Gregory Dudek and Michael Jenkin

Computational Principles of Mobile Robotics

SECOND EDITION

Dudek
Jenkin

Computational Principles of Mobile Robotics

SECOND EDITION

CAMBRIDGE

Praise for the first edition of *Computational Principles of Mobile Robotics*

> " . . . a good synthesis of robotics for computer science people, and is a useful tool for approaching the area."– G. Gini, *Computing Reviews*

> " . . . clearly presents the range of topics covered in this multidisciplinary field." – *Industrial Robot*

> "Technical libraries are well advised to shelve this milestone work. Readers from among upper-division undergraduates, graduates, and researchers will find a high level of legibility in the writing style, the attractive print layout, and ample quality illustrations, equations, and photographs." – *Choice*

Mobile robotics is a multidisciplinary field involving both computer science and engineering. Addressing the design of automated systems, it lies at the intersection of artificial intelligence, computational vision, and robotics.

This textbook for advanced undergraduates and graduate students emphasizes computation and algorithms for a range of strategies for locomotion, sensing, and reasoning. It concentrates on wheeled and legged mobile robots but also discusses a variety of other propulsion systems. The new edition presents advances in robotics and intelligent machines over the last 10 years, including significant coverage of SLAM (simultaneous localization and mapping) and multi-robot systems. It includes additional mathematical background and an extensive list of sample problems. Various mathematical techniques that were assumed in the first edition are now briefly introduced in appendices at the end of the text to make the book more self-contained.

Researchers and students in the field of mobile robotics will appreciate this comprehensive treatment of state-of-the-art methods and key technologies.

GREGORY DUDEK is James McGill Professor of Computer Science and the Director of the School of Computer Science and of the Mobile Robotics Laboratory at McGill University.

MICHAEL JENKIN is a Professor of Computer Science and Engineering at York University. He has coedited eight books on human and machine vision.

CAMBRIDGE
UNIVERSITY PRESS
www.cambridge.org

ISBN 978-0-521-69212-0

9 780521 692120

Cover design by Alice Soloway

Computational Principles of Mobile Robotics

Mobile robotics is a multidisciplinary field involving both computer science and engineering. Addressing the design of automated systems, it lies at the intersection of artificial intelligence, computational vision, and robotics.

This textbook for advanced undergraduates and graduate students emphasizes computation and algorithms for a range of strategies for locomotion, sensing, and reasoning. It concentrates on wheeled and legged mobile robots but also discusses a variety of other propulsion systems. The new edition presents advances in robotics and intelligent machines over the last 10 years, including significant coverage of SLAM (simultaneous localization and mapping) and multi-robot systems. It includes additional mathematical background and an extensive list of sample problems. Various mathematical techniques that were assumed in the first edition are now briefly introduced in appendices at the end of the text to make the book more self-contained.

Researchers and students in the field of mobile robotics will appreciate this comprehensive treatment of state-of-the-art methods and key technologies.

Gregory Dudek is James McGill Professor of Computer Science and the Director of the School of Computer Science and of the Mobile Robotics Laboratory at McGill University.

Michael Jenkin is a Professor of Computer Science and Engineering at York University. He has coedited eight books on human and machine vision.

Computational Principles of Mobile Robotics

Second Edition

Gregory Dudek
McGill University

Michael Jenkin
York University

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521692120

First published 2010

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication data

Dudek, Gregory, 1958–
Computational principles of mobile robotics / Gregory Dudek, Michael Jenkin. – 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-521-87157-0
1. Mobile robots. 2. Robotics – Mathematics. I. Jenkin, Michael, 1959– II. Title.
TJ211.415.D83 2010
629.8′932 – dc22 2010020795

ISBN 978-0-521-87157-0 Hardback
ISBN 978-0-521-69212-0 Paperback

For Krys and Heather

Contents

Acknowledgments

This book would not have been possible without the active support of our students and colleagues who suffered through early drafts, provided imagery and papers, and put up with us while this volume was being put together. The list of people who helped is much too long to include here, but some require special mention: International Joint Conferences on Artificial Intelligence (IJCAI), for letting us do a tutorial on mobile robotics that started us on the journey; students at McGill and York, including Eric Bourque, Andrew Hogue, and Yiannis Rekleitis, who suffered with photocopies of early drafts; Prof. Evangelos Milios for his helpful comments and Prof. Evangelos Papadopoulos for his help on space robots; Rob Sim for his figures; and Louis Dudek for his proofreading and helpful comments.

Finally, we thank Lauren Cowles and Cambridge University Press for encouraging us do this in the first place.

Preface to the Second Edition

The authors surrounded by a collection of some of their robots and sensors.

The first edition of this book arose from a tutorial that was initially presented in 1993. It evolved over a number of years and finally appeared in 2000. Robotics is, of course, a rapidly changing field, and even as the first edition was appearing, it was apparent that it would become dated rather quickly. Thus in late 2002, the first steps were taken toward a second edition.

The field of mobile robotics continues to evolve, and this book has (we hope) evolved with the field. Topics that were in their infancy when the first edition was published – such as SLAM and multi-robot systems – have evolved into much more mature disciplines. The mathematical foundations of much of mobile robotics has also matured, and this too is reflected in this volume. In addition to updating the various algorithms and methods described in the first edition, the second edition is somewhat more self-contained. Specifically, various mathematical techniques that were assumed in the first edition are now introduced, albeit briefly, in appendices at the end of the text.

1

Overview and motivation

"…let's start with the three fundamental Rules of Robotics – the three rules that are built most deeply into a robot's positronic brain." In the darkness, his gloved fingers ticked off each point.

"We have: one, a robot may not injure a human being, or through inaction, allow a human being to come to harm."

"Right!"

"Two," continued Powell, "a robot must obey the orders given it by human beings except where such orders would conflict with the First Law."

"Right!"

"And three, a robot must protect its own existence as long as such protection does not conflict with the First or Second Laws."[1]

Powell and Donovan discuss the laws of robotics.

