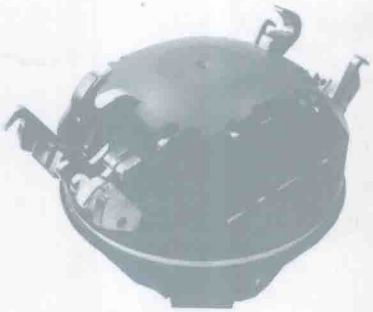

SELF-RECONFIGURABLE ROBOTS

An Introduction

KASPER STOY,
DAVID BRANDT, AND
DAVID J. CHRISTENSEN

Self-Reconfigurable Robots

An Introduction

Kasper Stoy
David Brandt
David J. Christensen

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Self-Reconfigurable Robots

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Foreword

Wouldn't it be great if we could not only change the shape that our arms or legs bend into, but disconnect and reconnect them in different places? Add extra arms or lengthen them? Self-reconfigurable robots aim to do something like that, changing their physical connectivity to suit a task. This idea is catching on. If you watch movies or read science fiction, there are countless examples of morphing robots, liquid-metal robots, nanorobots, and the like. While in science fiction self-reconfigurable robots are often world-conquering, with evil intent, this book presents research on self-reconfigurable robots that is growing worldwide, attracting active researchers and gaining public interest.

With this growth it is somewhat surprising that a book that explores this phenomenon has not yet been written. So the writing of this book is certainly timely; that Kasper Stoy, David Brandt, and David Christensen have done it in such wonderful fashion is especially gratifying to a person who has been active in the field for many years. This book collects and distills two decades' worth of research in a cogent fashion. It will be useful to students hoping to develop projects or thesis topics and even those robot movie enthusiasts who wonder how far we are from seeing a liquid-metal robot. However, most directly, this book will be valued by the self-reconfigurable robot research community.

This research community started with a handful of scientists and academics in the early 1990s and has grown to many dozens of groups located all over the world. The community has several opportunities each year to gather to discuss its members' research. In these conferences and workshops, researchers present their latest accomplishments in a positive light and talk about future directions and promises of their development. People are almost always congenial and congratulatory. It was in one of the many workshops held by this community that Kasper made his mark on me and set the tone for his research, and I think this book as well.

In the early 1990s I said that modular self-reconfigurable systems held three promises:

1. They can be versatile because they can change their shape and adapt to tasks as needed.
2. They can be robust because they have redundancy and the robots can self-repair, exploiting modularity.
3. They can be low cost as batch fabrication and economies of scale come into play.

As time went on, people would echo these words in various forms. However, in 2005 at the first Robotics Science and Systems conference in Boston, the self-reconfigurable robot community of the time gathered together and Kasper aired his thoughts on those promises. He said, "There are three promises for modular self-reconfigurable robots. The problem is that today, the systems are: (1) useless, (2) expensive and (3) they break all the time."

Given the standard congratulatory tenor of the workshop, the statement came as a shock. Kasper's comedic delivery of the statement was greeted with laughter, but at the same time he made everyone take a step back and think. After a decade of work have we made any progress? When would we be able to say something different? How would we even be able to tell when we crossed the threshold to "useful" or "low cost" or "robust"?

The central motivation behind these questions is figuring out how to take the concepts and the science fiction and make them real. It is in this spirit that I think this book makes its greatest contribution. In self-reconfigurable robots, where were we? Where are we now? How did we get here? And where do we need to go?

Mark Yim
Gabel Family Associate Professor of Mechanical Engineering
University of Pennsylvania

Preface

It requires significant amounts of motivation to start writing and later actually complete a book. The motivation for me came from two sources. In my everyday work at the University of Southern Denmark, I spend a large part of my time supervising students on projects related to the topic of this book. It became increasingly frustrating for me to supervise these students because I didn't have any efficient way to communicate the essential knowledge generated in the field of self-reconfigurable robots besides directing them to the rapidly growing number of research papers on the topic, which are now passing the 400 mark. This book is the cure for this frustration. Here I have compiled all the knowledge I find essential to an understanding of the field of self-reconfigurable robots and thus have made it possible for students to access it easily and use it to inform their own work.

