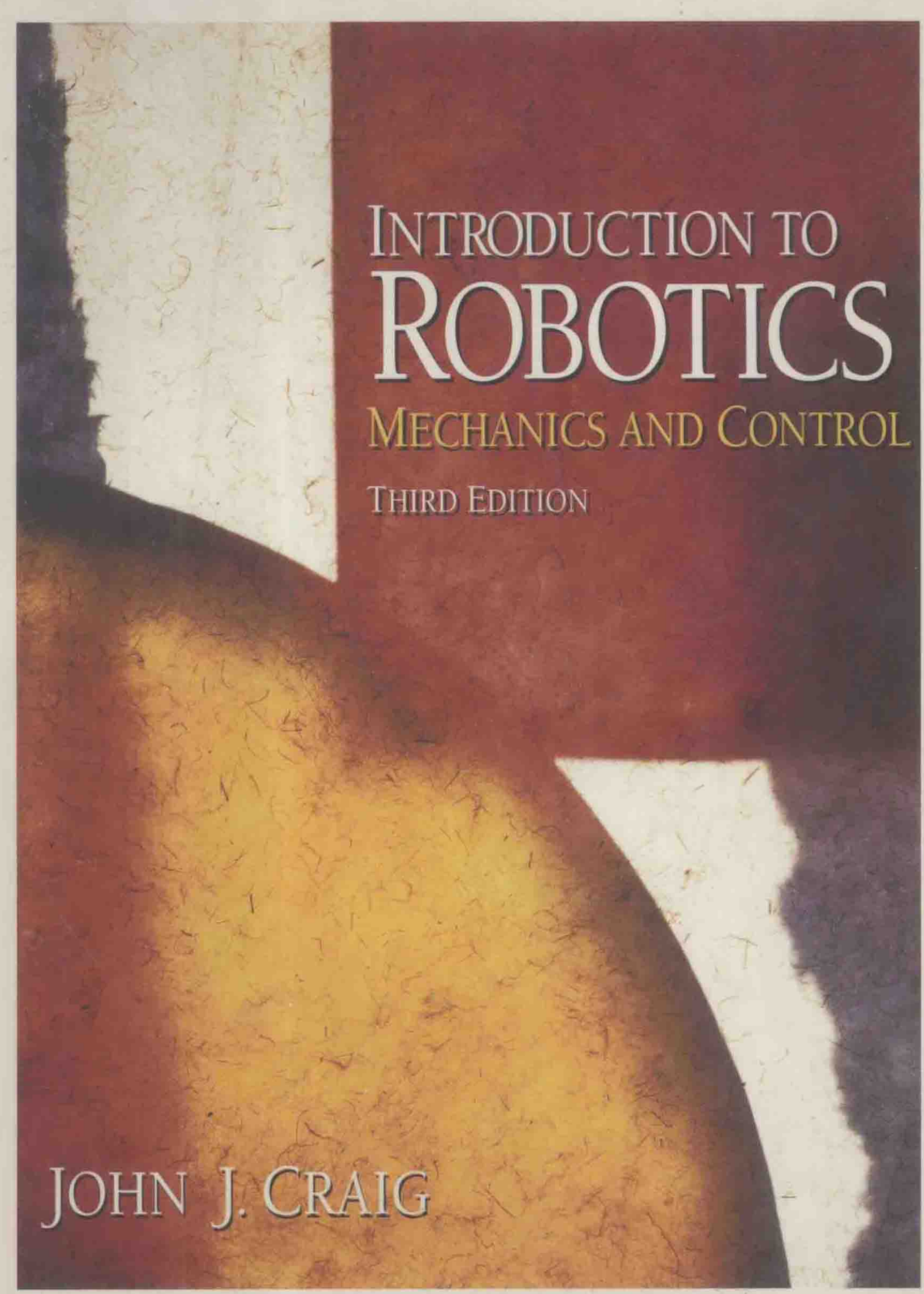
INTERNATIONAL EDITION



INTRODUCTION TO ROBOTICS

MECHANICS AND CONTROL

THIRD EDITION

JOHN J. CRAIG

Introduction to Robotics

Mechanics and Control

Third Edition

John J. Craig

PEARSON
Prentice
Hall
Pearson Education International

Vice President and Editorial Director, ECS: *Marcia J. Horton*
Associate Editor: *Alice Dworkin*
Editorial Assistant: *Carole Snyder*
Vice President and Director of Production and Manufacturing, ESM: *David W. Riccardi*
Executive Managing Editor: *Vince O'Brien*
Managing Editor: *David A. George*
Production Editor: *James Buckley*
Director of Creative Services: *Paul Belfanti*
Art Director: *Jayne Conte*
Cover Designer: *Bruce Kenselaar*
Art Editor: *Greg Dulles*
Manufacturing Manager: *Trudy Pisciotti*
Manufacturing Buyer: *Lisa McDowell*
Senior Marketing Manager: *Holly Stark*

Pearson Prentice Hall
Pearson Education, Inc.
Upper Saddle River, NJ 07458

Robotics Toolbox for MATLAB (Release7) courtesy of Peter Corke.

Printed in the United States of America

10 9 8 7 6 5 4 3 2

ISBN 0-13-123629-6

Pearson Education Ltd., *London*
Pearson Education Australia Pty. Ltd., *Sydney*
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd., *Hong Kong*
Pearson Education Canada, Ltd., *Toronto*
Pearson Educación de Mexico, S.A. de C.V.
Pearson Education—Japan, *Tokyo*
Pearson Education Malaysia, Pte. Ltd.
Pearson Education, Inc., *Upper Saddle River, New Jersey*

Preface

Scientists often have the feeling that, through their work, they are learning about some aspect of themselves. Physicists see this connection in their work; so do, for example, psychologists and chemists. In the study of robotics, the connection between the field of study and ourselves is unusually obvious. And, unlike a science that seeks only to analyze, robotics as currently pursued takes the engineering bent toward synthesis. Perhaps it is for these reasons that the field fascinates so many of us.

The study of robotics concerns itself with the desire to synthesize some aspects of human function by the use of mechanisms, sensors, actuators, and computers. Obviously, this is a huge undertaking, which seems certain to require a multitude of ideas from various "classical" fields.