The ability to navigate purposefully is fundamental to most animals and to every intelligent organism. In this book we examine the computational issues specific to the creation of machines that move intelligently in their environment. From the earliest modern speculation regarding the creation of autonomous robots, it was recognized that regardless of the mechanisms used to move the robot around or the methods used to sense the environment, the computational principles that govern the robot are of paramount importance. As Powell and Donovan discovered in Isaac Asimov's story "Runaround," subtle definitions within the programs that control a robot can lead to significant changes in the robot's overall behavior or action. Moreover, the interactions among multiple complex components can lead to large-scale emergent behaviors that may be hard to predict.

Mobile robotics is a research area that deals with the control of autonomous and semi-autonomous vehicles. What sets **mobile robotics** apart from other research areas such as conventional manipulator robotics, artificial intelligence, and computer vision is the emphasis on problems related to the understanding of **large-scale space**, that is, regions of space substantially larger than those that can be observed from a single vantage point. While at first blush the distinction between sensing in large-scale space, with its requirement for mobility, and local sensing may appear obscure, it has far-reaching implications. To behave intelligently in a large-scale environment not only implies dealing with the incremental acquisition of knowledge, the estimation of positional error, the

[1] I. Asimov, "Runaround" [37]. Reprinted by permission of the Estate of Isaac Asimov c/o Ralph M. Vicinanza, Ltd.

ability to recognize important or familiar objects or places, and real-time response, but it also requires that all of these functionalities be exhibited in concert. This issue of extended space influences all of mobile robotics; the tasks of moving through space, sensing about space, and reasoning about space are fundamental problems within the study of mobile robotics. The study of mobile robots in general, and this volume in particular, can be decomposed into the study of these three subproblems.

Mobile robots are not only a collection of algorithms for sensing, reasoning, and moving about space, they are also physical embodiments of these algorithms and ideas that must cope with all of the vagaries of the real world. As such, mobile robots provide a reality check for theoretical concepts and algorithms. They are the point where literally the "rubber meets the road" for many algorithms in path planning, knowledge representation, sensing, and reasoning.

In the context of humanity's ongoing quest to construct more capable machines – machines that match or even surpass human capabilities – the development of systems that exhibit mobility is a key hurdle. The importance of spatial mobility can be appreciated by observing that there are very few sophisticated biological organisms that cannot move or accomplish spatially distributed tasks in their environment. Just as the development of the wheel (and hence wheeled vehicles) marked a turning point in the evolution of manually operated tools, the development of mobile robots is an important stepping stone in the development of sophisticated machines.

Many different terms have come to be applied to the field of autonomous systems or mobile robotics. The words **autonomous**, as in autonomous system, and **automaton** have their roots in the Greek for *self-willed* (*auto+matos*: $\alpha\upsilon\tau o\ \mu\alpha\tau o\varsigma$). The term **robot** itself was introduced by Karel Čapek in his 1923 play *R.U.R.* (R.U.R. stands for Rossum's Universal Robots). The word 'robot' is derived from the Czech or Polish words 'robota,' meaning 'labour,' and 'robotnik,' meaning 'workman.' It is interesting to note that the word *automaton* implies a degree of self-will that is not conveyed by the term *robot*, and that **autonomous robot** might be construed as self-contradictory.

Robots that are manufactured following the same general structure as humans are known as **anthropomorphic robots** or **humanoid robots**, and in fiction, robots that are indistinguishable from humans are sometimes known as **androids**.

Although androids are beyond today's technology, anthropomorphic robots and robots with anthropomorphic features are quite common. There are many reasons why researchers develop robots in an anthropomorphic mold. In addition to a desire to develop an agent in "one's own image," there are practical reasons for developing systems with anthropomorphic features. The operating environment for many mobile robots is the same environment that humans inhabit, and we have adapted our environment to suit our performance specifications. By mimicking human structures, at least at an operational or functional level, a robot may be better suited to operate in our environment. Human physiology, perception, and cognitive processes have been studied extensively. Thus by using locomotive, sensing, and reasoning systems based on biological models, roboticists can exploit the extensive literature that already exists in these fields. In addition, people seem to have a fascination with human-looking robots that goes beyond the pragmatic. That being said, mobile robots are not limited to mimicking existing biological systems, and there exist many other mechanisms, from infrared sensors to alternative drive mechanisms, that can be exploited in the design of a mobile robot.

The study of mobile robots is an intrinsically interdisciplinary research area that involves:

Mechanical engineering: vehicle design and in particular locomotive mechanisms.
Computer science: representations and sensing and planning algorithms.
Electrical engineering: system integration, sensors, and communications.
Cognitive psychology, perception, and neuroscience: insights into how biological organisms solve similar problems.
Mechatronics: the combination of mechanical engineering with computer science, computer engineering, and/or electrical engineering.

Although many classes of the mobile robot systems currently in operation are fundamentally research vehicles and are thus experimental in nature, a substantial number of mobile robot systems are deployed in domestic or industrial settings. Real applications in which current mobile robots have been deployed successfully are characterized by one or more of the following attributes: the absence of an on-site human operator (often due to inaccessibility), a potentially high cost, long duty cycles, and the need to tolerate environmental conditions that might not be acceptable to a human. As such, mobile robots are especially well suited for tasks that exhibit one or more of the following characteristics:

- An environment that is inhospitable, so that sending a human being is either very costly or very dangerous.
- An environment that is remote, so that sending a human operator is too difficult or takes too long. Extreme instances are domains that are completely inaccessible to humans, such as microscopic environments.
- A task with a very demanding duty cycle or a very high fatigue factor.
- A task that is highly disagreeable to a human.

Successful industrial applications for mobile robots typically involve more than one of these characteristics. Consider the application of mobile robotics to underground mining as an example. The environment is dangerous, in that the possibility of rock fall or environmental contamination due to the release of hazardous gas or dust is quite real. The environment is remote, in that humans operating in underground mines must travel considerable distances, typically many kilometers, in order to reach the rock face being worked. At the rock face, the miner is confronted with an operational environment that can be cramped, poorly illuminated, hot, and dangerous. Other 'ideal' robotic operational environments include nuclear, extraterrestrial, and underwater environments.

