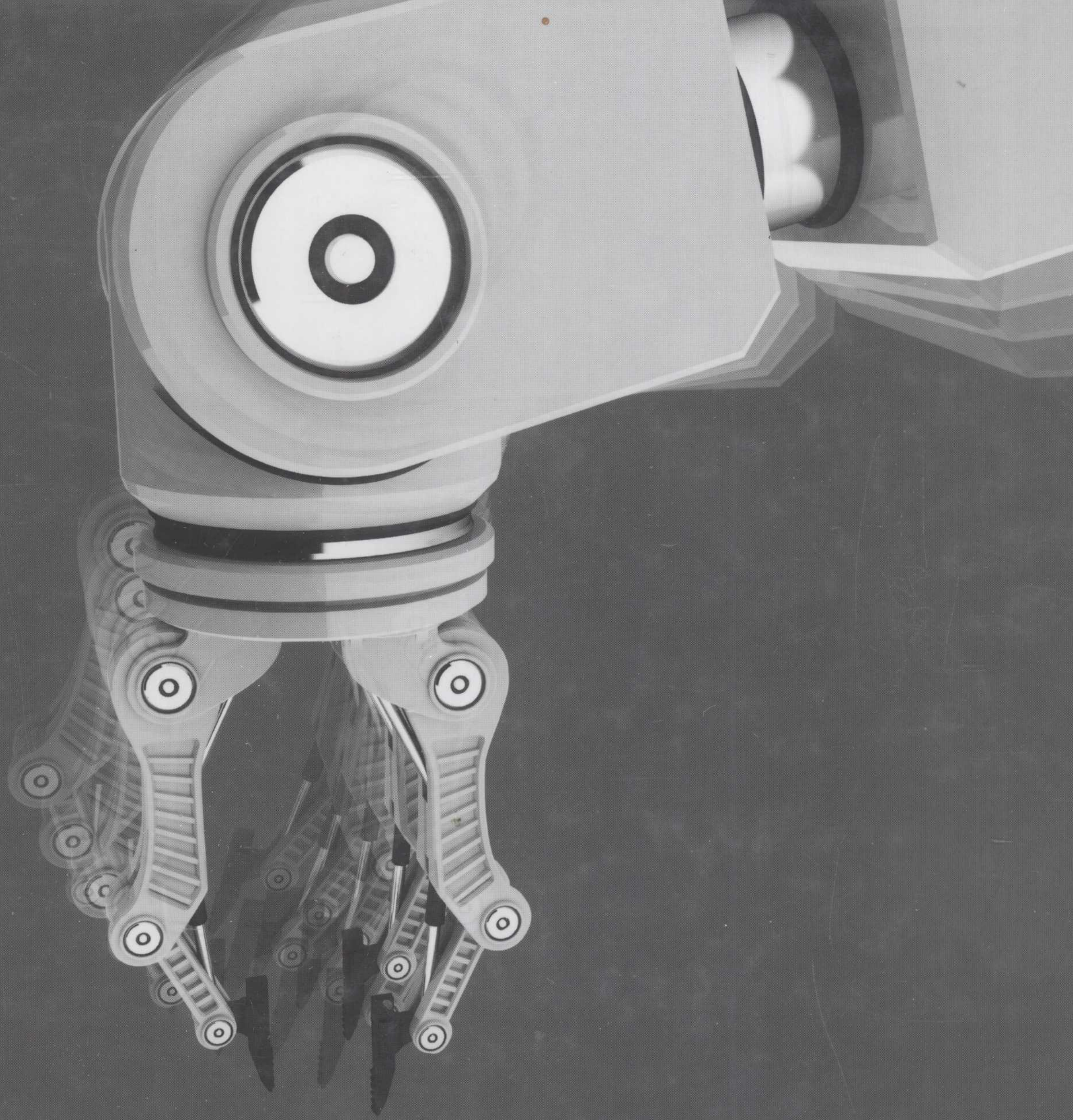

Second Edition

Introduction to ROBOTICS

Analysis, Control, Applications

SAEED B. NIKU

Introduction to Robotics

Analysis, Control, Applications

Second Edition

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Dedicated to
Shohreh, Adam, and Alan Niku
and to
Sara Niku and the memory of Saleh Niku

Preface

This is the second edition of the Introduction to Robotics textbook. As such, it has all the features and the material covered in the first edition, but also features more examples, more homework, new projects, more detailed material in all chapters, and as a new feature, it also includes a new chapter on automatic controls and control of robots as well as information about downloading a commercially available software system called SimulationX™.

What one of my students once said years ago still stands: "In the life of every product, there comes a time when you have to shoot the designer and go into production." Therefore, although no textbook is ever perfect, each has unique features that make it stand tall. So is this textbook. The intention behind writing this book was, and is, to cover most subjects that an undergraduate engineering student or a practicing engineer may need to know to be familiar with robotics, to be able to understand robots, design a robot, and integrate a robot in appropriate applications. As such, it covers all necessary fundamentals of robotics, robot components and subsystems, and applications.

The book is intended for senior or introductory graduate courses in robotics as well as for practicing engineers who would like to learn about robotics. Although the book covers a fair amount of mechanics and kinematics, it also covers microprocessor applications, control systems, vision systems, sensors, and actuators. Therefore, it can easily be used by mechanical engineers, electronic and electrical engineers, computer engineers, and engineering technologists. With the new chapter about control theory, even if the student has not had a controls course, he or she can learn enough material to be able to understand robotic control and design.