Currently, different aspects of robotics research are carried out by experts in various fields. It is usually not the case that any single individual has the entire area of robotics in his or her grasp. A partitioning of the field is natural to expect. At a relatively high level of abstraction, splitting robotics into four major areas seems reasonable: mechanical manipulation, locomotion, computer vision, and artificial intelligence.

This book introduces the science and engineering of mechanical manipulation. This subdiscipline of robotics has its foundations in several classical fields. The major relevant fields are mechanics, control theory, and computer science. In this book, Chapters 1 through 8 cover topics from mechanical engineering and mathematics, Chapters 9 through 11 cover control-theoretical material, and Chapters 12 and 13 might be classed as computer-science material. Additionally, the book emphasizes computational aspects of the problems throughout; for example, each chapter that is concerned predominantly with mechanics has a brief section devoted to computational considerations.

This book evolved from class notes used to teach "Introduction to Robotics" at Stanford University during the autumns of 1983 through 1985. The first and second editions have been used at many institutions from 1986 through 2002. The third edition has benefited from this use and incorporates corrections and improvements due to feedback from many sources. Thanks to all those who sent corrections to the author.

This book is appropriate for a senior undergraduate- or first-year graduate-level course. It is helpful if the student has had one basic course in statics and dynamics and a course in linear algebra and can program in a high-level language. Additionally, it is helpful, though not absolutely necessary, that the student have completed an introductory course in control theory. One aim of the book is to present material in a simple, intuitive way. Specifically, the audience need not be strictly mechanical engineers, though much of the material is taken from that field. At Stanford, many electrical engineers, computer scientists, and mathematicians found the book quite readable.

Directly, this book is of use to those engineers developing robotic systems, but the material should be viewed as important background material for anyone who will be involved with robotics. In much the same way that software developers have usually studied at least some hardware, people not directly involved with the mechanics and control of robots should have some such background as that offered by this text.

