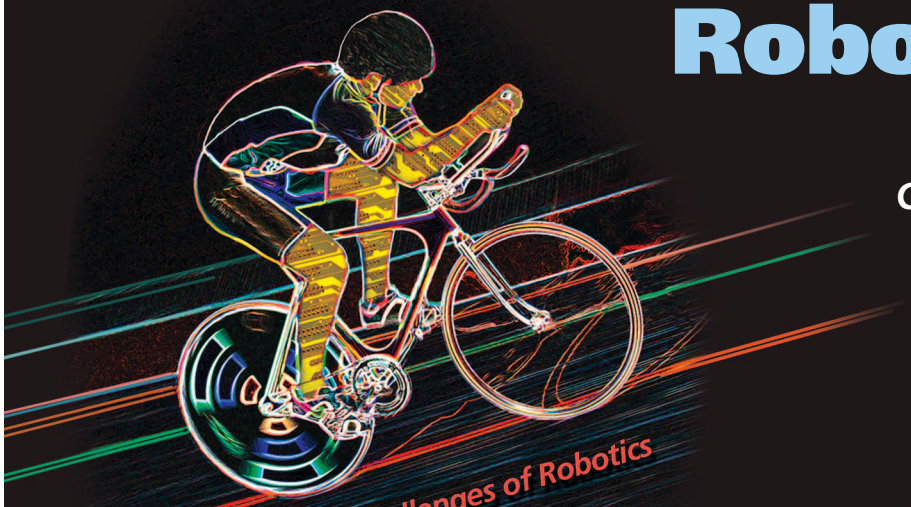
Modular Self-Reconfigurable Robot Systems

Challenges and Opportunities for the Future



Grand Challenges of Robotics

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The field of modular self-reconfigurable robotic systems addresses the design, fabrication, motion planning, and control of autonomous kinematic machines with variable morphology. Beyond conventional actuation, sensing, and control typically found in fixed-morphology robots, self-reconfigurable robots are also able to deliberately change their own shape by rearranging the connectivity of their parts in order to adapt to new circumstances, perform new tasks, or recover from damage.

Over the last two decades, the field of modular robotics has advanced from proof-of-concept systems to elaborate physical implementations and simulations. The goal of this article is to outline some of this progress and identify key challenges and opportunities that lay ahead.

A Taxonomy of Architectures

Modular robots are usually composed of multiple building blocks of a relatively small repertoire, with uniform docking interfaces that allow transfer of mechanical forces and moments, electrical power, and communication throughout the robot.

The modular building blocks often consist of some primary structural actuated unit and potentially some additional specialized units such as grippers, feet, wheels, cameras, payload, and energy storage and generation units. Figure 1 illustrates such a system in the context of a potential application.

Modular self-reconfigurable robotic systems can be generally classified into several architectural groups by the geometric arrangement of their units. Several systems exhibit hybrid properties.

- ***Lattice Architectures:*** Lattice architectures have units that are arranged and connected in some regular, three-dimensional pattern, such as a simple cubic or hexagonal grid. Control and motion can be executed in parallel. Lattice architectures usually offer simpler reconfiguration, as modules move to a discrete set of neighboring locations in which motions can be made open-loop. The computational representation can also be more easily scaled to more complex systems.

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- ***Chain/Tree Architectures:*** Chain/tree architectures have units that are connected together in a string or tree topology. This chain or tree can fold up to become space filling, but the underlying architecture is serial. Through articulation, chain architectures can potentially reach any point or orientation in space, and are therefore more versatile but computationally more difficult to represent and analyze and more difficult to control.
- ***Mobile Architectures:*** Mobile architectures have units that use the environment to maneuver around and can either hook up to form complex chains or lattices or form a number of smaller robots that execute coordinated movements and together form a larger "virtual" network.

Control of all three types of modular systems can be centralized or distributed among the modules, and can be executed in series or in parallel. Though most systems implemented today are composed of rigid components, compliant mechanisms and deformable units have also been explored.

Modular robotic systems can also be classified according to the way in which units are reconfigured (moved) into place.

