

robotics:

Basic Analysis and Design

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preface

Robotics, or the study of robots, is a highly complex and interdisciplinary field, including not only several scientific disciplines, but social, economic, and even political issues as well. As a consequence, there are numerous ways one can approach the study of this field, reflected by the myriad of robotic textbooks rapidly becoming available. Most of these texts explain many of the aspects of robotics, though no one text could possibly cover all of them, and so appropriate topical choices must be made by any author.

In my case, there were few topical choices available once I decided to write a basic engineering text on robotics.¹ From an engineering point of view, robotics should be studied formally and systematically, with quantitative mathematical rigor, as any other engineering discipline, such as aeronautics or aeronautical engineering. To elaborate somewhat, one normally begins a formal program in aeronautical engineering by studying the basic engineering analysis and design principles associated with the field, such as the flow of compressible (gaseous) fluids, including the kinematics and dynamics of a fluid field, classical hydrodynamics as applied to various types of airfoils, and general lifting surface theory. Most of these topics require the appropriate application (to aeronautics) of basic scientific and mathematical principles.

1. Although industrial robots will be stressed in this text, the material presented can be applied to most types of robots—see Appendix A for the definitions of and distinctions between these two terms.

A similar observation can also be made regarding the relatively new field of robotics, or robotical engineering. The formal study of robotics as an engineering discipline, should also begin with the underlying engineering analysis and design principles associated with this field, which have their foundation, to a large extent, in classical mechanics. As in aeronautics, one might logically ask what fundamental properties (which will not change with time) all robotic manipulators have in common. Those familiar with the field would undoubtedly choose kinematics, especially configuration and motion kinematics associated with open kinematic chains, the static force/torque relations between the links of a manipulator and their contact with the external world, the spatial trajectory planning necessary to achieve smooth controlled motion of a robot in Cartesian space, the dynamical behavior of manipulators combining the link forces and torques with corresponding motion, the basic control principles required to ensure coordinated link motion, and the shared features that all robotic programming languages should have in order to allow human operators to readily implement and modify the specific tasks which robots are required to perform.

The primary purpose of this text thus will be to introduce the reader to those basic engineering principles fundamental to the analysis and design of robotic manipulators, namely, *configuration kinematics* (Chapters 2 and 3), *motion kinematics* (Chapter 4), *statics* (Chapter 5), *dynamics* (Chapter 7), *trajectory planning* (Chapter 6), *basic robotic programming* (Section 1.5), and *control* (Chapter 8). Because most individuals are not as familiar with robots as they are with, say, aircraft, part of Chapter 1 will be an introductory qualitative discussion of the subject and (in Section 1.3) the auxiliary components associated with robotic manipulators, such as *sensors*, *actuators*, and *drive trains*. Several of the currently available robotics texts (e.g., refs. [C1] and [H1]) contain a more thorough and comprehensive discussion of these topics. Furthermore, more advanced robotic topics, such as *vision* and *tactile sensing*, *compliant control*, *obstacle avoidance*, and *dextrous hands* and *grasping*, will not be covered here, as they are best introduced after the fundamentals have been mastered, which is the main goal here.

The material presented here has evolved from classroom notes used to teach a one-semester introductory course in robotics to advanced undergraduate and beginning graduate science students at Brown University; thus the course is open also to students in applied math, computer science, physics, and so on, as well as those in engineering. The general prerequisites (beyond high school algebra and trigonometry) are an appropriate exposure to matrix-vector algebra, elementary calculus, basic mechanics (statics), ordinary linear differential equations, and Laplace transforms. Knowledge of dynamics, computer programming, and control, while helpful, is not really necessary to take the course.

