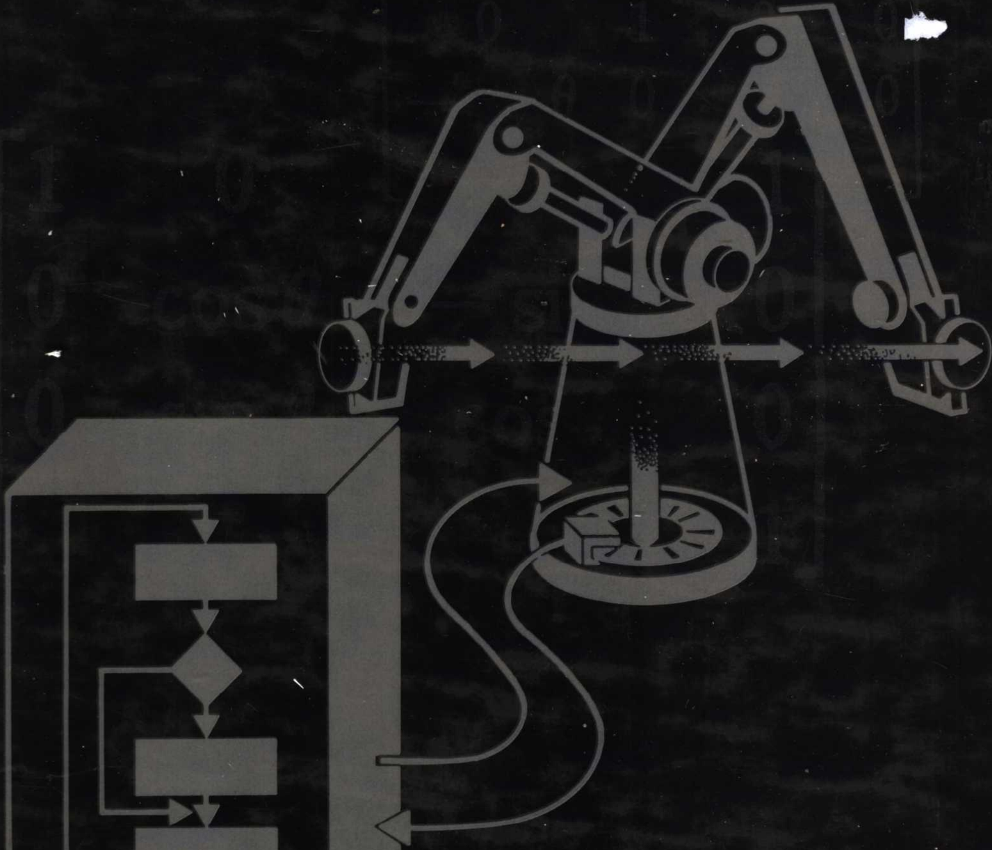
Industrial Robots: Computer Interfacing and Control

Wesley E. Snyder



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Computer Interfacing and Control

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PREFACE

In writing this book, I had three principal educational objectives:

To teach the basic principles of robotics and the design of robot systems.

To use the robot as motivating factor, example, and context in which to teach a number of important engineering concepts.

To collect in one volume pointers to much of the advanced literature and to explain the relevance of that literature in simple terms.

To meet my first objective, I introduce the student to a simple two-jointed (θ - r) manipulator. This elemental robot is used throughout the book to present the concepts of kinematics, servos, dynamics, path control, velocity control, and force control. In addition, the complete solutions for a six-degrees-of-freedom arm are provided in the chapters on kinematics.

The student who uses this book in a course will not emerge ready to design and build a sophisticated robot single-handedly, but he or she will require far less on-the-job training than was previously necessary. Furthermore, although relatively few of the students who use this text will become robot *designers*, nearly all of them will become robot *users*, many of whom will be making robot purchasing and utilization decisions. They will gain an understanding of the design, operation, and control of robots and, in addition, a knowledge of the capabilities and limitations of various types of robots which should be invaluable in that decision-making process.