Mobile robots are feats of engineering. The actuators, processors, user interfaces, sensors, and communication mechanisms that permit a mobile robot to operate must be integrated so as to permit the entire system to function as a complete whole. The physical structure of a mobile robot is complex, requiring a considerable investment of both human and financial resources in order to keep it operating. "Robot wranglers"[2] are an essential component for the successful operation of any robotic system. Thus, one of the goals of this book, in addition to provoking new research, is to act as a reference of mobile robot

[2] Graduate students and technicians.

tools and techniques for those who would develop or maintain a mobile robot. Rather than concentrate strictly on the sensors required for a mobile robot [204] or on the physical design of small autonomous robots [310] or collect the seminal papers of the field [143], this volume considers the computational processes involved in making a robot sense, reason, and move through its environment.

1.1 From Mechanisms to Computation

Robots can be considered from several different perspectives. At a physical, hardware, or mechanistic level, robots can be decomposed into the following:

- A power source, typically based on batteries.
- A mechanism for making the robot move through its environment – the physical organization of motors, belts, and gears that is necessary to make the robot move.
- A computer or collection of computers that controls the robot.
- A collection of sensors with which the robot gathers information concerning its environment.
- Communications hardware to enable the robot to communicate to an off-board operator and any externally based computers.

At the device level, the hardware details can be abstracted, and a robot can be considered as follows:

- A software-level abstraction of the motors, encoders, and motor driver boards that allow the robot to move. Most mobile robot hardware manufacturers provide support for the underlying hardware at this level rather than force the user to deal with the details of actually turning motors.
- Software-level mechanisms or libraries to provide access to the robot's sensors, for example, the current image obtained by a video camera as an array of intensities.
- A standard communications mechanism, such as a serial interface or network access to the outside world.

From a still more abstract perspective, we can consider mobile robots at a purely computational level such that the sensors, communications, and locomotive systems are seen simply as software modules that enable the robot to interact with its environment. Typical components in a software architecture include the following:

- A motion control subsystem,
- A sensor control subsystem,
- A sensor interpretation subsystem.
- A mission control subsystem.

Even higher levels of abstraction exist. The term **cognitive robotics** is used to refer to the use of Artificial Intelligence (AI) techniques within a mobile robot and often assumes the existence of an idealized computational abstraction of the robot.

1.2 Historical Context

Autonomous Robots in Fiction

Thou shalt not make a machine in the likeness of a human mind.[3]

Autonomous devices have a long and checkered past in legend and literature. From ancient legends to modern films and literature, many different robots and robot-like devices have been constructed to extend the will of their creator or owner. Much of the fictional literature on autonomous systems is cautionary in nature: the 'robot' may follow its instructions too literally, or it may grow to have a will of its own and not follow its instructions at all. For example, in Isaac Asimov's story "Runaway" a robot is told to "get lost," which of course it does, while "Robots of Empire" and "Robots of Dawn," also by Asimov, describe the process of robots evolving their own rules of operation. Given their supposed infallibility, fictional robots have also been proposed as final arbitrators of judgment. In the 1951 film *The Day the Earth Stood Still*, Gort is a universal policeman who enforces the law without being influenced by sentiment.

Perhaps the earliest reference to a 'robot' in literature can be found in Greek mythology. According to ancient Greek or Cretan mythology, Talos was an 'animated' giant man made of bronze who guarded the island of Crete. Talos guarded the island and enforced the law. One of Talos' flaws was that he was too literal minded in the interpretation of his directives, so that he became a burden. Even in this legend, problem specification and representation was an issue! This notion of the robot as protector also appears in Jewish folklore. According to legend, in sixteenth-century Prague, the Jewish population turned to a Golem to protect them from the gentiles who wanted to kill them. A rabbi fashioned the Golem out of clay and breathed life into it.

Clay and bronze are not the only potential building materials for fictional 'robots.' In works of fiction, autonomous agents are also constructed out of biological components. In 1818, Mary Shelley wrote *Frankenstein*, which tells the story of Dr. Frankenstein and his efforts to animate dead tissue. As one inspired job advertisement put it, "Dr. Frankenstein was more than just a scientist – he was an electrical engineer with the creative capability for bringing extraordinary ideas to life." Nor are all fictional accounts of robots based on anthropomorphic designs. In his 1880 *The Demon of Cawnpore*, Jules Verne describes a steam-powered elephant,[4] whereas more recently the film *Blade Runner* (based on Philip K. Dick's novel *Do Androids Dream of Electric Sheep?*) [166] describes a world in which animals are almost extinct and robotic pets are popular.

Isaac Asimov is often regarded as a key contributor to the genesis of robotics due to his copious science fiction writings on the topic and, most notably, his introduction of the "three laws of robotics." Introduced in 1942 in "Runaround" and reprinted at the beginning of this chapter, they are as follows:

1. A robot may not injure a human being, or, through inaction, allow a human being to come to harm.

[3] F. Herbert, *Dune* [267].
[4] The *Demon of Cawnpore* was also published as *The End of Nana Sahib*.

2. A robot must obey the orders given it by human beings except when 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.

In later works, Asimov added a zeroth law that required a robot not to injure humanity. Many of Asimov's stories center around robot (and human) attempts to find new definitions or loopholes in these laws. Although the relevance of these laws to real robotics research is questionable, they nevertheless have proven to be both inspirational and provocative.

Since the 1940s, mobile robots have become a common feature of science fiction literature and film. Famous fictional robots include Robbie (*Forbidden Planet*), Gort (*The Day the Earth Stood Still*), Rosie (*The Jetsons*), Robot (*Lost in Space*), Floyd (*Stationfall* and *Planetfall*), R2D2 and C3PO (*Star Wars*), Data and the partly biological Borg (*Star Trek*), HAL (*2001* and *2010*), Bender (*Futurama*), the Terminator (*Terminator*), and of course Marvin, the paranoid android (*The Hitchhiker's Guide to the Galaxy*). More details on the evolution of robots in literature can be found in [34]. (See also [257].) It is interesting to note that fictional robots usually do not suffer from the computational, sensing, power, or locomotive problems that plague real robots. How the Daleks (see Figure 1.1) from the long-running BBC television series *Doctor Who* managed to conquer most of the galaxy without having to navigate a set of stairs was only finally addressed in a recent episode. On the other hand, fiction serves not only to predict the future, but also to inspire those who might create it. Stork [585] provides some insights into the differences between a specific fictional autonomous system – HAL from *2001* – and the current state of the art in terms of real systems.