The second motivation is a similar concern about the research field as a whole. I find that since in the past it has been so time-consuming to obtain the knowledge contained in this book and the many articles on which it is based, new researchers were prevented from entering the field. If they did, they were at a high risk of reproducing results or using approaches that had become irrelevant. With this book, I hope to open the field to a new generation of researchers and at the same time jump-start their research efforts.

In this book I focus on the intuition behind self-reconfigurable robots and their control rather than the technical details. However, for the discussion of self-reconfiguration as search, some basic knowledge of search algorithms is assumed. The advantage of leaving out some technical details is that it makes the book accessible to a wider audience, but it also means that the reader sometimes has to be referred to the material on which it is based in order to obtain the technical details needed for implementation. The book is also written from a practical, engineering perspective. The idea behind this is that the reader should be compelled to put the book down and start contributing to the field of self-reconfigurable robots as fast as possible.

This book is of course subjective and as a result, other researchers may have different perspectives or would have chosen to include other references. I therefore apologize for any I have left out and recommend that researchers with different perspectives write another book!

Finally, I would like to thank the people who made this book possible. First of all thanks to the group of people with whom I have spent countless number of coffee breaks discussing the finer points of self-reconfigurable robots, two of whom also co-authored this book: David Brandt and David J. Christensen. I would also like to thank the broader group of people who participated in the European Union project HYDRA, which essentially got research on self-reconfigurable robot started in Europe; in particular I want to thank the people responsible for starting it: Henrik Hautop Lund, John Hallam, and Rolf Pfeifer. I also want to thank Wei-Min Shen from the University of Southern California's Information Sciences Institute, who introduced me to the field. Finally, I would like to thank my wonderful wife for providing endless support during the more agonizing periods of writing and for insisting on working in Cambodia and thereby giving me an excuse to take the sabbatical that allowed me to write this book.

Introduction

Alan Turing discovered in the 1940s a universal computing machine that is capable of simulating any other computing machine. In a similar way, a self-reconfigurable robot can be thought of as a universal robot: a self-reconfigurable robot is capable of simulating any other physical robot. This capability arises from the fact that these robots are composed of robotic modules, which can be connected in many different ways, allowing the robots to assume the shape of any other robot. In addition, these modules can move around on each other and, thereby, enable a self-reconfigurable robot as a whole to change shape autonomously. This ability to change shape makes it possible for self-reconfigurable robots to adapt and optimize their shape for any task. For example, a self-reconfigurable robot can change into the shape of a rolling track to quickly cover some distance, then become a snake to explore a narrow cave, and finally a hexapod to carry back a discovered artifact.

Significant progress has been made since the field was founded twenty years ago. Recently, researchers have demonstrated that the new generation of self-reconfigurable robots can both change shape in three dimensions and perform a wide range of gaits. These encouraging results are turning the attention of the research community toward applications, and currently the community is taking steps toward using self-reconfigurable robots in such tasks as planetary exploration and manipulation in a production setting. At this crucial point in time, this book collects the bits and pieces of research and ties them into an accessible whole that allows students and researchers alike to appreciate the advances in this exciting field. It includes the following topics:

- Introduction to self-reconfigurable robots, including a presentation of existing robots and a brief history of the field
- Module design considerations, including module geometry, connector design, and computing and communication infrastructure
- Control of self-reconfigurable robots: an in-depth presentation of strategies for controlling self-reconfiguration and locomotion

- Some of the remaining research challenges of self-reconfigurable robots that we need to address in order to realize the full potential of these robots

This book is targeted at students at the graduate level and researchers interested in the field of self-reconfigurable robots. It can work as a course book as well as for self-study. If it is used as a course book, for the topics a teacher finds most important, he or she can supplement the book with the papers referenced in the further reading sections. The book is written to appeal to and be accessible to a wide audience. It requires only some basic knowledge of search, and as such, it may also be useful for people who are not part of the core audience but who want to become aquainted with the field of self-reconfigurable robots.

... at a great distance from its empirical source, or after much "abstract" inbreeding, a mathematical subject is in danger of degeneration.... [W]henever this stage is reached, the only remedy seems to me to be the rejuvenating return to the source: the reinjection of more or less empirical ideas.

