

Self-Reconfigurable Robots

An Introduction

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**The MIT Press
Cambridge, Massachusetts
London, England**

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This book was set in Times New Roman on 3B2 by Asco Typesetters, Hong Kong.
Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Stoy, Kasper, 1973–

Self-reconfigurable robots : an introduction / Kasper Stoy, David Brandt, and David J. Christensen.
p. cm. — (Intelligent robotics and autonomous agents series)

Includes bibliographical references and index.

ISBN 978-0-262-01371-0 (hardcover : alk. paper) 1. Robotics. 2. Robots. I. Brandt, David, 1979–
II. Christensen, David J. III. Title.

TJ211.S794 2010

629.8'92—dc22

2009021060

10 9 8 7 6 5 4 3 2 1

1 Self-Reconfigurable Robots

Imagine that an unexpected event happens on a Mars planetary mission: a Mars rover has located a cave from which a strange light is coming. The entrance to the cave is too narrow for the rover to enter, but scientists are eager to examine the cave and find the light source. Luckily, they have brought a self-reconfigurable robot along. In the safe environment of their Martian habitat they assemble a snakelike robot and send it out on the surface of the planet through an airlock. The robot bites its own tail and forms a rolling track and rolls toward the cave at high speed. Upon arrival, the robot changes back into the shape of a snake and makes its way down into the narrow cave toward the light.

Imagine a crisis in the IKEA company: after many years of patience and prostration, customers have finally given up on assembling furniture themselves. IKEA decides to acquire one of the new morphing production lines that is based on self-reconfigurable robot technology to do the assembly. On the factory floor, workers feed furniture parts to the morphing production line. The production line engulfs the parts and changes its shape internally to sort, transport, align, and assemble the parts. Finally, the production line spits out assembled furniture at the other end.

These scenarios may seem like the product of a good imagination, but they are in fact scenarios that we are seriously considering today in the self-reconfigurable robot community. The focus of the ICRA 2008 Contingency Challenge, organized by Mark Yim, was to develop robotic solutions to unforeseen problems that can happen in a simulated Martian habitat (see figure 1.1). The competing teams were given four and a half hours to create a robot, program it, and solve such tasks as replacing and repairing solar panels outside the habitat, repairing damaged air ducts, and patching leaks in the habitat. To simulate space and weight restrictions on an extraplanetary mission, the teams were only allowed to bring what they could fit in a suitcase. The Morpheus team from the Information Sciences Institute at the University of Southern California (USC) in Los Angeles won the competition, perhaps because they had some experience from the SuperBot project sponsored by the National Aeronautics



Figure 1.1

Top: The ckBot practicing for the ICRA Contingency challenge. The robots enter the area through the “air-lock” in the upper right corner of the photo. Bottom: Some contestants gaining gray hairs at an alarming rate. (Courtesy of Sastra, © 2007)

and Space Administration (NASA) and led by Wei-Min Shen. The goal of this project was to develop self-reconfigurable robots for use in space.

The scenario of morphing production lines is inspired by the project of the same name that we are currently running at the University of Southern Denmark. Our goal is to develop a prototype of an assembly system based on self-reconfigurable robots.

These two projects represent a new generation of ambitious ventures undertaken by the self-reconfigurable robot community. That we dare to undertake such ambitious projects is due to the progress we have made in the field over the past twenty years and in particular within the past decade. It is this research that we will present in this book, but let us start with the basics.

1.1 What Is a Self-Reconfigurable Robot?

Self-reconfigurable robots are built from modules, which are a kind of robotic cell. Typically, a robot consists of ten to a hundred modules, but robots consisting of thousands of modules have been simulated. Each module is a simple robot containing all the on-board components required to create a robot: actuators, sensors, batteries, and processing power. In addition, a module has a way of communicating with other modules and active connectors that allow it to connect to neighboring modules and disconnect from them again. The on-board actuators allow a module to move itself with respect to connected, neighboring modules or to move a neighboring module. This, in combination with the active connectors, allows a module to wander around on a structure of modules by going through sequences of disconnect, move, and connect operations. Since all the modules of the robot can do this, the robot as a whole can change its shape. This ability to change shape is what sets self-reconfigurable robots apart from all other types of robots.

Let us look at a concrete example. Figure 1.2 shows a single module of the ATRON self-reconfigurable robot. This module is composed of two half-spheres that can rotate with respect to each other. The module has four male and four female connectors, two of each type on each hemisphere. The male connectors consist of two opposed sets of hooks that can grab onto the two bars of the female connectors as shown in figure 1.3. You can connect the ATRON modules in many ways, forming many different kinds of robots, including snakelike and carlike robots, as shown in figure 1.4. The robot can change between these shapes by going through a relatively complex sequence of self-reconfiguration steps. A single step is shown in figure 1.5, where an ATRON module disconnects from a neighboring module by contracting a male connector, is rotated by a neighboring module to a new position, and finally connects to a neighboring module at the new position.

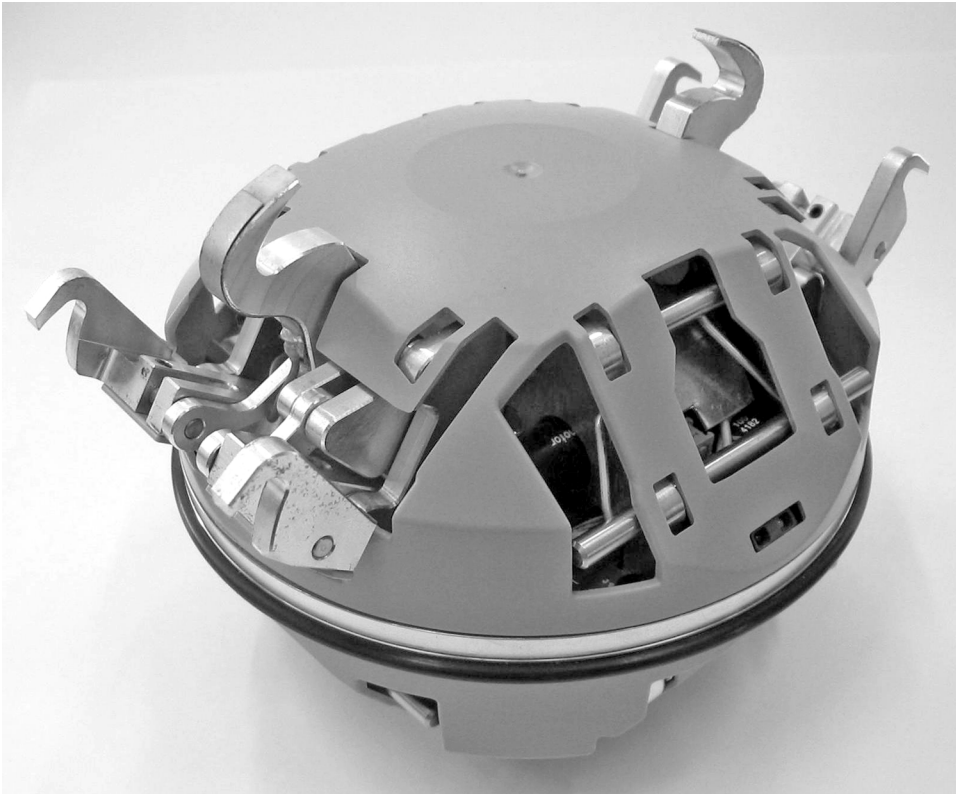


Figure 1.2

The ATRON module with its male, metallic connectors extended. The male connectors are actuated and can connect to a female connector of a neighboring module and thereby join the two modules.

