Reconnectable Joints for Self-Reconfigurable Robots

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Abstract

Self-reconfigurable robots are modular robots that can dynamically and intelligently reconfigure their shape and size to accomplish difficult missions. Such capability is highly desirable in tasks such as fire fighting, urban search and rescue after an earthquake, and battlefield reconnaissance, where robots must confront unexpected situations and obstacles and perform tasks that are difficult for fixed-shape robots. To build such robots, however, a number of technical challenges must be overcome. One critical problem is the design and implementation of the reconnectable joints (also called connectors), which allows modules to autonomously connect and disconnect from one another. Such a mechanism must be power efficient (a robot has a very limited on-board power supply), reliable (connections must endure various operations), and compact (the mechanism must fit into a tight space). This paper gives an overview of the CONRO self-reconfigurable robots, and then focuses on the reconnectable joints of the CONRO modules. The paper identifies a set of desired features and operation constraints for the joints, and describes our current design for the connectors.

1. Introduction

Metamorphic or self-reconfigurable robots offer a new approach in robotics, in which large-scale results may be accomplished by the coordinated actions of a large number of very small robots. These robots can self-assemble and/or reconfigure into new body shapes, with locomotive and sensory primitives suitable for many different tasks. Furthermore, metamorphic actions may be performed at two different levels. At the intra-robot level, a single metamorphic robot can change its shape and size by rearranging its body parts. At the inter-robot level, a group of metamorphic robots can join and coalesce into a larger and more complex robot, or a single large robot can decompose into a set of smaller, more agile robots.

The above tasks present a number of technical challenges in various areas of robotics research. Specifically, a metamorphic robot must be able to decompose and assemble at will from a set of basic connectable modules. These modules must be light (the actuator in a module must be able to lift several other modules), self-sufficient (each module must be able to see, act, and think during reconfiguration and task mission), and relatively homogeneous (no single damaged module should paralyze the entire system). Furthermore, the modules of the metamorphic robots must communicate and collaborate in the execution of complex tasks (e.g., locomotion, reconfiguration, analysis of sensor information), all within the resource limitation of the modules. All these issues (i.e., miniaturization, distributed control, autonomy) are technical challenges for today's robotic systems.

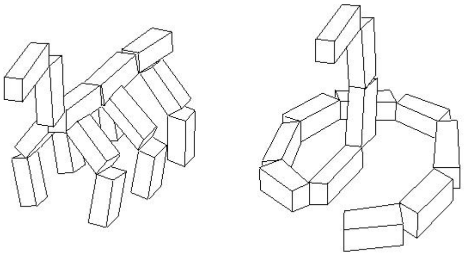

Figure 1: Hexapod and snake CONRO robots

The CONRO robots are built from a set of homogeneous, autonomous, and self-sufficient modules. Shown as in Figure 1, a CONRO robot can become a snake to maneuver through pipes or wired fences; or grow legs and turn into hexapods to climb stairs or travel on uneven terrain. Each CONRO module is a miniature robot with sensors, actuators, microprocessors, batteries, and communication devices, and reconnectable joints. All modules are structurally homogeneous so they can replace each other for basic functions such as docking, locomotion, and communication. Modules can connect not only to other modules of the same robot but also to modules of other robots to create larger robots. For example, a complex CONRO robot may disassemble itself into a set of small robots that crawl under the door of a closed room. Once inside, they may reassemble into the original robot and build the necessary locomotive and sensory components needed for a given task, such as carrying a heavy payload.

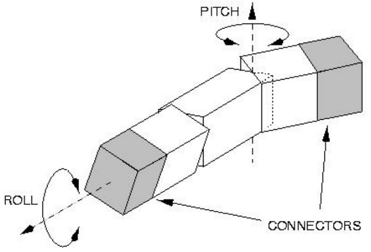

Figure 2: A CONRO module

As shown in Figure 2, each module has three segments connected in a chain. Two independent axes of rotation, located at the intersections of these segments, provide the module with motion capabilities. Each module has two reconnectable joints located at the two ends of the chain, as indicated by the gray areas in Figure 2. Each joint is a cube that has five reconnectable *facets* and every facet is capable of making a solid connection with any of the reconnectable facets of another module.

This paper reports our design and implementation of these CONRO connectors. For other aspects of the CONRO project, please see [1-6], or visit http://www.isi.edu/conro. The rest of the paper is organized as follows. Section 2 describes related work on metamorphic robots and connectors. Section 3 describes our design for reconnectable facets and joints. Section 4 describes the integration of multiple facets into a reconnectable joint, and describes how these joints work in the module. Section 5 discusses the design that allows two modules to dedocking from either side for self-repairing purpose. Section 6 concludes the paper with some future work.