Like the second edition, the third edition is organized into 13 chapters. The material will fit comfortably into an academic semester; teaching the material within an academic quarter will probably require the instructor to choose a couple of chapters to omit. Even at that pace, all of the topics cannot be covered in great depth. In some ways, the book is organized with this in mind; for example, most chapters present only one approach to solving the problem at hand. One of the challenges of writing this book has been in trying to do justice to the topics covered within the time constraints of usual teaching situations. One method employed to this end was to consider only material that directly affects the study of mechanical manipulation.

At the end of each chapter is a set of exercises. Each exercise has been assigned a difficulty factor, indicated in square brackets following the exercise's number. Difficulties vary between [00] and [50], where [00] is trivial and [50] is an unsolved research problem.[1] Of course, what one person finds difficult, another might find easy, so some readers will find the factors misleading in some cases. Nevertheless, an effort has been made to appraise the difficulty of the exercises.

At the end of each chapter there is a programming assignment in which the student applies the subject matter of the corresponding chapter to a simple three-jointed planar manipulator. This simple manipulator is complex enough to demonstrate nearly all the principles of general manipulators without bogging the student down in too much complexity. Each programming assignment builds upon the previous ones, until, at the end of the course, the student has an entire library of manipulator software.

Additionally, with the third edition we have added MATLAB exercises to the book. There are a total of 12 MATLAB exercises associated with Chapters 1 through 9. These exercises were developed by Prof. Robert L. Williams II of Ohio University, and we are greatly indebted to him for this contribution. These exercises can be used with the MATLAB Robotics Toolbox[2] created by Peter Corke, Principal Research Scientist with CSIRO in Australia.

Chapter 1 is an introduction to the field of robotics. It introduces some background material, a few fundamental ideas, and the adopted notation of the book, and it previews the material in the later chapters.

Chapter 2 covers the mathematics used to describe positions and orientations in 3-space. This is extremely important material: By definition, mechanical manipulation concerns itself with moving objects (parts, tools, the robot itself) around in space. We need ways to describe these actions in a way that is easily understood and is as intuitive as possible.

---

[1] I have adopted the same scale as in *The Art of Computer Programming* by D. Knuth (Addison-Wesley).

[2] For the MATLAB Robotics Toolbox, go to http:/www.ict.csiro.au/robotics/ToolBox7.htm.

Chapters 3 and 4 deal with the geometry of mechanical manipulators. They introduce the branch of mechanical engineering known as kinematics, the study of motion without regard to the forces that cause it. In these chapters, we deal with the kinematics of manipulators, but restrict ourselves to static positioning problems.

Chapter 5 expands our investigation of kinematics to velocities and static forces.

In Chapter 6, we deal for the first time with the forces and moments required to cause motion of a manipulator. This is the problem of manipulator dynamics.

Chapter 7 is concerned with describing motions of the manipulator in terms of trajectories through space.

Chapter 8 many topics related to the mechanical design of a manipulator. For example, how many joints are appropriate, of what type should they be, and how should they be arranged?

In Chapters 9 and 10, we study methods of controlling a manipulator (usually with a digital computer) so that it will faithfully track a desired position trajectory through space. Chapter 9 restricts attention to linear control methods; Chapter 10 extends these considerations to the nonlinear realm.

Chapter 11 covers the field of active force control with a manipulator. That is, we discuss how to control the application of forces by the manipulator. This mode of control is important when the manipulator comes into contact with the environment around it, such as during the washing of a window with a sponge.

Chapter 12 overviews methods of programming robots, specifically the elements needed in a robot programming system, and the particular problems associated with programming industrial robots.

Chapter 13 introduces off-line simulation and programming systems, which represent the latest extension to the man–robot interface.

I would like to thank the many people who have contributed their time to helping me with this book. First, my thanks to the students of Stanford's ME219 in the autumn of 1983 through 1985, who suffered through the first drafts, found many errors, and provided many suggestions. Professor Bernard Roth has contributed in many ways, both through constructive criticism of the manuscript and by providing me with an environment in which to complete the first edition. At SILMA Inc., I enjoyed a stimulating environment, plus resources that aided in completing the second edition. Dr. Jeff Kerr wrote the first draft of Chapter 8. Prof. Robert L. Williams II contributed the MATLAB exercises found at the end of each chapter, and Peter Corke expanded his Robotics Toolbox to support this book's style of the Denavit–Hartenberg notation. I owe a debt to my previous mentors in robotics: Marc Raibert, Carl Ruoff, Tom Binford, and Bernard Roth.

