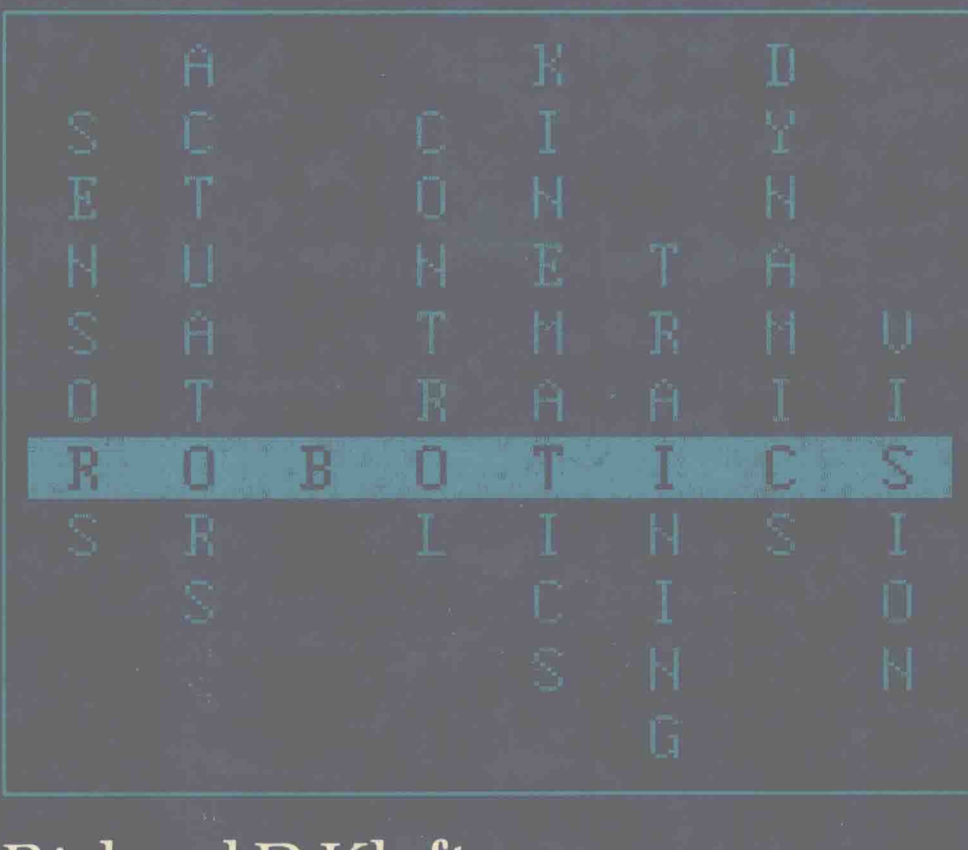
ROBOTIC ENGINEERING An Integrated Approach



Richard D. Klafter
Thomas A. Chmielewski
Michael Negin

Robotic Engineering

An Integrated Approach

Richard D. Klafter

Professor
Department of Electrical Engineering
Temple University
Philadelphia, Pennsylvania 19122

Thomas A. Chmielewski

Unit Manager
General Electric, Advanced Technology Laboratories
Moorestown, New Jersey
and
Drexel University
Electrical and Computer Engineering Department

Michael Negin

President
Mnemonics, Inc.
Mount Laurel, New Jersey 08054

Prentice Hall, Englewood Cliffs, New Jersey 07632

Library of Congress Cataloging-in-Publication Data

Klafter, Richard David.
Robotic engineering : an integrated approach / Richard D. Klafter, Thomas A. Chmielewski, Michael Negin.
p. cm.
Includes bibliographies and index.
ISBN 0-13-468752-3
1. Robotics. I. Chmielewski, Thomas A. II. Negin, Michael. III. Title.
TJ211.K555 1989
629.8'92—dc19 88-31899
CIP

Editorial/production supervision and interior design: *Denise Gannon*
Cover design: *Michael Negin adapted by 20/20 Services, Inc.*
Manufacturing buyer: *Mary Noonan*

Printed in the United States of America

10 9 8 7 6 5 4 3 2

ISBN 0-13-468752-3

PRENTICE-HALL INTERNATIONAL (UK) LIMITED, *London*
PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*
PRENTICE-HALL CANADA INC., *Toronto*
PRENTICE-HALL HISPANOAMERICANA, S.A., *Mexico*
PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*
PRENTICE-HALL OF JAPAN, INC., *Tokyo*
SIMON & SCHUSTER ASIA PTE. LTD., *Singapore*
EDITORA PRENTICE-HALL DO BRASIL, LTDA., *Rio de Janeiro*

TO
Marcia, Leslie, and Melissa (RDK)
Cindy, Corinne, and Tommy (TAC)
My Family (MN)
For Their Patience and Support

Preface

Although industrial robots have been available for a number of years, it is only since the early 1970s that research efforts into these sophisticated computer-controlled devices has begun to accelerate. The primary reasons for this are the advent and availability of the microprocessor and, in this country, the realization by industry that robots must be used to meet the increased competition from foreign manufacturers.

