph of self-reconfigurable robots. Finally, a model of self-reconfigurable robots is defined.

In this section we formalize the motion planning problem for self-reconfigurable robotic system. From (Pamecha et al., 1997), the regulations of the motion of one module over the surface of a connection of other modules are

1. Robotic modules can only move into spaces which are accessible and not already occupied.
2. Every module must remain connected to at least one other module.
3. Only one module move at each time-step.

Under these constraints, the modular robot's behaviours from any given initial configuration to any given final configuration become determination of the sequence of module motions in a reasonable number of moves. Fig. 6 shows a complete reconfiguration sequence from one serial structure to another.

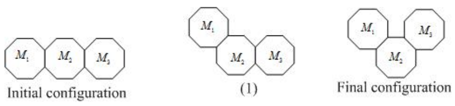
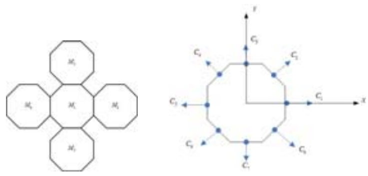


Fig. 6. A complete reconfiguration sequence

Because the form of self-reconfigurable modular robots are recombination through rotating motion, modular robot can be considered as a polygon unit and it motion in grid where the motion space is portioned into discrete elements according to geometry of the Octabots. Because of the limitations of form of modular robot, eight connection sides of a modular robot only connect with four neighbour modular robots as Fig. 7 (a). When two modular robots are connected, the contact sensor installed at the edge of a modular robot can sense what side of it to connect (or unconnected, attach/detach) with other robots. So, the nature of the information flow from sensors throughout the formation is central to a discussion of reconfiguration problem. The digraph can used to model this information flow. We use the sensor digraph to denote the digraph defined above section. The sensor digraph D for this system mean a directed edge from a modular robot i to another modular robot j (Saidani 2004 and Lin et al., 2005). The directed edges of a modular robot have eight adjacent directions. The adjacent direction state of each modular robot was labeled by $C_1, C_2, \cdots, C_8$ illustrated as Fig. 7 (b). The adjacent direction value $C_m \left(m=1,2,\cdots,8\right)$ is arranged according to anti-clockwise rule, so connection relation of self-reconfigurable robots was described by a $n \times 8$ matrix. For a shape graph $S_{\mathcal{D}}$, a shape matrix SM was defined.

$$SM\left(S_{\mathcal{D}}\right) = \left(b_{ij}\right)_{n\times m} \tag{3}$$



(a) (b)

Fig. 7. (a) A modular robot only connects with four neighbor robots. (b) A modular robot adjacent direction states

$$b_{ij} = \begin{cases} \text{M} & \text{index of module connecting in neighbor direction} \\ 0 & \text{no module in neighbor direction} \\ -\text{M} & \text{index of module but no connecting in neighbor direction} \end{cases} \tag{4}$$

n in the number of robots, m is the number of robot's connection side and M is the index of module connected to the jth connection direction of the i th module. From structure and shape of modular robots, the shape matrix can be deduced. It can represent the topology, relatively position and connection relation of modular robots accurately and uniquely.

In Fig. 6, the shape matrixes of this sequence are

$$SM\left(S_{\mathcal{D}}\right)_{initial} = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$SM\left(S_{\mathcal{D}}\right)_{(1)} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\ 3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 \end{bmatrix} \tag{6}$$

$$SM\left(S_{\mathcal{D}}\right)_{final} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 3 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \end{bmatrix} \tag{7}$$

From (5) to (7), these shape matrixes are enabled being used for confirming the states when robots are in self-reconfiguration process.

7. EXPERIMENTS

We build three modules based on the design explained in previous sections to test the actuators and model design of the Octabot. Their bodies have the same structure that the Octabot configured as a line would have.