Early Autonomous Robots

Various robotic or robotic-like systems can be found scattered throughout history. Mechanical robotic systems can be traced back to Greek and Roman times. The Roman historian Appian reported a mechanical simulation of Julius Caesar. In the fifteenth century, Leonardo da Vinci developed a number of robotic systems, perhaps the most famous of which was an anthropomorphic device with controllable arms and legs [543]. Less well

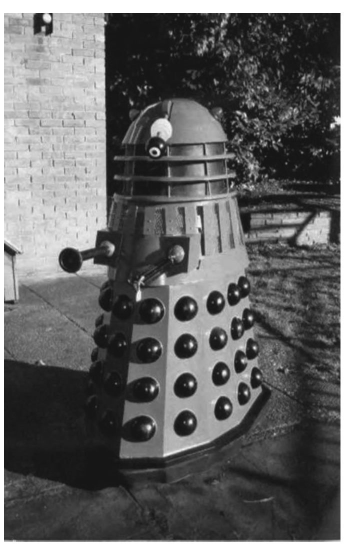
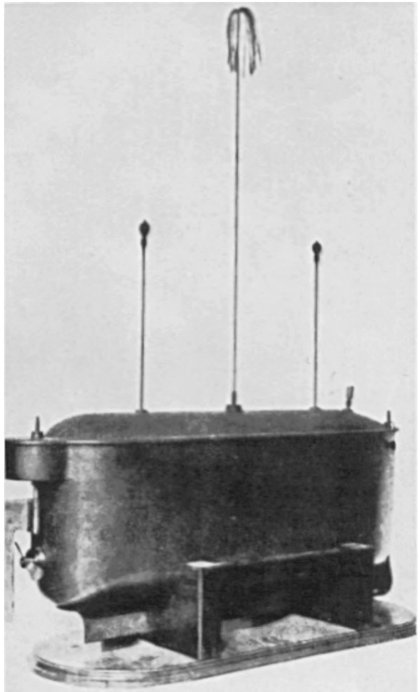
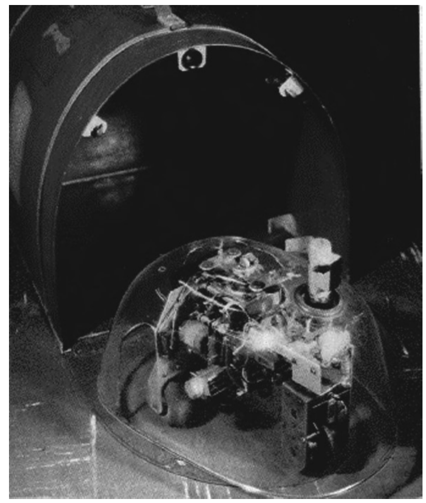


Figure 1.1. A Dalek, a half-robot/half-biological creature from the BBC TV series *Doctor Who*. Copyright Barry Angel. Used with permission.



(a) Tesla's robot



(b) Walter's robot

Figure 1.2. Analog robots. (a) Reprinted from M. Cheney, *Tesla: Man Out of Time*, Prentice-Hall [118]. Used with permission. (b) Copyright Owen Holland. Used with permission.

known perhaps is Leonardo's robotic car, or automata. This device resembled a differential drive robot and used springs and cams to program the robot to follow different trajectories as it moved. (See [543] for an in-depth review of the design of this vehicle). The late eighteenth-century autonomous Japanese tea carrier Karakuri is described in [541].

Autonomous vehicles built by Nikola Tesla in the 1890s are probably the earliest electrical mobile robots. In the 1890s, Tesla built wireless, radio-controlled vehicles [118]. One of his remote-controlled aquatic vehicles is shown in Figure 1.2a. The first steps towards modern electronic robotic systems were made during the early to mid 1940s. Norbert Wiener is considered the inventor of **cybernetics** and hence modern robotics. A mathematician, Wiener studied regulatory systems and their application to control. During World War II, he was involved in a project to develop a controlling device for an anti-aircraft gun. The development of such a device, which integrates sensory information (radar) via processing (simple control laws executing on an analog computer) into action (directing and firing the anti-aircraft gun), resulted in one of the first robotic systems. As Wiener mused in his January 1949 article in *Electronics*,

> It has long been clear to me that the modern ultra-rapid computing machine was in principle an ideal central nervous system to an apparatus for automatic control; and its input and output need not be in the form of numbers or diagrams, but might very well be, respectively, the readings of artificial sensors such as photoelectric cells or thermometers, and the performance of motors or solenoids.[5]

[5] *Electronics*, January 1949. Reprinted in [402].