2. Related Work

Metamorphic robots have been proposed by a number of robotics researchers. Fukuda and Kawauchi [7] proposed a cellular robotic system to coordinate a set of specialized modules. Yim [8, 9] studied how to achieve multiple locomotion modes using robots composed of basic modules. Murata et al. [10] and Yoshida et al. [11] separately, designed and constructed systems that can achieve planar motion by arranging modules. Pamecha, et al. [12] described metamorphic robots that can aggregate as stationary 2-D structures with varying geometry and that implement planar locomotion. Kotay, et al. [13] proposed and implemented metamorphic robots based on “robotic molecules.” Nilsson [14] designed and implemented a torsion-free joint for modular snake-like robots. Fujita, et al. [15] built a biologically inspired reconfigurable robot. Paredis and Khosla [16] proposed modular components for building fault-tolerant, multipurpose robots. Neville and Sanderson [17] proposed a module for the dynamic construction of complex structures. Chen [18] has characterized a number of important desired features for connectors of self-reconfigurable robots. Furthermore, a number of researchers [13, 19] have developed connectors based on the concept of electromagnets.

In contrasts with the above approaches to self-reconfigurable robots, CONRO modules are designed to be miniature and self-sufficient. A CONRO robot can separate locomotion from reconfiguration, while many other reconfigurable robots must rearrange their body parts to achieve locomotion. In addition, the joints in a CONRO are power efficient and they consume no energy when the connections are in the default state. Comparable with most existing joints for metamorphic robots (such as [10] and [20]), CONRO joints are simple in structure. This facilitates the integration of such joints into miniature reconfigurable modules, and increases the reliability of docking and dedocking between modules. Finally, the CONRO joint is equipped with sensors to guide the alignment during docking. The detailed procedure for controlling the docking process can be found in [6].

3. CONRO Reconnectable Facets

As we mentioned before, a CONRO joint is made of reconnectable facets. As illustrated in Figure 2, each facet is a square-shaped system with three groups of elements on the surface. The first group is at the center of the surface, and consists of two pins (the two columns with cone-shaped tips exposed above the surface) and two holes (for accepting the pins from the other facet). These pins and holes are located at the four corners of the inner most square in a symmetrical fashion, so that two facets can engage their pins and holes when joined. The second group is at the intermediate area and contains two pairs of emitting/sensing devices (shown as rectangular holes in Figure 2), which form a communication link for connected modules and a guiding system for the docking process. Finally, the third group contains the mounting apparatus at the corners of the facet. These are used to integrate five facets to form a complete, cube-shaped joint.

Four distinct and novel features in this design are considered crucial for the success of the CONRO reconnectable facets: (1) the symmetrical layout of the elements of each facet, (2) the position and number of docking devices (pins and holes) and their implications for the possible alignments in a connection, (3) the locking and unlocking mechanism and its robustness and effectiveness, and (4) the power considerations and the effects on the strength of the connection. We describe the rationale for these design issues in detail.

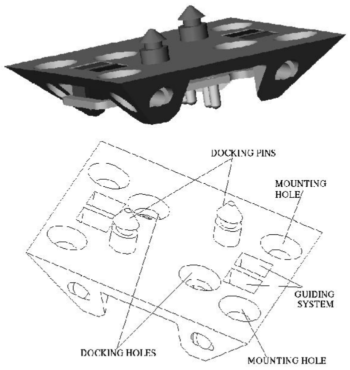

Figure 3: A CONRO reconnectable facet

3.1. The symmetric of facets

A common practice for the design of a mechanical joint is to have two non-symmetric opponents (a male and a female) that make a solid connection when they dock together. An example of such a configuration is a ball-and-socket joint. In a reconfigurable robot, however, such non-symmetric joints severely limit the flexibility of reconfiguration. For example, during a reconfiguration process, a robot may need to select two specific facets to form a desired connection, but would fail to do so if both facets happened to be the same type (i.e., they were both male or female). This type of failures may occur frequently and cause certain configurations become unreachable.

To avoid this type of failure, a CONRO reconnectable facet has a symmetric design: the docking pins and holes are arranged in such a way that the geometry of their positions is symmetric. This allows any facet to be connected to any other facets and greatly increases the flexibility of reconfiguration.

