Introduction to Autonomous Mobile Robots

second edition

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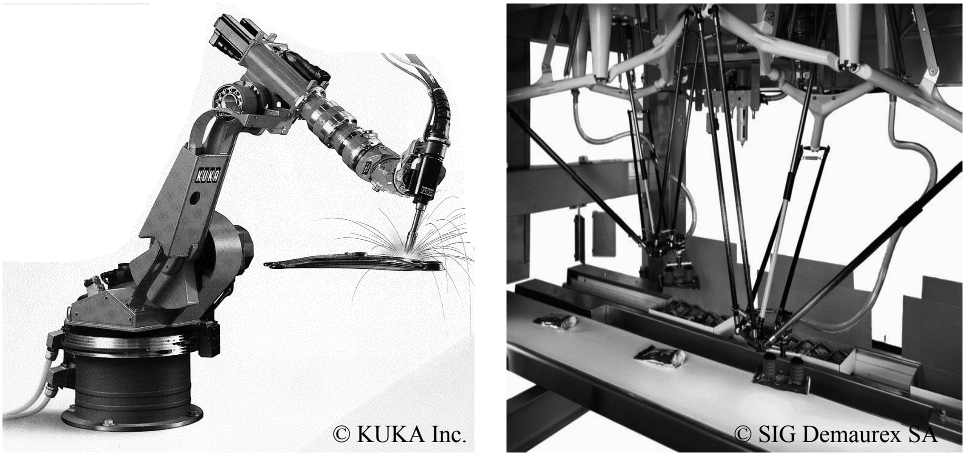
1 Introduction

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



© KUKA Inc.

© SIG Demaurex SA

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 [296]) 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.

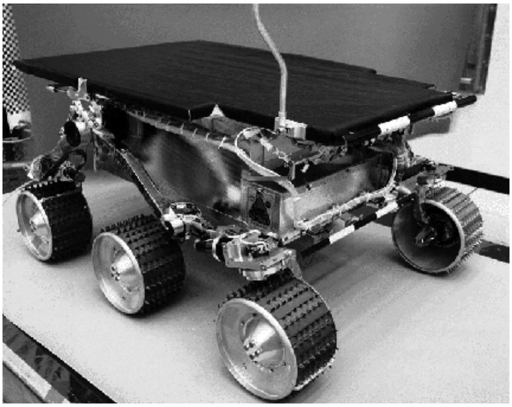


Figure 1.2
The mobile robot Sojourner was used during the Pathfinder mission to explore Mars in summer 1997. It was almost completely teleoperated from Earth. However, some on-board sensors allowed for obstacle detection (http://ranier.oact.hq.nasa.gov/telerobotics_page/telerobotics.shtm).
© NASA/JPL.

Figure 1.3
Plustech developed the first application-driven walking robot. It is designed to move wood out of the forest. The leg coordination is automated, but navigation is still done by the human operator on the robot. (http://www.plustech.fi). © Plustech.

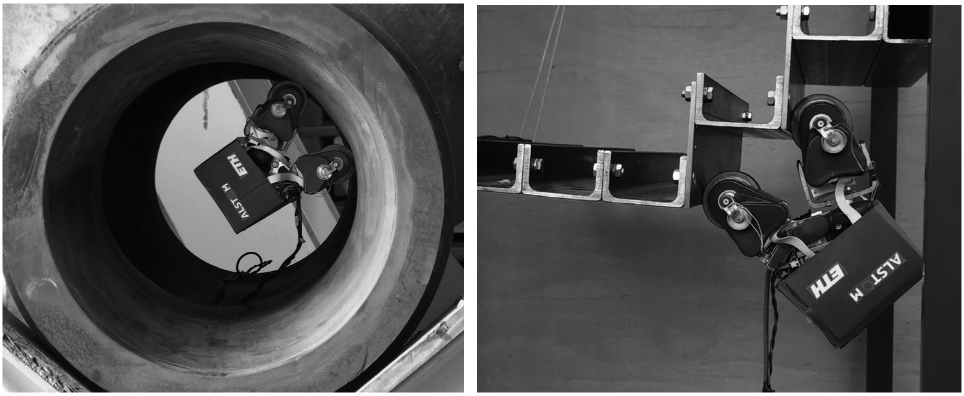


Figure 1.4
The MagneBike robot developed by ASL (ETH Zurich) and ALSTOM. MagneBike is a magnetic wheeled robot with high mobility for inspecting complex shaped structures such as ferromagnetic pipes and turbines (http://www.asl.ethz.ch/). © ALSTOM / ETH Zurich.