On a chapter-by-chapter basis, there are no specific prerequisites for Chapter 1, although some programming experience is helpful. The matrix-vector algebraic concepts outlined in Appendix B are required for Chapters 2, 3, 4, 5, and 7. In addition, some knowledge of statics, e.g., forces,

moments (couples), and three-dimensional equilibrium is required for Chapter 5. Chapter 6 requires none of these general prerequisites. Chapter 7 employs the moments of inertia material in Appendix E. Some exposure to Lagrangian mechanics is helpful but not necessary. Finally, the reader should understand the Laplace transform material in Appendix D before proceeding with Chapter 8. Some preliminary knowledge of classical control is also helpful but not necessary.

This text contains certain features that make it a useful teaching and/or independent learning tool. Numerous examples and illustrations are given in the main body of the text in order to clarify the discussion. Several problems are presented at the conclusion of each chapter, many of which refer to statements made in the main text. In this way, the reader is encouraged to actively participate in the development of a particular mathematical equation, or a specific numerical result. An instructor can, of course, elect to cover certain of these problems via classroom lectures, if it is felt to be advantageous.

Five appendices are provided to ensure a common level of understanding of a particular subject before it is introduced in the main text. Here again, an instructor may decide to discuss, say, Laplace transforms (Appendix D) in the classroom if enough students lack the appropriate background necessary to study positional control, as presented in Chapter 8. Likewise, the reader should be familiar with the material on matrix/vector algebra (Appendix B) before beginning to study Chapter 2. Here again, an instructor may elect to devote a lecture or two to reviewing some of this background material. The glossary of robotic terms and definitions (Appendix A) is a convenient central location for robotic term reinforcement. The trigonometric abbreviations and identities (Appendix C) are useful in working out many of the problems, especially those in the earlier chapters, and the trigonometric identities of Appendix C are shown inside the front cover for the reader's convenience. Finally, Appendix E contains the information necessary to solve some of the problems in Chapter 7.

Another of this text's helpful features is its Summary Sheets, which summarize the major results presented in one or more sections of text. I have used Summary Sheets for many years in the classroom and have found them to be much used and appreciated by my students.

Many individuals have contributed to this text. I am particularly grateful to Dave Grossman and Russ Taylor for permitting me to spend a nine-month sabbatical leave with them in the Automated Manufacturing (Robotics) Group at the IBM T. J. Watson Research Center in Yorktown Heights, NY. The numerous conversations I had with the many diversely talented individuals in that group, especially "Srini" Srinivasan, Ralph Hollis, and Jehuda Ish-Shalom, are gratefully acknowledged and appreciated. I would also like to thank John Hollerbach and Harry Asada of MIT for some highly informative discussions we had during certain of the more recent robotic conferences.

Professor Ben Freund, who helped me initiate the robotics course at Brown University, contributed many of the ideas in the text, especially with respect to the earlier material on kinematics. I would also like to thank Andrew Lee and Peter Kazanzides, two of the many exceptional graduate students we have here in our Laboratory for Engineering Man/Machine Systems (LEMS), for reviewing most of the notes used to produce this final version. Many clarifying insertions and corrections were made as a result of their help.

I am also grateful to Deborah Moore, senior editor for engineering at Holt, Rinehart and Winston, for enlisting the aid of numerous reviewers around the country, each of whom provided useful comments that have been incorporated into the text. They are Delbert Tesar of the University of Texas, Karen Hensley of American Robot, Donald Morin of the Rose-Hulman Institute of Technology, Tom Collins of the Georgia Institute of Technology, Jerzy Sasiadek of Carleton University, Yacov Shamash of Washington State University, E. Kafrissen of the New York Institute of Technology, Joseph Duffy of the University of Florida, V. Srinivasan of IBM, Malcolm Railey of the University of Akron, Michael Brady of MIT, and Michael Lightner of the University of Colorado.