—John von Neumann, *Theory of Self-Reproducing Automata*

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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

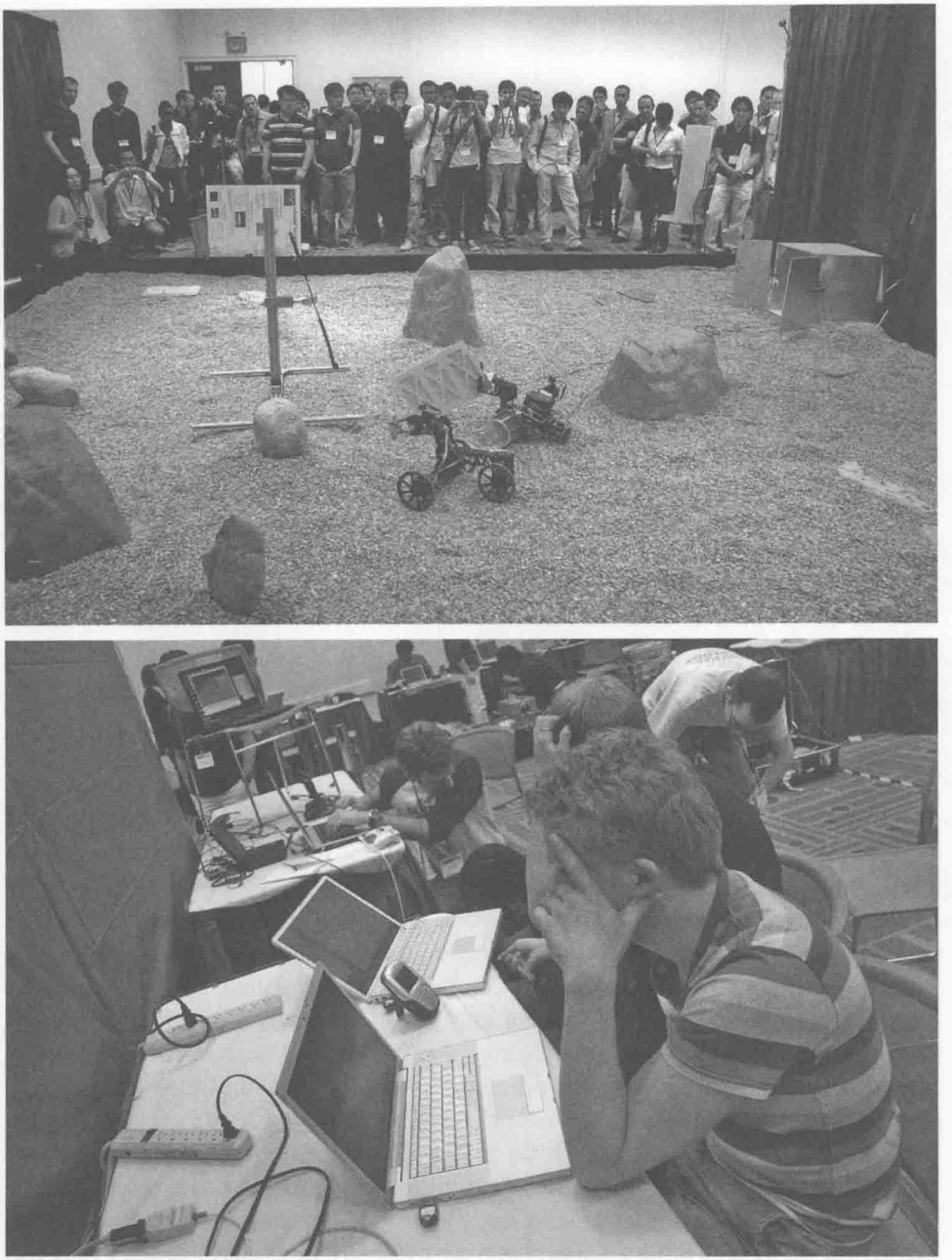

Figure 1.1
Top: The ckBot practicing for the ICRA Contingency challenge. The robots enter the area through the "air-lock" in the upper right corner of the photo. Bottom: Some contestants gaining gray hairs at an alarming rate. (Courtesy of Sastra, © 2007)