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Design of a Modular Self-Reconfigurable Robot

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Abstract

In this paper we examine the development of modular self-reconfigurable robots. A survey of existing modular robots is given. Some limitations of homogeneous designs and connection mechanisms are discussed. Therefore, we propose a heterogeneous self-reconfigurable robot with genderless, fail-safe connecting mechanisms. We initially design three basic types (joint, power and special units) of module.

1 Introduction

A modular robot can be defined as a robotic system constructed from a set of standardised components (or building blocks). Modular robots are of interest because they permit the construction of a wide variety specialised robots from the set of standard components. Over the last ten years, research efforts in the field of modular robotics have been directed towards robotic manipulations with the goal of versatility and adaptability [Hamlin and Sanderson, 1996; Yim *et al.*, 2000]. Less effort has been made in the field of self-reconfigurable modular robots, which are modular robots which can autonomously change their configuration. Most robots have been built to perform particular tasks. Stationary manipulators are designed to move materials, parts, or tools for industrial applications. While mobile robots are able to move effectively on hard and smooth terrains [Muir and Nueman, 1987], legged robots have been studied because of their agility in traversing uneven terrain [Todd, 1985]. In some applications, robots should have the ability to perform a wide range of tasks autonomously. The modular self-reconfigurable robot is proposed in order to make a system adaptable to the different given tasks and unknown environment.

Where would the modular reconfigurable robots be used? A modular, self-reconfigurable robot is most useful in an unknown, complex environment. For example, a building that has been damaged by earthquake contains a variety of obstructions and may not be not be suitable for any particular standard robot. A reconfigurable robot, with the ability to locomote over a variety of terrains, through gaps and over obstacles can perform well in this situation. With the adaptability of the modular robot, it can pass through narrow passageways (in a snake-like configuration), it could reshape into a legged robot and walk over rubble and it can climb stairs or even onto desks by self-reconfiguration. Another application is space/planetary exploration, where unpredictable terrains on a planet have to be explored by a robot before human beings are sent.

A variety of self-reconfiguring modular robots have been investigated [Tomita *et al.*, 1999; Yoshida *et al.*, 1999; Castano and Will, 2000; Rus and Vona, 2000; Ünsal and Khosla, 2000]. In this paper, we survey existing modular robots and propose our own design for heterogeneous self-reconfigurable modular robotic system. We believe that a successful self-reconfigurable modular robot must be heterogeneous simply because a homogeneous robot whose modules each contain all of the actuation, sensing, CPU and battery requirements will be physically too large. In this area, as in many others, it helps to mimic biological systems and to develop specialised heterogeneous modules.

This paper is organised as follows, in Section 2, we describe previous works have been done by many modular robotics research groups. Comparisons among the designs are made. In Section 3, we present our philosophy and the design of some basic modular components. In Section 4, we propose a set of experiments to evaluate our designs. In section 5, we present conclusions.

2 Survey

A variety of reconfigurable robots have been researched and developed, as follows:

2.1 ACM

The active cord mechanism (ACM), a snake-like robotic mechanism, was an early development by Hirose [Hirose, 1993]. The ACM is a homogeneous modular robot and it was used to try to mimic snake movement. Both manipulation and locomotion have been implemented in for the ACM.