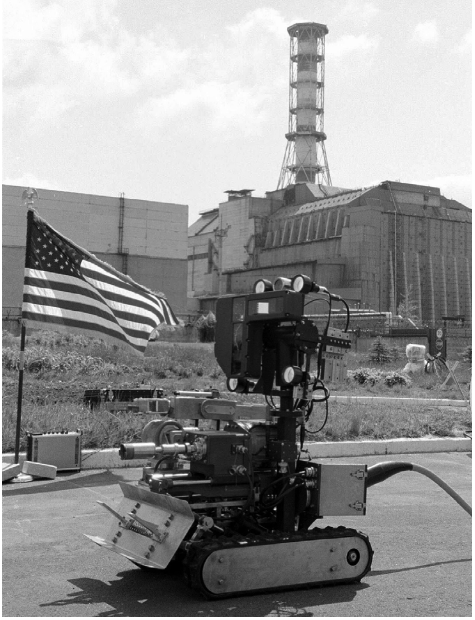


Figure 1.5
Picture of Pioneer, a robot designed to explore the Sarcophagus at Chernobyl. © Wide World Photos.

Figure 1.6
The autonomous underwater vehicle (AUV) Sirius being retrieved after a mission aboard the RV Southern Surveyor © Robin Beaman–James Cook University.

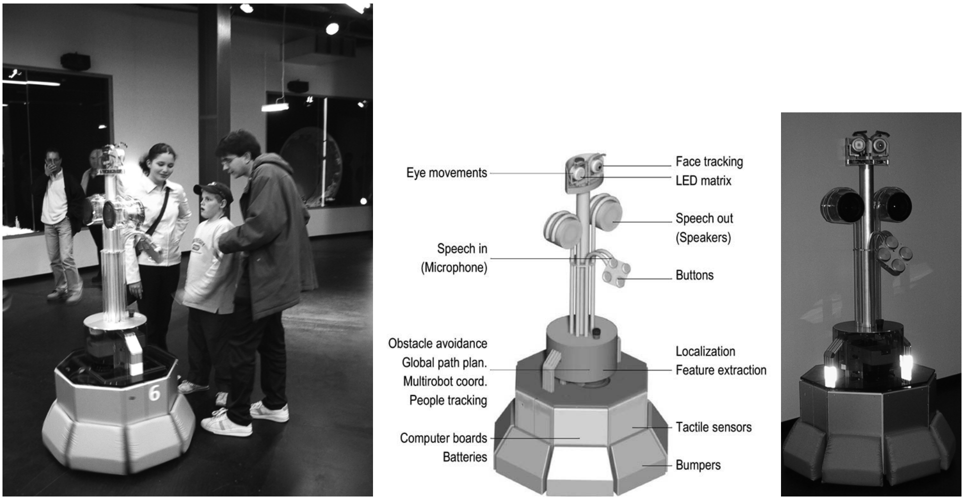
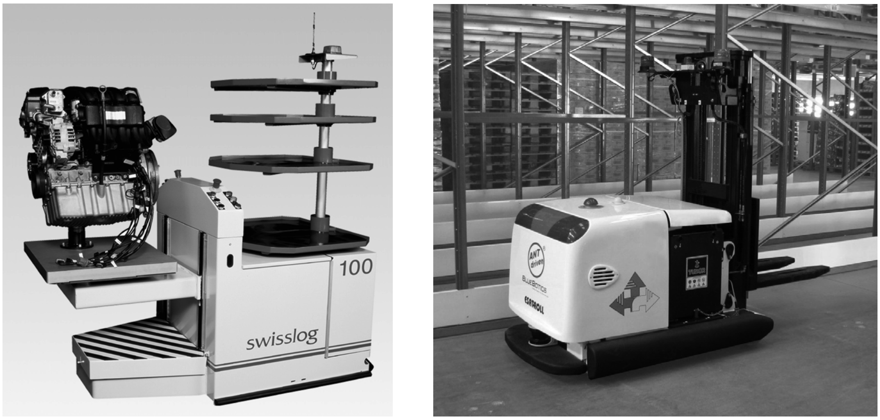