All self-reconfigurable robots of the *lattice type* perform self-reconfiguration in a way similar to that of the ATRON robot. Lattice-type robots are a type of self-reconfigurable robots in which modules are organized in a lattice structure similar to the way atoms are organized in a crystal. The exact implementation of a self-reconfiguration step varies from robot to robot, owing to the differences in module geometry, number of connectors, degree of freedom, etc., but fundamentally a self-reconfiguration step is based on a sequence of disconnect, move, and connect.

Another type of self-reconfigurable robot is *chain-type* robots. These robots are not organized in a lattice structure and therefore a self-reconfiguration step consists of an additional step in which two modules that are about to connect search for each other before connecting. They have to perform this search since they cannot rely on each other being in a certain position, as they would be in a lattice-type robot. Figure 1.6 shows an example of a self-reconfiguration step in a chain-type system.

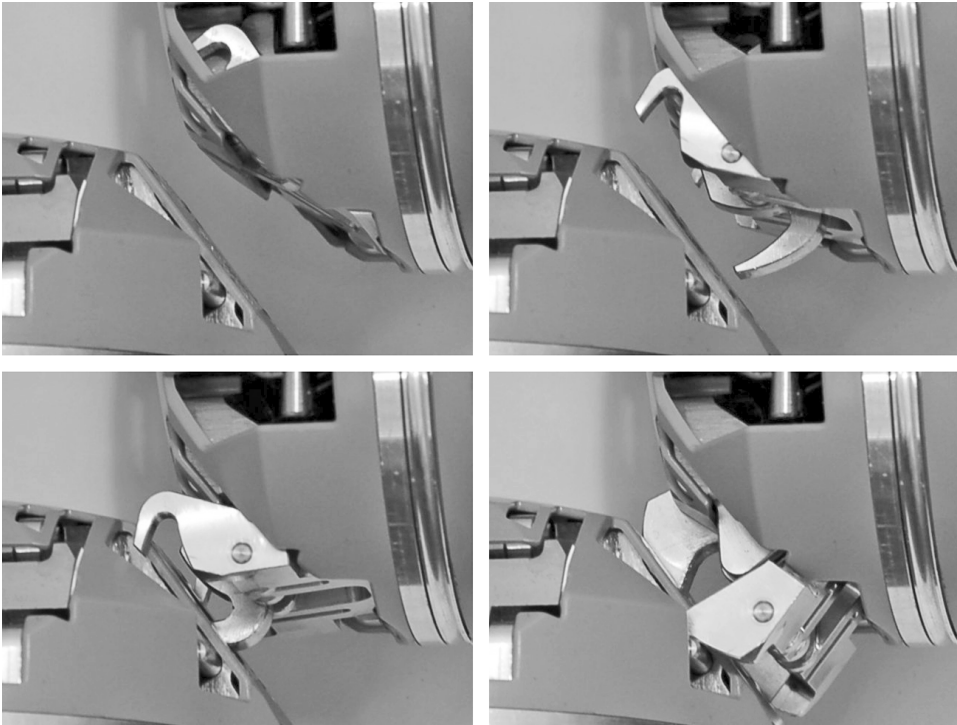


Figure 1.3

The ATRON module connects to a neighboring module by extending its male connector and can disconnect by retracting it.

The observant reader may note that the ATRON can also make a self-reconfiguration step outside its lattice, just like the chain-type robots. This is because ATRON, in fact, is a *hybrid* self-reconfigurable robot because it can exist in both forms: out of lattice and in lattice. Besides these three main types, there are a few alternative ways to implement self-reconfiguration, but we will postpone the discussion of these to chapter 3.

After this brief description of how self-reconfigurable robots are able to change shape, let us define what we mean by a self-reconfigurable robot. Even though it is always difficult to capture a concept such as self-reconfigurable robots, especially given the rapid development of the field, we give a definition inspired by E. H. Ostergaard [79]. Self-reconfigurable robots are robots that satisfy the following criteria:

Modular The robot is built from several physically independent units that encapsulate some of the complexity of their functionality.



Figure 1.4

Many different robots can be built by connecting modules in different ways. Here a number of ATRON modules are connected to form snakelike robots as shown on the left and a small, carlike robot shown on the right.

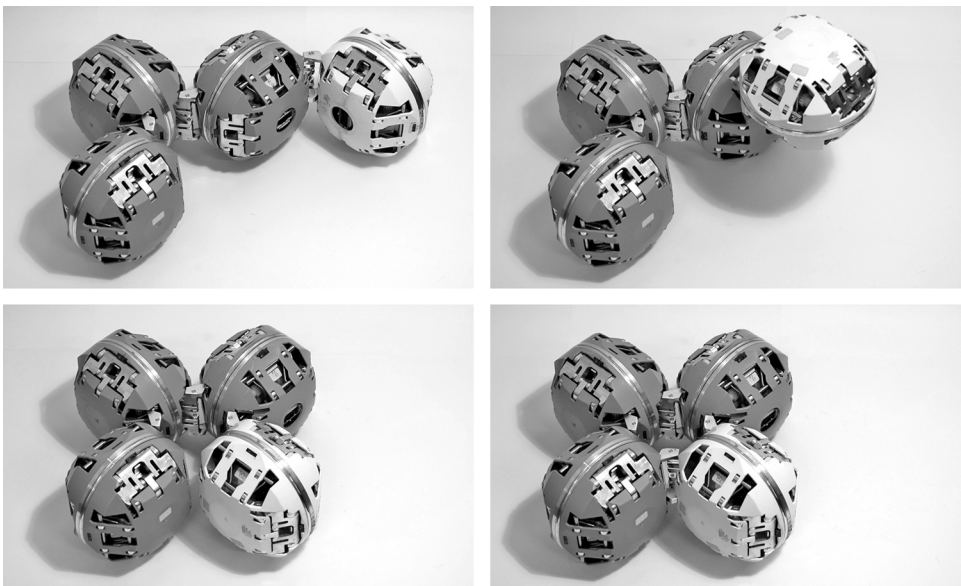


Figure 1.5

A self-reconfiguration step in the ATRON robot consists of a disconnect, a rotation, and a connect operation.