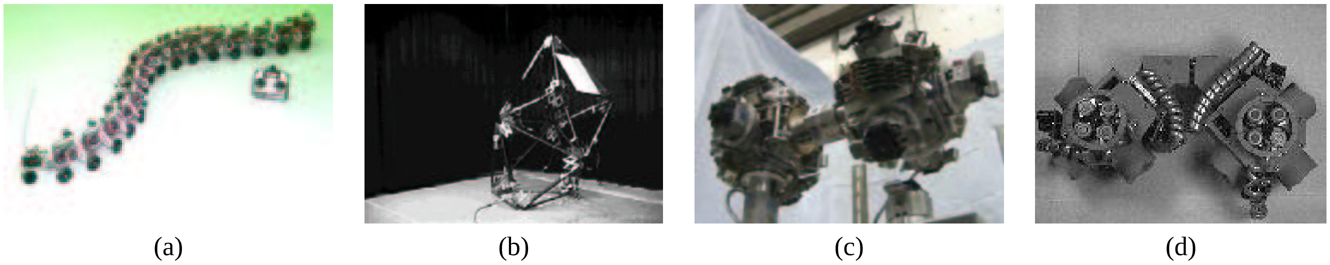


Figure 1: Examples of modular robots: (a) ACM-R1 (b) Tetrobot (c) Fracta (d) Molecule

ACM-R1 is shown in Figure 1(a). ACM operates in 3D but does not have the ability to self-reconfigure.

2.2 TETROBOT

Hamlin and Sanderson [Hamlin and Sanderson, 1996] implemented a modular system, TETROBOT. Novel spherical joints were used to design a homogeneous truss structured robot (see Figure 1(b)). The joint design allows the structure to spherically move around a centre of rotation. However, connecting parts are manually assembled. The authors presented possible configurations of the system as follows: Double Octahedral, Tetrahedral Manipulator (as shown in Figure 1(b)) and Six Legged Walker TETROBOT. Suggested applications were space/sea exploration and construction sites.

2.3 CEBOT

A cellular robotic system (CEBOT) was developed by Fukuda and Kawauchi [Fukuda and Kawauchi, 1990]. This is a homogeneous modular robot where each cell has limited sensing and computation. The problem of determining an optimal arrangement of cells for a particular task was studied. Experiments in automated re-configuration were carried out but the robot did not self-reconfigure, a manipulator arm was required for this.

2.4 Fracta

Murata *et al.* considered 3D [Murata *et al.*, 1998] and 2D [Tomita *et al.*, 1999] categories of homogeneous distributed system. In the 3D design, Fracta (as shown in Figure 1(c)) has three symmetric axes with twelve degrees of freedom. A unit is composed of a 265mm cube weighing 7kg with connecting arms attached to each face. Self-reconfiguration is performed by means of rotating the arms and an automatic connection mechanism. Each unit has an on-board microprocessor and communication system. The drawback of this approach is that each module is quite big and heavy. The connection mechanism uses six sensors and encoders, further increasing system complexity. However, this is one of the few systems that can achieve 3D self-reconfiguration. This system perfectly illustrates the problems with a homogeneous design: the modules become big and cumbersome.

2.5 Molecule

A similar type of 3D homogeneous self-reconfigurable system is the Molecule. Figure 1(d) shows a molecule. Each molecule consists of a pair of two-DOF atoms, connected by a link (called a bond). By suitably connecting a number of modules one can form 3D shapes [Rus and McGray, 1998]. Twelve movements of each atom can perform self-reconfiguration. Independent movement on a substrate of molecules including straight-line traversal and 90 degrees convex and concave transitions to adjacent surface can be performed.

2.6 Metamorphic Robotic System

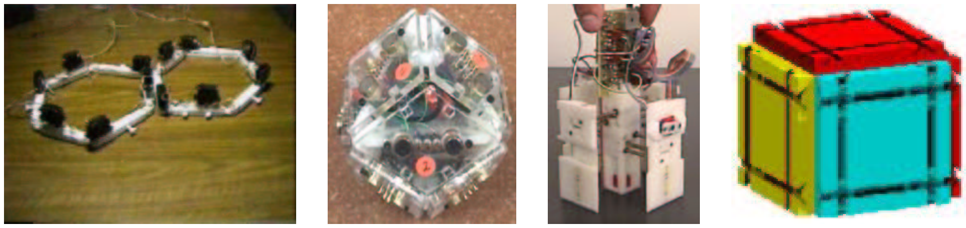
The Metamorphic robotic system was demonstrated by Chirikjian [Chirikjian, 1994; Pamecha and Chirikjian, 1996] (see Figure 2(a)). Each module is a planar hexagonal shape with three DOFs that can combine with others with varying geometry. Each module has abilities to connect, disconnect and rotate around its neighbours. However, it is a limited, planar mechanism.