Last, but certainly not least, I am most grateful to Sue Richardson, our truly superb secretary, who not only typed most of the first draft from my handwritten notes (which I myself often found difficult to read) but also prepared numerous tables and the index, copied, cut, and taped virtually all of the figures, and generally did most of the messy jobs associated with producing a final manuscript, all in a most cooperative and pleasant manner. Without Sue, this preface would undoubtedly be dated December 1985 instead of

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"The human race is now poised on the brink of a new industrial revolution which will at least equal, if not far exceed, the first industrial revolution in its impact on mankind. The first industrial revolution was based on the substitution of mechanical energy for muscle power. The next will be based on the substitution of electronic computers for the human brain in the control of machines and industrial processes."

(Dr. James Albus — "Automatic Factory: Identify Its Fingerprints")

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chapter 1

An Overview

1.1 A Chronological Perspective

People have always been fascinated by mechanical devices that emulate human or animal behavior. For example, archeologists discovered an Egyptian toy mechanical dog that dates back to approximately 2000 B.C. And, in the 18th book of the *Iliad*, Homer describes the assistants of the metalsmith god Hephaestus as “maids of gold, like living girls: intelligences, voices, powers of motion these maids have, and skills learnt from immortals.” Moreover, the metalwork of Hephaestus included many tripods with wheels “that each might roll of itself and roll home, a marvel to the eyes.” Even the Bible speaks of oracular heads or figures, and Indian legends contain descriptions of various mechanical elephants. However, early history offers little evidence of actual articulated objects other than simple figures and dolls with segmented parts, which often were used by witch doctors and entertainers to add emotional impact to a story or play. From these simple devices would emerge the marionettes, puppets, and moving toys of later centuries.

In the 1830s, the English inventor Charles Babbage devised his *analytical engine*, the forerunner of the modern digital computer, which was to become the “brains” of today’s industrial robots. But it was not until some forty or so years later that Herman Hollerith perfected the first *automatic calculator*, a device that actually implemented Babbage’s ideas. At about this time, two Americans, Charles Moore and Isaac Graff, achieved partial success in their

2 Chapter 1 An Overview

efforts to construct a steam-driven *automaton*. During this same period, Thomas Edison was involved in the mass-manufacture of a talking doll that was considerably more sophisticated than the traditional wind-up toys of that time.

Mechanization increased at an almost exponential rate during the 20th century, with the simultaneous introduction of many new phrases and concepts that ostensibly redefined the nature of life and work. In 1921, Karel Capek's satirical play *Rossum's Universal Robots* opened in Prague to rave reviews. The central theme of the play involved humanlike machines that go awry, Capek's personal reaction to the destructive mechanization of World War I. In the play, an eccentric scientist named Rossum devises a method of creating artificial humans, which he calls **robots**, a term derived from the Czech word *robata*, meaning "forced labor." Events in the play focus on the eventual takeover of humankind by the robots and their own inevitable destruction brought about by their inability to reproduce. In retrospect, *Rossum's Universal Robots* is perhaps most famous today for its introduction of the word *robot* to describe humanlike automatons.

Twentieth-century science fiction writers soon discovered that robots were lucrative subjects. In the early 1940s, Isaac Asimov and John Campbell, who later became the editor of *Analog* magazine, devised the concept of the intelligent robot that would follow human instructions and commands. They subsequently published numerous stories and articles that depicted robots as useful and subservient labor-saving devices. Their *Three Laws of Robotics* stated that

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given to it by human beings, except where such orders conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First and Second Laws.

Asimov's and Campbell's robot stories and these laws did much to eliminate the human misgivings and fears regarding robots caused by earlier writers such as Karel Capek and Mary Shelley, the author of *Frankenstein*, and subsequently to instill a certain degree of respectability in the newly emerging field of *industrial robotics*.

Modern industrial robots essentially evolved from *teleoperators* and *numerically controlled machine tools*, both of which appeared at almost the same time. A teleoperator is an articulated mechanism that is directly, and often remotely, controlled by a human operator. Teleoperators were first introduced during World War II to handle radioactive materials. These devices employ two identical, multiple degrees of freedom manipulators, with similar

geometries, in a so-called master-slave configuration, in which a human operator guides the *master unit* while viewing the response of a duplicated *slave unit*, generally from a remote location. Teleoperators are still used in hazardous areas where human viewing is achieved via a protective window or a remote camera.