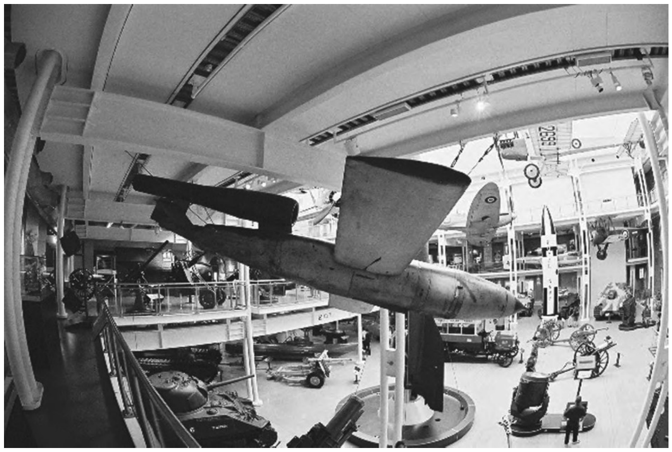


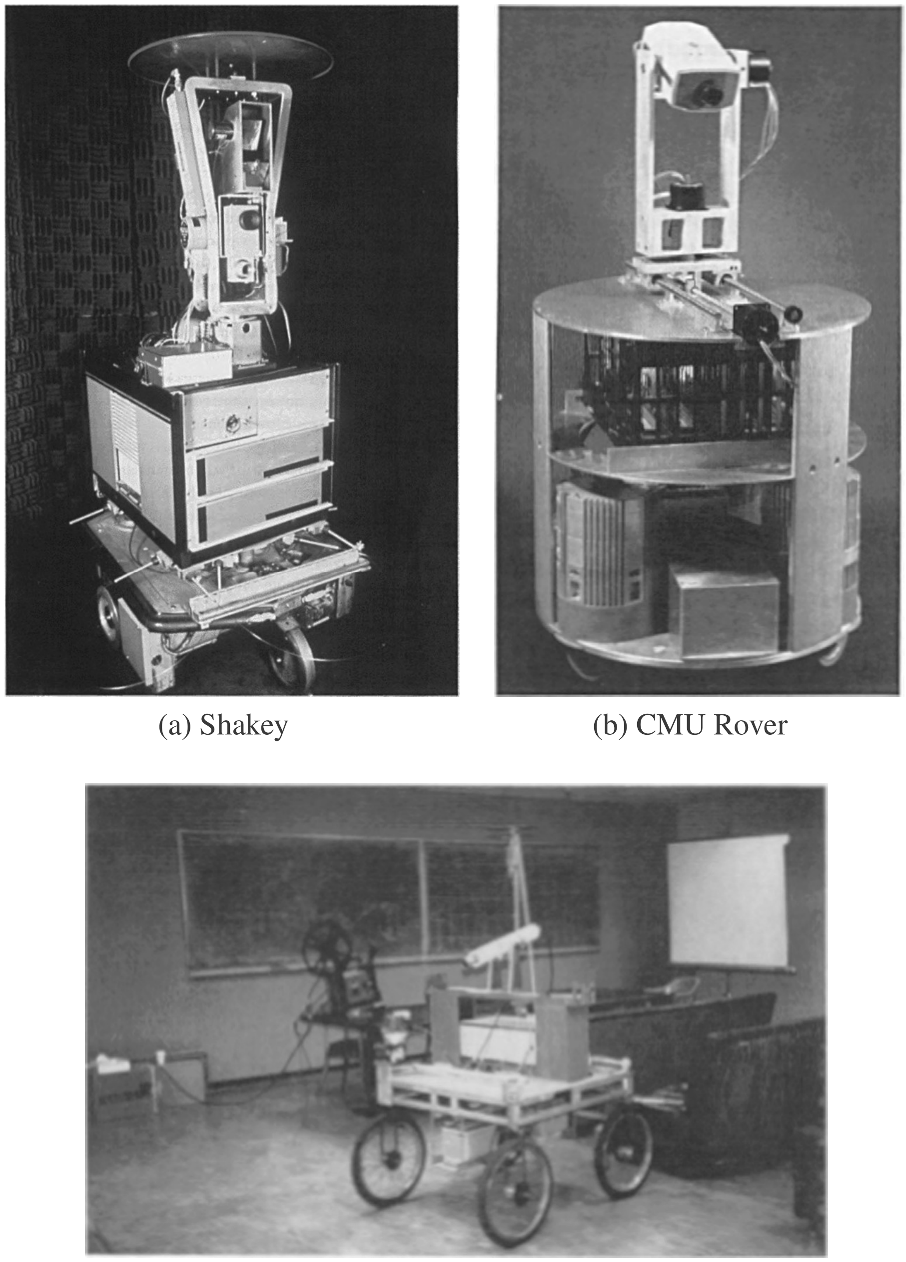
Figure 1.3. V1 flying bomb. Currently hanging in the Imperial War Museum, London.

At the same time that Wiener was developing an automatic anti-aircraft gun, work in Germany on the V1 and V2 – autonomous aircraft and self-guided rocketry – was establishing the basis for autonomous vehicle design (see Figure 1.3). The V1 and V2 were known as **Vergeltungswaffen** (reprisal weapons). The V1 was equipped with simple sensors to measure distance travelled (a propeller in the nose), altitude, and heading. This was sufficient to permit the device to be launched from France and Holland and to strike at population centers in England. Roughly 8000 were launched [526].

W. Grey Walter built one of the earliest fully autonomous vehicles. Described in a series of articles published in 1950 and 1951 in *Scientific American* and in his book *The Living Brain* [635], Walter's electronic turtle (see Figure 1.2b) had phototube eyes, microphone ears, contact-switch feelers, and capacitors used as memory devices to perform associations. Walter named the robot Tortoise after the creature in *Alice in Wonderland*. The Tortoise performed tasks such as heading towards well-lit regions, locating the recharging hutch, and wandering without mishap.

With the development of digital computers came the potential for more complex mobile robots. Between 1966 and 1972, Nils Nilssen, Charles Rosen, and other researchers at the Stanford Research Institute developed Shakey, the first mobile robot to be operated using artificial intelligence techniques [461]. The 5-foot-tall robot used two stepper motors in a differential drive arrangement to provide locomotion and was equipped with touch-sensitive bumpers. An optical rangefinder and vidicon television camera with controllable focus and iris were mounted on a tilt platform for sensing. Off-board communication was provided via two radio channels – one for video and the other providing command and control. Shakey is shown in Figure 1.4a.

Work on Shakey concentrated on automated reasoning and planning, which used logic-based problem solving based on **STRIPS** – the STanford Research Institute Problem Solver. The control of movement and the interpretation of sensory data were secondary to this logic-based component. Simple video processing was used to obtain local information about empty floor space, and Shakey constructed a global map of its environment based on this information. A typical mission for Shakey was to find a box of a given size, shape, and color in one of a specified number of rooms and then to move it to a designated position.



(a) Shakey (b) CMU Rover

(c) Stanford Cart

Figure 1.4. Early wheeled digital robots. (a) Reprinted from D. Stork (Ed.), *HAL's Legacy* [585], MIT Press, 1997. Used with permission. (b) and (c) Reprinted from H. P. Moravec, The Stanford Cart and the CMU Rover [433]. Used with permission.

Being able to accomplish these tasks depended on a simplified environment containing simple wooden blocks in carefully constrained shapes. Shakey had to cope with obstacles and plan actions using a total of 192K of memory (eventually upgraded to 1.35 MB).