Many others around Stanford, SILMA, Adept, and elsewhere have helped in various ways—my thanks to John Mark Agosta, Mike Ali, Lynn Balling, Al Barr, Stephen Boyd, Chuck Buckley, Joel Burdick, Jim Callan, Brian Carlisle, Monique Craig, Subas Desa, Tri Dai Do, Karl Garcia, Ashitava Ghosal, Chris Goad, Ron Goldman, Bill Hamilton, Steve Holland, Peter Jackson, Eric Jacobs, Johann Jäger, Paul James, Jeff Kerr, Oussama Khatib, Jim Kramer, Dave Lowe, Jim Maples, Dave Marimont, Dave Meer, Kent Ohlund, Madhusudan Raghavan, Richard Roy, Ken Salisbury, Bruce Shimano, Donalda Speight, Bob Tilove, Sandy Wells, and Dave Williams.

The students of Prof. Roth's Robotics Class of 2002 at Stanford used the second edition and forwarded many reminders of the mistakes that needed to get fixed for the third edition.

Finally I wish to thank Tom Robbins at Prentice Hall for his guidance with the first edition and now again with the present edition.

J.J.C.

Contents

CHAPTER 2

Spatial descriptions and transformations

2.1 INTRODUCTION

Robotic manipulation, by definition, implies that parts and tools will be moved around in space by some sort of mechanism. This naturally leads to a need for representing positions and orientations of parts, of tools, and of the mechanism itself. To define and manipulate mathematical quantities that represent position and orientation, we must define coordinate systems and develop conventions for representation. Many of the ideas developed here in the context of position and orientation will form a basis for our later consideration of linear and rotational velocities, forces, and torques.

We adopt the philosophy that somewhere there is a **universe coordinate system** to which everything we discuss can be referenced. We will describe all positions and orientations with respect to the universe coordinate system or with respect to other Cartesian coordinate systems that are (or could be) defined relative to the universe system.

2.2 DESCRIPTIONS: POSITIONS, ORIENTATIONS, AND FRAMES

A **description** is used to specify attributes of various objects with which a manipulation system deals. These objects are parts, tools, and the manipulator itself. In this section, we discuss the description of positions, of orientations, and of an entity that contains both of these descriptions: the frame.

CHAPTER 3

Manipulator kinematics

3.1 INTRODUCTION

Kinematics is the science of motion that treats the subject without regard to the forces that cause it. Within the science of kinematics, one studies the position, the velocity, the acceleration, and all higher order derivatives of the position variables (with respect to time or any other variable(s)). Hence, the study of the kinematics of manipulators refers to all the geometrical and time-based properties of the motion. The relationships between these motions and the forces and torques that cause them constitute the problem of dynamics, which is the subject of Chapter 6.

In this chapter, we consider position and orientation of the manipulator linkages in static situations. In Chapters 5 and 6, we will consider the kinematics when velocities and accelerations are involved.

In order to deal with the complex geometry of a manipulator, we will affix frames to the various parts of the mechanism and then describe the relationships between these frames. The study of manipulator kinematics involves, among other things, how the locations of these frames change as the mechanism articulates. The central topic of this chapter is a method to compute the position and orientation of the manipulator's end-effector relative to the base of the manipulator as a function of the joint variables.