Numerically controlled machine tools were developed shortly after teleoperators, in the early 1950s, in response to a need for precisely machined aircraft parts. Such devices employed the rapidly developing technologies of control system (servomechanism) design and digital computation. The modern industrial robot essentially replaced the human teleoperator controller by the automatic and programmable, numerical machine tool controller, thus producing a multifunctional device with the motion flexibility of the teleoperator and the reprogrammability feature of the numerical machine tool, i.e., **flexible automation**, or the ability to change easily from one manufacturing operation to another.

By the 1960s, industrial robots were becoming a reality, due in large part to the development of relatively low cost digital computers, the element necessary to coordinate the control functions associated with the various links and the end effector. The design of the first industrial robot built in the United States was based on the pioneering efforts of George Devol, who eventually amassed numerous robotic patents, to the ultimate benefit of Unimation, Inc. The first industrial robot was actually built at Unimation in Danbury, Connecticut, a company started by Joseph Engelberger, who happened to meet George Devol at a cocktail party in 1956. Although the first Unimate robot was installed in 1961 (to tend a die-casting machine), Unimation did not show a profit until 1975.

Although industrial robots could have been employed immediately in the 1950s in a variety of industrial applications, especially to replace human workers in certain types of hazardous and mundane occupations, their initial use was hampered by both economics and hardware. In 1960, the hourly cost of operating a robot was over nine dollars an hour, compared with a human hourly wage of less than five dollars an hour. Today, the hourly wage in, say, the automotive industry is nearly twenty dollars an hour, whereas the hourly cost of operating a robot has declined to less than six dollars an hour. Furthermore, although a trained human operator can generally outperform a robot, this is not always the case, especially in well-defined, repetitive operations.¹ This factor, combined with worker wages, which continue to increase, contributed to an annual growth rate from 1983 to 1984, of about 50%² in the use of industrial robots.

1. For example, current robots can work much faster than humans can at tasks such as arc welding and spray painting. They also are generally more precise than human operators are.

2. As reported in the February 1985 issue of *Robot Times*.

The development of the microprocessor, i.e., the "computer on a chip," has also played an important role in the rapid growth of industrial robotics. Although the robots that were available prior to 1970 had remarkable versatility (compared with other types of fixed or hard automation), the continual development of the microprocessor since the early 1970s has provided current industrial robots with far more "intelligence" at a much lower cost, and this trend will no doubt continue with concurrent advances in microprocessor technology. Other technological advances, for example, in rare earth magnets for electric motors, high-power transistors for motor control, direct motor/link couplings, and improved gearing and bearings, have also improved both the performance capabilities and the reliability of robots, making them increasingly more desirable in industrial applications.

Today, industrial robots are used in a wide diversity of applications, such as welding, materials handling, assembly, and paint spraying. Spot welding accounts for the highest percentage ($\approx 35\%$) of current use, due primarily to the automotive industry, which was the first to employ robots on a large scale. But this particular application is nearing saturation, and most forecasts predict that assembly operations will utilize the largest number of robots in future industrial applications.

Many of these future assembly operations will involve more than just single, independently controlled robots, which perform specific tasks exclusive of their surroundings. More likely, appropriate groups of robots, along with associated peripheral equipment, such as conveyors, sensors, buffers, and feeders will be combined to form an entire **manufacturing cell** for the production of more complex products, such as the manufacturing cell for the assembly of printed circuit cards, which is depicted and described in Figure 1.1.1.