The **Stanford Cart** [431–433] (see Figure 1.4c) was developed at SAIL (the Stanford Artificial Intelligence Laboratory) between 1973 and 1979 and moved to Carnegie Mellon University (CMU) in 1980. Throughout this period it underwent major modifications and served as the initial test device upon which solutions to a number of classic robot problems

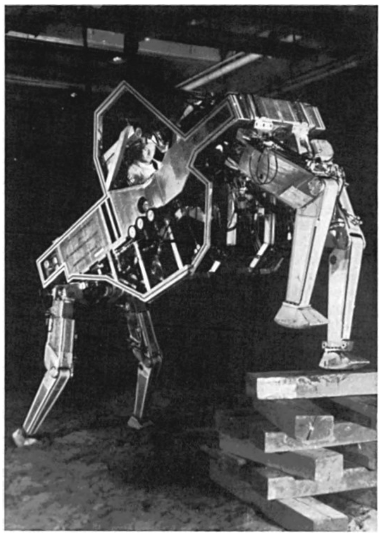


Figure 1.5. The GE Quadruped. Reprinted from Song and Waldron, *Machines That Walk* [575], MIT Press, 1989. Used with permission.

were developed. The Stanford Cart relied on stereo vision in order to locate objects and planned paths to avoid sensed obstacles using a world model based on stereo data. The stereopsis algorithm was based on a single camera that was mounted on a sliding track that was perpendicular to the camera's optical axis. A single 'view' of the environment was based on nine images taken at different positions along this track. A comparison of the images over time was used to determine the motion of the cart, whereas comparisons of the images from a single position were used to build an environmental model. The robot was controlled by an off-board computer program that drove the cart through cluttered spaces. The cart moved roughly 1 m every 10 to 15 min.

The kinematic structure of the Stanford Cart introduced a number of limitations in the robot. Recognizing these limitations, the CMU Rover project (started in 1980) developed a robot that relied on a synchronous drive-like assembly rather than the car-like steering of the Stanford Cart. The Rover added infrared and sonar proximity sensors to the robot and modified the camera mount for the video sensor so that it could pan and tilt as well as slide, which were not possible with the Stanford Cart.

Another early robot system, the **Hilare** project and robot family developed at Laboratoire & Analyse et d'Architecture des Systèmes (LAAS) in France [93, 243], also represented a milestone in performance. Hilare I, developed in 1977, was an indoor mobile robot based on a differential drive system (two powered wheels and one free wheel for balance) and included a laser rangefinder. Hilare's perceptual system relied on sonar units, a video camera, and a laserrange finder. The laser and camera were mounted on a pan-and-tilt station in order to direct the sensor in different directions.

In parallel with these early wheeled mobile robots, legged robotic systems began to appear in the 1960s. The first legged or walking robots appeared in a patent for a mechanical horse in 1893, but it was not until the early 1960s that an operational walking vehicle was constructed. Perhaps the most famous of the early legged vehicles is the General Electric Quadruped (see Figure 1.5) [373, 437]. Each of the four legs of this vehicle had three simple joints; the knee joint was composed of a single joint, and the hip joint used two. As can be seen in Figure 1.5, the GE Quadruped was controlled by an on-board operator. In practice it was a very difficult device to control, although the vehicle did exhibit considerable mobility.

From the mid 1980s on, there was an explosion in mobile robot design. A number of companies began to manufacture and market mobile robot platforms. With the availability of standard platforms, many different robotic projects emerged, but almost all could trace their underlying design to one of these early robot designs. A survey of mobile robot systems prior to 1986 can be found in [92].

1.3 Biological Inspiration

As in many AI-related fields, the designers of autonomous robots often find motivations and inspiration from biological systems. These inspirations may influence the physical design or the sensory mechanisms or even the underlying model of computational control. Perhaps the most often-cited reason for examining biological systems for inspiration in autonomous robots is that biology provides an existence proof that the problem can indeed be solved. Even very simple biological systems – such as ants or bees – are capable of locomotion, sensing, and reasoning tasks under a wide variety of environmental conditions, conditions that mechanical autonomous systems cannot yet hope to handle.

It is interesting to note that researchers studying biological systems have found robots to be a useful tool for testing models of sensing and communication. For example, specially equipped autonomous robots have been used to validate sensing and navigation models used by desert ants [350], [638], computational fish schooling models have been used to model animations [534], and a dancing bee robot has been used to communicate with real bees [424].

1.4 Operational Regimes

There are only a few fully autonomous robots in general use today. Most robots are designed to operate with some level of human guidance or control. Even 'autonomous' systems are expected to obey their programming and accept task specifications on a regular basis.

When a robotic system is described as being **fully autonomous**, the system is typically designed to operate without full-time external human control. This is to be distinguished from **semi-autonomous** systems, in which an operator is required full-time. Within the continuum of semi-autonomous systems, two different operational regimes can be identified: **teleoperated systems**, in which the remote device is controlled moment by moment at a very low level, and **telerobotic systems**, in which low-level operator commands are interpreted or filtered by complex software layers that may use sensors located on the robot to limit, complement or filter the operator's actions.

1.5 Operational Modes

Simple robotic systems can be controlled by a single central processor. More sophisticated systems incorporate subsidiary processors to deal with real-time device

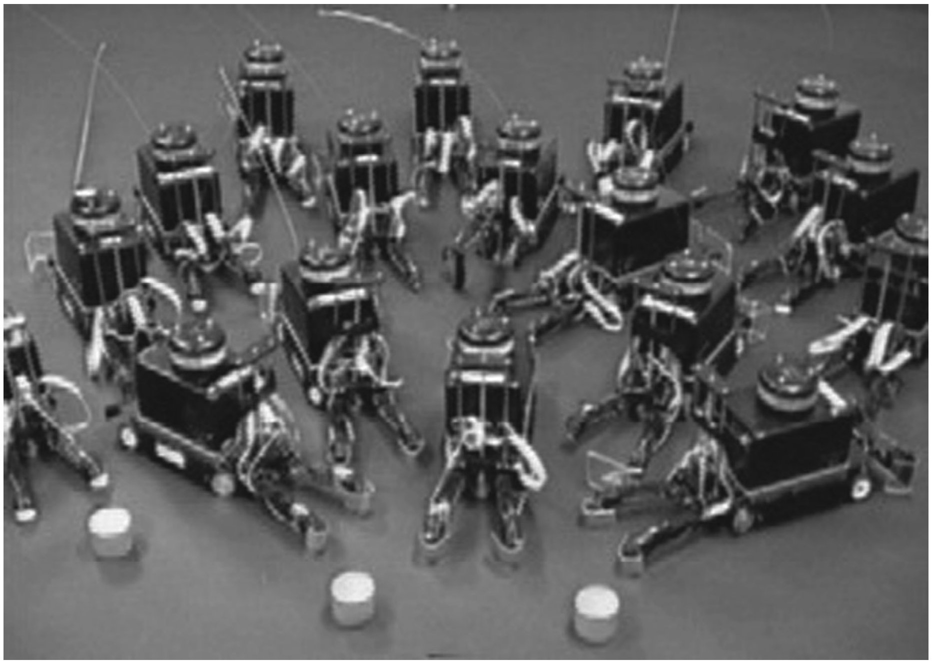


Figure 1.6. A swarm of robots: "The Nerd Herd: a family of 20 IS Robotics R1 mobile robots." Taken at the Interaction Lab at USC. Copyright Dr. Maja Mataric. Used with permission.

