Chapter

1 Introduction

The term robot means different things to different people. Science fiction books and movies have strongly influenced what many people expect a robot to be or what it can do. Sadly the practice of robotics is far behind this popular conception. One thing is certain though – robotics will be an important technology in this century. Products such as vacuum cleaning robots are the vanguard of a wave of smart machines that will appear in our homes and workplaces.

In the eighteenth century the people of Europe were fascinated by automata such as Vaucanson's duck shown in Fig. 1.1a. These machines, complex by the standards of the day, demonstrated what then seemed *life-like* behaviour. The duck used a cam mechanism to sequence its movements and Vaucanson went on to explore mechanization of silk weaving. Jacquard extended these ideas and developed a loom, shown in Fig. 1.1b, that was essentially a programmable weaving machine. The pattern to be woven was encoded as a series of holes on punched cards. This machine has many hallmarks of a modern robot: it performed a physical task and was reprogrammable.

The term robot was coined in a 1921 Czech science fiction play "Rossum's Universal Robots" by Karel Čapek. The robots were artificial people or androids and the word, in Czech, is derived from the word for worker. In the play, as in so many robot stories that follow, the robots rebel and it ends badly for humanity. Isaac Asimov's robot series, comprising many books and short stories written between 1950 and 1985, explored issues of human and robot interaction and morality. The robots in these stories are equipped with "positronic brains" in which the "Three laws of robotics" are encoded. These stories have influenced subsequent books and movies which in turn have shaped the public perception of what robots are. The mid twentieth century also saw the advent of the field of *cybernetics* – an uncommon term today but then an exciting science at the frontiers of understanding life and creating intelligent machines.

The first patent for what we would now consider a robot was filed in 1954 by George C. Devol and issued in 1961. The device comprised a mechanical arm with a gripper that was mounted on tracks and the sequence of motions was encoded as magnetic patterns stored on a rotating drum. The first robotics company, Unimation, was founded by Devol and Joseph Engelberger in 1956 and their first industrial robot shown

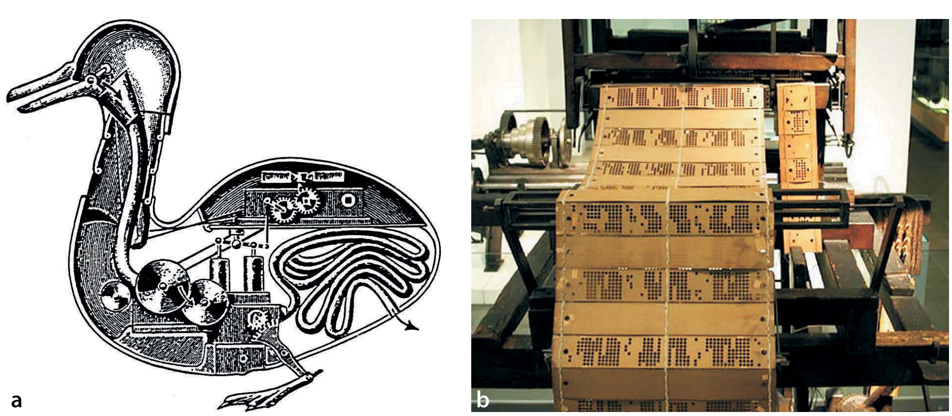


Fig. 1.1. Early programmable machines. **a** Vaucanson's duck (1739) was an automaton that could flap its wings, eat grain and defecate. It was driven by a clockwork mechanism and executed a single program; **b** The Jacquard loom (1801) was a reprogrammable machine and the program was held on punched cards (photograph by George P. Landow from www.victorianweb.org)

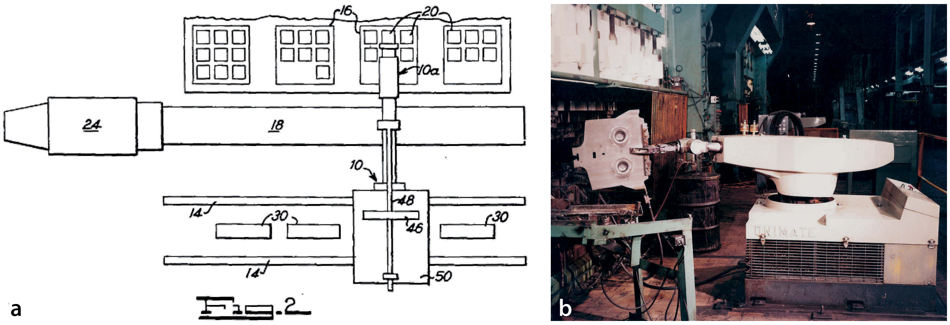


Fig. 1.2. Universal automation. **a** A plan view of the machine from Devol's patent; **b** the first Unimation robot working at a General Motors factory (photo courtesy of George C. Devol)

in Fig. 1.2 was installed in 1961. The original vision of Devol and Engelberger for robotic automation has become a reality and many millions of arm-type robots such as shown in Fig. 1.3 have been built and put to work at tasks such as welding, painting, machine loading and unloading, electronic assembly, packaging and palletising. The use of robots has led to increased productivity and improved product quality. Rather than take jobs it has helped to keep manufacturing industries viable in high-labour cost countries. Today many products we buy have been assembled or handled by a robot.