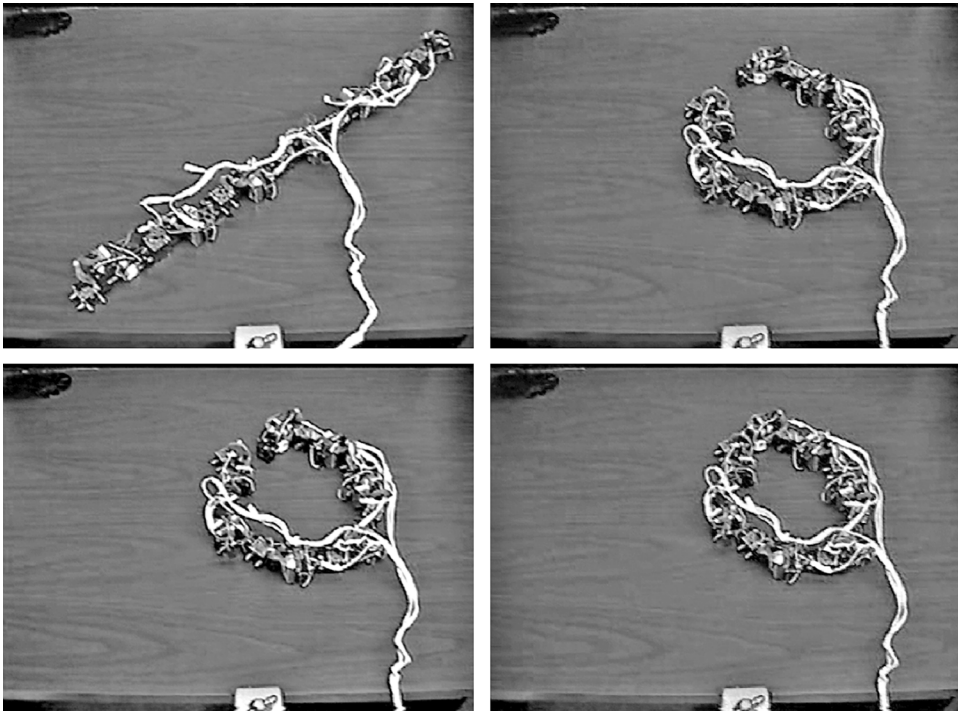


Figure 1.6

A self-reconfiguration step in the CONRO robot. (a) The robot starts in a long, snakelike configuration. (b) It then bends in on itself. (c) The two ends search and locate each other using infrared sensors and transmitters. (d) The two ends connect: the right module connects to a side connector of the left module. (Courtesy of Shen)

Reconfigurable The modules can be connected in several different ways to form different robots in terms of size, shape, or function.

Dynamically reconfigurable The modules can be disconnected and connected while the robot is active.

Self-reconfigurable The robot can change the way modules are connected by itself.

The nature of being modular is to encapsulate some of the complexities of the functionality of a module. This means that while regular screws are not modules, a drilling machine is. However, in order to be part of a modular robot, a drilling machine has to be connected to at least another module, e.g., a robot arm.

Our example drilling robot is not a reconfigurable robot. However, if we extend it with more tool modules, which can replace the drilling machine, then it becomes reconfigurable. If, furthermore, we are able to change modules while the robot is active, it becomes a dynamically reconfigurable robot. For example, if we can replace

the tools of our example robot, it becomes dynamically reconfigurable. Finally, if the robot can change by itself the way modules are connected, it becomes a self-reconfigurable robot. That is, if our example robot arm can change its tools, it is a self-reconfigurable robot.

The example robot arm with replaceable tools represents an extreme of what defines a self-reconfigurable robot. However, it is clear that it is not a typical self-reconfigurable robot. A typical self-reconfigurable robot is extendible with regard to the number of modules; the complexity of different modules is often comparable; and the number of modules is often higher. We could have created a more restrictive definition, but the proposed definition serves as a good guideline for what defines a self-reconfigurable robot. In fact, from this definition we are able to derive the potential features of self-reconfigurable robots, as we will see in the following section.

1.2 Features

Self-reconfigurable robots have some unique features that make them interesting from an engineering point of view. Owing to their modular nature, self-reconfigurable robots have a high degree of redundancy, which they can exploit to become *robust*. A hardware failure or a software error may cause a module to fail. This, however, does not cause the self-reconfigurable robot as a whole to fail. The remaining modules can compensate for the loss of a module. Therefore the system is robust and its performance degrades gracefully with the number of failed modules. It may also be possible for the robot to use its ability to change shape to replace broken modules with spare ones in the system if any exist. Through this self-repair ability, the robot may stay functional even if a substantial number of modules fail.

A self-reconfigurable robot is *versatile*: the modules can be combined in many different ways, allowing them to form the basis for a wide range of different robots. Furthermore, a self-reconfigurable robot is *adaptable* because it can continually adapt and even completely change shape if a task requires it.

Self-reconfigurable robots are *cheap compared with their complexity*. The individual modules are quite complex and, as such, are expensive to produce. However, a self-reconfigurable robot consists of many identical modules and therefore, the cost of the individual module can be lowered because they can be mass produced.

In summary, self-reconfigurable robots are versatile, adaptable, robust, and cheap considering their complexity. It is important to note that these features are only potential features. In theory, it should be possible to realize these features based on the concept of self-reconfigurable robots. However, in practice, the features are often realized only to a limited degree, as we will see in later chapters. Before we go into the technical details, let us put these robots into context by taking a tour through their history.

1.3 Brief History

The hope of creating robust, versatile, adaptable, and cheap robots has led researchers to develop a succession of ever-improving self-reconfigurable robots. In this section we review the history of self-reconfigurable robots so we can understand and appreciate the advances that have resulted in the modern generation of these robots.

1.3.1 From the Industrial Revolution to Robot Manipulators

Self-reconfigurable robots and robots in general are probably best understood in the context of the Industrial Revolution. The Industrial Revolution started around 1733 in the textile industry with inventions such as Sir Richard Arkwright's spinning frame, the first automated spinning machine. During the eighteenth century, many other machines were invented and the revolution picked up pace. It was further reinforced by James Watt's steam engine, introduced in 1769, which replaced water as a power supply.

After the invention of the worm gear, introduced by Ramsdan's dividing engine in 1774, the precision of machines was increased and spread to other industries. Improved precision also meant that the concept of replaceable parts became possible because the machines now had high enough precision to make things to specification every time. This opened the path to mass production, which was refined during the nineteenth century to culminate in Henry Ford's car factory in 1908, which pioneered the first conveyor belt assembly line.

On the assembly line, tasks were cut into small simple tasks so that an unskilled worker could do quickly and efficiently. The simplification of these tasks made it possible to introduce the next generation of machines—the robot manipulators. General Motors introduced the Unimation 1000 into their car assembly line in 1961. Unimation Inc., founded by George Devol five years earlier, produced this robot. In the following years, and even today, robot manipulators are optimized for doing one task fast and precisely. The result of this is the incredibly fast and precise robot manipulators we have today. The ABB IRB340 FlexPicker, shown in figure 1.7, has a top speed of 10 m/s, a precision of 0.1 mm, and can carry a payload of 2 kg. Other trade-offs between speed and payload exist, such as the KUKA KR 6/2, which can handle a payload of 6 kg and a top speed of 4 m/s.

1.3.2 Robots in Fiction

In 1920 the author Josef Capek published his play "Rossum's Universal Robots," in which he described machine slaves, i.e., robots, that would aid humanity. Little did he know that this idea would form the guiding light and inspiration for many engineers and scientists for the rest of the twentieth century and into the twenty-first. The technology at the time was of course not mature enough to even attempt to realize



Figure 1.7

The IRB 340 FlexPicker. This is the culmination so far in the continuous effort of creating faster and more precise robot manipulators. (Courtesy of ABB, © 2005)

this dream; rather, mechanical multiplication machines were at the cutting edge in the 1930s.

