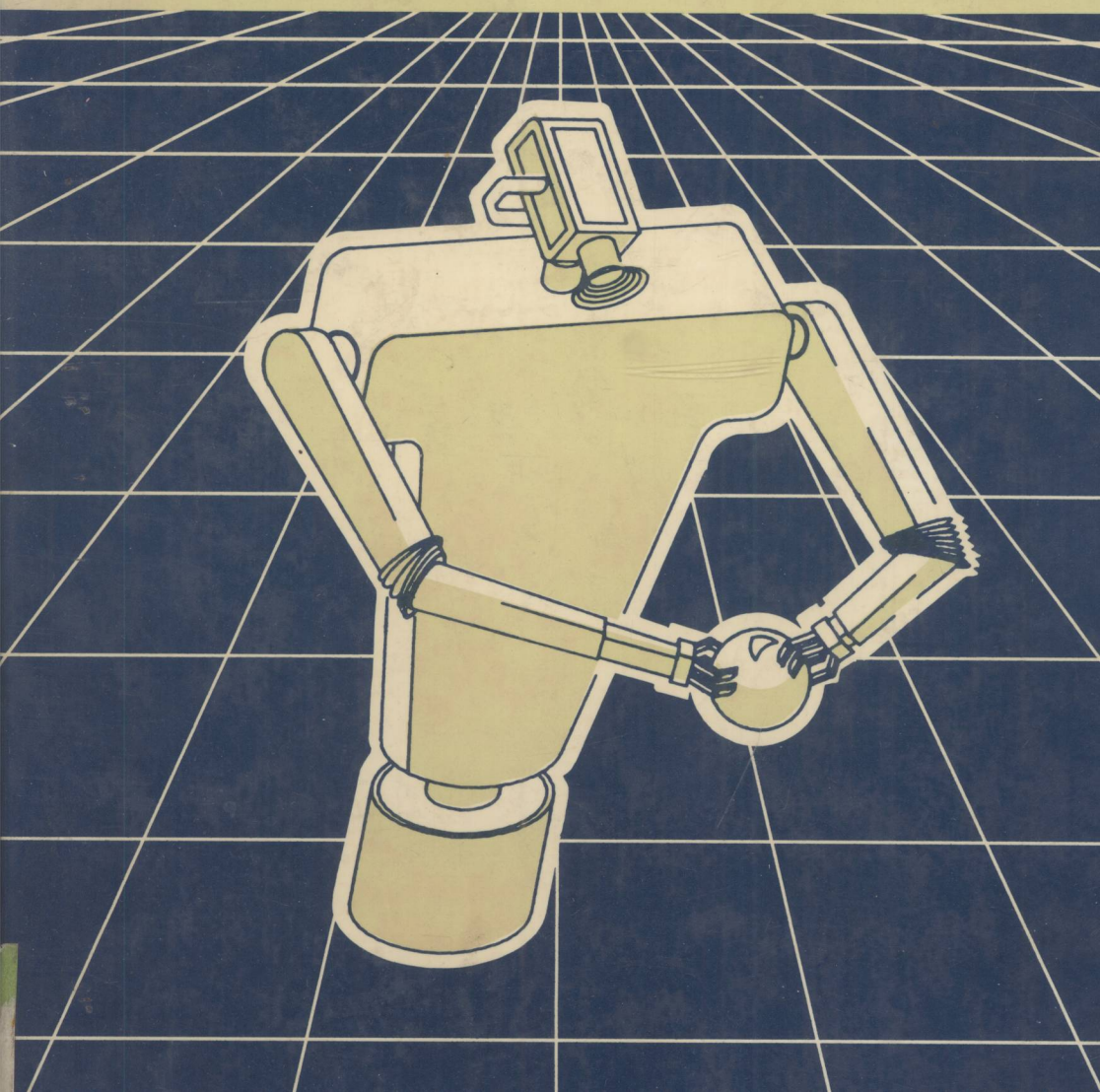
A Robot Engineering Textbook

Mohsen Shahinpoor



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A Robot Engineering Textbook