control (such as the use of programmable microcontrollers to control and monitor sensors). As the processing needs of the robotic system increase, multiple computing units may be necessary, and the control of the robot becomes distributed over these processors. Because on-board computation is limited by weight and power consumption (not to mention economics), some of these processors may be deployed offboard at the far end of a slow communications link. The effective distribution of tasks in such a heterogeneous environment can be very difficult. In addition to distributing the computation among multiple processors, some of which may be located off-board, it is also possible to distribute the robotic work over multiple robots. This **collective** or **swarm** of robots could itself be centrally controlled, or both the robotic task and the computation may be distributed. Figure 1.6 shows a sample robot collective. The design of a collective with distributed computation and task achievement is very complex.

1.6 A Guide to This Book

Chapter 2 introduces some of the fundamental computational issues that underlie mobile robotics. Chapter 3 provides a brief overview of non-sensor robot hardware. It concentrates on different models of locomotion for wheeled robots but also considers other locomotive strategies. Chapters 4 and 5 cover non-visual and visual sensors and their algorithms. Chapter 6 considers the task of representing and reasoning about space, and Chapter 7 looks at how the software modules that make up a mobile robot can be constructed. Chapters 8 and 9 look at pose maintenance and maps. Chapter 10 looks at the problems faced by groups of robots. Chapter 11 surveys practical robot tasks and the robots that have been constructed for them, and Chapter 12 looks forward to the future of mobile robots. The appendixes provide a (short) introduction to some of the mathematical concepts used throughout the book.

1.7 Further Reading

Autonomous robots in literature A reading list of books and short stories that feature mobile robots of one form or another follows. Many of the better stories have become the basis of movies (see the following), but some have yet to undergo such reinterpretation. Even if you have *seen the film*, the book on which it was based often presents a completely different take on the problem.

The Hitchhiker's Guide to the Galaxy by Douglas Adams [3] introduces Marvin, the Paranoid Android, plus a collection of other interesting robotic devices. There are four other titles, *The Restaurant at the End of the Universe* [4], *Life, the Universe and Everything* [5], *So Long, and Thanks for All the Fish* [6], and *Mostly Harmless* [7], in the misnamed "trilogy."

The Complete Robot by Isaac Asimov [35]. Isaac Asimov's robot stories are, in general, short stories and have been published in a number of anthologies. *The Complete Robot* brings all of these stories together.

Half Past Human by T. J. Bass [56]. In the future humankind lives underground, and the surface of the planet is tended by robots. This world appears in many of T. J. Bass' stories, including *The Godwhale* [57], which features a cyborg whale.

In the Ocean of Night by Gregory Benford [65]. A computer-controlled spaceship and mechanical machines are out to destroy organic life.

Do Androids Dream of Electric Sheep? by Philip K. Dick [166]. A world of replicants (androids), pet robots (which look like animals), and Deckard, a bounty hunter. The basis of the film *Blade Runner* (see following list).

Camelot 30K by Robert L. Forward [226]. A story about the telerobotic exploration of a microscopic world.

The Star Diaries by Stanislaw Lem [361]. A collection of stories concerning Ijon Tichy, who encounters robots.

The Ship Who Sang by Anne McCaffrey [412]. A disabled woman is equipped with a mechanical spaceship and goes out to explore the stars.

The Berserker Wars by Fred Saberhagen [548]. A collection of stories concerning robot-controlled spaceships that rampage throughout the galaxy. There are a number of other collections of "Berserker" stories, including anthologies by other authors on the same theme.

Frankenstein by Mary Wollstonecraft Shelley [563]. The classic story of a doctor/engineer trying to bring his creature to life. Required reading for any creator of autonomous systems.

Autonomous robots in film The following is a collection of movies that conspicuously feature mobile robots of one form or another. Some robot movies, such as the 1951 version of *The Day the Earth Stood Still*, can be considered as classics. Others, such as *Robot Monster*, are less memorable. Nevertheless, these moves do show how robots are perceived by the public.

Metropolis (1927). The classic Fritz Lang silent film that started it all. A mad scientist creates a seductive female robot.

Frankenstein (1931). The original, with Boris Karloff playing the role of the monster. Dr. Frankenstein animates dead tissue.

The Perfect Woman (1949). An inventor builds a robot that looks like his niece, who then pretends to be the robot.

The Day the Earth Stood Still (1951). Klaatu and the robot Gort tell us that we must live peacefully.

Robot Monster (1953). Ro-Man – a gorilla in a diving helmet – is sent to Earth as part of an invasion force.

Forbidden Planet (1956). An expedition to Altair IV encounters Dr. Morbius, his daughter, and Robby, the Robot.

The Invisible Boy (1957). Robby the Robot (of *Forbidden Planet* fame) teams up with a boy to prevent world domination.

Kill Me Quick! (1964). A mad scientist builds android women.

Frankenstein Meets the Space Monster (1965). An android and an atomic war on Mars.

Dr. Goldfoot and the Bikini Machine (1965). Vincent Price constructs bikini-clad female androids.

Dr. Who and the Daleks (1965). The Doctor battles the Daleks.

Daleks' Invasion Earth: 2150 AD (1966). The Doctor battles the Daleks on Earth.

Dr. Goldfoot and the Girl Bombs (1966). Yet more female androids in this sequel to the 1965 *Dr. Goldfoot and the Bikini Machine*.