Isaac Asimov was the next to elaborate on robots with his famous short stories “Robbie” in 1940 and “Runaround” in 1942 (both short stories can be found in the 1950 book titled *I, Robot*). Asimov’s writing on robots mainly considered the ethical aspects of robots and he also formulated the now-famous three laws of robotics (from “Runaround”):

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey orders given to it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

After this, robots were a recurring theme in science fiction. However, for self-reconfigurable robots, the big breakthroughs were in the movies *Terminator 2: Judgment Day* (1991), *The Matrix Revolutions* (2003), and the series of transformers comic books and movies, culminating in the movie *Transformers* (2007). All these movies featured robots that could automatically change their own shapes. Perhaps some of these works of fiction inspired Toshio Fukuda, who among others, created the philosophical foundation for the field of self-reconfigurable robots as we know it today.

1.3.3 The Cellular Robot

In the 1980s the idea of distributed robotic systems emerged. The idea was that instead of building robots as monolithic, inflexible pieces of hardware optimized for speed and precision, they could be built using a cellular design not unlike the one employed by nature. These cellular robots could autonomously split into their constituent cellular, robotic modules that later could recombine to form a new robot. One example Toshio Fukuda gave was a robot that could move into environments that are difficult to reach, e.g., accessible only through narrow openings, and once inside change shape by itself to accomplish a task (see figure 1.8). The hope was that this approach would provide robots with an unprecedented level of versatility and robustness.

The early work was mainly conceptual in nature because the technology was not mature enough at the time to realize many of the ideas. For example, in 1991 G. Beni and J. Wang [4, 47] concluded, after having worked in the area for a while, that:

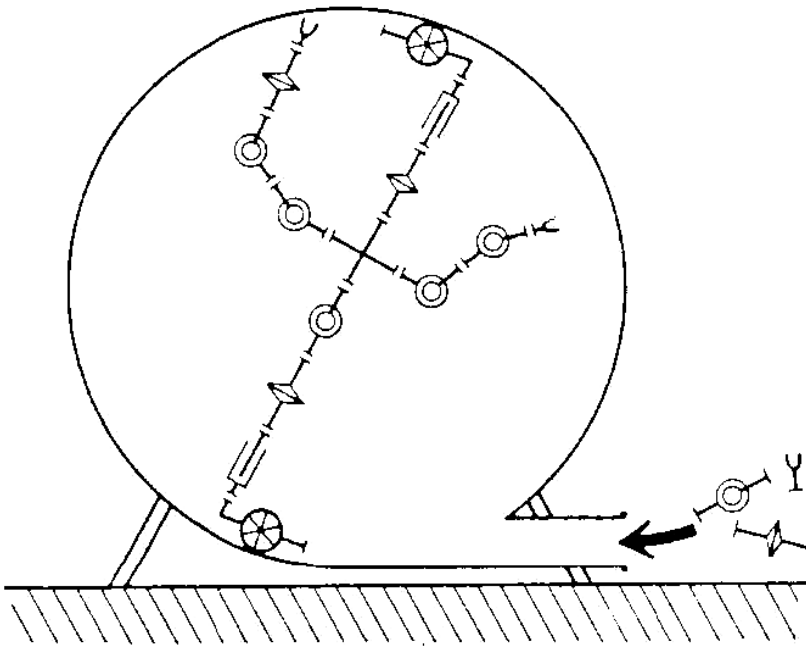


Figure 1.8

An early artistic impression by Fukuda [45] of cellular robots doing maintenance work in a storage tank. (Courtesy of Fukuda, © 1988 IEEE)

While the most urgent problem for the realization of distributed robotic systems is the construction of the physical structure of the units, the most fundamental problem remains the design of algorithms. [4: 1919]

One of the people who started to implement part of the conceptual framework was Toshio Fukuda. He began by considering which types of modules were needed to build a robot. In his original work he proposed a heterogeneous system consisting of three types of modules. Type 1 modules would be used for actuation, i.e., joints and wheeled modules. Type 2 modules would be structure modules, i.e., branching modules or power modules. Type 3 modules would be modules with tools and other special-purpose modules. He was also interested in how they could be combined to accomplish a task. In the following years Fukuda worked toward realizing this vision through many iterations of the CEBOT system (CELLular roBOT), which in essence became a multirobot system consisting of mobile robots [44].

In this early work, self-reconfigurable robots were not as clearly defined as today since the distinctions between other types of robots such as multirobot systems, sensor networks, or cyborg, were not made yet. Instead they were all considered distrib-

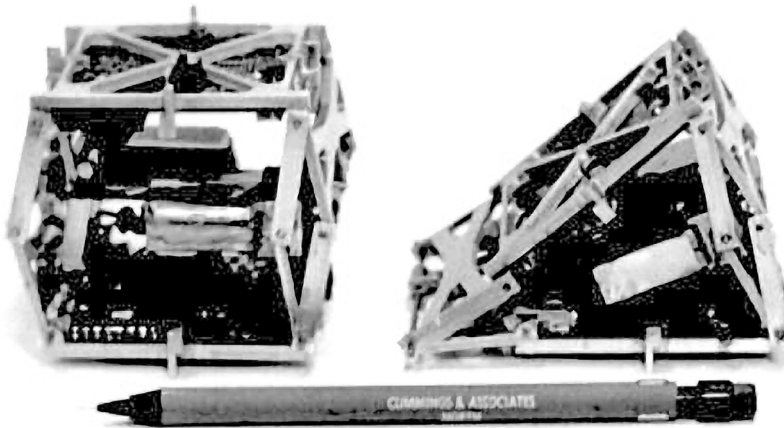


Figure 1.9

A segment module of the PolyPod robot, a predecessor of chain-type self-reconfigurable robots. (Courtesy of Yim, © 1994)

uted robotic systems. However, in this early beginning, the motivation for creating self-reconfigurable robots, which still drives us today, became clear.

1.3.4 The First Self-Reconfigurable Robots

The first self-reconfigurable robots became reality a few years later. In 1993 Mark Yim [139] built PolyPod, which demonstrated the versatility of a modular design (see figure 1.9). Yim showed that by connecting the two types of modules of the PolyPod in different ways, he could implement many different gaits [140]. The PolyPod robot was dynamically reconfigurable, but was unable to change shape by itself and therefore is not a self-reconfigurable robot. Mechanically, PolyPod is an important predecessor to the class of chain-type self-reconfigurable robots we introduced in section 1.1 and that we will describe in more detail in section 3.1 in chapter 3. However, for now, the important aspects of chain-type robots are that they form chains and treelike structures, possibly also containing loops, and are mainly geared toward locomotion.