Figure 1.7
Tour-guide robots are able to interact and present exhibitions in an educational way [83, 246, 281, 302,]. Ten Roboxes have operated during five months at the Swiss exhibition EXPO.02, meeting hundreds of thousands of visitors. They were developed by EPFL [281] (http://robotics.epfl.ch) and commercialized by BlueBotics (http://www.bluebotics.com).

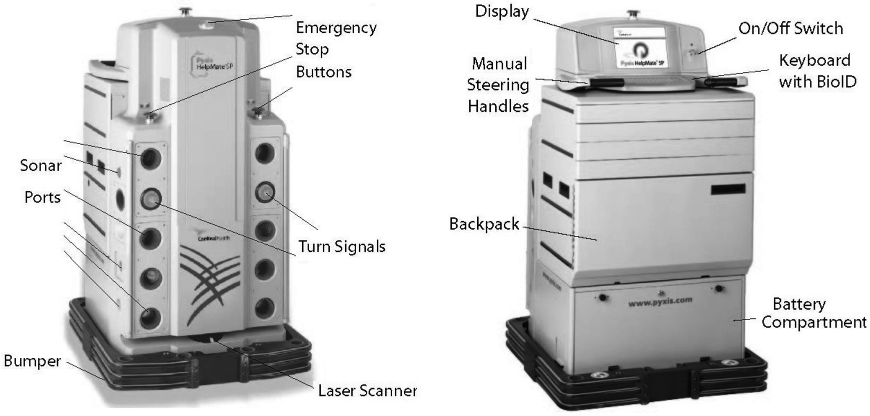
For example, AGV (autonomous guided vehicle) robots (figure 1.8) autonomously deliver parts between various assembly stations by following special electrical guidewires installed in the floor (figure 1.8a) or, differently, by using onboard lasers to localize within a user-specified map (figure 1.8b). The Helpmate service robot transports food and medication throughout hospitals by tracking the position of ceiling lights, which are manually specified to the robot beforehand (figure 1.9). Several companies have developed autonomous cleaning robots, mainly for large buildings (figure 1.10). One such cleaning robot is in use at the Paris Metro. Other specialized cleaning robots take advantage of the regular geometric pattern of aisles in supermarkets to facilitate the localization and navigation tasks.

Research into high-level questions of cognition, localization, and navigation can be performed using standard research robot platforms that are tuned to the laboratory environment. This is one of the largest current markets for mobile robots. Various mobile robot platforms are available for programming, ranging in terms of size and terrain capability. Very popular research robots are the Pioneer, BIBA, and the *e-puck* (figures 1.11-1.13) and also very small robots like the Alice from EPFL (Swiss Federal Institute of Technology at Lausanne) (figure 1.14).



a) *b)*

Figure 1.8
(a) Autonomous guided vehicle (AGV) by SWISSLOG used to transport motor blocks from one assembly station to another. It is guided by an electrical wire installed in the floor. © Swisslog.
(b) Equipped with the Autonomous Navigation Technology (ANT) from BlueBotics, Paquito, the autonomous forklift by Esatroll, does not rely on electrical wires, magnetic plots, or reflectors, but rather uses the onboard safety lasers to localize itself with respect to the shape of the environment. Image courtesy of BlueBotics (http://www.bluebotics.com).



front *back*

Figure 1.9
HELPMATE is a mobile robot used in hospitals for transportation tasks. It has various on-board sensors for autonomous navigation in the corridors. The main sensor for localization is a camera looking to the ceiling. It can detect the lamps on the ceiling as references, or landmarks (http://www.pyxis.com). © Pyxis Corp.

a) *b)*

Figure 1.10
(a) The Robot40 is a consumer robot developed and sold by Cleanfix for cleaning large gymnasiums. The navigation system of Robo40 is based on a sophisticated sonar and infrared system (http://www.cleanfix.com). © Cleanfix. (b) The RoboCleaner RC 3000 covers badly soiled areas with a special driving strategy until it is really clean. Optical sensors measure the degree of pollution of the aspirated air (http://www.karcher.de). © Alfred Kärcher GmbH & Co.