These first generation robots are now a subclass of robotics known as manufacturing robots. Other subclasses include service robots which supply services such as cleaning, personal assistance or medical rehabilitation; field robots which work outdoors such as those shown in Fig. 1.4; and humanoid robots such as shown in Fig. 1.6b that have the physical form of a human being.

A manufacturing robot is typically an arm-type manipulator on a fixed base that performs repetitive tasks within a local work cell. Parts are presented to the robot in an orderly fashion which maximizes the advantage of the robot's high speed and precision. High-speed robots are hazardous and safety is achieved by excluding people from robotic work places.

Field and service robots face specific and significant challenges. The first challenge is that the robot must operate and move in a complex, cluttered and changing environment. A delivery robot in a hospital must operate despite crowds of people and a time-varying configuration of parked carts and trolleys. A Mars rover must navigate rocks and small craters despite not having an accurate local map in advance of its travel. Robotic cars, such as demonstrated in the DARPA Grand Challenges (Buehler et al. 2007), must follow roads, obey traffic signals and the rules of the road.

The second challenge for these types of robots is that they must operate safely in the presence of people. The hospital delivery robot operates amongst people, the robotic car contains people and a robotic surgical device operates *inside* people.

Fig. 1.3. A modern six-axis robot from ABB that would be used for factory automation. This type of robot is a technological descendant of the Unimate shown in Fig. 1.2

Rossum's Universal Robots (RUR). In the introductory scene Helena Glory is visiting Harry Domin the director general of Rossum's Universal Robots and his robotic secretary Sulla.

Domin Sulla, let Miss Glory have a look at you.
Helena (stands and offers her hand) Pleased to meet you. It must be very hard for you out here, cut off from the rest of the world [the factory is on an island]
Sulla I do not know the rest of the world Miss Glory. Please sit down.
Helena (sits) Where are you from?
Sulla From here, the factory
Helena Oh, you were born here.
Sulla Yes I was made here.
Helena (startled) What?
Domin (laughing) Sulla isn't a person, Miss Glory, she's a robot.
Helena Oh, please forgive me …

The full play can be found at http://ebooks.adelaide.edu.au/c/capek/karel/rur. (Image on the right: Library of Congress item 96524672)

George Devol, Jr. (1912–2011) was a prolific American inventor. He was born in Louisville, Kentucky, and in 1932 founded United Cinephone Corp. which manufactured phonograph arms and amplifiers, registration controls for printing presses and packaging machines. In 1954, he applied for US patent 2,988,237 for Programmed Article Transfer which introduced the concept of Universal Automation or "Unimation". Specifically it described a track-mounted polar-coordinate arm mechanism with a gripper and a programmable controller – the precursor of all modern robots.

In 2011 he was inducted into the National Inventors Hall of Fame. (Photo on the left: courtesy of George C. Devol)

Joseph F. Engelberger (1925–) is an American engineer and entrepreneur who is often referred to as the "Father of Robotics". He received his B.S. and M.S. degrees in physics from Columbia University, in 1946 and 1949, respectively. Engelberger has been a tireless promoter of robotics. In 1966, he appeared on *The Tonight Show Starring Johnny Carson* with a Unimate robot which poured a beer, putted a golf ball, and directed the band. He promoted robotics heavily in Japan, which led to strong investment and development of robotic technology in that country, and and gave testimony to Congress on the value of using automation in space. He has written two books *Robotics in Practice* (1980) and *Robotics in Service* (1989), and the former was translated into six languages.

Engelberger served as chief executive of Unimation until 1982, and in 1984 founded Transitions Research Corporation which became HelpMate Robotics Inc. and was later sold. He remains active in the promotion and development of robots for use in elder care. He was elected to the National Academy of Engineering and received the Beckman Award and the Japan Prize. Each year the Robotics Industries Association presents an award in his honour to "persons who have contributed outstandingly to the furtherance of the science and practice of robotics."