Around the same time, another two new robots, shown in figure 1.10, arrived: the Fracta robot built by Satoshi Murata, Haruhisa Kurokawa, and Shigeru Kokaji [73] at the National Institute of Advanced Science and Technology in Tsukuba, Japan and the Metamorphic robot built by Gregory Chirikjian [27] at Johns Hopkins University, in Baltimore, Maryland. These robots demonstrated the ability to change shape in two dimensions. Interestingly enough, the self-reconfiguration ability was implemented in two completely different ways. In Fracta it was realized using electromagnets, and in the Metamorphic robot it was realized mechanically. In these

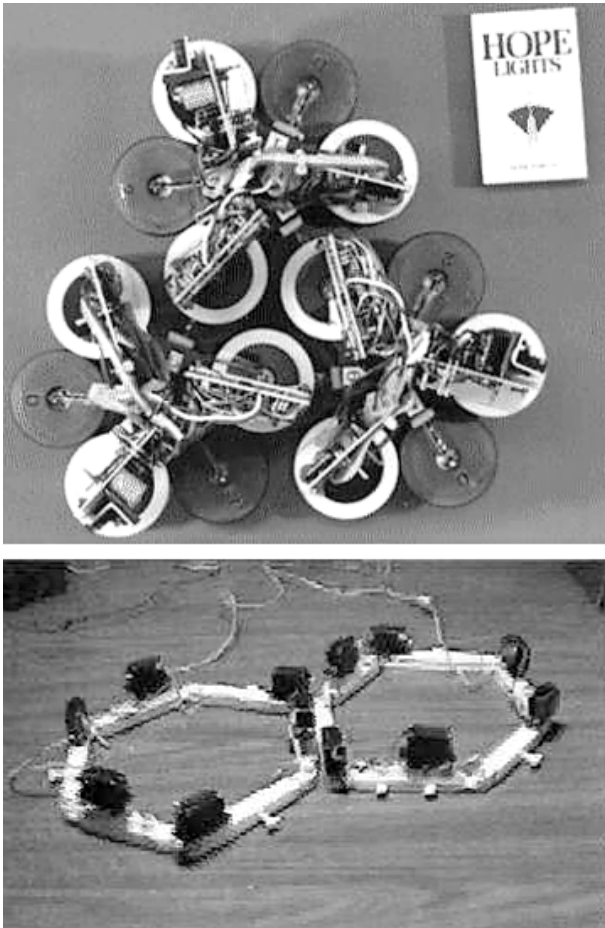


Figure 1.10

Early lattice-type self-reconfigurable robots: Top: Three Fracta modules. (Courtesy of Murata) Bottom: Two modules of the Metamorphic robot. (Courtesy of Chirikjian)

robots the configuration of modules forms a lattice, which is why they later became known as lattice-type self-reconfigurable robots, which, as mentioned, are robots in which the modules are organized like atoms in a crystal.

1.3.5 The Exploration Phase

In these early years the split between chain-type and lattice-type self-reconfigurable robots was made. In the following years, the chain-type systems were improved to be able to do self-reconfiguration, and the lattice-type systems were improved to achieve three-dimensional self-reconfiguration.

A new chain-type self-reconfigurable robot, CONRO [24], was introduced in 1999 by Andres Castaño et al. [24] and the following year Yim et al. [142] presented an improved version of PolyPod, the PolyBot robot (both shown in figure 1.11). Although both systems excelled in demonstrating a wide range of locomotion patterns, both systems struggled to demonstrate self-reconfiguration. It turned out to be more difficult than expected to make two chains meet and connect based on infrared sensing alone. A systematic solution to this problem has actually been proposed recently [89], but it remains a significant problem.

Self-reconfiguration in three dimensions was also a difficult problem, owing to gravity and geometrical constraints. In three dimensions, modules have to be strong enough to lift other modules against gravity to achieve self-reconfiguration. In two dimensions, the third dimension is unconstrained and it was used as extra space and was an obvious place to attach wires for a power supply. This was no longer possible in three dimensions; the complete module had to fit into the lattice structure. The earlier Fracta and Metamorphic robots had used a method of “rolling around” neighbors using tracks running around modules. It was not obvious how that generalized to three dimensions because the “tracks” then would have to cross each other. It was therefore a breakthrough when in 1997, Keith Kotay and Daniella Rus [95], then at Dartmouth College in Hanover, New Hampshire, presented the Molecule and Murata et al. [75] presented the 3D-Unit, the first three-dimensional self-reconfigurable robots (see figures 1.12 and 1.13). The solution adopted was an internal actuator in a module that allowed one part of a module to rotate with respect to the other. In the earlier systems, moving and connecting were the same physical action. However, in the Molecule for the first time these actions were split into a sequence consisting of a disconnection, a move, and a connection. This split the self-reconfiguration problem into, on one side, connecting and disconnecting and, on the other, moving, and thus making the mechanical problem more manageable. Ünsal et al. [129] at Carnegie Mellon University in Pittsburgh, Pennsylvania, also used a similar idea in the I-Cubes system. This system was heterogeneous and consisted of passive cubes and active links.

Another implementation of self-reconfiguration is to make modules contract and expand rather than rotate. This approach was pioneered in two dimensions in Rus and Vona’s [97] Crystalline robot in 1999 and in three dimensions in Suh et al.’s [122] Telecube in 2001, shown in figure 1.14. A self-reconfiguration step would then typically consist of an expansion, a connection to a module in a neighboring lattice position, a disconnection from neighboring modules in the original lattice position, and a contraction. The contraction and expansion were implemented using telescoping arms, which is a mechanically fragile solution.

An attempt was also being made to miniaturize the two-dimensional Fracta, the result of which was the Micro-Unit developed by Eiichi Yoshida et al. [150] at the

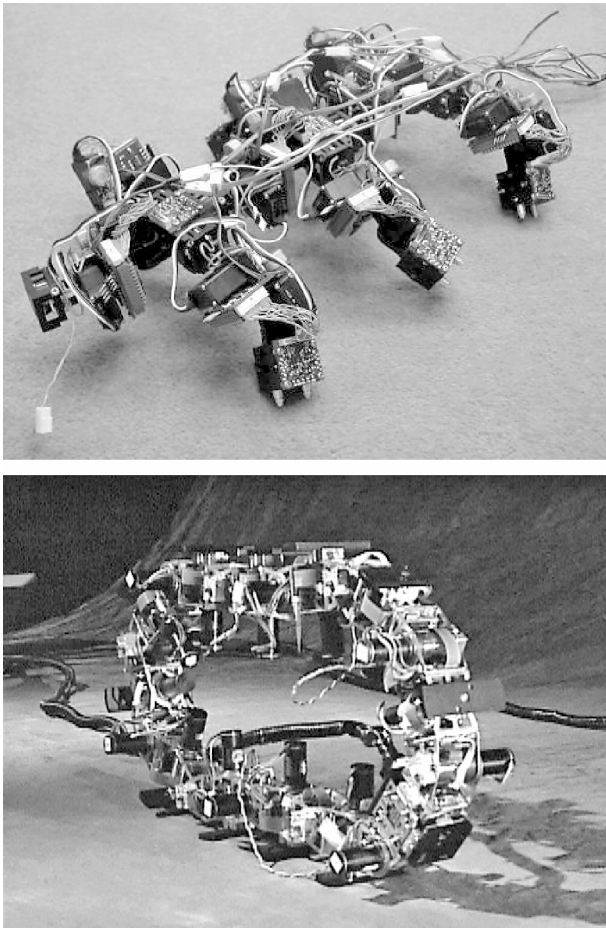


Figure 1.11
Chain-type self-reconfigurable robots. Top: CONRO in a hexapod configuration. (Courtesy of Stoy, © 2002 IEEE) Bottom: Second-generation PolyBot in a loop configuration. (Courtesy of Yim, © 2000 IEEE)