Robot
Battery 12.4
State Connected
Mode Going to Goal
X -1863 mm
Y 702 mm
Heading 90 degrees
Velocity -2 mm/second

Camera
Pan 0
Tilt 0
Zoom 0

Laser
● Laser Connected

Ready.

Figure 1.11
PIONEER is a modular mobile robot offering various options like a gripper or an on-board camera. It is equipped with a sophisticated navigation library developed at SRI, Stanford, CA. Reprinted with permission from ActivMedia Robotics, http://www.MobileRobots.com.

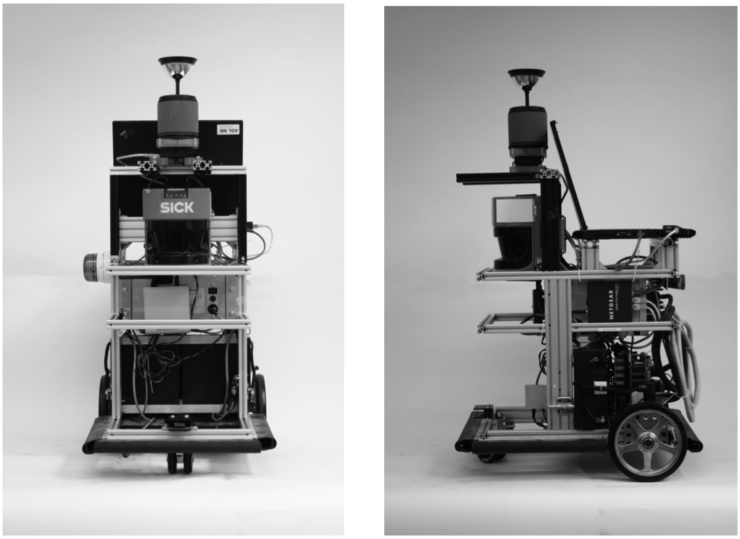


Figure 1.12
BIBA is a very sophisticated mobile robot developed for research purposes and built by BlueBotics (http://www.bluebotics.com/). It has a large variety of sensors for high-performance navigation tasks.

Figure 1.13
The *e-puck* is an educational desktop mobile robot developed at the EPFL [222]. It is only about 70 mm in diameter. As extensions to the basic capabilities, various modules such as additional sensors, actuators, or computational power have been developed. In this picture, two example extensions are shown: (center) an omnidirectional camera and (right) an infrared distance scanner (http://www.e-puck.org/). © Ecole Polytechnique Fédérale de Lausanne (EPFL).

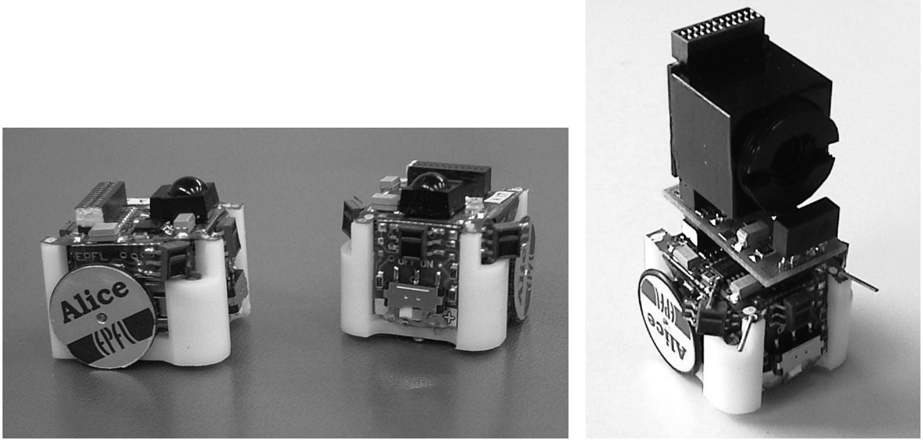


Figure 1.14
Alice is one of the smallest fully autonomous robots. It is approximately $2 \times 2 \times 2$ cm, it has an autonomy of about 8 hours and uses infrared distance sensors, tactile whiskers, or even a small camera for navigation [91].