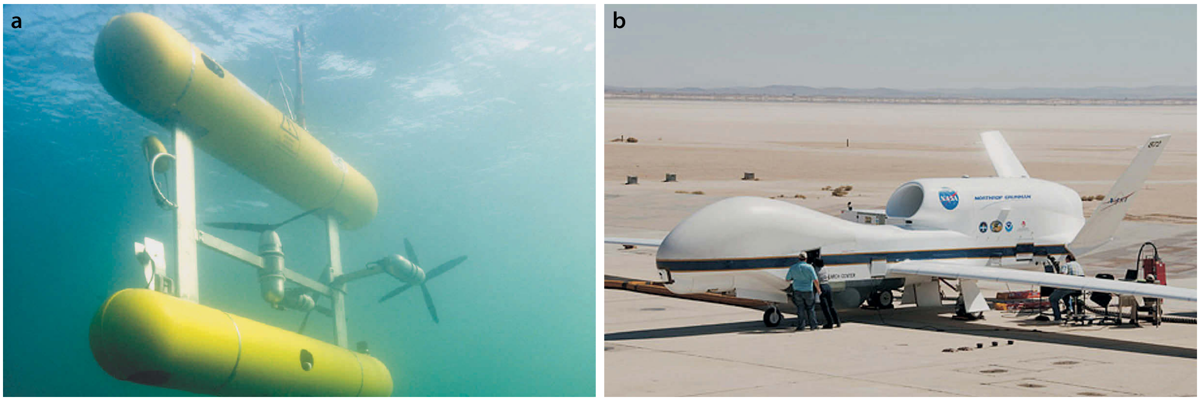


Fig. 1.4. Non land-based mobile robots. **a** SeaBed type Autonomous Underwater Vehicle (AUV) operated by the Australian Centre for Field Robotics (photo by Roger T. Hanlon), **b** Global Hawk unmanned aerial vehicle (UAV) (photo: courtesy of NASA)

So what is a robot? There are many definitions and not all of them are particularly helpful. A definition that will serve us well in this book is

a goal oriented machine that can sense, plan and act.

A robot *senses* its environment and uses that information, together with a goal, to *plan* some *action*. The action might be to move the tool of an arm-robot to grasp an object or it might be to drive a mobile robot to some place.

Sensing is critical to robots. Proprioceptive sensors measure the state of the robot itself: the angle of the joints on a robot arm, the number of wheel revolutions on a mobile robot or the current drawn by an electric motor. Exteroceptive sensors measure the state of the world with respect to the robot. The sensor might be a simple contact switch on a vacuum cleaner robot to detect collision. It might be a GPS receiver that measures distances to an orbiting satellite constellation, or a compass that measures the direction of the Earth's magnetic field relative to the robot's heading. It might also be an active sensor

Cybernetics, artificial intelligence and robotics. Cybernetics flourished as a research field from the 1930s until the 1960s and was fueled by a heady mix of new ideas and results from neurology, feedback, control and information theory. Research in neurology had shown that the brain was an electrical network of neurons. Harold Black, Henrik Bode and Harry Nyquist at Bell Labs were researching negative feedback and the stability of electrical networks, Claude Shannon's information theory described digital signals, and Alan Turing was exploring the fundamentals of computation. Walter Pitts and Warren McCulloch proposed an artificial neuron in 1943 and showed how it might perform simple logical functions. In 1951 Marvin Minsky built SNARC (from a B24 autopilot and comprising 3000 vacuum tubes) which was perhaps the first neural-network-based learning machine as his graduate project. William Grey Walter's robotic tortoises showed life-life behaviour. Maybe an electronic brain could be built!

An important early book was Norbert Wiener's *Cybernetics or Control and Communication in the Animal and the Machine* (Wiener 1965). A characteristic of a cybernetic system is the use of feedback which is common in engineering and biological systems. The ideas were later applied to evolutionary biology, psychology and economics.

In 1956 a watershed conference was hosted by John McCarthy at Dartmouth College and attended by Minsky, Shannon, Herbert Simon, Allen Newell and others. This meeting defined the term artificial intelligence (AI) as we know it today with an emphasis on digital computers and symbolic manipulation and led to new research in robotics, vision, natural language, semantics and reasoning. McCarthy and Minsky formed the AI group at MIT, and McCarthy left in 1962 to form the Stanford AI Laboratory. Minsky focused on artificially simple "blocks world". Simon, and his student Newell, were influential in AI research at Carnegie-Mellon University from which the Robotics Institute was spawned in 1979. These AI groups were to be very influential in the development of robotics and computer vision in the USA. Societies and publications focusing on cybernetics are still active today.

