Current Trends and Miniaturization Challenges for Modular Self-Reconfigurable Robotics

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***Abstract*—An overview of the field of modular self-reconfigurable robots is presented. The background and objectives of the field are reviewed, along with a description of several successful designs, categorized by actuator type. Control algorithms are mentioned, along with a method for evaluating complexity of multi-robot control. Several challenges to miniaturization are discussed, focusing on power and actuation requirements for large networks of modular robots.**

I. Introduction

The idea of fine-grained modular self-reconfigurable robots is compelling. One can imagine large numbers of tiny robotic modules working together to create larger robots. In contrast to large, expensive and complex robots, self-reconfigurable systems present the idea of a crate of identical modules which can be programmed to arrange themselves in multiple configurations for multiple tasks. Rather than deploy a family of fragile, custom-made robots to construct a remote outpost, for instance, a container of modules could be delivered, configuring themselves as necessary, self-repairing, planning and communicating.

Mark Yim [4] describes three benefits of modular self-reconfigurables: reliability, versatility, and cost. While large robots created for a specific task are often suited only to that task, reconfigurable robots are able to adapt to different tasks in different environments. Large custom-made robots are always expensive, and often unreliable, while small modules can be mass-produced for vast cost savings.

An important benefit of a massively parallel homogeneous robot system is the ability to self-repair an internal failure. In the event of a hardware malfunction, surrounding modules would be able to move the offending part to a passive location, or eject it completely from the system. Effective self-repairing robots have not been demonstrated, but improved modular hyper-redundant systems are a clear path toward this goal.

Most of the extant designs are based on homogeneous modules; systems of identical components which connect with each other to form lattice-like assemblies. Outside of the laboratory, however, heterogeneous systems will dominate. Most useful robots need many specialized parts, including specific sensors, actuators and tools. Including every part in every module is impossible, so modules of various types will need to be included in a viable system. In addition, when self reconfigurable robots are further miniaturized, fewer components can be included in each module, so heterogeneity must increase.

II. Review of Existing Designs

Since 1990, many modular self-reconfiguring systems have been built. For a catalog of designs, see [17]. Here, we discuss three main categories of homogeneous module designs, those which expand and contract, those which rotate about their neighboring modules, and link-centric modules, which feature more complex linking mechanisms.

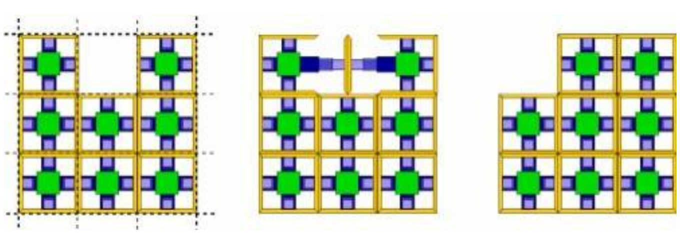

Figure 1. Basic motion step for an expanding module [11]

A. *Expanding Modules*

Several projects have created systems based on individual modules which expand and contract in order to change their configuration. As shown in Figure 1, if cubic modules are able to expand to twice their dimension, they become able to traverse a single module gap and, additionally, create several locomotion patterns.

The first successful project of this sort was the Crystalline Atom [8], shown in figure 2. Although only able to move in two dimensions, the hardware was robust enough for experimentation, and acted as a platform upon which Rus and Vona [8] could construct their *Melt-Grow Planner* to control expanding modules.

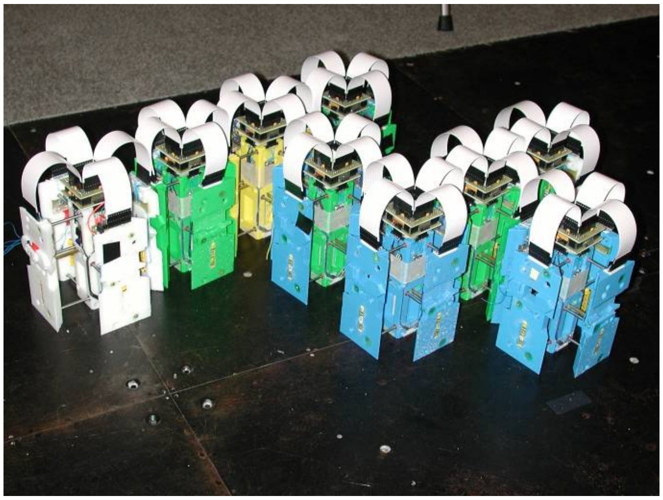

Figure 2. A set of crystalline atoms. Each is 50cm per side when contracted. [8]

Telecubes were created at PARC [11] in an attempt to emulate the expanding module idea in three dimensions. Although the project showed promise as a feasible implementation of a 3D lattice structure self-reconfigurable, it seems to have been abandoned.

