

The background of the cover is a large, semi-transparent red gear. The gear has several teeth, and its center is visible. The overall color scheme is dominated by red and white.

Roland SIEGWART
Illah R. NOURBAKHS
Davide SCARAMUZZA

SECOND EDITION

Introduction to

Autonomous Mobile Robots

Introduction to Autonomous Mobile Robots

second edition

Roland Siegwart, Illah R. Nourbakhsh, and Davide Scaramuzza



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Introduction to Autonomous Mobile Robots

Intelligent Robotics and
Autonomous Systems

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Intelligent Robotics and Autonomous Agents

Edited by Ronald C. Arkin

A list of the books published in the Intelligent Robotics and Autonomous Agents series can be found at the back of the book.

To Luzia and my children, Janina, Malin, and Yanik, who give me their support and freedom to grow every day — RS

To my parents, Susi and Yvo, who opened my eyes — RS

To Marti, Mitra, and Nikou, who are my love and my inspiration — IRN

To my parents, Fatemeh and Mahmoud, who let me disassemble and investigate everything in our home — IRN

To my parents, Paola and Ermanno, who encouraged and supported my choices every day and introduced me to robotics at the age of three — DS

To my sisters, Lisa and Silvia, for their love — DS

Slides and exercises that go with this book are available at:

<http://www.mobilerobots.org>

Acknowledgments

This book is the result of inspirations and contributions from many researchers and students at the Swiss Federal Institutes of Technology Zurich (ETH) and Lausanne (EPFL), Carnegie Mellon University's Robotics Institute, Pittsburgh (CMU), and many others around the globe.

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This book was also inspired by other courses, especially by the lecture notes on mobile robotics at the Swiss Federal Institutes of Technology, both in Lausanne (EPFL) and Zurich (ETH). The material for this book has been used for lectures at EPFL, ETH, and CMU since 1997. We thank the hundreds of students who followed the lecture and contributed through their corrections and comments.

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Preface

Mobile robotics is a young field. Its roots include many engineering and science disciplines, from mechanical, electrical, and electronics engineering to computer, cognitive, and social sciences. Each of these parent fields has its share of introductory textbooks that excite and inform prospective students, preparing them for future advanced coursework and research. Our objective in writing this textbook is to provide mobile robotics with such a preparatory guide.

This book presents an introduction to the fundamentals of mobile robotics, spanning the mechanical, motor, sensory, perceptual, and cognitive layers that comprise our field of study. A collection of workshop proceedings and journal publications could present the new student with a snapshot of the state of the art in all aspects of mobile robotics. But here we aim to present a foundation—a formal introduction to the field. The formalism and analysis herein will prove useful even as the frontier of the state-of-the-art advances due to the rapid progress in all of the subdisciplines of mobile robotics.

This second edition largely extends the content of the first edition. In particular, chapters 2, 4, 5, and 6 have been notably expanded and updated to the most recent, state-of-the-art acquisitions in both computer vision and robotics. In particular, we have added in chapter 2 the most recent and popular examples of mobile, legged, and micro aerial robots. In chapter 4, we have added the description of new sensors—such as 3D laser rangefinders, time-of-flight cameras, IMUs, and omnidirectional cameras—and tools—such as image filtering, camera calibration, structure-from-stereo, structure-from-motion, visual odometry, the most popular feature detectors for camera (Harris, FAST, SURF, SIFT) and laser images, and finally bag-of-feature approaches for place recognition and image retrieval. In chapter 5, we have added an introduction to probability theory, and improved and expanded the description of Markov and Kalman filter localization using a better formalism and more examples. Furthermore, we have also added the description of the Simultaneous Localization and Mapping (SLAM) problem along with a description of the most popular approaches to solve it such as extended-Kalman-filter SLAM, graph-based SLAM, particle filter SLAM, and the most recent monocular visual SLAM. Finally, in chapter 6 we have added the description of graph-search algorithms for path planning such as breadth-first, depth first, Dijkstra, A^* , D^* , and rapidly exploring random trees. Besides these many new additions, we have also provided state-of-the-art references and links to online resources

and downloadable software.

We hope that this book will empower both undergraduate and graduate robotics students with the background knowledge and analytical tools they will need to evaluate and even criticize mobile robot proposals and artifacts throughout their careers. This textbook is suitable as a whole for introductory mobile robotics coursework at both the undergraduate and graduate level. Individual chapters such as those on perception or kinematics can be useful as overviews in more focused courses on specific subfields of robotics.

The origins of this book bridge the Atlantic Ocean. The authors have taught courses on mobile robotics at the undergraduate and graduate level at Stanford University, ETH Zurich, Carnegie Mellon University and EPFL. Their combined set of curriculum details and lecture notes formed the earliest versions of this text. We have combined our individual notes, provided overall structure and then test-taught using this textbook for two additional years before settling on the first edition in 2004, and another six years for the current, published text.