As a result of the industrial experience gained during a leave of absence, the principal author organized a senior/graduate course in robotics in the early 1980s. In assemblying the material for this course, the author found that very little was written on the specific subject of robotics. The reason for this is that, quite simply, robotics is not a single discipline. Rather, it is a highly multidisciplinary field that combines the areas of controls, computers (both the hardware and software aspects), measurement technology (i.e., sensors), pattern-recognition techniques and hardware (e.g., vision systems), and various aspects of mechanical engineering, including statics, dynamics, kinematics, and mechanical design. A complete study of the subject should also involve some discussion of applications as well as the economics of robots and the sociological consequences of placing them in the workplace. Although it was certainly possible, at the time, to find material on many of these individual subjects, there was no single compilation of the topics that existed which would permit a comprehensive course to be taught. Moreover, many of the papers written were extremely low level and were often nothing more than glorified sales pitches.

A number of years later, the situation has changed somewhat, with a relatively large number of books on the subject having come out in the interim. However, these are, for the most part, descriptive, rather low-level texts that are aimed primarily at the two-year technology student and are therefore inappropriate for engineering courses at any level. Of the few that are written at a higher level, some are rather sketchy and others are extremely detailed in only a few areas. Thus neither group is really applicable for comprehensive "core" (or first-level) courses that seniors and/or graduate students would (and it is our feeling should) want to take.

It is quite apparent that robotics is a "hot" area and that there will be a definite need for a book that will permit an engineering core course (or courses) to be taught. Although there are still relatively few of these being offered at universities throughout the country, it seems to us that this is a result of there being *no appropriate text available* rather than there being a lack of interest in teaching such a course. Clearly, people will always want to teach their "specialties" (e.g., robotic controls, machine vision, etc.). It is our belief, however, that the more specialized courses that cover only a few topics in depth will have a greater impact on the student, and therefore, should be taught only after the relationship among the various disciplines that go into producing a working robot are clearly understood. Thus we feel, for example, that it is not appropriate to begin talking about optimal or adaptive control of a robot until one fully appreciates the advantages and disadvantages of the type of control currently utilized and how the large swings in inertia (inevitably occurring as the manipulator moves in its work volume) affects the particular control strategy selected. Having said this, it is our judgment that a comprehensive text such as this one should provide the reader with the "why" and "how to" aspects of robotics. Theorems and proofs are better left to follow-up specialty courses. This *does not* mean, however, that we utilize the anecdotal, often pseudotechnical approach that characterizes many of the currently available texts and papers on the subject. Rather, we have utilized our extensive pedagogical and practical experience (with robots) to present to the reader many of the theoretical and practical concepts and ideas that are essential to understanding how a robot is designed and how it works. In doing this, it is our hope that the book will be extremely useful in the (engineering) academic sector and in the engineering workplace. With these ideas in mind, we have organized the book in the following manner:

In Chapter 1, a fairly detailed introduction is presented where the terminology and various robot types, as well as the history, sociological, and economic implications of these forms of automation, are discussed. In addition, current and future applications are given. The chapter goals are for the reader to be able to understand what an industrial robot is and what it is not, where it is applicable and where it is not, and finally, how such devices have evolved and how they well may cause another industrial revolution to occur.

Chapter 2 deals with the robot's various component parts as well as how these devices are normally utilized in an *automated system*. At the conclusion of the chapter, it is expected that the reader will be able to identify the major system components of a robot from a high-level, black-box point of view and will also be able to understand the considerations that go into both the development of robotic systems specifications and the selection of system components.

The next chapter presents the mechanical structure and discusses a variety of devices and components as they relate to robots. Various methods of converting rotary to linear motion are given from both the ideal and "real-world" points of view. It is the purpose of this chapter to provide an understanding of how certain mechanical components behave and how power is transmitted from an actuator to a load. The reader will also learn about how many of these devices are used in a practical manner to produce a working robotic manipulator.

The typical control structure of modern industrial robots is presented along with a fairly detailed discussion of various types of actuators and power amplifiers in Chapter 4. The reader will not only gain an understanding of how classical servo theory is applied to a robotic system to produce the desired robotic joint performance but will also learn about the various actuators and amplifiers available to the robot designer and which are preferred in a given application. Many practical considerations that affect the proper operation of a robotic joint are included here.

In the following chapter, the topic of nonvision-based robotic sensors is presented in great detail. A large number of internal sensors are discussed, with special emphasis being given to the practical aspects of several, including the optical encoder. External sensors are also introduced, with the topics of proximity, welding, and tactile sensors being discussed. The purpose of the chapter is to demonstrate clearly the role played by internal sensors in the control of individual robotic joints and also by external sensors in providing the robot with knowledge about its external environment. Also, the practical aspects of the presentation should assist the reader in understanding why certain sensors are to be preferred over others in a given application.