B. Rotating Modules

The most prominent design for self-reconfigurable robots involves modules that rotate around themselves or their neighboring modules.

Polybot, developed at PARC [4] was an early entry into the field. Equipped with only one degree of freedom per module, it can link with neighboring modules at 90 degree angles, creating hyper-redundant assemblies. Shown in Figure 3, the most recent Generation III has been miniaturized to a 5cm cube.

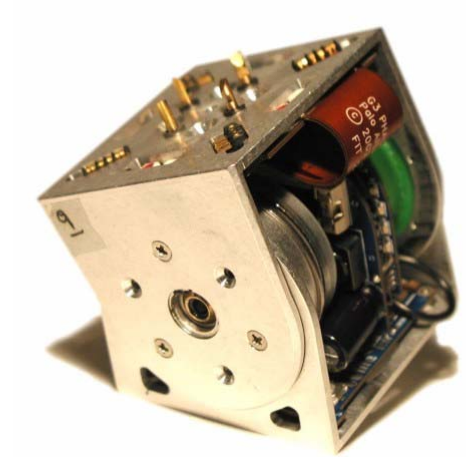

Figure 3. A 50mm cube Generation III Polybot module [4]

Other successful larger-scale hinged robots include MTRAN [7] and ATRON [6].

The smallest self-reconfigurable modules have been created by Yoshida et. al. [9]. As shown in Figure 4, the modules are 2cm diamonds, with mechanical connectors which rotate and latch via shape-memory alloy (SMA) actuators. Light, strong, and inexpensive, modules like this show promise for further miniaturization, although their mechanical connectors may not scale well.

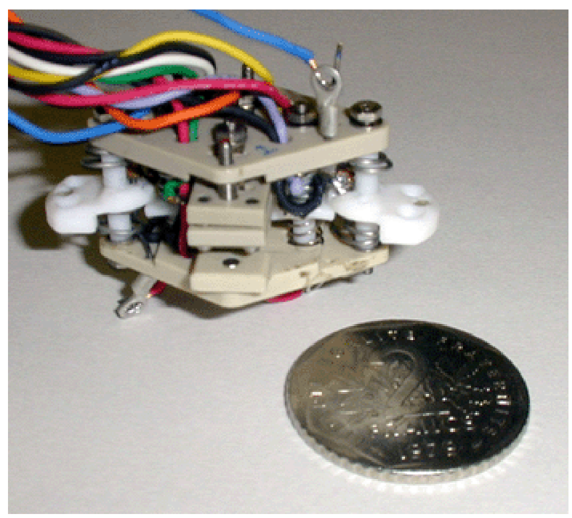

Figure 4. 20mm SMA-actuated module [9]

The Claytronics team at Carnegie Mellon has created a prototype Catom (for Claytronics atom) which measures 44mm diameter [5]. Although this design is a prototype in their goal of creating 1mm spherical modules, it is worth noting for its novel actuation mechanisms. As shown in Figure 5, small programmable electromagnets on the perimeter can be toggled on and off to allow the modules to rotate around each other.

Figure 5. 44mm "Catom" modules [5]

C. Link-Centric Modules

A third category of self-reconfigurable systems includes those in which the inter-module connectors play a primary role.

A unique heterogeneous system is ICES-Cubes [3], composed of two types of modules: cubes, which contain power and active connector sockets, and links, which have 3DOF and effectively move between cubes, and move the cubes themselves. The inherent design of ICES-Cubes, which relies on 7 servo motors for each cube/link combo, precludes further miniaturization.

The CONRO project at USC [13], with only three motors per module, is a robust implementation of a link-centric system and like Polybot, has been shown in configurations which enable various gaits; spider-, snake-and four-legged assemblies.