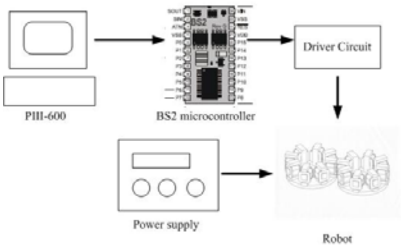


Fig. 8. Experimental setup

The electromagnet pair was used to attract each other for the form procedure. The specification is given in Table 4.

Fig. 8 shows the experimental setup of these Octabots. The Octabots are free, controlled from a host PC and powered by an external power supply. The eight electromagnets are actuators driven by eight relay circuits. The control software is composed of two programs. The first program provides an interface to a library of functions, serial port and controller drivers, synchronization routines and a motion scheduler. Second is used to specify motions, their on-off or their duration.

Fig. 9 is a experimental result, test to verify its capacity to attract another module and motion. The glass is used for reducing frictional force. Because the weight of these three modular is nearly equal, they cause rotation in the original position while attracting each other.

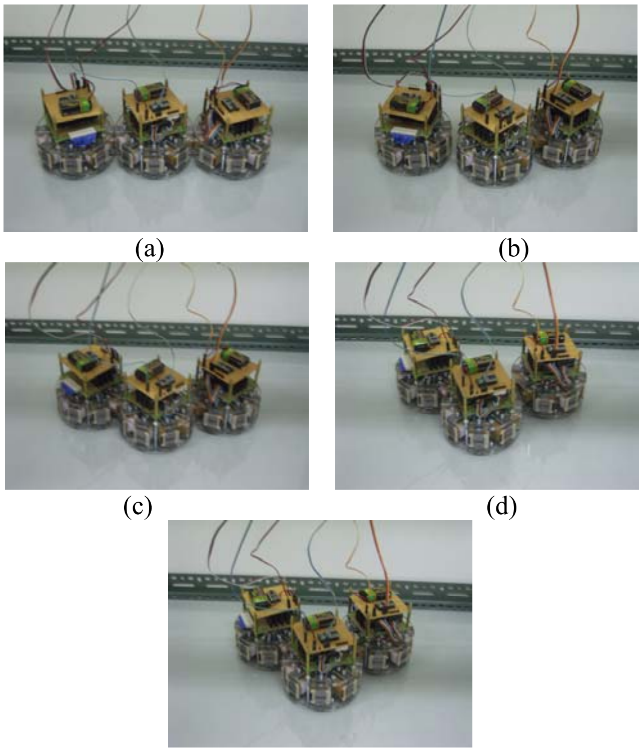
It also demonstrates of the self-reconfiguration process of the actual Octabot system. According to the command sequence from the host PC, the modules change their relative connections. Fig. 9 demonstrates of the self-reconfiguration process of the actual Octabot system. From the experiment, three modular are formed as a line in Fig. 9 (a). At Fig. 9 (b) to Fig. 9 (c), two modular Octabot are connected together on the left but that modular Octabot on the right attracts and rotates through the magnetic force. It can achieve the goal of motion through the displacement of the centre of gravity in such a design. These Octabots are connected in this process. At Fig. 9 (d) to Fig. 9 (e), two modular Octabots are connected together on the right but that modular Octabot on the left attracts and rotates through the magnetic force. From experiment, they have finished repeated rotator motion. They are proved that only uses the single type component to make the robot reach the movement and connected characteristics.

Table 4. The hardware specification

Size	135 mm (the diameter of the robot)
Weight	1.5kg
electromagnets	8
driven circuit	8
Processor	Basic Stamp II
Power supply	DC40V

8. CONCLUSIONS

In this paper we described a detailed design of a new type two dimensional self-reconfigurable robotic system. The magnetic force of e-type electromagnet is described. A methodology is used to represent the configurations of them and have applied it to the Octabot. A shape matrix was represented with an adjacent direction state. To verify the feasibility of the proposed design, the experiments with three real physical modular robot are significantly important. Its simple structure and reliable operation enables us to construct 2-D self-reconfigurable system in a large scale. We have examined its basic design concept and verified its reliable operation of self-reconfiguration.



(a) (b) (c) (d) (e)

Fig. 9. The experimental result.

Acknowledgment

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