- ***Deterministic Reconfiguration:*** This type of reconfiguration relies on units moving or being directly manipulated into their target location during reconfiguration. The exact location of each unit is known at all times or can be discovered and calculated at run time, and reconfiguration times can be guaranteed. Feedback control is often necessary to assure precise manipulation, for example, in the chain and mobile architecture. Macroscale systems are usually deterministic.
- ***Stochastic Reconfiguration:*** This type of reconfiguration relies on units moving around using statistical processes (like Brownian motion). The exact location of each unit is only known when it is connected to the main structure, but it may take unknown paths to move between locations. Reconfiguration times can be guaranteed only statistically. Stochastic architectures are more favorable at microscales. The environment, whether natural or manmade, provides much of the energy for transporting modules around in this type of system.

Other modular robotic systems exist that are not self-reconfigurable, and thus do not formally belong to this

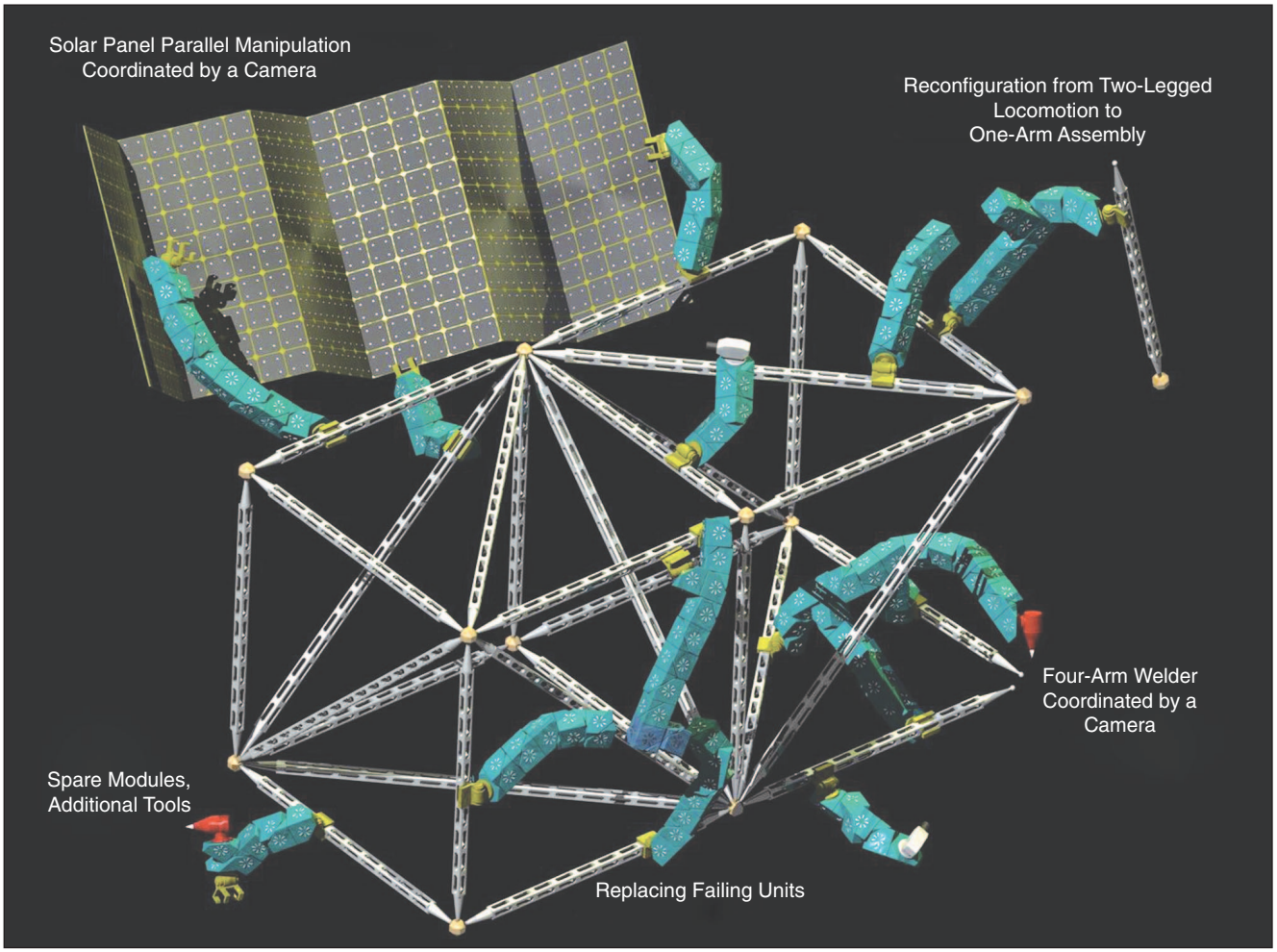


Figure 1. *Artist rendition of a space application of modular robotics, showing a truss-building colony of chain/tree robots composed of cubical modules, configured in various morphologies for a variety of tasks including assembly, cooperative manipulation, and self-repair (from [1]).*