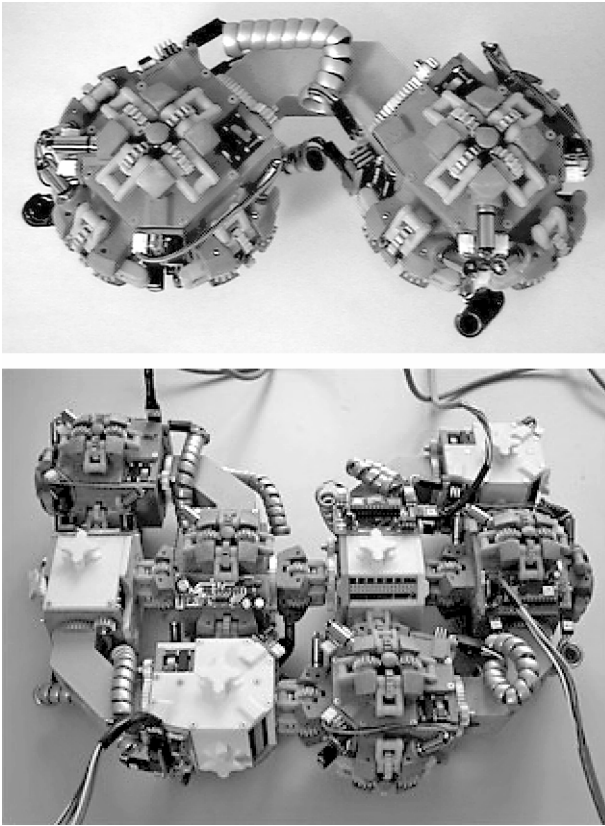


Figure 1.12

Top: A module of the Molecule self-reconfigurable robot. (Courtesy of Kotay, © 2005 IEEE) Bottom: A configuration of four modules. (Courtesy of Rus) The Molecule robot was the first self-reconfigurable robot able to perform self-reconfiguration in three dimensions.

National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan. The final prototype of the Micro-Unit [151] was very small, with a volume of 8 cm^3 , excluding electronics.

Toward the end of this period the two branches of self-reconfigurable robots had matured. Chain-type and lattice-type robots complemented each other: chain-type robots were able to produce advanced locomotive gaits and lattice-type robots could change shape in three dimensions.

1.3.6 The Hybrids

In 1999 the two branches of lattice-type and chain-type self-reconfigurable robots were merged in the M-TRAN robot by Murata et al. [76] (see figure 1.15). Owing

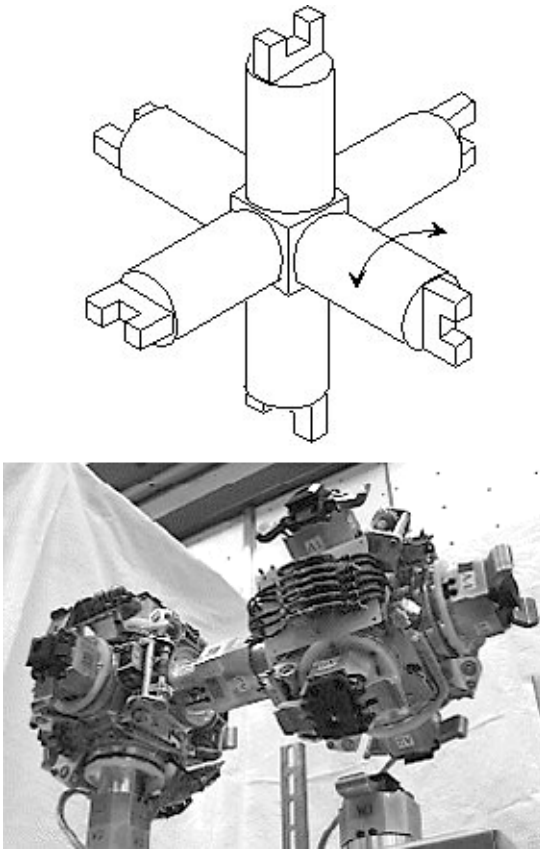


Figure 1.13

The 3D-Unit module. Top: The basic design of a single module; each module has six connectors and six rotational joints. Bottom: A picture of two connected 3D-Unit modules. (Courtesy of Murata)

to an innovative mechanical design, an M-TRAN could exist in both a lattice structure, making self-reconfiguration relatively easy, and in a chain-type structure, making locomotion easy. In 2006 Shen et al.'s [103] SuperBot appeared, which included an extra degree of freedom compared with the M-TRAN robot. In M-TRAN the actuators were parallel to each other; in SuperBot a degree of freedom was added to make the orientation between these two actuators controllable. The ATRON robot developed in 2003 by Jorgensen et al. [52, 82] at the University of Southern Denmark, Odense, was the second hybrid robot. It introduced the novel idea that three-dimensional self-reconfiguration could be achieved even though each module only had one actuator. This was accomplished by arranging modules, and thus their rotational axes, perpendicular to each other. Victor Zykov et al. [159] at Cornell University in Ithaca, New York, used a similar idea in the design of the Molecube robot.

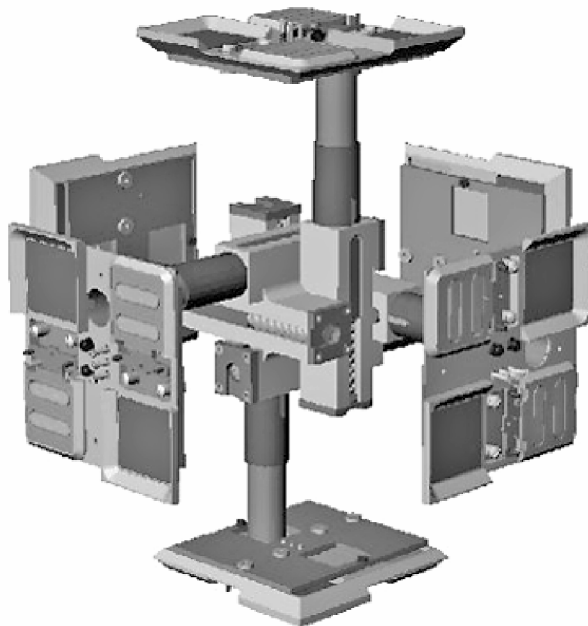
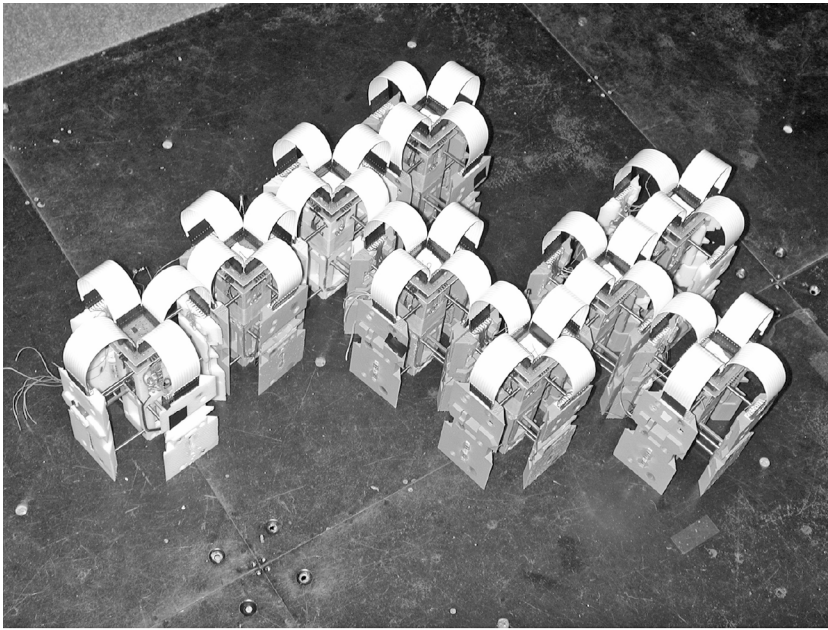


Figure 1.14
The Crystalline robot (top, courtesy of Rus) and the Telecube (bottom, courtesy of Suh, © 2002 IEEE).
The modules of these robots are able to contract and expand.