连杆

3.2 LINK DESCRIPTION

关节

A manipulator may be thought of as a set of bodies connected in a chain by joints. These bodies are called links. Joints form a connection between a neighboring pair of links. The term **lower pair** is used to describe the connection between a pair of

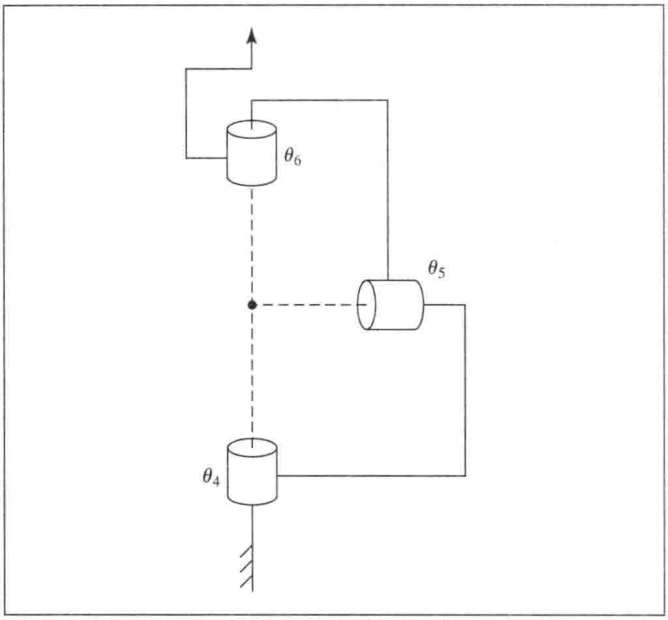


FIGURE 3.20: Schematic of a 3*R* wrist in which all three axes intersect at a point and are mutually orthogonal. This design is used in the PUMA 560 manipulator and many other industrial robots.

i	$\alpha_i - 1$	$a_i - 1$	d_i	θi
1	0	0	0	θ_1
2	−90°	0	0	θ_2
3	0	a_2	d_3	θ_3
4	−90°	a_3	d_4	θ_4
5	90°	0	0	θ_5
6	−90°	0	0	θ_6

FIGURE 3.21: Link parameters of the PUMA 560

CHAPTER 1

Introduction

1.1 BACKGROUND

The history of industrial automation is characterized by periods of rapid change in popular methods. Either as a cause or, perhaps, an effect, such periods of change in automation techniques seem closely tied to world economics. Use of the **industrial robot**, which became identifiable as a unique device in the 1960s [1], along with computer-aided design (CAD) systems and computer-aided manufacturing (CAM) systems, characterizes the latest trends in the automation of the manufacturing process. These technologies are leading industrial automation through another transition, the scope of which is still unknown [2].

In North America, there was much adoption of robotic equipment in the early 1980s, followed by a brief pull-back in the late 1980s. Since that time, the market has been growing (Fig. 1.1), although it is subject to economic swings, as are all markets.

Figure 1.2 shows the number of robots being installed per year in the major industrial regions of the world. Note that Japan reports numbers somewhat differently from the way that other regions do: they count some machines as robots that in other parts of the world are not considered robots (rather, they would be simply considered "factory machines"). Hence, the numbers reported for Japan are somewhat inflated.

A major reason for the growth in the use of industrial robots is their declining cost. Figure 1.3 indicates that, through the decade of the 1990s, robot prices dropped while human labor costs increased. Also, robots are not just getting cheaper, they are becoming more effective—faster, more accurate, more flexible. If we factor these *quality adjustments* into the numbers, the cost of using robots is dropping even faster than their price tag is. As robots become more cost effective at their jobs, and as human labor continues to become more expensive, more and more industrial jobs become candidates for robotic automation. This is the single most important trend propelling growth of the industrial robot market. A secondary trend is that, economics aside, as robots become more capable they become *able* to do more and more tasks that might be dangerous or impossible for human workers to perform.

The applications that industrial robots perform are gradually getting more sophisticated, but it is still the case that, in the year 2000, approximately 78% of the robots installed in the US were welding or material-handling robots [3].