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family of robots, though they may share similar design and control challenges. For example, self-assembling systems may be composed of multiple modules but cannot dynamically control or reconfigure their target shape. Tensegrity robots may be composed of multiple interchangeable modules, but cannot self-reconfigure. Swarm robots are composed of multiple units, but do not typically connect to form more complex physical structures. Even industrial robots with tool changers can be considered modular, but the degree to which they self-reconfigure is very limited in comparison with the kinds of systems reviewed in this article.

Motivation and Inspiration

There are three key motivations for designing modular self-reconfigurable robotic systems.

- ***Versatility:*** Self-reconfigurable robotic systems are potentially more adaptive than conventional systems. The ability to reconfigure allows a robot or a group of robots to disassemble and reassemble machines to form new morphologies that are better suited for new tasks, such as changing from a legged robot to a snake robot and then to a rolling robot.
- ***Robustness:*** Since robot parts are interchangeable (within a robot and between different robots), machines can also replace faulty parts autonomously, leading to self-repair.
- ***Low Cost:*** Self-reconfigurable robotic systems can potentially lower overall robot cost by making many copies of one (or relatively few) type of modules so economies of scale and mass production come into play. Also, a range of complex machines can be made from one set of modules, saving costs through reuse and generality of the system.

These three advantages have not yet been fully realized. The added degrees of freedom make modular robots more versatile in their potential capabilities, but also incur a performance tradeoff and increased mechanical and computational complexities. A modular robot is likely to be inferior in performance to any single custom robot tailored for a specific task. Consequently, the advantage of modular robotics is only apparent when considering multiple tasks that would normally require a set of different fixed-morphology robots, or when the nature of tasks cannot by fully determined before the robots are deployed.

Application Areas

Given these advantages, where would a modular self-reconfigurable system be used? While the system has the promise of being capable of doing a wide variety of tasks, finding the "killer application" has been somewhat elusive. Here are several examples.

Space Exploration

Long-term space missions (Figure 1) require a self-sustaining robotic ecology that can handle unforeseen situations and may require self-repair. Self-reconfigurable systems are better able to handle tasks that are not known a priori, especially compared to fixed-configuration systems. In addition, space missions are highly volume and mass constrained. Sending a robot system that can reconfigure to achieve many tasks saves shipping mass and volume as compared to sending many robots that each can accomplish one task.

Modular self-reconfigurable robotic systems can be generally classified into several architectural groups by the geometric arrangement of their units.

Bucket of Stuff

A third long-term vision for these systems has been called "bucket of stuff." In this vision, consumers of the future have a container of self-reconfigurable modules. When the need arises, the consumer calls forth the robots to achieve a task such as "clean the gutters" or "change the oil in the car," and the robot assumes the shape needed and does the task.

One source of inspiration for the development of these systems comes from envisioned applications. A second source of inspiration originates in biological systems that self-construct out of a relatively small repertoire of lower-level building blocks (cells or amino acids, depending on the scale of interest). This architecture underlies the ability of biological systems to physically adapt, grow, heal, and even self-replicate—capabilities that would be desirable in many engineered systems.

History and State of the Art

The roots of the concept of modular self-reconfigurable robots can be traced back to the "quick change" end effecter and automatic tool changers in computer numerical controlled machining centers in the 1970s. Here, special modules, each with a common connection mechanism, could be automatically swapped out on the end of a robotic arm. Taking the basic concept of the common connection mechanism and applying it to the whole robot was introduced by Toshio Fukuda with the CEBOT (short for cellular robot) [2] in the late 1980s.

The early 1990s saw further development from Greg Chirikjian, Mark Yim, and Satoshi Murata. Chirikjian and Murata developed lattice reconfiguration systems, while Yim developed a chain-based system. These researchers started with a mechanical engineering emphasis, designing and building modules and then developing code to program them. The work of Daniela Rus and Wei-Min Shen developed hardware, but had a greater impact on the programming aspects. They started a trend towards provable or verifiable

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distributed algorithms for the control of large numbers of modules, as well as for dynamically discovering topological changes and automatically shifting behaviors according to new topologies.