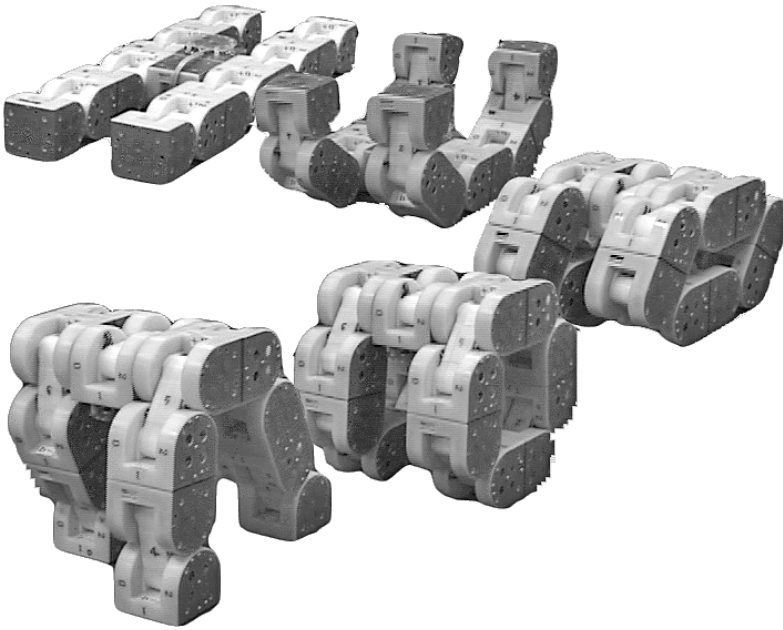


Figure 1.15

The M-TRAN robot combined the features of lattice-type and chain-type robots in one system through an innovative mechanical design. (Courtesy of Murata)

In the meantime, other systems were also created to improve on earlier designs. There is the Gear-Type unit introduced by Hiroko Tokashiki et al. [126] at the University of Ryukyus, Japan, in which modules are magnetic gears and thus can roll around each other quickly, and Chobie, developed by Michihiko Koseki et al. [59] at the Technical University of Tokyo, Japan, which is a vertical, two-dimensional module. However, like the early designs, it is not obvious how to generalize these to three dimensions.

1.3.7 State of the Art

Self-reconfigurable robots have undergone almost twenty years of development and today we have several self-reconfigurable robots that can reliably perform different locomotion patterns and change their own shape. This essentially means that the basic technical challenges that prevented the early thinkers from realizing their vision have been overcome. However, new challenges await the research community as self-reconfigurable robots leave the realm of basic research and move toward application. We postpone the discussion of these challenges to chapter 10, at which point we will have gained a deep insight into the design and control of these robots and thus a better basis for understanding the challenges.

1.4 Pack, Herd, and Swarm Robots

Self-reconfigurable robots vary in terms of how many modules it takes to construct a robot and how small the individual modules are. Here we define three categories of self-reconfigurable robots. Even though they are not standard categories in the literature, we have found them to be useful in this book. The categories are pack, herd, and swarm robots.

Pack robots consist of tens of modules. The modules are generally characterized by having a strength comparable to the group's size. This means that the individual module by itself is useful and certainly can lift itself, but also is able to lift a large fraction of the other modules in the robot and thus make it possible for one module to be a functional unit in the robot, such as a leg. Each module in the system plays a crucial role and it is therefore of crucial importance that they are strictly coordinated to work together to achieve the robot's goal. We can compare this to a pack of wolves hunting, where the performance of each wolf is significant to the outcome of the hunt. We therefore refer to these robots as pack robots.

Herd robots consist of hundreds of modules. The strength of these modules is moderate compared with the group size, and the functionality of the individual is limited. This means that one module is still able to lift itself but cannot be a functional unit in the robot by itself. Functional units are always built from groups of modules. In these systems there is enough redundancy to allow less strict coordination without significantly affecting the performance of the system. It is still possible to control each module centrally, but at a significant cost in performance. In these robots the modules generally work together to perform the robot's task, but not as tightly as in pack robots; modules can stray from time to time. Modules in these robots can be compared to deer in a herd and thus we call these robots herd robots.

Swarm robots are a more common term. These robots consist of myriads of modules. Individual modules are weak and have limited influence on the robot as a whole. Only by coming together can the modules do something that influences the robot, and massive numbers of modules are needed to create a functional unit in the robot. In these robots it is impossible to control the myriads of modules centrally and therefore the modules must be autonomous to a high degree. These robots act as swarms that cannot be controlled, but live and develop according to their own rules, similar to swarms of bees or ants. We therefore refer to these robots as swarm robots. To summarize:

Pack robots These robots consist of tens of modules and must usually be tightly coordinated because the actions of individual modules are crucial for the performance of the robot.

Herd robots These robots consist of hundreds of modules and can be globally coordinated only with difficulty; they are better controlled as a collection of groups since

the actions of individual modules are still important but not crucial for the performance of the robot.

Swarm robots These robots consist of myriads of modules and, owing to the number of modules, are difficult to coordinate globally. Instead each module is controlled locally, which is possible because each module has little effect on the overall behavior of the robot.

The rationale for having a herd category requires a little more explanation. The main point is that robots in the herd category are problematic. Algorithms designed for pack robots that are either centralized or require modules to be tightly coupled typically start to face scaling problems: it is difficult to keep hundreds of modules tightly coordinated, particularly for robots relying on local communication. On the other hand, it is difficult to scale down the highly scalable algorithms for swarm robots because the movement of each module is important for the herd as a whole and therefore the stochastic processes of swarm robots are not well suited. In other words, you still need the tight coordination of pack robots even though the robot is medium sized. It may be possible to break this barrier between pack robots and swarm robots by organizing the system in a hierarchy, but for now we view herd robots as problematic.

The classification described here does not apply only to hardware. We can also talk about pack controllers, herd controllers, or swarm controllers. This distinction is important because on the one hand, in the pack controllers randomness cannot be used since each module has to be controlled carefully; on the other hand, in the swarm controllers randomness is a powerful mechanism and it is impossible to control each module carefully (i.e., provide it with all the information it needs to select the optimal action). We find this distinction useful for classification of systems and it can help a researcher decide when to apply which algorithm. For example, we cannot hope to apply pack algorithms to swarms and the other way around, although there may exist smaller groups of modules within the swarms that we want to control as packs or herds. This is one of the challenges of controlling self-reconfigurable robots: how can we maintain tightly coordinated control in critical parts of the robot while allowing larger parts of the robot to work as a swarm with looser coordination?