2.7 Proteo

A metamorphic robot, Proteo, was proposed by Bojinov *et al* [Bojinov *et al.*, 2000]. Each module is a rhombic dodecahedron with twelve identical connection faces which allow other modules to attach. Electromagnets are used for module connection. Motion is simply composed of a number of rotations about the edges of the faces (however, only simulations have been given of this). This robot consists of compact homogeneous rhombus units. This is an interesting concept but the use of twelve connecting faces leads to high complexity and high cost.

2.8 Crystalline

The concept of a Crystalline module was described by Rus and Vona [Rus and Vona, 2000] (see Figure 2(c)). Each module has a square cross-section with a connection mechanism using channels and rotating keys to lock modules together. A distributed robotic system is actuated by expanding and contracting each module. Each module can expand its size by a factor of two from original size. The module has an on-board CPU, IR communication and power supply. Note that



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

Figure 2: Examples of modular robots: (a) Metamorphic system (b) Proteo (c) Crystalline (d) Fractal robot

the Crystalline robot is planar but it could be extended to 3D. The connection mechanism has male and female parts which limits possible mating configurations.

2.9 Fractal Robot

Figure 2(d) shows a novel polymorphic robot called "Fractal robot" which was proposed by Michael [Michael, 1994]. The Fractal robot is composed of homogeneous cubes with screw and groove mechanisms at each cubic face to allow the robot to perform geometry changes and tasks. The structure formation is performed by sliding one or a group of cube to another location along attached face(s). This mechanism seems difficult to implement and the results appear to be mainly in simulation. It is suggested that each module can attach special devices such as camera, gripper, etc.

2.10 Fractum

Fractum is a 2D homogeneous system developed by Tomita *et al* [Tomita *et al.*, 1999] (see Figure 3(a)). Each unit has six arms, three electromagnet male arms and three permanent magnet female arms. Based on simple magnetics, connection occurs when a neighbour(male) has a same polarity of permanent magnet (female). On the other hand, reversing the polarity of the electromagnets causes disconnection. A unit has three ball wheels under a body, its own processor and optical communication. The Fractum robot has simple mechanism so it can only achieve motion in the plane (2D).

2.11 Miniaturized Self-reconfigurable System

The miniaturized self-reconfigurable robot was presented by Yoshida *et al* [Yoshida *et al.*, 1999] (see Figure 3(b)). A male and female connection mechanism is used, with locking pins holding the modules together. A shape memory alloy (SMA) spring is used to release the lock. Its size is approximately 40mm high, 50mm long and weighs 80g. This is a planar design but the researchers are considering a 3D mechanism. This system has been designed using novel SMA actuators which reduced size of system. However, limited torque and a short range of movement are disadvantages.

2.12 CONRO

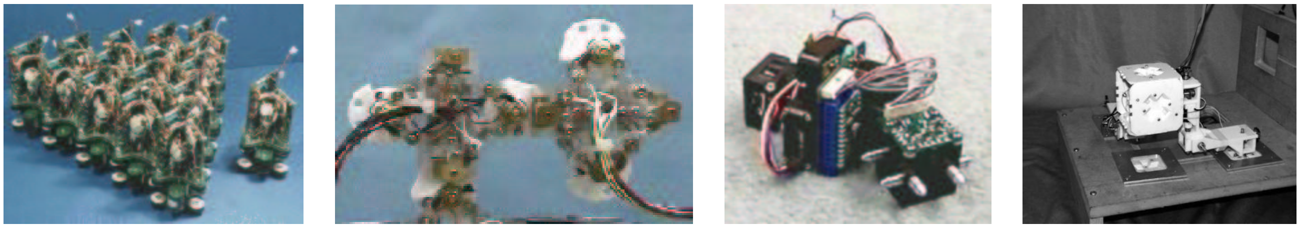
CONRO [Shen *et al.*, 2000], is a self-reconfigurable robot composed of two-DOF homogeneous modules (Figure 3(c) shows a module). Each module is 108mm long and weighs 115g. Docking connectors (active and passive) using a SMA locking mechanism allow modules to connect with pins and holes for alignment. Each module has two motors, two batteries, a micro-controller and IR communication system. The design of homogeneous CONRO robot allows for self-reconfiguration. Its size is compact to reconfigure. However, the use of a bipartite active/passive connection mechanism limits reconfiguration.