One of the more interesting hardware platforms recently developed has been the modular transformer (MTRAN) series by Satoshi Murata et al. [3]. This system is a hybrid chain and lattice system. It has the best of both systems: the good task performance of a chain system mixed with the good reconfiguration performance of a lattice system.

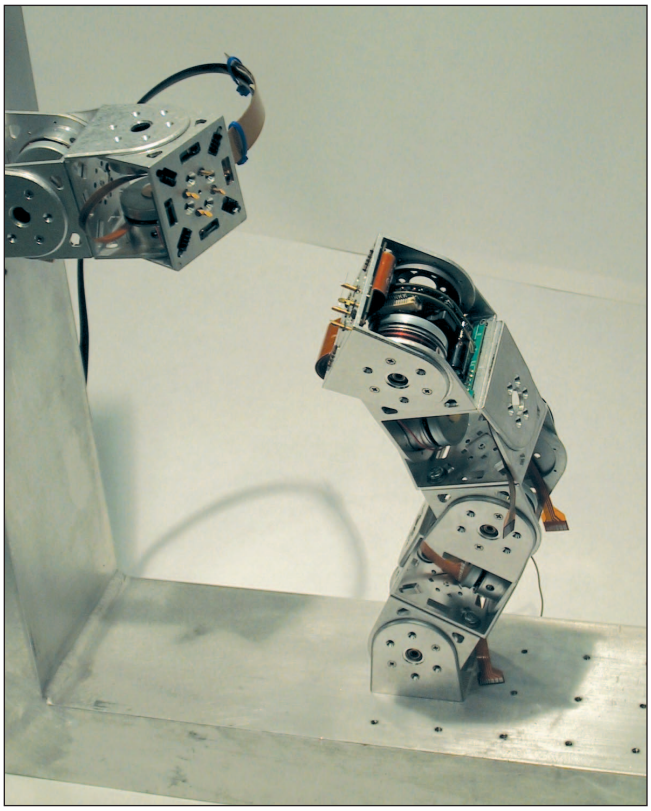


Figure 2. *PolyBot G3 from PARC.*

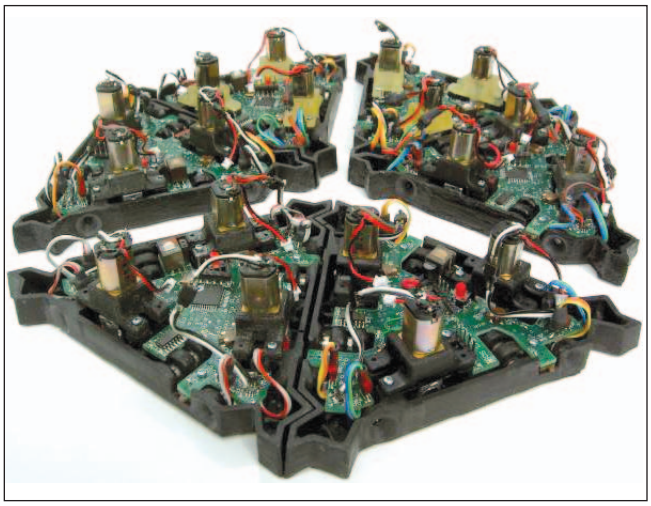


Figure 3. *Self-organizing programmable parts from the University of Washington.*

More recently, new efforts in stochastic self-assembly have been pursued by Hod Lipson and Eric Klavins. Thousands of modules have been simulated, with some (less than ten) hardware module demonstrations as well. These works build on demonstrations of Penrose dating back to the 1950s, and more recently the work of chemist G. Whitesides.

A large effort at Carnegie Mellon University (in collaboration with Intel Research Pittsburgh) headed by Seth Goldstein and Todd Mowry has started looking at issues in developing millions of modules [4], focusing on simplifying hardware and addressing scalability issues. So far, they use large numbers in simulation with a few hardware module prototypes.

Many tasks have been shown to be achievable, especially with chain reconfiguration modules. This demonstrates the versatility of these systems. However, the other two advantages—robustness and low cost—have not been demonstrated. In general, the prototype systems developed in the labs have been fragile and expensive, as would be expected during any initial development.

There is a growing number of research groups actively involved in modular robotics research, as can been seen in the survey paper [5], a survey chapter in [6], and two special issues in robotics journals [7] and [8]. A number of algorithmic advances have complemented hardware development. See, for example, [6]–[10] and [12]–[14].