1.5 From Vision to Application

Self-reconfigurable robots have not been used yet since it is only within the past few years that they have matured to a degree where applications are possible. However, in the twenty years since the idea of self-reconfigurable robots was conceived, numerous applications have been envisioned; they range from being realizable today to pure science fiction. At the immediately realizable end are advanced robot applica-

tions that benefit from the unique features of self-reconfigurable robots. At the futuristic end, the idea that self-reconfigurable robots are universal robots, in the sense that they can simulate any robot, is taken to its extreme.

Pack robots are the ones closest to application. They have the advantage that a relatively limited and therefore affordable number of modules are used. The coordination of a limited number of modules is also significantly easier, and solutions to basic tasks such as locomotion and self-reconfiguration exist. Therefore, applications for these types of robots are technologically within reach; the question is whether there is a niche in the marketplace in which pack robots will fit.

Pack robots are generally well suited for exploration and inspection applications. In these applications the pack robot can exploit its versatility to adopt a locomotion style that fits the different environments and terrains it encounters. Locomotion styles may include swimming, running, climbing, and rolling. One proposed application for pack robots is to assist in search and rescue in collapsed buildings. The pack robot could search the building using its ability to change shape to gain access to places human rescue workers cannot reach. Another, similar application from a technical point of view, is sewer inspection. The pack robot becomes even more useful in applications where it can take advantage of its robustness and ability to self-repair. One such application is exploration of extraterrestrial environments. In such hard-to-reach environments it is important that the robot is able to maintain some level of functionality even if some modules fail. A concrete example is the SuperBot project in which the ambition was to support life on other planets [99]. The SuperBot robot would land on another planet, find a suitable location to plant a seed, and finally protect the seed from the environment in the early phases of its life.

The pack robots are small and agile and this gives them advantages in exploration and inspection applications, but as soon as the robot needs to interact with the environment, it needs to be larger and stronger. Therefore, herd robots are often better suited than pack robots for tasks that require interaction with heavy objects. Herd robots, for instance, would be better suited for search and retrieval tasks than pack robots: a herd robot could search a cave for interesting rock samples and transport them back to a lab for further analysis, or it could find and retrieve humans from a collapsed building. The herd robot could also reinforce a collapsed building to make it safe for rescue workers to enter. Herd robots have a sufficiently high number of modules to make it possible to differentiate functionalities of different parts of the robot. We have therefore proposed to make a *morphing production line*.

This production line could handle many of the handling operations in industry today, such as transporting, sorting, manipulating, and assembling objects. A herd robot could take advantage of its adaptability by adapting its shape to the objects being handled, making categorization and sorting easy, and it could also change configuration to match changing demands on the production line. For instance, a herd

robot could decide to perform time-intensive tasks in parallel. Another task is creating ergonomic furniture. Here again the idea is to use the adaptability of the herd robot to fit a piece of furniture to the person using it and the task that person is doing. It may even be possible to use furniture as a highly adaptable user interface.

Realizing swarm robots is still an ongoing basic research effort, but if it is successful, the potentials are enormous, depending on the cost. We may inject swarm robots into a blood vessel and have them perform surgery. We may use them for physical rendering, as proposed in the Claytronics project at Carnegie Mellon University, that is, physical three-dimensional displays that can change shape and allow easy user interaction. In a far future, we may start to think of swarm robots as a new type of automatic construction material from which everybody can create the artifacts that surround us today. Maybe all you need to do is to obtain a seed (a module carrying a DNA string if you will) from which you can automatically grow an artifact that has superior features compared to conventional materials, such as self-repair capabilities, recyclability, and adaptability.

Let us elaborate a little on this science fiction scenario. We rely on machines and robots to aid us in our everyday life. Some machines are versatile, but only to a limited degree. Once installed, it is unlikely that machines will or can perform different types of tasks. Robots are slightly more versatile because they can be reprogrammed for new tasks, but only tasks that are within their physical limitations; e.g., a robot arm is not going to drive you to work. The problem is that the physical structure of robots, and man-made objects in general, cannot easily and in-place be changed or, using a computer analogy, be reprogrammed for a new application. For a moment imagine that this is not the case. Imagine that man-made objects can in fact change shape on demand. What if two chairs can merge and make a couch? A couch can divide and become a table and a chair? A table and a chair can melt to become a carpet? Let's look at a science fiction scenario:

John wakes up and presses the button on his bed to morph his studio apartment into a bathroom. John sighs. "Maybe it is time to update the bathroom." The bathroom is an old revision from last year with no massage chair and tiles on the walls. John calls up the catalogue from the bathroom supplier with whom he has a subscription. A miniature bathroom appears next to the sink. He flips through a couple of bathrooms until one appears that has what looks like wooden walls and even an old-fashioned toilet. The traditional toilet became obsolete years ago since the entire room is self-cleaning, but John likes the retro style. He presses "OK" and within thirty seconds his bathroom is morphed. The revised bathroom even includes his fern; he could have chosen a tropical forest theme, but he likes to have a good old-fashioned plant. Also it is a lot easier to have now that the apartment takes care of it. At that point, a signal indicates that the studio has arrived at his work place. John finishes up while the studio morphs into an office. John takes one last look in the mirror before it disappears and walks out of his studio to greet his colleagues Marvin and Louis.

In John's world everything surrounding him is made from *morphing materials* except for a few things kept for nostalgic reasons. A morphing material is a kind of material that can intelligently control its own shape. It is a material not unlike the one from which Hollywood built their Terminator robots. Applications of morphing materials are of course not limited to killing machines like the Terminator, but may literally be unlimited, depending on the characteristics of the material, including cost and energy consumption. If we invent morphing materials it may, as in John's life, completely change the way we design, manufacture, use, and recycle our everyday objects because morphing materials will provide an extreme level of versatility. Morphing materials are of course science fiction, but self-reconfigurable robots may in the long, long term be the way to implement them.

1.6 Structure of This Book

In order to realize the advantages of self-reconfigurable robots and perhaps in the longer term the futuristic vision described here, we face two types of challenges. One is the challenge of how to build the modules of self-reconfigurable robots; the other is the challenge of their control. These two challenges are the main topics of this book. We will look at module design in chapters 3–4 and control in chapters 5–9. The core part of the book is followed by the final chapter on research challenges in the field of self-reconfigurable robots. However, we will begin by looking at the general design goals and characteristics of self-reconfigurable robots.

1.7 Further Reading

We list here two articles that introduce self-reconfigurable robots, which may give the reader an alternative introduction to this field. In addition we list a doctoral thesis in which the reader can find information regarding the question of how to define self-reconfigurable robots.

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M. Yim, Y. Zhang, and D. G. Duff. Modular robots. *IEEE Spectrum*, 39(2):30–34, 2002.

E. H. Ostergaard. Distributed control of the ATRON self-reconfigurable robot. PhD thesis, Maersk McKinney Moller Institute for Production Technology, University of Southern Denmark, Odense, 2004.