3.2. The number of docking alignments

Since the pins and holes form a symmetric geometry, the number of possible docking alignments between two facets depends on the number of pins/holes and their positions on the surface. It is interesting to see that the number of possible docking alignments is directly related to the number of pins/holes on a facet. Let p be the number of pairs of pins/holes on a facet. Assume that the pins and holes are evenly positioned along a circle centered on the facet in a symmetric fashion, then the separation degree d between two consecutive pins (or holes) along the circle is $d=2\pi/p$. When two facets are to be docked with each other, the rotation that a docking facet must perform to find the next possible alignment is equal to d in the worst case. For example, a docking facet with $p=1$ may have to rotate $d=2\pi$ to find an alignment, while a docking facet with $p=8$ only needs to rotate $\pi/4$ to find a docking alignment. Thus we know in theory that the more pins/holes we have in a facet, the easier the docking process. However, we must balance the flexibility of docking with the complexity of constructing the facets. Limited by the size of our facets (18mm^2), we are forced to choose $p=1$.

3.3. The latching mechanism

The locking and unlocking mechanism is one of the crucial components of a reconnectable joint. Due to the unique features of reconfigurable robots, such a mechanism must be power efficient (a robot has a very limited on-board power supply), reliable (connections must endure various operations), compact (the mechanism must fit into a tight space), and flexible to operate (easy to connect and disconnect).

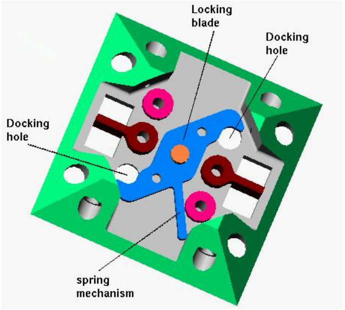

Figure 4: The latching mechanism in CONRO facet

As shown in Figure 4, the locking mechanism of a CONRO facet is located at the back of the facet. The main component is a thin metal blade (the dark, S-shaped piece at the center) that can rotate around the center with a spring motion (the spring is provided by a thin extension from the blade that leans against the wall at the lower right-hand corner of the figure). The two curve-shaped tips of this blade are positioned at the back of the docking holes. When a docking pin enters the hole, the flexible blade snaps into the groove of the pin, locking it into position. To unlock the pins, the blade is pulled back by a SMA wire so that the blade disengages the groves of the pins and releases the pins to be pulled away.

This SMA-activated blade-locking mechanism has a number of advantages. First, it is energy efficient because the mechanism is in a passive state most of the time, consuming energy only during dedocking. Second, the mechanism can be made in a very thin layer of space, because the thickness of this mechanism is determined by the thickness of the blade. This makes multiple-facet integration possible in the CONRO modules. Finally, this mechanism is robust and reliable because it is simple to construct and operate. Based on our experiments, the lifetime of this mechanism is more than 60,000 times of SMA activations in our laboratory condition.

3.4. Designs for energy efficiency

Because CONRO modules are self-sufficient, a major concern for the design of connectors is the power consumption. Of course, energy is required at some states of the connection, but when and where to apply energy can make a big difference in power saving. We have considered three possibilities in the design and each has a different purpose of applying power: to maintain an established connection, to docking only, and to dedocking only.

In the first design, energy is required to maintain the connection between two facets. Electromagnet is a typical example of this. Such a design can help during docking because activating the electromagnets can create an attractive force between the docking modules. The disadvantage is that maintaining the electromagnets while two facets are connected consumes a large amount of power and such devices are hard to be miniaturized. Furthermore, such connections will break when modules are not powered.

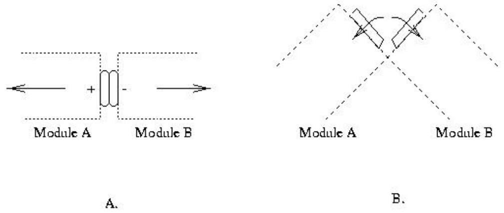

Figure 5: Dedocking permanent magnets

The second design is to activate the mechanism for docking only. An example of this is a combination of an electromagnet and a permanent magnet. The electromagnet is activated during docking to increase the success of docking. Once a docking is done, the electromagnet is deactivated, and permanent magnets assume the responsibility of maintaining the connection. The advantage of this mechanism is its low power consumption, because it uses the electromagnets only during docking. The disadvantage is that dedocking must break the force of magnets that can be quite strong in some cases. One way to achieve dedocking in this design is to rotate the dedocking modules to bend the connector in a direction, as illustrated in Figure 5. In practice, however, it is hard to determine the force magnitude of the permanent magnets. If the force is too strong, the dedocking will be problematic. If the force is too weak, then the connection will be fragile.

The third design for the connector mechanism is the use of an actuator only during dedocking. In such a design, the docking and the maintenance of an established connection are accomplished by some passive mechanism. In CONRO, for example, we have selected a spring-loaded latch mechanism for this purpose. To dedock two facets, we activate a shape-memory alloy wire that pulls the latch and free the pins. The amount of energy consumed by a shape memory alloy is very small and the period of activation can be kept short when combined with a fast dedocking procedure.