Although mobile robots have a broad set of applications and markets as summarized above, there is one fact that is true of virtually every successful mobile robot: its design involves the integration of many different bodies of knowledge. No mean feat, this makes mobile robotics as interdisciplinary a field as there can be. To solve locomotion problems, the mobile roboticist must understand mechanism and kinematics, dynamics and control theory. To create robust perceptual systems, the mobile roboticist must leverage the fields of signal analysis and specialized bodies of knowledge such as computer vision to properly employ a multitude of sensor technologies. Localization and navigation demand knowledge of computer algorithms, information theory, artificial intelligence, and probability theory.

Figure 1.15 depicts an abstract control scheme for mobile robot systems that we will use throughout this text. This figure identifies many of the main bodies of knowledge associated with mobile robotics.

This book provides an introduction to all aspects of mobile robotics, including software and hardware design considerations, related technologies, and algorithmic techniques. The intended audience is broad, including both undergraduate and graduate students in introductory mobile robotics courses, as well as individuals fascinated by the field. Although it is not absolutely required, a familiarity with matrix algebra, calculus, probability theory, and computer programming will significantly enhance the reader's experience.

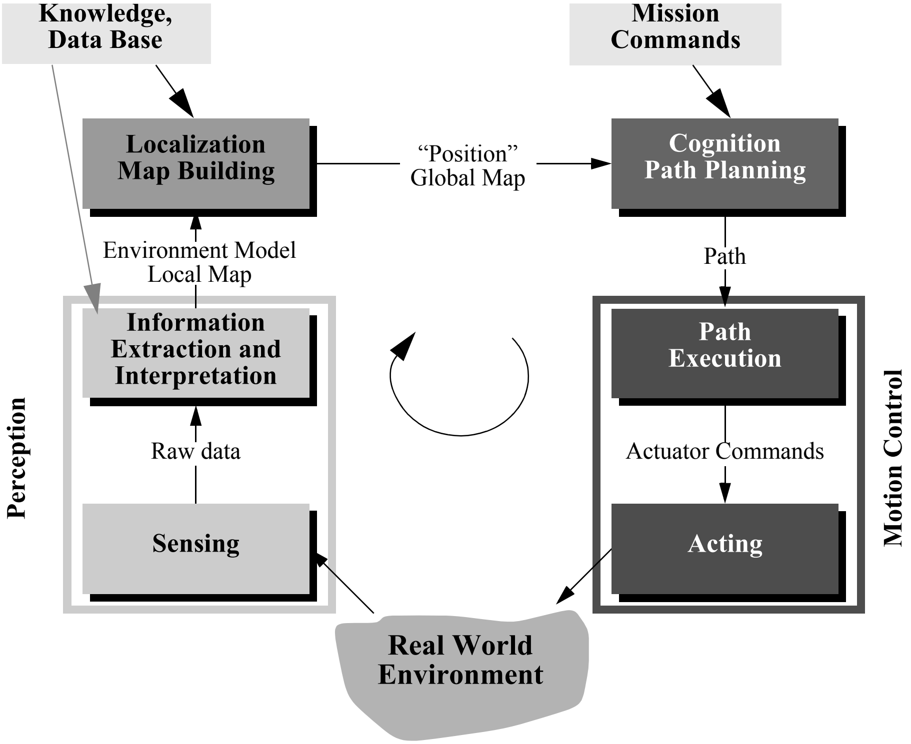


Figure 1.15
Reference control scheme for mobile robot systems used throughout this book.

Mobile robotics is a large field, and this book focuses not on robotics in general, or on mobile robot applications, but rather on mobility itself. From mechanism and perception to localization and navigation, this book focuses on the techniques and technologies that enable robust *mobility*.