Figure 1.1.1 shows a view of a manufacturing cell for printed circuit cards. Two robots are employed: (a) a four degree of freedom assembly robot and (b) a six degree of freedom transport robot. In addition, the cell has (c) a molten solder bath, (d) two manually loaded gravity feeders for integrated circuits, (e) a buffer for empty cards, (f) a buffer for populated soldered cards, (g) a fixture for holding cards during assembly, and (h) a card tester. The cell also has (i) an industrial machine vision system for inspecting the incoming empty cards for proper hole patterns, as well as determining the position and orientation of the cards on (j) the conveyor belt, for pickup by the transport robot, as well as a number of auxiliary sensors (not shown), i.e., sensors that determine the number of cards in the buffers, sensors for determining whether or not the feeders are empty, force and part-presence sensors in the fingers of the assembly robot, a temperature sensor in the solder bath, and a sensor in the gripper of the transport robot for determining the depth of immersion of the fingers in the solder bath.

More advanced assembly facilities could combine several manufacturing cells in order to automate virtually all aspects of production in an entire

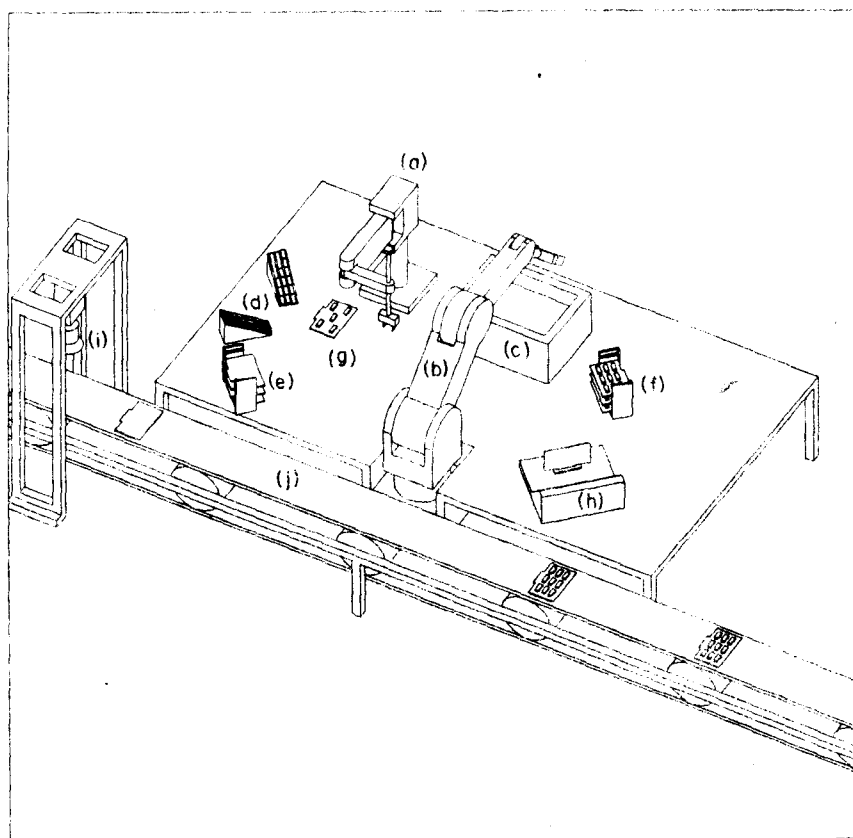


Figure 1.1.1
A Manufacturing Cell for Printed Circuit Cards
 (Reproduced here by permission of R. Jayaraman—see ref. [J1])

factory. The vision of such a fully automated “factory of the future,” filled with robots tirelessly working away, is gradually becoming a reality. Just as high overhead and labor costs made it necessary for many U.S. manufacturers to move their assembly plants to locations such as the Caribbean or Asia, automation is now making it economically possible to bring the plants back home. The automated factory gives its owners the prospect of one day offering the highest-quality customized products on the market at the lowest possible price.

Many companies are already moving in this direction. For example, a Macintosh personal computer rolls off the assembly line every 27 seconds at Apple’s highly automated “just-in-time” inventory plant in Milpitas, California. North American Philips is moving production of its Magnavox,