Example Self-Reconfigurable Systems

PolyBot G3 (2002)

PolyBot, seen in Figure 2, was created at Palo Alto Research Center (PARC), formerly known as Xerox PARC, by Yim et al. [9]. It is a chain self-reconfiguration system. Each module is roughly cubic shaped, about 50 mm on a side, and has one rotational degree of freedom (DOF). It is part of the PolyBot modular robot family that has demonstrated many modes of locomotion including: walking: biped, 14 legged, slinky-like; snake-like: concertina in a gopher hole, inchworm gaits, rectilinear undulation, and sidewinding gaits; rolling like a tread at up to 1.6 m/s; riding a tricycle; and climbing: stairs, poles, pipes, ramps, etc. The modules have brushless flat motors with harmonic drive transmission, force torque sensors, whisker touch sensors, and infrared proximity sensors. They use hermaphroditic connectors with shape memory alloy actuated latches.

The Programmable Parts (2005)

Figure 3 shows a testbed built by Klavins et al. at the University of Washington to explore what amount to programmable chemical reactions [10]. The programmable parts are stirred randomly on an air hockey table by randomly actuated air jets. When they collide and stick, they can communicate and decide whether to stay stuck or if and when to detach. Local interaction rules can be devised and optimized to guide the robots to make any desired global shape. The system, programmed by local rules, can be modeled using the chemical master equation and the analysis of its

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behavior follows standard ideas in nonequilibrium statistical dynamics. The resulting theory being developed is being applied to microscale self-assembly and even molecular self-assembly. The ultimate goal is to understand how to program stochastic self-assembly at all scales.

Molecubes (2005)

Figure 4 shows the Molecube system developed by Zykov et al. at Cornell University [1], built to physically demonstrate kinematic self-reproduction. Each module is a 0.65-kg cube with 100-mm long edges and one rotational DOF. The axis of rotation is aligned with the cube's longest diagonal. Physical self-reproduction of a three- and a four-module robot was demonstrated, and the theoretical existence of arbitrarily sized self-replicating machines has been mathematically demonstrated. Other self-replicating morphologies and controllers have been shown to emerge spontaneously in a simulation of a "primordial soup" of thousands of 2-D Molecubes automata.

SuperBot (2006)

The SuperBot, seen in Figure 5, has been developed by Shen et al. at the University of Southern California as a deployable self-reconfigurable robot for real-world applications outside laboratories. Its modules have a hybrid chain and lattice architecture [11]. The modules have three DOF (pitch, yaw, and roll) and can connect to each other through one of the six identical dock connectors. They can communicate and share power through their dock connectors. For high-level communication and control, the modules use a real-time operating system and the hormone-inspired control developed for CONRO [12] as a distributed, scalable protocol that does not require the modules to have unique IDs. Movies for CONRO and SuperBot can be found at http://www.isi.edu/robots/.

Miche (2006)

The Miche system, shown in Figure 6, has been developed by Rus et al. at MIT. It is a modular lattice system capable of arbitrary shape formation. This system achieves self-assembly by disassembly and has demonstrated robust operation over hundreds of experiments. Each module is an autonomous robot cube capable of connecting to and communicating with its immediate neighbors. The connection mechanism is provided by switchable magnets. The modules use face-to-face communication implemented with an infrared system to detect the presence of neighbors. When assembled into a structure, the modules form a system that can be virtually sculpted using a computer interface and a distributed process. The group of modules collectively decides who is and is not on the final shape using algorithms that minimize the information transmission and storage. Finally, the modules not in the structure let go and fall off under the control of an external force, in this case gravity. All the algorithms controlling these processes are distributed and are very efficient in their space and communication consumption.