2.13 I-Cubes

Ünsal and Khosla [Ünsal and Khosla, 2000] has designed I-Cubes(or ICES-Cubes) a modular self-reconfigurable robotic system (see Figure 3(d)). I-Cube is a bipartite system composed of a three-DOFs link and a passive element as connector. The link is 80mm long and weighs 370g. The passive element is a cubic shape which has six faces for connecting. A novel mechanism provides inter-module attachment and detachment to perform various tasks such as moving over obstacles.

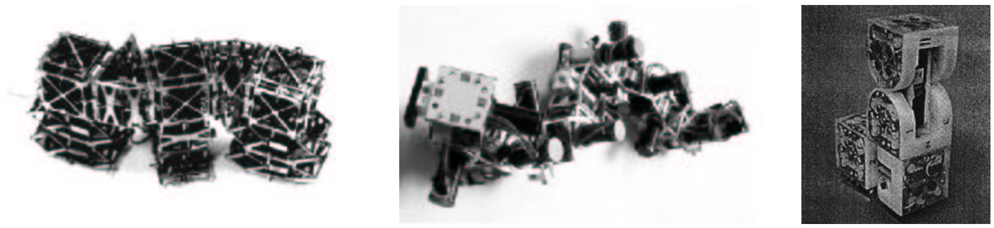
2.14 Polypod and PolyBot

Yim proposed Polypod, a modular reconfigurable robot, with two types of modules: a two-DOF *segment* with two connection ports and a passive cubic *node* with six connection ports. The modules are manually bolted in different ways in order to achieve versatility to many modes of locomotion gaits [Yim, 1994] (Figure 4(a) shows Polypod). Each module is approximately a 60mm cube. Now at Xerox Palo Alto Research Centre, his research team works with PolyBot [Yim *et al.*, 2000] (see Figure 4(b)). PolyBot(G2) is comprised of homogeneous one DOF modules with hermaphroditic (genderless) connection plates. Each PolyBot module has a quite powerful on-board computer but limited sensing. It is about 50mm each side (with the motor protruding by about 50mm) and weighs 416g. Infrared is used to communicate between modules. Polypod and PolyBot are homogeneous systems. They are simple and versatile. On the other hand, Polypod has to be manually reconfigured to form different structures and the mechanical shape of the PolyBot(G2) leaves something to be desired.



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

Figure 3: Examples of modular robots: (a) Fractum (b) Miniaturized unit of Yoshida *et al* (c) CONRO (d) I-Cubes structure



(a) (b) (c)

Figure 4: Examples of modular robots: (a) Polypod (b) PolyBot(G2) (c) Semi-cylindrical robot