Robotics is not a discipline unto itself; rather, it is an amalgam of engineering topics. As such, it is a superb context in which to teach some of those elusive topics known as *systems science.* It also provides a unifying theme in which to cover those practical engineering issues that are often reduced in emphasis in undergraduate curricula.

Thus, we unify under the one theme of robot system design selected topics from

Digital design (Chapter 2)
Electromagnetics (Chapter 3)
Controls (Chapters 5 and 9)
Motors (Chapter 4)
Mechanics (Chapter 6)
Numerical methods (Chapters 8 and 9)
Dynamics (Chapters 7, 8, and 10)
Software engineering (Chapters 5, 14, and 15)
Architectures (Chapter 14)
Languages (Chapter 15)
Instrumentation (Chapter 12)
Computer vision (Chapter 13)

In meeting my third objective, I have tried to provide simple explanations of concepts; occasionally, I have sacrificed realism in favor of simplicity. The index and reference lists are fairly complete, so that the more advanced student will be directed to state-of-the-art publications in each area. The practicing engineer will find this book to be a useful general reference for robotics concepts and a pointer to detailed literature which he or she may need.

I have used the term "engineer" several times in this preface, and the book is indeed written principally for engineers and computer scientists. The manuscript has been used three times in a senior-level electrical engineering design course at North Carolina State University, and I have found that non-EEs require at least one course in electrical engineering prior to reading Chapter 3. However, I have observed that mechanical engineers who have had the single required EE course had no problems with the Chapter 3 material, and they performed on the average slightly better than the EEs on the material in Chapters 6 through 8.

The NCSU course includes a project which adds additional relevance to the material and introduces the students to such real-world engineering problems as project group dynamics and electrical noise. Suggestions on running such a project are included, along with other suggestions for the instructor, in Notes to the Instructor.

In the interest of pedagogical soundness, I have included examples, vocabulary lists, definitions of terms and notation, and homework problems. For the same reason, there is some deliberately introduced redundancy of material.

The objective of this book is to teach concepts, not to report research results. However, developments in robotics are occurring so rapidly that references to current literature are essential. I hope that those who read this book will gain, in addition to a thorough understanding of what a robot *is*, a taste of the excitement in this young field of technology.

Wesley E. Snyder

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Production of a textbook is never the work of a single person, especially not a book in a field as multi-disciplinary as robotics. I am most grateful to the following people for reviewing various pieces of the manuscript: A. Bejczy, W. Fisher, A. Goetz, W. Gruver, G. Hirzinger, F. Kauffman, R. Kelly, H. Kone, R. Paul, J. Rebman, W. Reiter, A. Sanderson, D. Stancil, and A. Yarur.

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Of course, most of the credit goes to my wife, Rosalyn, who not only put up with my general irritability during the creation of the manuscript, but also typed the entire document (more than once), and edited it to convert what I had written into English. Her support was, and continues to, be invaluable.

Finally, I would like to thank my Rainbow personal computer for not repeatedly crashing the diskettes and blowing away entire chapters. To my TRS-80 (may it rest in peace), I can only say that it was a nice try.

NOTES TO THE INSTRUCTOR

This book is designed to support a senior-level course for students in engineering, particularly those in electrical engineering and computer science. Prerequisites include calculus through one course in differential equations, rudimentary understanding of matrix manipulation, one undergraduate course in electronics, and one undergraduate course in digital systems.

It can also serve as a valuable reference for the practicing engineer.

The emphasis in the course is on the digital computer and its involvement in the control and operation of manipulators. From a technical point of view, it is a course about how the computer may be used to solve the relationship problems which are critical in robotics. For example, coordinate frames relate points and orientations in Cartesian space to other such points and orientations, kinematics relates the position of the hand to the angles of the joints, and vision relates perception to control. These relationships are evolved and explained through the course.