To the memory
of my parents

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Preface

This book has been written to provide a modern text for engineering students who are taking an initial course in robot engineering. *Robot engineering* is defined as the analyses and functional design of robots, robotic manipulators, and flexible manufacturing systems. This book has emerged from a compilation of my class notes and lectures, at both the senior and graduate levels, on the fundamentals of robotics and the design and control of industrial robots. My intense interest in the subject was one reason for writing this book; however, the prime motivation was the growing acceptance by engineering professors of the importance of robot engineering education in universities and the growing demand for increasing productivity across the nation. Robot engineering is a very complex subject and requires a diversified technical background. The engineering students and staff who will be using this book as a first college text in robot engineering should have a solid knowledge of engineering statics, Lagrange–Euler dynamics, the theory of machines and mechanisms, machine design, control, differential calculus, matrix analysis, computer programming, digital electronics, microprocessor engineering, and mathematics of coordinate transformations. An added feature of the book is the use of bond graph dynamic modeling of robotic systems for those students who have some familiarity with bond graph modeling of complex systems. Even more esoteric engineering subjects, such as modern transducer engineering, computer vision, and sensing, are involved in robot engineering. These subjects constitute the foundation for the practice of robot engineering. Most robotics experts agree that robot engineering integrates and uses a greater number of mathematical tools and the sciences than any other professional engineering study. Probably the only engineering subject that comes close to it in this regard is "engineering design."

Each chapter is complemented by the material covered in previous chapters, so it is best to cover the material in the order given.

Chapter 1 deals with a general introduction to computer-based robotic manipulators and their definitions and areas of application, a history on robotics evolution and revolution, robot geometrical configurations and workspace, the wrist and gripper subassemblies, robot drive systems, and the importance of resolution, accuracy, and repeatability for robotic manipulators as well as some examples and problem assignments. It is essential for students and staff to obtain an introductory knowledge of robotics evolution and fundamentals through the material covered in Chapter 1. The remaining chapters have been designed in accordance with ASEE's stated goal:

> The technical goal of engineering education is preparation for performance of the functions of analysis and design or of the functions of construction, production, or operation with full knowledge of analysis and design of the structure, machine, or process involved.

Chapter 2 discusses the kinematics of robotic manipulators and the significance of robotic coordinate transformations. The notion of homogeneous transformations of manipulator joint coordinates and the derivation of Denavit–Hartenberg representations are discussed fully. Direct and inverse kinematics problems are covered in depth to familiarize students with the significance of robotics kinematics. A large number of illustrative examples pertaining to various types of robot are presented. A number of inverse kinematics problems, which are at the core of automated manufacturing, are solved in this chapter.

Chapter 3 is intended to familiarize the students with the differential transformations encountered in dealing with moving objects and moving robotic manipulators. This is an important chapter that emphasizes the problems encounterd in robotic differential chase in the presence of digital cameras that are either attached to the manipulator or mounted elsewhere. Again a number of examples are presented and discussed thoroughly.

Chapter 4 deals with the mathematics of robotic workspaces, work envelopes, constraints imposed on robot extremities, and the numerical construction of robotic workspaces. The problem of robotic motion trajectory planning is discussed fully, and a universal algorithm for the design of 4–3–4 and 3–5–3 robotic trajectories is presented along with a set of numerical data pertaining to such trajectories for six-axis robots. It is essential that students obtain a minimal knowledge of the design of robotic workspaces, trajectories, and task descriptions for object manipulation, so a number of examples pertaining to these topics have been worked out and discussed.

Chapter 5 is concerned with the dynamics of robotic manipulators. This is an extremely important and involved area of robot engineering. For an undergraduate course on the fundamentals of robotics, a good portion of this chapter can be skipped. However, in a graduate course on the design and control of industrial robots, this chapter should be covered in full. The reason is that undergraduate students find this chapter a very difficult one. To compen-

sate for the lack of complete coverage of this chapter, undergraduate students should be given more hands-on experience in the robotics laboratory. Chapter 5 also discusses three different methods of obtaining the equations for the dynamics of robotic manipulations. The first approach and probably the easiest is the bond graph modeling of robotic dynamics. This needs some prior knowledge on bond graph modeling of complex systems (which some undergraduate students may not have). The technique is then used to derive the governing dynamic equations of a number of robotic manipulators. Then, the Lagrangian dynamics of robot manipulators is elaborated upon with a number of illustrative examples. Another approach in formulating the robotics dynamics, namely, the Newton–Euler formulation, is fully discussed and the significance of recursive formulations are highlighted with worked out examples. The problem of inverse dynamics and its connection with the inverse kinematics is also discussed.

Chapter 6 concentrates on the problems associated with the control of robot motions, velocities, and accelerations. Obviously, robot control is at the heart of flexible automation and deserves detailed consideration. Essentially, the robot control problem is inherently nonlinear and thus rather hard to digest for undergraduate students. However, the subject of robot motion control is presented here in a manner comprehensible for both undergraduate and graduate students. First, the robotic open- and closed-loop control systems are discussed and then the significance of error-controlled robotic dynamics is considered. Second, the chapter further discusses the control structure of the amplifier as well as a generalized algorithm for the control of slow-moving robotic manipulators and the important computed-torque technique. Third, because of their importance, the problems of coordinated movement for both variable- and constant-speed controllers are discussed. Finally, a discussion is presented on typical joint torque control for robotic manipulators. On the whole, this chapter is an indispensible part of any text on modern robot engineering and the treatment given is adequate for a first course on robotics.