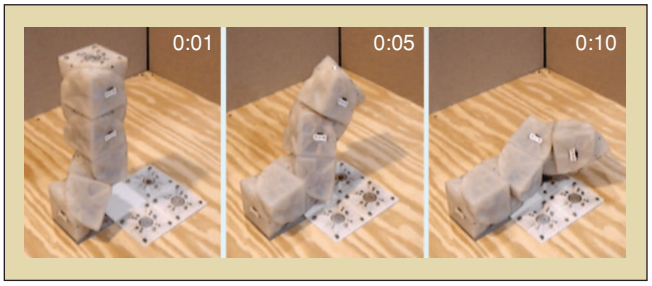


Figure 4. *Molecube system from Cornell.*

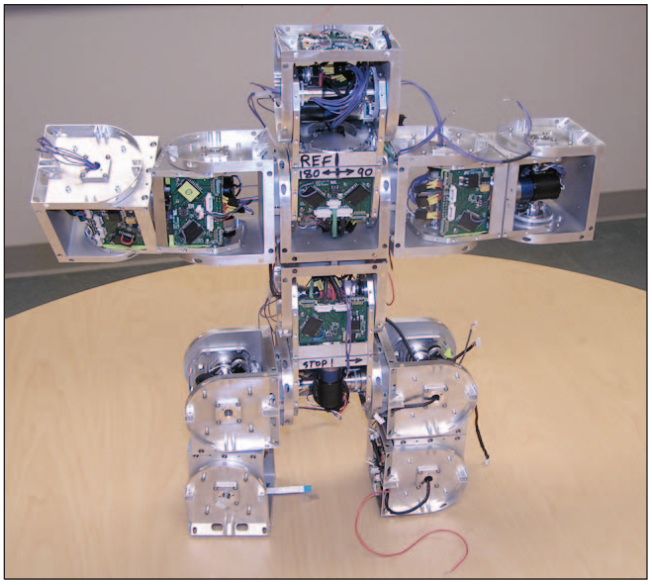


Figure 5. *SuperBot from USC/ISI.*



Figure 6. *Miche from MIT.*

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Self-reconfigurable robots are also able to deliberately change their own shape by rearranging the connectivity of their parts.

Table 1 lists many of the other instantiated modular robot systems. In addition to the name, class, and author, the table lists DOF. This describes the number of actuated DOFs for module motion (e.g., not latch DOFs) as well as whether the system motion is planar (2-D) or 3-D. The year is the estimated first public disclosure.

Challenges for the Future

Challenges and Opportunities

Since the early demonstrations of modular self-reconfigurable systems, size, robustness, and performance have been continuously improving. The extent to which the promise of self-reconfigurable robotic systems can be realized depends on the number of modules in the system. To date, only systems with up to about 50 units have been demonstrated, with this number stagnating for over almost a decade.

In parallel, planning and control algorithms have been progressing to handle millions of units. There are, however, several key steps that are necessary for these systems to realize their promise of adaptability, robustness, and low cost. These steps can be broken down into challenges in the hardware design, in planning and control algorithms, and in application.

Hardware Design Challenges

Performance of a self-reconfigurable robot is highly dependent on its mechanical and electronic control design. To date, a number of different designs have been developed and evaluated. Each design has primarily focused on some factors such as flexible form factor, utilizing many degrees of freedom, high torque-to-weight ratio, ease of docking/undocking, and power management. However, an optimal and general-purpose module design is yet to be proposed. The fundamental limiting factors that govern this problem include:

- limits on strength, precision, and field robustness (both mechanical and electrical) of bonding/docking inter faces between modules
- limits on motor power, motion precision, and energetic efficiency of modules (i.e., specific power, specific torque)
- limits on dexterity of individual modules, which limits the flexibility of the robot as a whole.

Table 1. List of self-reconfigurable modular systems.

System	Class	DOF	Author	Affiliation	Year
CEBOT	mobile	various	Fukuda et al.	Nagoya	1988
Polypod	chain	2 3-D	Yim	Stanford	1993
Metamorphic	lattice	3 2-D	Chirikjian	JHU	1993
Fracta	lattice	3 2-D	Murata	MEL	1994
Tetrobot	chain	1 3-D	Hamlin et al.	RPI	1996
3D Fracta	lattice	6 3-D	Murata et al.	MEL	1998
Molecule	lattice	4 3-D	Kotay & Rus	Dartmouth	1998
CONRO	chain	2 3-D	Will & Shen	USC/ISI	1998
PolyBot	chain	1 3-D	Yim et al.	PARC	1998
TeleCube	lattice	6 3-D	Suh et al.	PARC	1998
Vertical	lattice	2-D	Hosakawa et al.	Riken	1998
Crystal	lattice	4 2-D	Vona & Rus	Dartmouth	1999
I-Cube	lattice	3-D	Unsal	CMU	1999
Pneumatic	lattice	2-D	Inoue et al.	TiTech	2002
Uni Rover	mobile	2 2-D	Hirose et al.	TiTech	2002
MTRAN II	hybrid	2 3-D	Murata et al.	AIST	2002
Atron	lattice	1 3-D	Stoy et al.	U.S Denmark	2003
Swarm-bot	mobile	3 2-D	Mondada et al.	EPFL	2003
Stochastic 2D	stochastic	0 2-D	White et al.	Cornell U.	2004
Superbot	hybrid	3 3-D	Shen et al.	USC/ISI	2005
Stochastic 3D	stochastic	0 3-D	White et al.	Cornell U.	2005
Catom	lattice	0 2-D	Goldstein et al.	CMU	2005
Prog. parts	stochastic	0 2-D	Klavins	U. Washington	2005
Molecube	chain	1 3-D	Zykov et al.	Cornell U.	2005
YaMoR	chain	1 2-D	Ijspeert et al.	EPFL	2005
Miche	lattice	0 3-D	Rus et al.	MIT	2006