2.15 Semi-Cylindrical Reconfigurable Robot

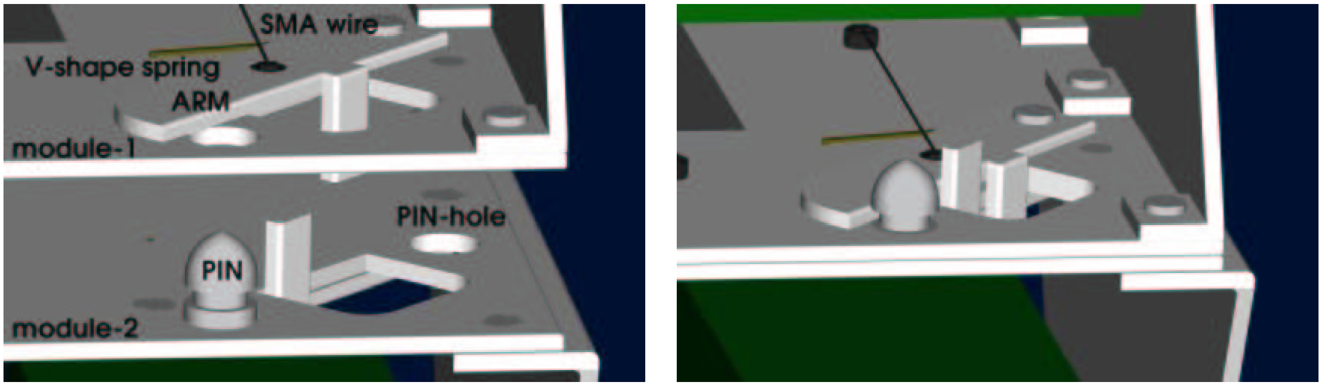
Another 3D homogeneous self-reconfigurable structure was designed by Kurokawa [Murata *et al.*, 2000] which is composed of two semi-cylindrical boxes (with a servo each) connected by a link mechanism (see Figure 4(c)). The size of semi-cylinder is 66mm and it weighs 350g. The connecting mechanism utilises rare-earth magnets for attaching and SMA coil springs for detaching (on one side of the connection). A processor and communication system are embedded in each module. The proposed mechanism allows robot to global move in 3D by moving each local module. The attachment and detachment are limited by the force of the magnets, therefore, a problem might occur if a module has to lift several other modules. The use of magnets for connections severely limits the available connections (connection faces are either active or passive).

2.16 Comparisons

Table 1 shows the comparisons of specification of existing modular reconfiguration robots. Clearly, there is a wide range of possibilities. However, some general characteristics can be observed. Most reconfigurable robot research is based on a homogeneous design and aims to operate in 3D. Mostly, each proposed module can move over neighbours and reconfigure themselves. The number of internal degrees of freedom per module varies from zero to twelve depending on desired mobility of each module (with two-DOF the most common). The smallest unit size is about 40×50mm [Yoshida *et al.*, 1999]. The emphasis on connecting mechanism has not focused on genderless connecting mechanisms, generally they are separated into male and female types. There appears to be no

	Number of DOF(s) per unit	Homogeneous	3D	Self-reconfiguring	Genderless connecting mechanism	Fail-safe connecting mechanism
ACM	$1-3$	√	√	×	×	×
Tetrobot	$3-5$	√	√	×	×	×
CEBOT	$1-3$	√	×	×	×	×
Fracta	12	√	√	√	√	×
Molecule	4	√	√	√	×	×
Metamorphic	3	√	×	√	√	×
Proteo	0	√	√	√	√	×
Crystalline	2	√	√	√	×	×
Fractal robot	6	√	√	√	√	×
Fractum	0	√	×	√	×	×
Miniaturized unit	2	√	×	√	×	×
CONRO	2	√	√	√	×	×
I-Cubes structure	3	×	√	√	×	×
Polypod	2	×	√	×	×	×
PolyBot	1	√	√	×	×	×
SemiCylindrical	2	√	√	√	×	×

Table 1: Comparisons of features of existing modular robots



(a) (b)

Figure 5: Connecting mechanism: (a) Before connection (b) After connection

design with a fail-safe connection (by which we mean that a failed module can be disconnected by it's healthy neighbours). Instead, we propose a heterogeneous reconfigurable robot, with a genderless and fail-safe connecting mechanism.