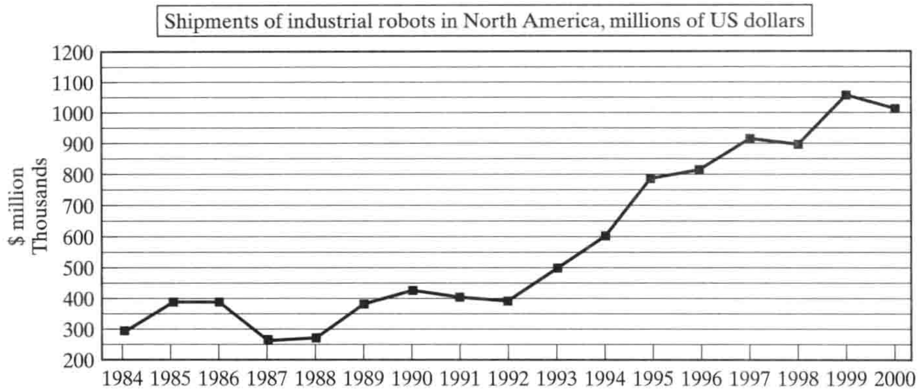


FIGURE 1.1: Shipments of industrial robots in North America in millions of US dollars [3].

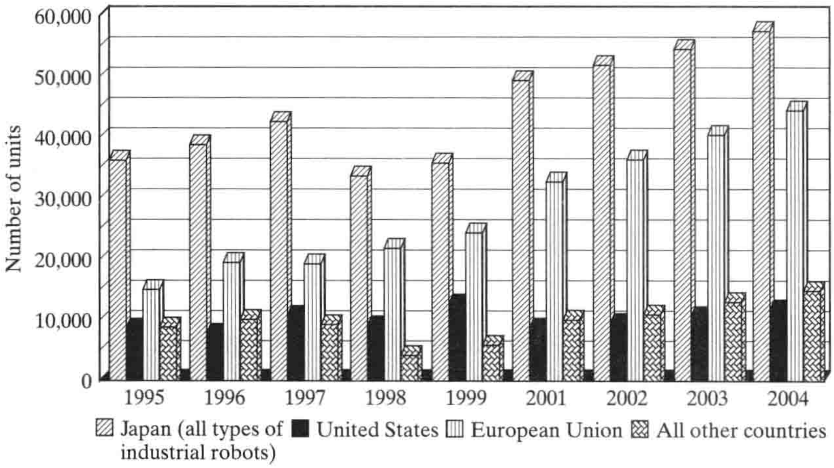


FIGURE 1.2: Yearly installations of multipurpose industrial robots for 1995–2000 and forecasts for 2001–2004 [3].

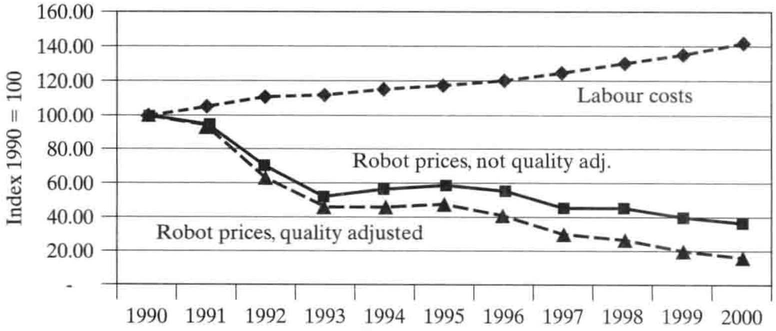


FIGURE 1.3: Robot prices compared with human labor costs in the 1990s [3].

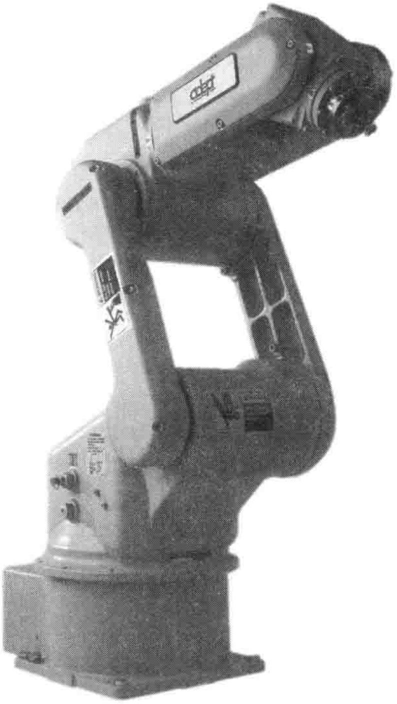


FIGURE 1.4: The Adept 6 manipulator has six rotational joints and is popular in many applications. Courtesy of Adept Technology, Inc.