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Planning and Control Challenges

Though algorithms have been developed for handling millions of units under specific ideal conditions, challenges to scalability remain both in low-level control and in high-level planning to overcome realistic constraints such as:

- algorithms for parallel motion for large-scale manipulation and locomotion with and without obstacles,
- algorithms for optimal (time, energy) reconfiguration planning with and without obstacles,
- algorithms for robustly handling a variety of failure modes, from misalignments and dead units (not responding, not releasing) to units that behave erratically,
- algorithms that determine the optimal configuration for a given task and environment, and
- efficient and scalable (asynchronous) communication among multiple units.

Mixed Software and Hardware Challenges

Self-reconfigurable systems arguably have more tightly coupled hardware and software than any other existing system. So, there are many issues for which solutions can lie in either or both hardware and software classification. These issues include:

- ***The role of sensors in self-reconfigurable robotics:*** For many applications, the modules in a self-reconfigurable robot should be cognizant of their environment and their own state through a series of sensors. Due to the distributed nature of the network of modules, sensory information is available in a distributed form and, hence, this information must be fused for autonomous decision-making or communicated to a remote controller host.

Over the last two decades, the field of modular robotics has advanced from proof-of-concept systems to elaborate physical implementations and simulations.

Table 2. Quantitative hardware achievements.

Accomplishment	Robot	Author	Affiliation	Quantity	Units
Most active modules in connected system	PolyBot	Yim et al.	PARC	56	modules
Smallest actuated module	Miniature	Yoshida et al.	AIST	$40 \times 40 \times 50$	mm
Largest actuated module	Helium Catoms	Goldstein et al.	CMU	8	m^3
Strongest actuation	Polybot	Yim et al.	PARC	5	modules cantilever
Fastest modular robot system	CKBot rolling	Sastra et al.	U. Penn	26	module lengths/s
Longest distance running, one charge	SuperBot	Shen et al.	USC/ISI	750	m
Mobile unconnected modules docking	Swarm-bot	Mondada et al.	IRIDIA	16	connecting components
Most robust self-reconfiguration	MTRAN II	Murata et al.	AIST/TiTech	14	nonrepeating attach/detach steps

Table 3. Quantitative software achievements.

Accomplishment	Software	Author	Affiliation	Quantity	Units
Most generic algorithm	CA planning	Rus et al.	MIT	Instantiated on three types See [13]	Systems
Tightest bounds for reconfiguration with volume-traveling units	PAC planning for crystal	Rus, Vona, and Butler	Dartmouth	O(1) for repositioning one module	Time complexity
Tightest bounds for surface-traveling single-module locomotion	N/A	Chirikjian et al.	JHU	see [14]	see [14]
Most behaviors based on topology	Hormone	Shen et al.	USC/ISI	3	Behaviors
Largest simulated system	Million module march	Butler and Fitch	RIT and NICTA	2.2 mil.	# of modules

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The added degrees of freedom make modular robots more versatile in their potential capabilities, but also incur a performance tradeoff and increased mechanical and computational complexities.

- ***Interaction with obstacles in real-world applications:*** In real-world applications, self-reconfigurable robots are required to perform locomotion, manipulation, and self-reconfiguration tasks in the presence of obstacles and in an uncontrolled environment.

Quantitative Accomplishments

So far, some of the challenges listed above have been met to some degree. Some of the more quantitative accomplishments are listed in Table 2 for hardware and Table 3 for software.

Note that the maximum number of hardware modules is lagging by several orders of magnitude behind algorithmic capabilities, suggesting that many of the barriers to physical scalability remain unaddressed. Both technical improvements, such as better bonding mechanisms, and conceptual progress, such as stochastic control, self-repair, and parallel manipulation, may ultimately play out in quantitative improvements, such as dramatically increasing the number of modules or making smaller ones.