Upon successful completion of the course, the student will be prepared to make competent purchasing and utilization decisions regarding robots in manufacturing or, with minimal additional training, to be a productive member of the staff of a robot manufacturer. In the applications environment, the student will be able to assess the degree of automation required for particular manufacturing tasks, evaluate candidate robots, and if necessary, modify those robots to suit specific needs.

This course does not address the mechanical engineering aspects of robotics, such as strength of materials, mechanical time constants, or resonances. Neither does it address the aspects of power such as supplies, amplification, or control. Mention is given, however, to shielding, bypassing, and otherwise protecting digital logic from electrically noisy industrial environments.

Chapter 3 places considerable emphasis on coping with electrical noise. This chapter, more than any other, requires some background in electrical engineering. The entire chapter or selected sections may be skipped at the discretion of the instructor without serious impact on the remainder of the course.

There is more material in this book than can be covered in a one-semester course. Additional material is included to provide the student with a complete and functional reference in the fundamentals of robotics. The instructor using this as a text may choose to teach a two-semester course or may selectively exclude material. For example, electrical engineers might deemphasize much of Chapters 8 and 15; computer scientists might deemphasize Chapters 2 through 4, while placing special emphasis on Chapters 14 and 15; and mechanical engineers might place special emphasis on Chapters 8 and 10, while spending less time on Chapters 3 and 15.

STRUCTURE OF THE COURSE

A course in robotics can be made more meaningful if it is accompanied by a project such as the one described in the next section. The project involves the design and construction of a microprocessor-based servo controller interfaced to a single manipulator joint.

Before the students begin this project, the instructor should cover the first four or five chapters of the text. The students are introduced to optical encoders, both as the recommended input device for angular position information and as a mechanism for teaching general concepts of synchronization and timing. Then, some preliminary interfacing concepts are covered, including techniques for dealing with electrical noise.

A discussion of actuators prepares the students for the presentation of the principles of control. DC motors and step motors are discussed first. The subsequent discussion of hydraulic and pneumatic actuators is intended to show the generality of the second-order differential models.

Control is presented without the Laplace transform. Only three lectures are intended for the topic of control, and only simple PE, PD, and PID methods are covered. By remaining in the time domain, the student gains a better grasp of the physical realities of mechanical system control than could be presented in such a brief period with transform techniques. The book is intended to be read and understood by students who have not had control theory.

At this point, the students are prepared to begin their projects. Specific recommendations concerning the project are given in the next section.

Once the students have begun the project work, the emphasis of the course is directed toward the computational aspects of robotics.

Mathematical representations for positions and orientations in Cartesian space are derived, initially using vectors and rotation matrices and later with homogeneous coordinates. The concept of the coordinate frame that represents both position and orientation is then presented, also using the homogeneous representation.

Using the homogeneous representation (A and T matrices), the kinematic equations which relate hand coordinate frames to joint angles are derived. The derivations follow closely the approaches of Richard Paul.

Kinematic velocity relationships are derived initially using differential methods, and then extended to the general Jacobian form.

At this point, the students should be able to write (non-real-time) software in a higher-level language to perform the kinematic transformations for the laboratory arm. Such an assignment must be carefully structured to avoid consuming too much student time and diverting effort from the principal project.

Trajectory control covers methods for moving the hand with respect to some externally defined (possibly moving) coordinate frame. Applications to conveyor tracking are discussed. Specific techniques include coordinate position control and joint interpolated control. An excellent supplementary project is the implementation of path control on the laboratory arm. Again, the demand on student time and effort is a consideration.

Dynamics are discussed in terms of a single joint with inertia and friction. Time-varying loads and gravity are incorporated to show the need for compensation. Physical and mathematical models for centripetal and Coriolis forces are defined, but in a limited way, for one- and two-joint arms. The difficulties of cross-coupling between joints are described and thorough studies which utilize Lagrangian mechanics are cited.