A more challenging domain, **assembly** by industrial robot, accounted for 10% of installations.

This book focuses on the mechanics and control of the most important form of the industrial robot, the **mechanical manipulator**. Exactly what constitutes an industrial robot is sometimes debated. Devices such as that shown in Fig. 1.4 are always included, while numerically controlled (NC) milling machines are usually not. The distinction lies somewhere in the sophistication of the programmability of the device—if a mechanical device can be programmed to perform a wide variety of applications, it is probably an industrial robot. Machines which are for the most part limited to one class of task are considered **fixed automation**. For the purposes of this text, the distinctions need not be debated; most material is of a basic nature that applies to a wide variety of programmable machines.

By and large, the study of the mechanics and control of manipulators is not a new science, but merely a collection of topics taken from "classical" fields. Mechanical engineering contributes methodologies for the study of machines in static and dynamic situations. Mathematics supplies tools for describing spatial motions and other attributes of manipulators. Control theory provides tools for designing and evaluating algorithms to realize desired motions or force applications. Electrical-engineering techniques are brought to bear in the design of sensors and interfaces for industrial robots, and computer science contributes a basis for programming these devices to perform a desired task.

1.2 THE MECHANICS AND CONTROL OF MECHANICAL MANIPULATORS

The following sections introduce some terminology and briefly preview each of the topics that will be covered in the text.

Description of position and orientation

In the study of robotics, we are constantly concerned with the location of objects in three-dimensional space. These objects are the links of the manipulator, the parts and tools with which it deals, and other objects in the manipulator's environment. At a crude but important level, these objects are described by just two attributes: position and orientation. Naturally, one topic of immediate interest is the manner in which we represent these quantities and manipulate them mathematically.

In order to describe the position and orientation of a body in space, we will always attach a coordinate system, or **frame**, rigidly to the object. We then proceed to describe the position and orientation of this frame with respect to some reference coordinate system. (See Fig. 1.5.)

Any frame can serve as a reference system within which to express the position and orientation of a body, so we often think of *transforming* or *changing the description of* these attributes of a body from one frame to another. Chapter 2 discusses conventions and methodologies for dealing with the description of position and orientation and the mathematics of manipulating these quantities with respect to various coordinate systems.

Developing good skills concerning the description of position and rotation of rigid bodies is highly useful even in fields outside of robotics.

Forward kinematics of manipulators

Kinematics is the science of motion that treats motion without regard to the forces which cause it. Within the science of kinematics, one studies position, velocity,

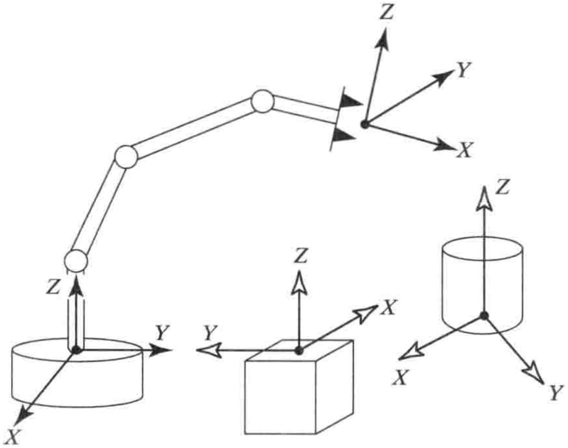


FIGURE 1.5: Coordinate systems or "frames" are attached to the manipulator and to objects in the environment.

acceleration, and all higher order derivatives of the position variables (with respect to time or any other variable(s)). Hence, the study of the kinematics of manipulators refers to all the geometrical and time-based properties of the motion.

Manipulators consist of nearly rigid **links**, which are connected by **joints** that allow relative motion of neighboring links. These joints are usually instrumented with position sensors, which allow the relative position of neighboring links to be measured. In the case of rotary or **revolute** joints, these displacements are called **joint angles**. Some manipulators contain sliding (or **prismatic**) joints, in which the relative displacement between links is a translation, sometimes called the **joint offset**.