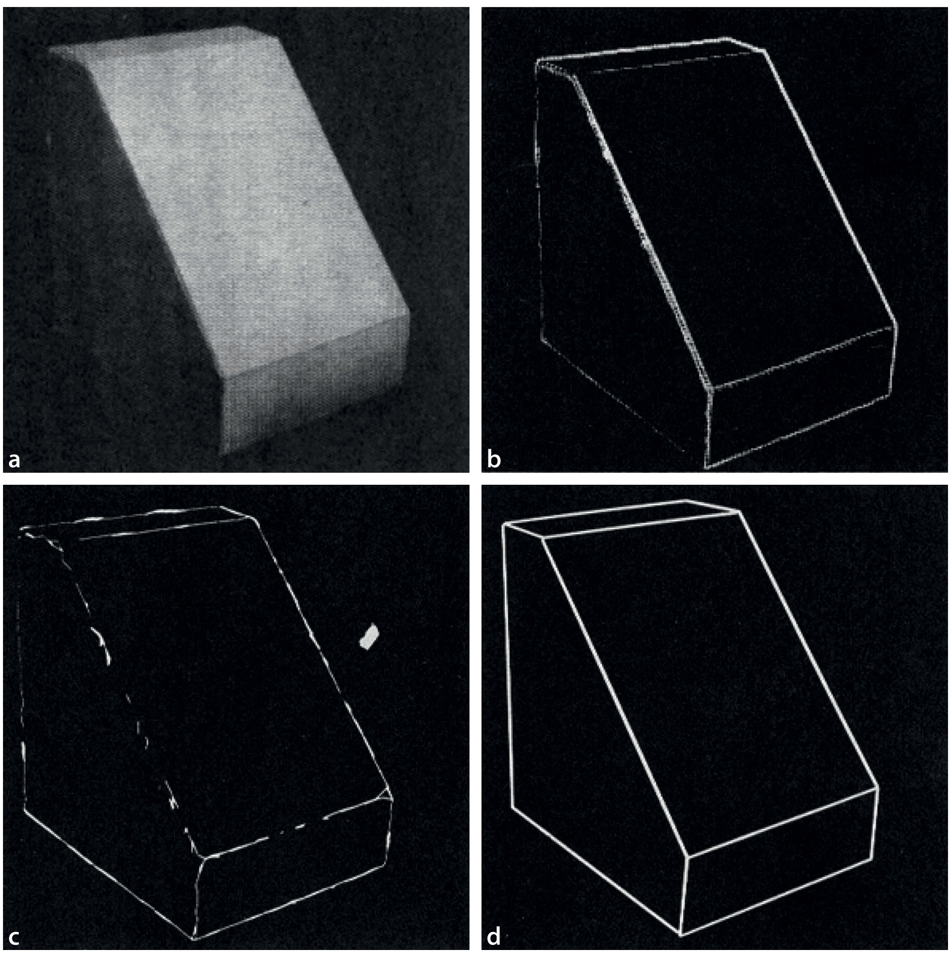


Fig. 1.5.
Early results in computer vision for estimating the shape and pose of objects, from the PhD work of L. G. Roberts at MIT Lincoln Lab in 1963 (Roberts 1963). **a** Original picture; **b** gradient image; **c** connected feature points; **d** reconstructed line drawing

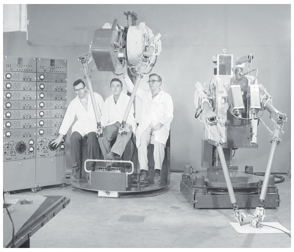
that emits acoustic, optical or radio pulses in order to measure the distance to points in the world based on the time taken for a reflection to return to the sensor.

A camera is a passive captures patterns of energy reflected from the scene. Our own experience is that eyes are a very effective sensor for recognition, navigation, obstacle avoidance and manipulation so vision has long been of interest to robotics researchers. Figure 1.5 shows early work in reconstructing a 3-dimensional wireframe model from an image and gives some idea of the difficulties involved. An important limitation of a single camera is that the 3-dimensional structure must be inferred from the 2-dimensional image. An alternative approach is stereo vision, using two or more cameras, to compute the 3-dimensional structure of the world. The Mars rover shown in Fig. 1.6a has a stereo camera on its mast.

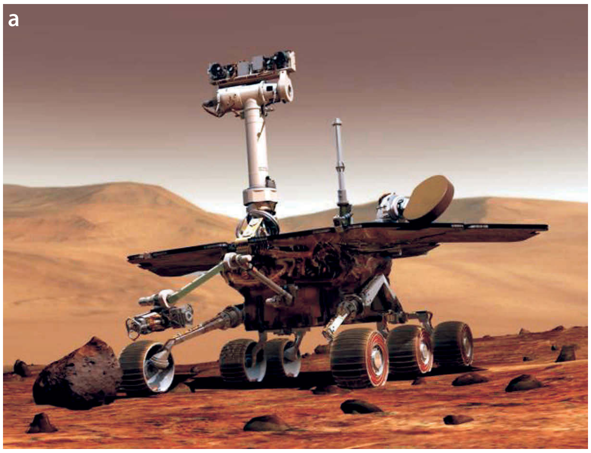
In this book we focus on the use of cameras as sensors for robots. Machine vision, discussed in Part IV, is the use of computers to process images from one or more cameras and to extract numerical features. For example determining the coordinate of a round red object in the scene, or how far a robot has moved based on how the world appears to move relative to the robot.

If the robot's environment is unchanging it can make do with an accurate map and have little need to sense the state of the world, apart from determining where it is. Imagine driving a car with the front window covered over and just looking at the GPS navigation system. If you had the roads to yourself you could probably drive from A to B quite successfully albeit slowly. However if there were other cars, pedestrians, traffic signals or roadworks then you would be in some difficulty. To deal with this you need to look outwards – to sense the world and plan your actions accordingly. For humans this is easy, done without conscious thought, but it is not easy to program a machine to do the same.