Robotic (or machine) vision is discussed in Chapter 6. Various components of a vision system, as well as a number of image recognition techniques are presented. The reader will be able to understand the similarities and dissimilarities of computer vision relative to other types of sensors and will appreciate the magnitude of the information-processing problem associated with using computer vision in a robotics application. The material in the chapter covers various vision sensors and systems, and discusses the capabilities (e.g., object detection versus inspection) of currently available, practical cost-effective vision technology.

In Chapter 7 the architectural and hardware considerations related to the computers utilized in a robotic system are discussed. In addition, the role played by the computational elements in robotic applications is given and a summary of various robotic programming languages is presented. Various trade-offs that are required when using different computer architecture implementations for robotic systems are discussed. The reader will also learn about the practical considerations that go into the selection of a robot computer system, including the hardware, software, and task programming aspects.

The important topics of coordinate transformations, along with how to obtain the forward and inverse or back solutions, are presented in Chapter 8. Homogeneous transformations are introduced and how they are applied to a robot's kinematic structure. Additional discussion involves the method used in a robot to represent points in space and then how to utilize this information to produce continuous-path, straight-line, and other types of coordinated motions.

Chapter 9, the concluding chapter, brings together many of the important technological ideas presented in the preceding chapters. This is accomplished by designing various aspects of a robot required to perform a specific task (e.g., sorting eggs). From the material in this chapter it is expected that the reader will be able to take a set of given specifications and actually come up with a potential robot design. This should include the mechanical configuration, the control and computer structures, and the choice of actuators that will meet all of these specs.

Three appendices are included and should be of interest. The first is a compilation of existing commercial robots and their specifications/attributes. The second presents an orderly method of selecting a servomotor for a specific task. The last one discusses the digital control of a single robotic joint.

As a text, the book is ideal for courses at the senior/graduate level in electrical engineering since it places a good deal of emphasis on subjects that are traditionally considered to be "electrical in nature." However, many modern mechanical engineering curricula now require their students to take courses in controls (and systems), computers, and mathematics beyond the standard calculus, analytic geometry, and differential equations sequence. For such departments, this book could be utilized in a robotics course with the assurance that much of the material would be within the abilities of their students. In fact, over the years that the authors have used the manuscript in a classroom environment, there have always been a number of mechanical engineers who successfully completed the course. The same is also true for the few computer science students, although, admittedly, they had a much more difficult time because of their lack of specific engineering knowledge. Although this book is definitely not an engineering technology text, since it assumes a fairly extensive analytical background, there are a *small number* of four-year technology programs (primarily, electrical) that could use some of the material in a robotics course at the senior level.

As mentioned above, we have utilized the book in graduate courses that had both graduate and selected undergraduate students enrolled. There is more than enough material provided to cover a two-semester course. Clearly, the instructor may wish to elaborate in some areas and gloss over others. This would obviously depend on the backgrounds of the students and their needs. In our case, Chapters 1 and 2 were covered in about three classes with the remaining part of the semester devoted to (sometimes expanded versions of) the third, fourth, and parts of the fifth and seventh chapters. Also included was much of the material contained in Appendices B and C. The second semester was then devoted to sensors (vision and nonvision based), kinematics, and computer systems and robotic languages. Also, Chapter 9 was discussed in great detail, with the students encouraged to submit other designs for the same task.

As a final word, it is our belief that the practical engineering approach that is utilized throughout the text will most certainly interest engineers who are working in the fields of controls and automation (e.g., those with backgrounds in electrical engineering, mechanical engineering, and computer science/engineering). In addition, engineers working in industries that may be *users* of robots may find this book helpful in providing them with the background needed to select the correct type of robot (and the various options) to perform a specific task at their company's plant.

ACKNOWLEDGEMENT

The authors wish to thank a number of people who have made this book a better work with their constructive criticisms, helpful suggestions, and overall support. In particular, we wish to extend our appreciation to our former colleagues at United States Robots, Inc. with special thanks going to John Stetson. Also, our colleagues and friends at Drexel University's ECE Department and Temple University's EE Department were extremely supportive. Special mention is due Dr. Paul Kalata of Drexel University who assisted in the preparation of Appendix C.

As is usually the case with a project that is carried out within a university environment, our undergraduate and graduate students have greatly influenced the final version of the text. Thus, we would like to thank all those students who gave us comments and suggestions concerning various aspects of the book. In this respect, the following individuals (at Temple University) are worthy of special mention: J. Coyle-Byrne, D. Knoll, B. Maber, K. Reed, and K. Roy.

In addition, Mrs. Rachel Balaban, Mrs. Oksana Bilyk, Mrs. Carol Dahlberg, and Ms. Pat Taddei assisted in the (intelligent) proofreading of the manuscript and in performing other important clerical activities associated with the project.

Contents