The number of **degrees of freedom** that a manipulator possesses is the number of independent position variables that would have to be specified in order to locate all parts of the mechanism. This is a general term used for any mechanism. For example, a four-bar linkage has only one degree of freedom (even though there are three moving members). In the case of typical industrial robots, because a manipulator is usually an open kinematic chain, and because each joint position is usually defined with a single variable, the number of joints equals the number of degrees of freedom.

At the free end of the chain of links that make up the manipulator is the **end-effector**. Depending on the intended application of the robot, the end-effector could be a gripper, a welding torch, an electromagnet, or another device. We generally describe the position of the manipulator by giving a description of the **tool frame**, which is attached to the end-effector, relative to the **base frame**, which is attached to the nonmoving base of the manipulator. (See Fig. 1.6.)

A very basic problem in the study of mechanical manipulation is called **forward kinematics**. This is the static geometrical problem of computing the position and orientation of the end-effector of the manipulator. Specifically, given a set of joint

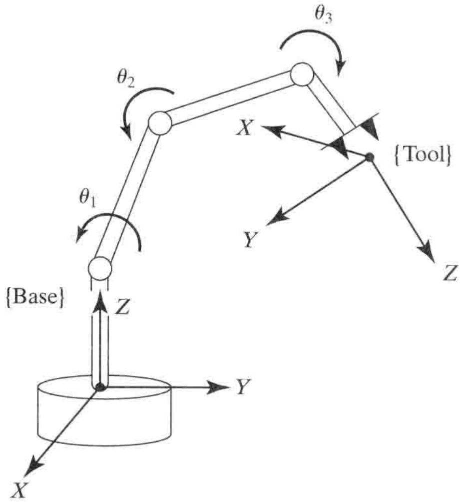


FIGURE 1.6: Kinematic equations describe the tool frame relative to the base frame as a function of the joint variables.

angles, the forward kinematic problem is to compute the position and orientation of the tool frame relative to the base frame. Sometimes, we think of this as changing the representation of manipulator position from a **joint space** description into a **Cartesian space** description.[1] This problem will be explored in Chapter 3.

Inverse kinematics of manipulators

In Chapter 4, we will consider the problem of **inverse kinematics.** This problem is posed as follows: Given the position and orientation of the end-effector of the manipulator, calculate all possible sets of joint angles that could be used to attain this given position and orientation. (See Fig. 1.7.) This is a fundamental problem in the practical use of manipulators.

This is a rather complicated geometrical problem that is routinely solved thousands of times daily in human and other biological systems. In the case of an artificial system like a robot, we will need to create an algorithm in the control computer that can make this calculation. In some ways, solution of this problem is the most important element in a manipulator system.

We can think of this problem as a *mapping* of "locations" in 3-D Cartesian space to "locations" in the robot's internal joint space. This need naturally arises anytime a goal is specified in external 3-D space coordinates. Some early robots lacked this algorithm—they were simply moved (sometimes by hand) to desired locations, which were then recorded as a set of joint values (i.e., as a location in joint space) for later playback. Obviously, if the robot is used purely in the mode of recording and playback of joint locations and motions, no algorithm relating

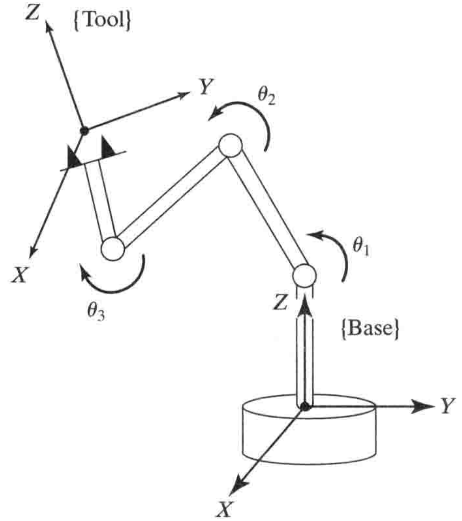


FIGURE 1.7: For a given position and orientation of the tool frame, values for the joint variables can be calculated via the inverse kinematics.

---

[1] By *Cartesian space*, we mean the space in which the position of a point is given with three numbers, and in which the orientation of a body is given with three numbers. It is sometimes called *task space* or *operational space*.