Tele-robots are robot-like machines that are remotely controlled by a human operator. Perhaps the earliest was a radio controlled boat demonstrated by Nikola Tesla in 1898 and which he called a teleautomaton. According to the definition above these are not robots but they were an important precursor to robots and are still important today (Goldberg and Siegwart 2001; Goldberg 2001) for many tasks where people cannot work but which are too complex for a machine to perform by itself. For example the underwater robots that surveyed the wreck of the Titanic were technically remotely operated vehicles (ROVs). The Mars rovers Spirit and Opportunity



The Manhattan Project in World War 2 (WW II) developed the first nuclear weapons and this required handling of radioactive material. Remotely controlled arms were developed by Ray Goertz at Argonne National Laboratory to exploit the manual dexterity of human operators while keeping them away from the hazards of the material they were handling. The operators viewed the task they were doing through thick lead-glass windows or via a television link. Telerobotics is still important today for many tasks where people cannot work but which are too complex for a machine to perform by itself, for instance the underwater robots that surveyed the wreck of the Titanic. (Photo on the left: Courtesy Argonne National Laboratory)



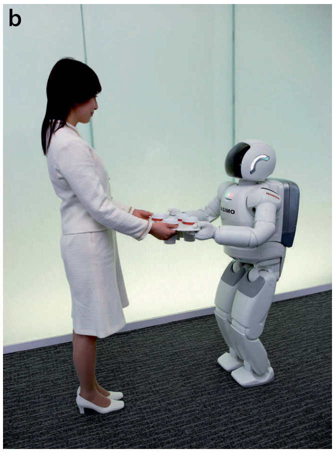


Fig. 1.6.
Two very different types of mobile robots. **a** Mars rover. Note the two cameras on the mast which provide stereo vision from which the robot can compute the 3-dimensional structure of its environment (image courtesy of NASA/JPL/Cornell University); **b** Honda's Asimo humanoid robot (photo courtesy Honda Motor Co. Japan)

Unimation Inc. (1956–1982). Devol sought financing to develop his unimation technology and eventually met with Joseph Engelberger who was then an engineer with Manning, Maxwell and Moore. In 1956 they jointly established Unimation, the first robotics company, in Danbury Connecticut. The company was acquired by Consolidated Diesel Corp. (Condec) and became Unimate Inc. a division of Condec. Their first robot went to work in 1961 at a General Motors die-casting plant in New Jersey. In 1968 they licenced technology to Kawasaki Heavy Industries which produced the first Japanese industrial robot. Engelberger served as chief executive until it was acquired by Westinghouse in 1982. People and technologies from this company have gone on to be very influential on the whole field of robotics.

autonomously navigate the surface of Mars but human operators provide the high-level goals. That is, the operators tell the robot where to go and the robot itself determines the details of the route. Local decision making on Mars is essential given that the communications delay is several minutes. Some robots are hybrids and the control task is shared or traded with a human operator. In traded control, the control function is passed back and forth between the human operator and the computer. For example an aircraft pilot can pass control to an autopilot and take back control back. In shared control, the control function is performed by the human operator and the computer working together. For example an autonomous passenger car might have the computer keeping the car in the lane and avoiding collisions, while the human operator just controls the speed.

1.1 About the Book

This book is about robotics and computer vision – separately, and together as robotic vision. These are big topics and the combined coverage is necessarily broad. The intent is not to be shallow but rather to give the reader a flavour of what robotics and vision is about and what it can do – consider it a grand tasting menu.

The goals of the book are:

- to provide a broad and solid base of understanding through theory and examples;
- to tackle more complex problems than other textbooks by virtue of the powerful numerical tools and software that underpins it;
- to provide instant gratification by solving complex problems with relatively little code;
- to complement the many excellent texts in robotics and computer vision;
- to encourage intuition through hands on numerical experimentation; and
- to limit the number of equations presented to where (in my judgement) they add value or clarity.

The approach used is to present background, theory and examples in an integrated fashion. Code and examples are first-class citizens in this book and are not relegated to the end of the chapter or an associated web site. The examples are woven into the discussion like this

```
>> Ts = ctraj(T1, T2, t);
>> p = transl(Ts);
>> plot(t, p);
```

where the MATLAB® code illuminates the topic being discussed and generally results in a figure or a crisp numerical result that is then discussed. The examples illustrate how to use the associated MATLAB® Toolboxes and that knowledge can then be applied to other problems. Most of the figures in this book have been generated by the code examples provided – in fact the book is just one very large MATLAB® script.

1.1.1 The MATLAB® Software

To do good work, one must first have good tools.
Chinese proverb

The computational foundation of this book is MATLAB®, a product of The Mathworks Inc. MATLAB® is an interactive mathematical software environment that makes linear algebra, data analysis and high-quality graphics a breeze. MATLAB® is a popular package and one that is very likely to be familiar to students and researchers. It also supports a programming language which allows the creation of complex algorithms.