Application Challenges

Besides the technical challenges, there are nontechnical challenges as well. Though the advantages of modular self-reconfigurable robotic systems have largely been established, it has been difficult to identify specific application domains where those benefits can be demonstrated. Many of the researchers developing this field have determined that finding an application that clearly drives the need for these systems is one of the major challenges.

Grand Challenges

The research described in this article represents an ultimate goal shared by the authors that modular robots may one day be used in vast numbers for practical applications where unsupervised, adaptive self-organization is crucial. Several key technical difficulties stand in the way, however. In this section, we describe several grand challenges that, if overcome, would enable a next generation of modular robots with vastly superior capabilities.

- ***Big systems:*** Most systems of modular robots have been small in number, especially compared to, for example, the number of components in a living cell (which many researchers view as the best example of a self-organizing modular system). The demonstration of a system with at least 1,000 individual units would suggest that modular robots have come of age. The physical demonstration of such a system will require rethinking key hardware issues, such as binding mechanisms, power distribution, dynamics, and vibrations. It will also require new distributed algorithms that account for noise, errors, failures, and changing connection topologies.
- ***Self-repairing systems:*** Besides reconfiguring itself into a new shape, a system comprised of modular robots would be able to recover from serious damage, such as that which might result from an external collision or internal failure. A demonstration of a self-healing structure made up of many distributed, communicating parts would require rethinking algorithms for sensing and estimation of the global state, as well as truly robust hardware and algorithms for reconfiguration that work from any initial condition. A concrete example would be having a system blown up (randomly separated into many pieces) and then self-assemble, or recover from failure of a certain percentage of faulty units.
- ***Self-sustaining systems:*** Recently, NASA pushed a concept called Robosphere that looks at creating a self-sustaining robotic ecology, isolated for a long period of time, which needs to sustain operation and accomplish unforeseen tasks without any human presence. The current state of the art with modular robots is nowhere near this goal, and so a demonstration of a system actively running for, say, one year is crucial. New techniques in power management and energy harvesting would be required, as well as the ability to cope with the inevitable failures that would occur in such a long mission.
- ***Self-replication and self-extension:*** While simple robotic self-replication has been demonstrated using a few high-level modules, a significant challenge remains to demonstrate self-replication using many low-level modules, and ultimately from elementary components and even raw materials. Such a system could build active elements as well as passive structures, leading to a self-replicating and even self-improving system from environmental resources. The demonstration of a "seed" group of modular robots that can build copies of themselves from raw materials would require advancing beyond a level of complexity that Von Neumann identified as essentially the equivalent of the sound barrier for engineered systems.
- ***Reconciliation with thermodynamics:*** Modular robots are, in many ways, examples of the kinds of self-organizing systems studied by molecular biologists and nanotechnologists. However, there are key differences. Most existing systems overcome entropy through brute force and unreasonable amounts of

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energy. Molecular systems, on the other hand, employ random diffusive processes in fundamental ways. Furthermore, they are entirely robust to the intrinsic noise found at the nanoscale. If modular robots are to be miniaturized to micro- and/or nanoscale, or if the ideas discovered in this community are even to be tied to nanotechnology, the stochastic nature of nanoscale systems must be addressed. The demonstration of a system where stochastic fluctuations are the dominant factor would represent a fundamental advance: For example, pour a large collection (e.g., 1,000) of simple robots into a solution, mix them, and have them aggregate into a predetermined structure, independent of initial conditions.

A number of these issues were discussed in [15] (and the references therein) and will be addressed in greater detail in a forthcoming issue of *IEEE Robotics & Automation Magazine* devoted to robotic self-replication and self-repair.

Conclusions

Modular self-reconfigurable systems have the promise of making significant technological advances to the field of robotics in general. Their promise of high versatility, high value, and high robustness may lead to a radical change in automation. Currently, a number of researchers have been addressing many of the challenges. While some progress has been made, it is clear that many challenges still exist. By illustrating several of the outstanding issues as grand challenges that have been collaboratively written by a large number of researchers in this field, this article has shown several of the key directions for the future of this growing field.

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Keywords

Modular, self-reconfigurable, self-reconfiguring, robot, grand challenges.

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Modular self-reconfigurable systems have the promise of high versatility, high value, and high robustness, making significant technological advances to the field of robotics that may lead to a radical change in automation.

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