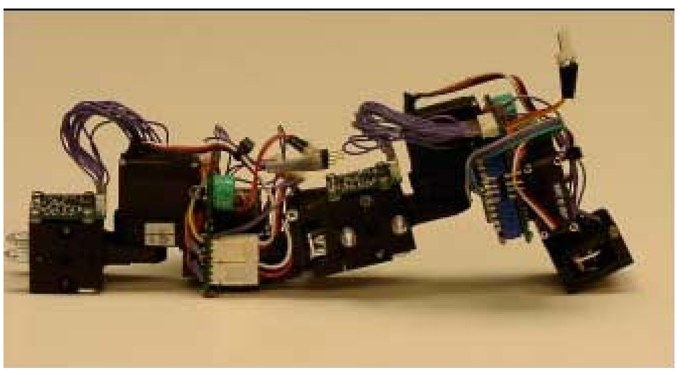

Figure 5. Two docked CONRO modules [13]

III. CONTROL

Controlling a system with many discrete modules is not a trivial task. Several systems have been developed [4] [7] [8] [10], although a successful hardware-independent system has been elusive.

Rus and Vona [8] have created the *Melt-Grow Planner*, which doesn't allow for parallel movement of multiple modules, and Yim's group at PARC have created a parallel distributed algorithm which is dependent on expanding-cube modules.

An interesting approach toward the analysis of multi-robot coordination has been proposed by Klavins [14], whose Computation and Control Language (CCL) is presented as a way to determine the communication complexity of certain multi-robot tasks. Several scenarios are presented along with a formalism for describing coordination. Unfortunately, many systems described so far depend on $O(n^2)$ communication, where every robot must communicate with every other robot. In order to be scalable at all, $O(n)$ communication algorithms must be implemented, where bandwidth will scale linearly with the number of robots in the system.

IV. MINIATURIZATION CHALLENGES

A. Power

For each module to be completely autonomous, it must supply its own power. Current battery technology is only feasible down to about the size of CONRO (10.8cm long), but recent advances in thin-film and micro-batteries hold promise for miniaturized robots. Smaller existing modular robots are either tethered prototypes [9] or operate on a powered surface [5]. Autonomy is not necessarily required, however, and several systems [15] operate from a single source, transmitting power through each module.

Several non-modular robots have been successfully powered by remotely, either with microwaves or inductive beaming, but the possibility of a beam being unable to penetrate to an interior module demands either heterogeneous robots or the ability for modules to transfer power to one another.

Arguably, the ultimate power source for robots of any sort is solar or existing environmental energy, but the high energy demands of self-reconfiguration coupled with the limited power density of existing solar cells makes environmentally powered reconfigurables unlikely.

B. Actuation

Electric motors lose efficiency rapidly when scaled down as the torque necessary to rotate an object scales exponentially according to length.

The Claytronics [5] project has built macro-scale prototypes which use electromagnets to rotate connected modules around each other but miniaturization will be difficult as the force generated by an electromagnet scales down at the cube of its length.

Yoshida et. al. [9] use SMA actuators employed as both linear and torsional springs, actuating both an unlocking pin and the connector's rotation. The actuator force of SMA scales well with miniaturization, but low efficiency, high power consumption, and low speed present challenges to scaling.

Piezoelectric actuators show promise for micro and even nano-scale modular robots, but their small displacement and high voltage requirements make them infeasible for the current scale of connectors and controllers.

C. Communication and Processing

Most modular robotic systems use a microcontroller inside each module for control and communication. Although processors can effectively be miniaturized more than other components in the system, other electronics which support power supply, data flow, and actuator control can take up significant space. The use of simple actuators like SMA and piezo/polymers can reduce much of this circuitry, and simple serial communication can eliminate the need for infrared drivers or wireless antennae.

D. Connectors

Existing modular robots connect with one another using either mechanical or magnetic connectors. While mechanical connectors may scale well down to the micro-scale, their strength will vary as the square of their length, and current macro-scale designs have suggested reliability and strength problems with their use. The force exerted by permanent magnets scales at the cube of the magnet's length, and electromagnets, which offer control over polarity, scale even more poorly, and require an additional mass of drive electronics.

At micro- and nano-scales, an exciting possibility arises for inter-module connection. Electrostatic and surface area-dependent forces become dominant over volume-dependent forces, since volume scales down equivalent to the cube of length. When modules are miniaturized at this level, connection may be less of a problem, although it may be necessary to design equivalent disconnection mechanisms to overcome attractive forces.

V. Conclusion

This paper has presented a brief overview of the current field of modular, self-reconfigurable robotics, and demonstrated some of the challenges involved in further miniaturizing the modules. The primary obstacle is power. The combination of energy-inefficient actuators and the demand for continuously repeated large movements creates a power demand that is difficult to supply even at the macro-scale. As modules are miniaturized, the force required to actuate them is reduced at the cube of their length, but the amount of actuation increases in order to reconfigure on the same scale. Advances in small, discrete power sources will spur the next, smaller, generation of modular, self-reconfigurable robotic systems.

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