Chapter 7 discusses the significance of robotic forces, moments, and torques, inverse statics, and compliant robotic motions. These topics are felt to be extremely important in the design of robotic manipulators for higher load carrying capacities and more compliance with disturbing forces in assembly operations. Again, this is a chapter that must be included in any first text on robot engineering. Specifically, the importance of compliant motion cannot be overlooked and must be given top priority. This is achieved in this chapter by a number of detailed examples. The chapter covers the equilibrium of robotic forces and moments, the inverse statics problem, compliance analyses, force and kinematically constrained motions, and force sensing systems. Finally, problems associated with robotic jamming are covered and the Simunovic jamming criterion is discussed.

Chapter 8 concentrates on sensors for robotic manipulators, an important addition to any first course in robotics. Students should gain a basic knowledge on how to make robots more intelligent by equipping them with various sensing devices. These devices are force sensors, digital TV cameras, and computer

vision. Some currently used tactile, force, and vision systems also are discussed to familiarize students with current technology on robotic sensing and vision. Obviously, for a broader knowledge on these topics the students should take a course on robotic sensing and vision.

Chapter 9 deals with robot motion programming. It first discusses the significance of "manual teaching," or "show-and-teach," and "lead-and-teach," or "guiding." It then discusses the programming languages and examines their historical evolution. For a number of popular robot programming languages, such as the MINI, WAVE, AL, VAL, and AML, the fundamental programs of the insertion of a peg in a hole are presented. Finally, a complete set of robotic teach-assembly programs are presented. These programs include the robotic "RESET," the "TEST," the "Create a Move File," the "Play Back a Move File," the "Edit a Move File," and the "Inverse Kinematics," all applied to an educational robotic manipulator.

I would like to thank my colleages and students, both at Clarkson University Robotic Center and the University of New Mexico's Robotic Laboratories, without whose help this textbook could not have been written. Among them are Professor R. A. Schilling of Clarkson University, Professor M. Jamshidi of the University of New Mexico, and Dr. H. Seraji of the Jet Propulsion Laboratory who helped me with some of the material covered in Chapter 6; Professor G. Starr of the University of New Mexico, and graduate students, Ali Meghdari, Ali Akbarzadeh, Ali Tabesh, Mike Caporali, David Campbell, Robert Cook, Young Tao Kim, and Bing Ching Chiou. I also thank my secretaries, Gayla Angel, Terri Grandon, and Rhonda Price, for the preparation of the manuscript; and Mr. Massoud Ahghar, who created the original drawings on the CADAM system. Last, but not least, I thank Mr. Cliff Robichaud, for his encouragement and support; Thomas R. Farrell, for his superb technical supervision of the project; and the staff of Harper & Row, Publishers, who did an excellent job of preparing the final text.

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Chapter 1

General Considerations of Robotic Manipulators

1.1 INTRODUCTION

Humankind appears to be on the brink of another industrial revolution, one that will involve the use and implementation of increasingly flexible, intelligent, sensitive, and efficient robots in the factory, field, office, and every other aspect of our everyday lives. This fact combined with a more acute awareness of human safety has been instrumental in creating the demand for a larger number of robotic manipulators. As a result, in recent years, the use of robotic manipulators has increased rapidly, particularly in industrial settings where the quest for greater productivity and tighter quality control has been paramount because of intense international competition.

The word *robot* seems to have first become popular when the Czech playwright Karel Čapek's play entitled *R.U.R.* (or *Rossum's Universal Robots*) was first performed in Paris, France, in the 1920s. In that play, small, artificial, and anthropomorphic creatures strictly obeyed their master's orders. In Czech and Russian these creatures were called *robotnic*, from *robota*, which is the Czech and Russian word for "drudgery" and "hard work." In the play *R.U.R.*, the robots eventually turned against their creators, but in doing so they set the stage for their own destruction with the appearance of two robots named Primus and Helina who fell in love with each other. The reader with an interest in the folkloric history of robotics is referred to Cohen (1966), Kato (1983), and "Surveys Reveal Robot Populations and Trends" (1982).

The first robots were thought to be evil human-looking machines. Isaac Asimov in the 1970s introduced the idea of good robots, whom he called droids, and popularized the word *robotics*. Some droids such as R2-D2 and C3-PO became famous in recent years thanks to the motion picture industry. Recently,

real droids with high intelligence have been manufactured in the United States (Heath's Hero) and Japan (Sumitomo's Android; see Cohen, 1985).