Clearly, a useful, commercially viable mobile robot does more than just move. It polishes the supermarket floor, keeps guard in a factory, mows the golf course, provides tours in a museum, or provides guidance in a supermarket. The aspiring mobile roboticist will start with this book but will quickly graduate to coursework and research specific to the desired application, integrating techniques from fields as disparate as human-robot interaction, computer vision, and speech understanding.

1.2 An Overview of the Book

This book introduces the different aspects of a robot in modules, much like the modules shown in figure 1.15. Chapters 2 and 3 focus on the robot's low-level *locomotive ability*. Chapter 4 presents an in-depth view of *perception*. Chapters 5 and 6 take us to the higher-level challenges of *localization* and *mapping* and even higher-level *cognition*, specifically the *ability to navigate robustly*. Each chapter builds upon previous chapters, and so the reader is encouraged to start at the beginning, even if his or her interest is primarily at the high level. Robotics is peculiar in that solutions to high-level challenges are most meaningful only in the context of a solid understanding of the low-level details of the system.

Chapter 2, "Locomotion," begins with a survey of the most important mechanisms that enable locomotion: wheels, legs, and flight. Numerous robotic examples demonstrate the particular talents of each form of locomotion. But designing a robot's locomotive system properly requires the ability to evaluate its overall motion capabilities quantitatively. Chapter 3, "Mobile Robot Kinematics," applies principles of kinematics to the whole robot, beginning with the kinematic contribution of each wheel and graduating to an analysis of robot maneuverability enabled by each mobility mechanism configuration.

The greatest single shortcoming in conventional mobile robotics is, without doubt, perception: mobile robots can travel across much of earth's man-made surfaces, but they cannot perceive the world nearly as well as humans and other animals. Chapter 4, "Perception," begins a discussion of this challenge by presenting a clear language for describing the performance envelope of mobile robot sensors. With this language in hand, chapter 4 goes on to present many of the off-the-shelf sensors available to the mobile roboticist, describing their basic principles of operation as well as their performance limitations. The most promising sensor for the future of mobile robotics is vision, and chapter 4 includes an overview of the theory of camera image formation, omnidirectional vision, camera calibration, structure from stereovision, structure from motion, and visual odometry. But perception is more than sensing. Perception is also the *interpretation* of sensed data in meaningful ways. The second half of chapter 4 describes strategies for feature extraction that have been most useful in both computer vision and mobile robotics applications, including extraction of geometric shapes from range sensing data, as well as point features (such as Harris, SIFT, SURF, FAST, and so on) from camera images. Furthermore, a section is dedicated to the description of the most recent bag-of-feature approach that became popular for place recognition and image retrieval.

Armed with locomotion mechanisms and outfitted with hardware and software for perception, the mobile robot can move and perceive the world. The first point at which mobility and sensing must meet is localization: mobile robots often need to maintain a sense of position. Chapter 5, "Mobile Robot Localization," describes approaches that obviate the need for direct localization, then delves into fundamental ingredients of successful localization strategies: belief representation and map representation. Case studies demonstrate various localization schemes, including both Markov localization and Kalman filter localization. The final part of chapter 5 is devoted to a 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.

Mobile robotics is so young a discipline that it lacks a standardized architecture. There is as yet no established robot operating system. But the question of architecture is of paramount importance when one chooses to address the higher-level competences of a mobile robot: how does a mobile robot navigate robustly from place to place, interpreting data, and localizing and controlling its motion all the while? For this highest level of robot competence, which we term *navigation competence*, there are numerous mobile robots that showcase particular architectural strategies. Chapter 6, “Planning and Navigation,” surveys the state of the art of robot navigation, showing that today’s various techniques are quite similar, differing primarily in the manner in which they *decompose* the problem of robot control. But first, chapter 6 addresses two skills that a competent, navigating robot usually must demonstrate: obstacle avoidance and path planning.

There is far more to know about the cross-disciplinary field of mobile robotics than can be contained in a single book. We hope, though, that this broad introduction will place the reader in the context of the collective wisdom of mobile robotics. This is only the beginning. With luck, the first robot you program or build will have only good things to say about you.