As we can see, among all three designs, the strategy of applying energy to dedocking only seems to be the most appropriate choice for the CONRO robot.

4. Integration of Multiple Facets

As we described earlier, each CONRO module has two reconnectable joints located at the two ends of the module. Since each joint is an integration of five facets, it allows other modules to be connected from five different directions: up, down, left, right, and straight. Figure 6 illustrates the five possible ways to connect to a joint.

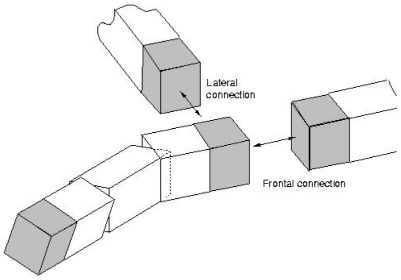

Figure 6: Five possible connections of modules

To build such a joint, one must integrate five reconnectable facets into a cube and attach the cube to the main body of the module. In the CONRO design, as shown in Figure 7, each joint is made of five reconnectable facets, and the five facets are integrated together with the screws and holes located at the four corners of each facet. Because of the thinness of each facet, the resultant cube has space at the center of the cube to host electric components and wires. It is desirable to locate the CPU at the center of the cube so that the amount of wiring needed to control other devices can be reduced to minimum.

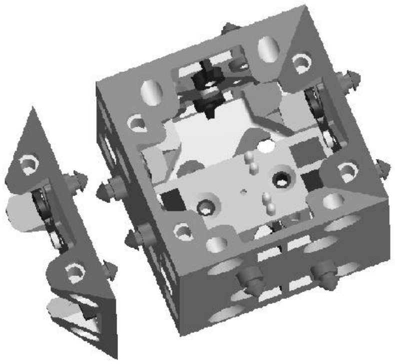

Figure 7: The integrated joint with five facets

As shown in Figure 8, each facet has a fixed space to hold the electronic and mechanical components of the face. Although the shape of this volume is not symmetric, it is possible to connect six faces together to form a cube. The joint is constructed by putting together the set of facets in such a way that each facet holds four of the other facets. This design has a dual purpose: to reduce the weight of the structure and to allow flexible facet replacement.

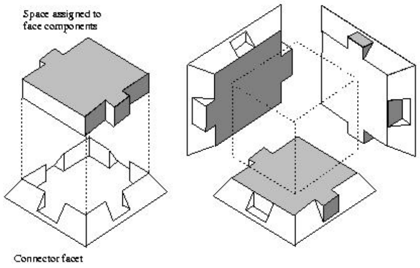

Figure 8: Facets and the inner empty space

In practice, only five sides of the cube have facets on them, leaving the sixth available for mounting the joint to the main body of the module. The connection between a joint and a module body is the same as the connection between facets. This design increases the modularity of the module parts considerably.

5. Dedocking from either side

In a normal design of connector, two connected modules must agree and act together in order to disconnect from each other. This constraint for dedocking, however, is not desirable for the purpose of self-repairing. Ideally, if a module is damaged, then its neighbors should be able to disconnect it from the system without any constraints from the damaged module. For this purpose, we have designed an electric circuit that allows dedocking to be accomplished at either side of the connection. This is critical for a self-reconfigurable robot is to discard any damaged modules for self-repairing.

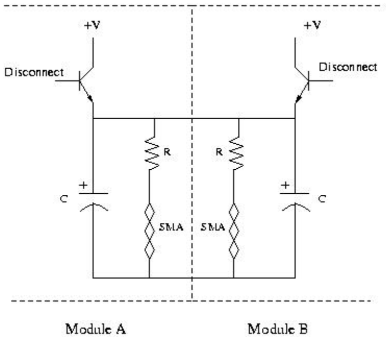

Figure 9: Flexible dedocking circuit

Such a mechanism is shown in Figure 9. The idea is that when a dedocking signal from either side of the connection is activated, the capacitors in both modules are charged, and thus activate the SMAs in both modules. As the modules are disconnecting from each other, the electric contacts between modules will be broken but the capacitors would keep the SMAs activated for some time, allowing the dedocking process to be completed without requiring any actions from the damaged module.

6. Conclusions

We have presented the designs of CONRO connectors for reconfigurable robot modules, and considered a number of parameters such as capability to connect from multiple directions, size, power consumption, capability to connect in multiple orientations, complexity of electrical and mechanical design, difficulty of machining the parts, and weight. These design decisions are particularly suitable for miniature robots and are used in the prototypes of CONRO reconfigurable robots.

7. Acknowledgements

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