A strength of MATLAB® is its support for Toolboxes which are collections of functions targeted at particular topics. Toolboxes are available from The MathWorks, third party companies and individuals. Some Toolboxes are products and others are open-source. This book is based on two open-source Toolboxes written by the author: the Robotics Toolbox for MATLAB® and the Machine VisionToolbox for MATLAB®. These Toolboxes, with MATLAB® turn a modern personal computer into a powerful and convenient environment for investigating complex problems in robotics, machine vision and vision-based control. The Toolboxes are free to use and distributed under the GNU Lesser General Public License (GNU LGPL).

The *Robotics Toolbox* (RTB) provides a diverse range of functions for simulating mobile and arm-type robots. The original toolbox, dating back to the early 1990s, was concerned only with arm-type robots and supported a very general method of representing the structure of serial-link manipulators using matrices and later MATLAB® objects. Arbitrary serial-link manipulators could be created and the Toolbox provides functions for forward and inverse kinematics and dynamics. The Toolbox includes functions for manipulating and converting between datatypes such as vectors, homogeneous transformations, 3-angle representations and unit-quaternions which are necessary to represent 3-dimensional position and orientation.

The Toolbox released with this book adds significant new functionality for simulating mobile robots. The RTB now includes models of car-like vehicles and quadrotors and controllers for these vehicles. It also provides standard algorithms for robot path planning, localization and map making.

The *Machine Vision Toolbox* (MVTB) provides a rich collection of functions for camera modeling, image processing, image feature extraction, multi-view geometry and vision-based control. This Toolbox is younger than the Robotics Toolbox but it is

The MATLAB® software we use today has a long history. It starts with the LINPACK and EISPACK projects run by the Argonne National Laboratory in the 1970s to produce high quality, tested and portable mathematical software. LINPACK is a collection of routines for linear algebra and EISPACK is a library of numerical algorithms for computing eigenvalues and eigenvectors of matrices. These packages were written in Fortran which was then, and even today is, the language of choice for large-scale numerical problems.

Cleve Moler, then at the University of New Mexico, contributed to both projects and wrote the first version of MATLAB® in the late 1970s. It allowed interactive use of LINPACK and EISPACK for problem solving without having to write and compile Fortran code. MATLAB® quickly spread to other universities and found a strong audience within the applied mathematics and engineering community. In 1984 Cleve Moler and Jack Little founded The MathWorks Inc. which exploited the newly released IBM PC – the first widely available desktop computer.

Cleve Moler received his bachelor's degree from Caltech in 1961, and a Ph.D. from Stanford University. He was a professor of mathematics and computer science at universities including University of Michigan, Stanford University, and the University of New Mexico. He has served as president of the Society for Industrial and Applied Mathematics (SIAM) and was elected to the National Academy of Engineering in 1997.

See also http://www.mathworks.com/company/aboutus/founders/clevemoler.html which includes a video of Cleve Moler and also http://history.siam.org/pdfs2/Moler_final.pdf.

not a clone of the MATLAB® Image Processing Toolbox (IPT). Although there is some common functionality the Machine Vision Toolbox predates IPT by many years. The MVTB contains many functions for image acquisition and display; filtering; blob, point and line feature extraction; mathematical morphology; image warping; stereo vision; homography and fundamental matrix estimation; robust estimation; visual Jacobians; geometric camera models; camera calibration and color space operations. For modest image sizes on a modern computer the processing rate can be sufficiently "real-time" to allow for closed-loop control.

The Toolboxes are provided in source code form. The bulk of the code is written in the MATLAB® M-language but some functions are written in C for increased computational efficiency.▸ In general the Toolbox code is written in a straightforward manner to facilitate understanding, perhaps at the expense of computational efficiency. If you're starting out in robotics or vision then the Toolboxes are a significant initial base of code on which to build your project.

These are implemented as MEX files, which are written in C in a very specific way that allows them to be invoked from MATLAB® just like a function written in M-language.

This book provides examples of the usage of many Toolbox functions in the context of solving specific problems but it is not a reference manual. Comprehensive documentation of all Toolbox functions is available through MATLAB's builtin help mechanism. This approach allows the code to evolve and develop new features over time while maintaining backward compatibility and not obsoleting the book.

Appendix A provides details of how to obtain the Toolboxes and pointers to online resources including discussion groups.

1.1.2 Audience and Prerequisites

The book is intended primarily for third or fourth year undergraduate students and graduate students in their first year. For undergraduates the book will serve as a companion text for a robotics or machine vision course or to support a major project in robotics or vision. Students should study Part I and the appendices for foundational concepts, and then the relevant part of the book: mobile robotics, arm robots, computer vision or vision-based control. The Toolboxes provide a solid set of tools for problem solving, and the exercises at the end of each chapter provide additional problems beyond the worked examples in the book.