Webster's dictionary defines a *robot* as "an automatic apparatus or device that performs functions ordinarily ascribed to human beings." However, we all know that this is not a very accurate description. In fact, many robots can perform certain tasks in a far superior and more sophisticated manner than human beings can. It is also true that by the above definition even washing machines can be considered as programmable robots. Thus, it is necessary to devise a universal definition for robotic manipulators. In this book we adopt the following definition:

> A robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks.

This definition covers a broad spectrum of robot manipulators, and within this definition there are different classes of robots. These classes include the following:

1. *Automated or Flexible Manufacturing.* These "industrial" robots are employed in a wide range of manufacturing processes, including parts assembly and inspection, materials handling, welding, and materials painting.
2. *Remote Exploration.* This class of robotic manipulators is designed to survive in environments that humans cannot tolerate. They can be used to explore the unknown from the edge of our solar system to the depths of earth's oceans.
3. *Prosthetic and Biomedical.* Robotic technology and its accompanying sensor technology can be teamed to provide prosthetic limbs with touch sensation. Someday miniature robots under a surgeon's control may probe the human body to operate on patients from within their bodies.
4. *Hazardous Material Handling.* Robots in this class have been employed to remove bombs and handle hazardous materials.
5. *Service.* Some present uses for service robots include security, janitorial, mail delivery, fire sentry, fire fighter, and voice-commanded errand robots. The use of service robots will increase as technology progresses and manufacturing costs fall.

1.2 A BRIEF HISTORY OF TELEOPERATORS AND MANIPULATORS

The robot manipulator made its debut with the onset of the nuclear age. The first manipulators were known as teleoperators. These devices allowed an operator to perform tasks from a safe distance, such as handling radioactive

materials (Goetz, 1963). The first automatic electric-powered teleoperator was developed in 1947. The teleoperator was constructed so that the operator had control of the manipulator by means of a slave unit; that is, the manipulator repeated the motions made by the operator. This first manipulator did not give any form of force feedback, and therefore tasks such as turning a wrench or placing objects on work surfaces were difficult to perform. In 1948, General Electric developed a teleoperator (Handy Man) that provided force feedback by backdriving the slave with forces felt at the manipulator (Goetz, 1963). Later, the basic concept of this teleoperator was reintroduced by General Electric (Krsnak and Howe, 1975) in the form of their Man-Mate manipulator. The Man-Mate allowed an operator to move objects that were heavy or dangerous by moving a small lever. The Man-Mate translated the information from the lever into signals to the manipulator. The operator also had a feel for the operation being performed by means of the force feedback to the lever.

Whereas the teleoperator was controlled by a human, the computer-controlled systems for present day robots had their advent in the numerical-controlled machines. M.I.T. demonstrated the first servo-controlled numerical milling machine in 1953, with support from the U.S. Air Force (Rosenberg, 1972). The dimensional information of the piece to be milled was stored in digital form on paper tape, and an optical reader converted the holes in the tape to signals that ultimately controlled the mill. The most important aspect of this new technology was that tooling up to produce another piece involved little more than putting a new tape on the mill. This was the dawn of flexible tooling, in which a machine was simply reprogrammed to perform multiple tasks (Engleberger, 1980). Ernst (1961) incorporated the two technologies in a thesis entitled, "A Computer Operated Mechanical Hand." A teleoperator equipped with touch sensors was coupled with a computer to perform tasks by processing the tactile information received from the touch sensors.

The robot developed by Ernst led to the development of robots that were able to repeat a finite number of predefined moves indefinitely. These limited-sequence robots could be used to perform pick-and-place operations as described by Potter (1975). The pick-and-place tasks must be well defined. Incoming parts must be placed by the robot in a uniform manner, parts must be preinspected to ensure uniformity, and the placing operation should not allow parts to get jammed. Although the constraints are many, the limited-sequence robot is used for tasks such as material transfer, packaging, and simple assembly.

The use of the simple-sequence robot is restricted in the number of tasks it can perform. It assumes that the working conditions will be almost perfect. Unfortunately, conditions seldom are. In 1962, Tomoric and Boni (1962) developed a robotic hand with pressure sensors that could determine the size and weight of objects, and Reswick and Meyler [12] developed a device for quadriplegics (paralysis of four extremities) that enabled them to handle objects. Roberts (1963, 1965) demonstrated in 1963 the feasibility of processing digital halftone images by means of homogeneous transformations. In 1966, McCarthy,

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