3 Outline of Modular Design

The goal of the research is to design a heterogeneous self-reconfigurable robotic system that can perform a wide range of tasks. To achieve as wide a range of tasks as possible, it is clear that a heterogeneous design is called for (the number of sensors and actuators needed for a wide range of tasks is simply too great for a single module). Clearly of great significance is the ability to self-reconfigure and the range of possible configurations should be as wide as possible. Therefore, we consider the following parameters:

- a robot must have good sensing,
- a module must have enough space to contain all basic components, e.g. actuators, connecting mechanisms, CPU, sensors and communication systems,
- a robot must have genderless connectors, which means each module can universally self-mate at any connecting face of neighbours,
- the robot must be small enough to be fit in confined spaces.

We propose a modular design which (initially) has three module types: joint, power and wheel units.

3.1 Joint Unit

The modular joint or body is an important part of a robot. It has one DOF which is a revolute joint at this stage. We plan to extend the design to linear and rotational joints in the future. Currently, its body design is $70{\times}70{\times}80mm$ (see Figure 6(a)). Two genderless connecting mechanisms are attached at the top and bottom face of the body. A RC hobby servo will be used to generate motion at about $8kg/cm$ torque. Processors and circuitry will be on board. Communication system using IR transmitter/receiver will be attached around connecting mechanism. Four pairs of pins and holes near the conner of each connecting face align the modules during the reconfiguration process.

Genderless Connecting Mechanism

This mechanism is composed of a rotational arm, a torsion spring and a SMA wire. The V-shape torsion spring rotates the locking arm to connect the modules. The SMA wire is used to rotate the arm to unlock the connection (see Figure 5(a)). Note that the projecting levers mean that retraction of either latch causes the retraction of both latches so that either module can disconnect the connection unilaterally.

3.2 Power Unit

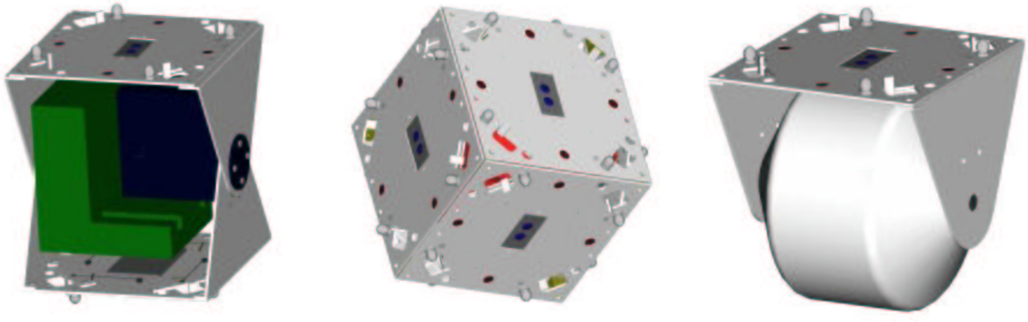
This cubic part is designed as power source and ports of a robot. It contains batteries and has six connecting ports, one on each face (see Figure 6(b)).

3.3 Special Unit

As a heterogeneous system, our robot will have some special function units. Initially, we propose a wheel module. This module consists of wheel and connecting mechanism (see Figure 6(c)). The wheel is driven by a small servo. In the future, we will develop camera and gripper modules. Special units use the same connection mechanism and so can be attached anywhere.

4 Progress

To date, we have developed several prototype connection mechanisms, finally selecting the one shown in Figure 5(a). The design of the on-board electronics and computation has been completed. Finally, we are in the process of constructing a prototype of the one-DOF module shown in Figure 6(a).



(a) (b) (c)

Figure 6: Module types: (a) Joint unit (b) Power units (c) Wheel unit

5 Conclusion

A variety of reconfigurable robots has been surveyed in this paper. We also propose a novel design of a heterogeneous self-reconfigurable robot which has genderless connecting mechanisms. Our next target is to build and test the proposed design.

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