For students commencing graduate study in robotics, and who have previously studied engineering or computer science, the book will help fill in the gaps between what you learned as an undergraduate and what will be required to underpin your deeper study of robotics and computer vision. The book's working code base can help bootstrap your research, enabling you to get started quickly and working productively on your own problems and ideas. Since the source code is available you can reshape it to suit your need, and when the time comes (as it usually does) to code your algorithms in some other language then the Toolboxes can be used to cross-check your implementation.

For those who are no longer students, the researcher or industry practitioner, the book will serve as a useful companion for your own reference to a wide range of topics in robotics and computer vision, as well as a Handbook and guide for the Toolboxes.

The book assumes undergraduate-level knowledge of linear algebra (matrices, vectors, eigenvalues), basic set theory, basic graph theory, probability, dynamics (forces, torques, inertia), the Laplace transform and transfer functions, linear control (proportional control, proportional-derivative control, proportional-integral control) and block diagram notation. Computer science students are less likely to have encountered the Laplace transform and classical control but this appears only in Sect. 9.4, and Hellerstein et al. (2004) may be a useful introduction to the topics. The book also assumes the reader is familiar with programming in MATLAB® and also familiar with object-oriented programming techniques (perhaps C++, Java or Python). Familiarity with Simulink®, MATLAB's graphical block-diagram modeling tool will be helpful but not essential. The appendices provide concise refreshers on many of these topics.

1.1.3 Notation and Conventions

The mathematical notation used in the book is summarized in the nomenclature section on page xvii. Since the coverage of the book is broad there are just not enough good symbols to go around, so it is unavoidable that some symbols have different meanings in different parts of the book.

There is a lot of MATLAB® code in the book and this is indicated in blue fixed-width font such as

```
>> a = 2 + 2
a =
     4
```

The MATLAB® command prompt is >> and what follows is the command issued to MATLAB® by the user. Subsequent lines, without the prompt, are MATLAB's response. All functions, classes and methods mentioned in the text or in code segments are cross-referenced and have their own indexes at the end of the book. All the MATLAB® code segments are available from the book's web page as described in Appendix A. This book is not a manual and although it illustrates the use of many functions within the Toolbox the definitive source for information about all Toolbox functions is the online documentation. Every MATLAB® and Toolbox function used in the code examples is included in the index of functions on page 554 allowing you to find different ways that particular functions have been used.

Colored boxes are used to indicate different types of material. Orange informational boxes highlight material that is particularly important while orange and red warning boxes highlight points that are often traps for those starting out. Blue boxes provide technical, historical or biographical information that augment the main text but they are not critical to its understanding.

They are placed as marginal notes near the corresponding marker.

As an author there is a tension between completeness, clarity and conciseness. For this reason a lot of detail has been pushed into notes◂ and blue boxes and on a first reading these can be skipped. However if you are trying to understand a particular algorithm and apply it to your own problem then understanding the details and nuances can be important and the notes are for you.

Each chapter ends with a *Wrapping up* section that summarizes the important lessons from the chapter, discusses some suggested further reading, and provides some exercises. References are cited sparingly in the text of each chapter. The *Further reading* subsection discusses prior work and references that provide more rigour or more complete description of the algorithms. *Exercises* extend the concepts discussed within the chapter and are generally related to specific code examples discussed in the chapter. The exercises vary in difficulty from straightforward extension of the code examples to more challenging problems.

1.1.4 How to Use the Book

The best way to learn is by doing. Although the book shows the MATLAB® commands and the response there is something special about doing it for yourself. Consider the book as an invitation to tinker. By running the commands yourself you can look at the results in ways that you prefer, plot the results in a different way, or try the algorithm on different data or with different parameters. You can also look at the online documentation for the Toolbox functions, discover additional features and options, and experiment with those, or read the code to see how it really works and then modify it.

Most of the commands are quite short so typing them in to MATLAB® is not too onerous. However the book's web site, see Appendix A, includes all the MATLAB® commands shown in the book (more than 1 600 lines) and these can be cut and pasted into MATLAB® or downloaded and used to create your own scripts.

1.1.5 Teaching with the Book

The book can be used in support of courses in robotics, mechatronics and computer vision. All courses should include the introduction to coordinate frames and their composition which is discussed in Chap. 2. For a mobile robotics or image processing course it is sufficient to teach only the 2-dimensional case. For robotics or multi-view geometry the 2- and 3-dimensional cases should be taught. Most figures (MATLAB-generated and line drawings) in this book are available as a PDF format file from the book's web site and are free to use with attribution. All the code in this book can be downloaded from the web site and used as the basis for demonstrations in lectures or tutorials.

The exercises at the end of each chapter can be used as the basis of assignments, or as examples to be worked in class or in tutorials. Most of the questions are rather open ended in order to encourage exploration and discovery of the effects of parameters and the limits of performance of algorithms. This exploration should be supported by discussion and debate about performance measures and what *best* means. True understanding of algorithms involves an appreciation of the effects of parameters, how algorithms fail and under what circumstances.