2001: A Space Odyssey (1968). An expedition is sent to Jupiter. The robotic spaceship is managed by the HAL 9000 computer.

Silent Running (1972). A lone crew member and three robots (Huey, Dewey, and Louie) care for Earth's last nature reserves aboard a spaceship.

Sleeper (1973). A frozen Woody Allen is revived in a future in which robots are commonplace.

Westworld (1973). A futuristic amusement park in which androids are used to populate the park. Things go wrong.

Futureworld (1976). A sequel to *Westworld* in which androids are used to replace humans with robot doubles.

Demon Seed (1977). An Artificial Intelligence rapes his creator's wife.

Star Wars (1977). Assisted by the robots R2D2 and C3PO, Luke Skywalker leaves his home planet in search of Princess Leia.

Battlestar Galactica (1978). Cobbled together from the TV show of the same name, this movie pits the robotic Cylons against the remnants of human civilization and the Battlestar Galactica.

Alien (1979). A mining ship lands on a distant planet and runs into an alien. One of the crew members is an android.

The Black Hole (1979). A research vessel finds a missing ship manned by robots and one human inhabitant.

The Empire Strikes Back (1980). The second installment of the first *Star Wars* saga brings back R2D2 and C3PO.

Galixina (1980). The crew of an interstellar police ship interact with their female android.

Saturn 3 (1980). A couple on a remote base on Saturn are visited by an official delegation including a robot.

Android (1982). A robot designer and his assistant carry out research into androids on a space station.

Blade Runner (1982). Deckard tracks down and terminates replicants (biological androids).

Return of the Jedi (1983). The third and final chapter in the first *Star Wars* trilogy brings back R2D2 and C3PO.

2010 (1984). A sequel to *2001: A Space Odyssey* in which an expedition is sent to Jupiter to learn what happened to the *Discovery* and HAL 9000.

The Terminator (1984). A robot (the Terminator) is sent from the future to influence the past.

D.A.R.Y.L. (1985). A story about an android boy.

Aliens (1986). The first sequel to *Alien*. Again one of the crew is an android.

Deadly Friend (1986). Bad things happen when a teen implants his robot's brain into his dead friend.

Short Circuit (1986). A military robot (Number 5) becomes intelligent and escapes.

Cherry 2000 (1987). The adventures of a businessman and his android wife.

Making Mr. Right (1987). A scientist builds a male robot to go on a long space mission.

RoboCop (1987). A wounded police officer is rebuilt as a cyborg.

Short Circuit 2 (1988). Number 5 (from *Short Circuit*) goes to the big city.

RoboCop 2 (1990). A sequel to *RoboCop* in which the RoboCop fights a bigger, stronger cyborg.

Terminator 2: Judgment Day (1991). A sequel to *The Terminator* in which one terminator robot is sent back in time to change history and a second one is sent back to maintain it.

Alien 3 (1992). Another installment of the *Alien* saga. Once again, one of the cast is an android.

Star Trek: Generations (1994). The first *Star Trek* film with the android Commander Data.

Star Trek: First Contact (1996). The Star Trek Next Generation crew confront the half-machine Borg.

Lost in Space (1998). A remake of the TV series of the same name. The Robinson family (including the robot) become lost in space.

Star Trek: Insurrection (1998). Yet more adventures of the Next Generation crew, including the android Commander Data.

The Iron Giant (1999). A boy befriends a giant robot that the government wants to destroy.

Star Wars: Episode I – The Phantom Menace (1999). R2D2, C3PO, and huge robot armies controlled by a single control ship.

Red Planet (2000). Astronauts go to Mars to save a dying Earth, bringing along a dog-like robot (AMEE) whose military programming becomes enabled.

AI (2001). A highly advanced robot boy longs to become a real boy.

Star Wars: Episode II – Attack of the Clones (2002). R2D2, C3PO, and huge robot armies.

Star Wars: Episode III – Revenge of the Sith (2003). Yet more robots and androids in George Lucas' Star Wars world.

I, Robot (2004). Lots and lots and lots of centrally controlled robots try to take over the world.

Robots (2005). A robot makes its way to the big city.

Stealth (2005). An autonomous air vehicle goes haywire.

Transformers (2007). Transforming robots make Earth their battlefield.

The Day the Earth Stood Still (2008). A remake of the 1951 classic but with a decomposible robot.

Transformers: Revenge of the Fallen (2009). Yet more robots in disguise battle on Earth.

Early autonomous robots More details of the life of Grey Walter can be found in Owen Holland's review [279]. See also Cox and Wilfong's collection of papers prior to 1990 [143].

Other robotics texts Since the publication of the first edition, a number of general texts on autonomous robots have appeared. These include [278], [569], [122], [568], and [90].

1.8 Problems

1. There are a large number of robotics sources available, including the Internet and local libraries. Identify which robotics journals are available locally and which robot conference proceedings are available. Search the World Wide Web for the resources available there. There are a number of international robotics conferences. Try to find proceedings of the following:
- IEEE International Conference of Robotics and Automation (ICRA)
- IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
- Robotics: Science and Systems (RSS)

2. If there is a mobile platform available locally, obtain a copy of the system documentation for the device. How is it powered? Recharged? Controlled? Learn how to power the device on and off and how to control it.

3. Take a robot from film or literature. What is the robot designed to do? How was the robot constructed? How does it sense its environment? How does it move about within its environment? Ignoring issues related to power and our ability to construct self-aware, perfectly sensing vehicles, is the robot *as presented* suitable for the task that it is designed to do in the book or film?

4. Compute the *Shakey number* of your robot, where the Shakey number is the minimum number of researchers removed your robot project is from Shakey. The Shakey Robot

Project has a Shakey number of 0. A robot project worked on by one of the researchers who worked on Shakey has a Shakey number of 1.

5. In *The Complete Robot*, Asimov divides the bulk of robot stories into one of two groups: robot-as-menace and robot-as-pathos. Asimov conjectured that there were few stories that fell outside these two groups. Go through the films and stories listed in this chapter and categorize them in terms of these two groups. Have other groups of robot stories begun to emerge?
6. A large number of mobile robot simulators exist that are either open source or released under license for academic work. Find a simulator that is suitable for your environment and download and build it.