In the static case, sensing of forces and torques provides a problem environment which can easily be discussed by students at this level. Sensing of hand forces using the joint torques and the Jacobian is discussed first, and such sensing is shown to be not very effective. Then, the 3-D force/moment sensor is introduced, with a brief discussion of strain gauges.

The immediate follow up to any discussion of force sensing is compliance, and both active and passive compliance are presented and explained.

Probably the sensor with most potential for affecting the performance of robots is vision, and several lectures are intended to be devoted to this subject. The text covers the initial concepts of television and raster scanning, including references to the sampling theorem. The terms *enhancement* and *restoration* are defined to be added to the student's vocabulary, but the emphasis of this section is on image understanding.

DESCRIPTION OF THE PROJECT

We have found that the value of the course is considerably enhanced when it incorporates a laboratory project. Groups of two or three are encouraged, since the intent of the project is to give the student first hand experience in a number of different aspects of robotics. These include

- Computer interfacing, including the ability to deal with the "nasty" parts of electrical engineering such as noise
- Use of single-chip microprocessors
- Real-time control
- Assembly language programming

These components, as well as the more computational aspects of robotics such as kinematics, will be learned through the student's work on the project.

The objective of the project is for the students to build and program a controller for a servo motor using a single-chip microprocessor. The project assumes the availability of a laboratory robot with a DC-servo motor and a optical encoder on at least one joint. There are a number of such products available; the "Rhino" is one. In the absence of a laboratory robot, a simple DC motor with encoder will suffice; however, the experience of controlling a robot joint is more effective in terms of student motivation.

In the text, interfacing and electrical noise are covered initially so that the student may begin the hardware organization of the project. The next items discussed are optical encoders and other position sensing devices. Finally, simple, single-variable control control schemes are covered. This organization enables the students to begin work on their projects about one-third of the way through the semester.

The student groups should build an interface between a single-chip microprocessor, a position sensor, and a drive mechanism. We have used both the Motorola 6801 and the Intel 8748 with some success for this application.

We have found the use of optical encoders to be advantageous, since they provide a fully digital input and eliminate the necessity for A/D converters. Furthermore, the optical encoder provides a framework in which to teach a number of digital design concepts such as timing and race conditions.

The output can be driven either from a D/A converter or by pulse-width modulation. PWM avoids the necessity of analog interfaces and provides exercise in real-time programming. We have tried using analog input and outputs and found that the students tended to consume an excessive amount of time in the analog construction without compensating learning experiences.

Each group should build a circuit board with the processor, appropriate buffer chips, bypassing, and cable connectors, to connect to the encoder/motor driver system. A mechanism must also be provided for the microprocessor to obtain input of desired position from an external source such as a terminal, other computer, or bank of switches.

The control and software aspects of the project can be graduated in levels of difficulty. PE control should be implemented first, with follow-up extensions for fast-moving groups to PD and PID or even gravity-compensated controllers.

CONTENTS

1 OVERVIEW OF ROBOTICS

This book is about robots, and about the ways in which computers are involved with robots. The book is directed primarily toward seniors in engineering or computer science.

Industrial Robots has two primary objectives: to teach robotics and to use robotics as an application domain in which to present many of the concepts that are important to practicing engineers and are often omitted from current curricula. These concepts include interfacing, electrical noise, synchronizing circuits, and so on.

Although we will concentrate on the industrial robots popular today, we will first briefly discuss the historical development of the concept of robotics.

1.1 BACKGROUND

In 1921, the Czechoslovakian playwright Karel Capek wrote a play entitled *R.U.R.* (Rossum's Universal Robots). In the Slavic languages such as Czech or Polish, the word *robot* means worker. (It may come as a surprise to a visitor to Warsaw to see posters about organizations for robots.) Today, in these countries, the word has both meanings, human and mechanical.

Capek's story, in which the mechanical servants of man revolted, became the first of a series of stories in which the robot became the "bad guy," reflecting the disenchantment with technology which was