The teaching approach could also be inverted, by diving headfirst into a particular problem and then teaching the appropriate prerequisite material. Suitable problems could be chosen from the Application sections of Chap. 7, 14 or 16, or from any of the exercises. Particularly challenging exercises are so marked.

For graduate students the papers and textbooks mentioned in the *Further Reading* could form the basis of a student's reading list. They could also serve as candidate papers for a reading group or journal club.

1.1.6 Outline

I promised a book with instant gratification but before we can get started in robotics there are some fundamental concepts that we absolutely need to understand, and understand well. Part I introduces the concepts of pose and coordinate frames – how we represent the position and orientation of a robot and objects that the robot needs to work with. We discuss how motion between two poses can be *decomposed* into elementary translations and rotations, and how elementary motions can be *composed* into more complex motions. Chapter 2 discusses how pose can be represented in a computer, and Chap. 3 discusses how we can generate a sequence of poses that smoothly follow some path in space and time and the relationship between velocity and the derivative of pose.

With these formalities out of the way we move on to the first main event – robots. There are two important classes of robot: mobile robots and manipulator arms and these are covered in Parts II and III respectively.

Part II begins, in Chap. 4, with a discussion of robot mobility which covers concepts such as under-actuation and non-holonomy and then introduces motion models for a car-like vehicle and a quadrotor flying vehicle. Various control laws are discussed for the car-like vehicle such as moving to a point, following a path and moving to a specific pose. Chapter 5 is concerned with navigation, that is, how a robot finds a path between points A and B in the world. Two important cases, with and without a map, are discussed. Most navigation techniques require knowledge of the robot's position and Chap. 6 discusses various approaches to this problem based on dead-reckoning, or landmark observation and a map. We also show how a robot can make a map, and even determine its location while simultaneously mapping an unknown region.

Part III is concerned with arm-type robots, or more precisely serial-link manipulators. Manipulator arms are used for tasks such as assembly, welding, material handling and even surgery. Chapter 7 introduces the topic of kinematics which relates the angles of the robot's joints to the 3-dimensional pose of the robot's tool. Techniques to generate smooth paths for the tool are discussed and two examples show how an arm-robot can draw a letter on a surface and how multiple arms (acting as legs) can be used to create a model for a simple walking robot. Chapter 8 discusses the relationships between the rates of change of joint angles and tool pose. It introduces the Jacobian matrix and concepts such as singularities, manipulability, null-space motion, and resolved-rate motion control. It also discusses under- and over-actuated robots and the general numerical solution to inverse kinematics. Chapter 9 introduces the dynamic equations of motion for a serial-link manipulator and the relationship between joint forces and joint motion. The design of joint control systems is discussed and covers important topics such as variation in inertia and payload, flexible transmissions and independent joint versus non-linear control strategies.

Computer vision is a large field concerned with processing images in order to enhance them for human benefit, interpret the contents of the scene or create a 3D model corresponding to the scene. Part IV is concerned with machine vision, a subset of computer vision, and defined here as the extraction of numerical features from images to provide input for control of a robot. The discussion starts in Chap. 10 with the fundamentals of light, illumination and color. Chapter 11 describes the geometric model of perspective image creation using lenses and discusses topics such as camera calibration and pose estimation. We also introduce non-perspective imaging using wide-angle lenses and mirror systems and the relationship to perspective images. Chapter 12 discusses *image processing* which is a domain of 2-dimensional signal processing that transforms one image into another image. The discussion starts with acquiring real-world images and then covers various arithmetic and logical operations that can be performed on images. We then introduce spatial operators such as convolution, segmentation, morphological filtering and finally image shape and size changing. These operations underpin the discussion in Chap. 13 which describe how numerical features are extracted from images. The features describe homogeneous regions (blobs), lines or distinct points in the scene and are the basis for vision-based robot control. Chapter 14 discusses how features found in different views of the scene can provide information about its underlying three-dimensional geometry and the spatial relationship between the camera views.

Part V discusses how visual features extracted from the camera's view can be used to control arm-type and mobile robots – an approach known as vision-based control or visual servoing. This part pulls together concepts introduced in the earlier parts of the book. Chapter 15 introduces the classical approaches to visual servoing known as position-based and image-based visual servoing and discusses their respective limitations. Chapter 16 discusses more recent approaches that address these limitations and also covers the use of non-perspective cameras, under-actuated robots and mobile robots.

This is a big book but any one of the parts can be read standalone, with more or less frequent visits to the required earlier material. Chapter 2 is the only mandatory material. Parts II, III or IV could be read standalone for an introduction to mobile robots, arm robots or machine vision respectively. An alternative approach, following the instant gratification theme, is to jump straight into any chapter and start exploring – visiting the earlier material as required.