For an overview of the organization of the book and summaries of individual chapters, refer to section 1.2.

Finally, for the teacher and the student: we hope that this textbook will prove to be a fruitful launching point for many careers in mobile robotics. That would be the ultimate reward.

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1 Introduction

1.1 Introduction

Robotics has achieved its greatest success to date in the world of industrial manufacturing. Robot arms, or *manipulators*, comprise a \$ 2 billion industry. Bolted at its shoulder to a specific position in the assembly line, the robot arm can move with great speed and accuracy to perform repetitive tasks such as spot welding and painting (figure 1.1). In the electronics industry, manipulators place surface-mounted components with superhuman precision, making the portable telephone and laptop computer possible.

Yet, for all of their successes, these commercial robots suffer from a fundamental disadvantage: lack of mobility. A fixed manipulator has a limited range of motion that depends

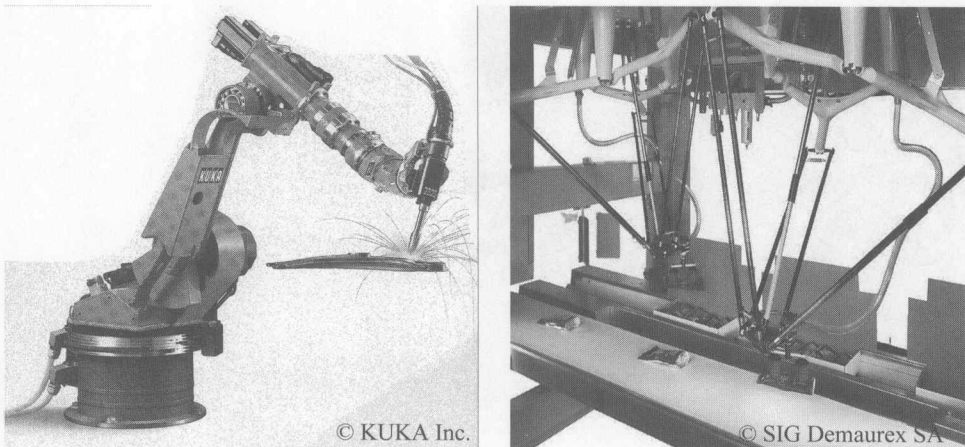


Figure 1.1
Picture of auto assembly plant-spot welding robot of KUKA and a parallel robot Delta of SIG Demaurex SA (invented at EPFL [305]) during packaging of chocolates.

on where it is bolted down. In contrast, a mobile robot would be able to travel throughout the manufacturing plant, flexibly applying its talents wherever it is most effective.

This book focuses on the technology of mobility: how can a mobile robot move unsupervised through real-world environments to fulfill its tasks? The first challenge is locomotion itself. How should a mobile robot move, and what is it about a particular locomotion mechanism that makes it superior to alternative locomotion mechanisms?

Hostile environments such as Mars trigger even more unusual locomotion mechanisms (figure 1.2). In dangerous and inhospitable environments, even on Earth, such *teleoperated* systems have gained popularity (figures 1.3-1.6). In these cases, the low-level complexities of the robot often make it impossible for a human operator to control its motions directly. The human performs localization and cognition activities but relies on the robot's control scheme to provide motion control.

For example, Plustech's walking robot provides automatic leg coordination while the human operator chooses an overall direction of travel (figure 1.3). Figure 1.6 depicts an underwater vehicle that controls three propellers to stabilize the robot submarine autonomously in spite of underwater turbulence and water currents while the operator chooses position goals for the submarine to achieve.

Other commercial robots operate not where humans *cannot* go, but rather share space with humans in human environments (figure 1.7). These robots are compelling not for reasons of mobility but because of their *autonomy*, and so their ability to maintain a sense of position and to navigate without human intervention is paramount.

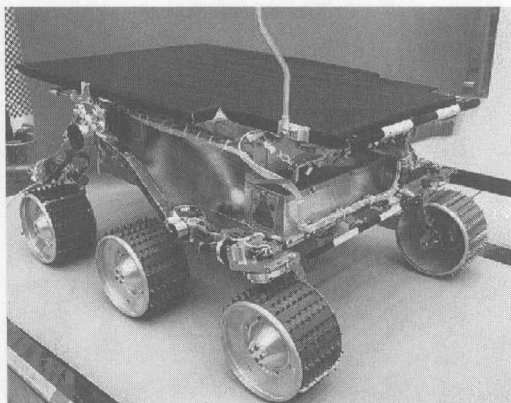


Figure 1.2

The mobile robot Sojourner was used during the Pathfinder mission to explore Mars in summer 1997. It was almost completely teleoperated from Earth. However, some on-board sensors allowed for obstacle detection (http://ranier.oact.hq.nasa.gov/telerobotics_page/telerobotics.shtml).

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