The book is comprised of 10 chapters. Chapter 1 covers introductory subjects that familiarize the reader with the necessary background information. This includes some historical information, robot components, robot characteristics, robot languages, and robotic applications. Chapter 2 explores the forward and inverse kinematics of robots, including frame representations, transformations, position and orientation analysis, as well as the Denavit-Hartenberg representation of robot kinematics. Chapter 3 continues with differential motions and velocity analysis of robots and frames. Chapter 4 presents an analysis of robot dynamics and forces. Lagrangian mechanics is used as the primary method of analysis and development for this chapter. Chapter 5 discusses methods of path and trajectory planning, both in joint-space and in Cartesian-space. Chapter 6 covers fundamentals of control engineering, including analysis and design tools. Among other things, it discusses root locus, proportional, derivative, and integral control as well as electromechanical system modeling. Chapter 6 also includes an introduction to multi-input-multi-output (MIMO) systems, digital systems, and nonlinear systems. However, the assumption is that students will need additional instruction to be proficient in actually designing systems. One chapter on this subject cannot be adequate, but can nicely serve as an introduction for majors in which a separate course in control engineering is not offered. Chapter 7 covers actuators, including hydraulic devices, electric motors such as DC servomotors and stepper motors, pneumatic devices, as well as many other novel actuators. It also covers microprocessor control of these actuators. Although this book is not a complete mechatronics book, it does cover a fair amount of mechatronics. Except for the design of a microprocessor, many aspects of mechatronic applications are covered in this chapter. Chapter 8 is a discussion of sensors used in robotics and robotic applications. Chapter 9 covers vision systems, including many different techniques for image processing and image analysis. Chapter 10 discusses the basic principles of fuzzy logic and its applications in microprocessor control and robotics. This coverage is not intended to be a complete and thorough analysis of fuzzy logic, but an introduction. It is believed that students and engineers who find it interesting will continue on their own. Appendix A is a quick review of matrix algebra and some other mathematical facts that are needed throughout this book. Appendix B covers image acquisition. Appendix C presents the application of MATLAB in control engineering. Appendix D includes references to commercial software that can be used to model and simulate robots and their dynamics. The student version of this program can be downloaded for free. Consequently, if robotic simulation is to be covered, the program and associated tutorials may be used without additional cost to students.

Most of the material in this book is generally covered in a four-unit, 10-week course at Cal Poly, with three one-hour lectures and one three-hour lab. However, it is easily possible to cover the entire course in a semester-long course as well. The following breakdown can be used as a model for setting up a course in robotics in a quarter system. In this case, certain subjects must be eliminated or shortened, as shown:

Introductory material and review: 3 lectures
Kinematics of position: 7 lectures
Differential motions: 4 lectures
Robot dynamics and force control: 2 lectures
Path and trajectory planning: 1 lecture
Actuators: 3 lectures
Sensors: 3 lectures
Vision systems: 5 lectures
Fuzzy logic: 1 lectures
Exam: 1 lecture

Alternately, for a 14-week long semester course with three lectures per week, the course may be set up as follows:

Introductory material and review: 3 lectures
Kinematics of position: 7 lectures
Differential motions: 5 lectures
Robot dynamics and force control: 5 lectures
Path and trajectory planning: 3 lectures
Robot control and modeling: 5 lectures
Actuators: 5 lectures
Sensors: 2 lectures
Vision systems: 5 lecture
Fuzzy logic: 1 lectures
Exam: 1 lecture

The book also features design projects that start in Chapter 2 and continue throughout the book. At the end of each chapter, the student is directed to continue with the design projects in reference to the present subject. Therefore, by the end of the book, complete systems may be designed.

I would like to thank all the people who, in one way or another, have helped me. This includes my colleagues, including Bill Murray, Charles Birdsong, Lynne Slivovsky, and John Ridgely, all the countless individuals who did the research, development, and hard work that came before my time and which enabled me to learn the subject myself, all the users and students and anonymous reviewers who made countless suggestions to improve the first draft, including Thomas Cavicchi, Ed Foley, and the students who helped with the design and development of projects at Cal Poly, including the Robotics Club. I also thank Mike McDonald, the acquisition editor at John Wiley and Sons, who was instrumental in getting the second edition published, Renata Marchione, Don Fowley, Linda Ratts, and Yee Lyn Song for their assistance throughout, and the editors and the artists who made the book look as it does. I also would like to thank the staff at Prentice Hall who published the first edition. Finally, I thank my family, Shohreh, Adam, and Alan, who let me work on this manuscript for long hours instead of spending time with them. Their patience is much appreciated. To all of you, my sincere thanks.

I hope that you will enjoy reading the book and, more importantly, that you will learn the subject. The joy of robotics comes from learning it.

Saeed Benjamin Niku, Ph.D., P.E.
San Luis Obispo, California
2010

Brief Contents

Contents

CHAPTER 1

Fundamentals

1.1 Introduction

Robotics, in different forms, has been on humans' minds since the time we could build things. You may have seen machines that artisans made that try to mimic human motions and behavior. Examples include the statues in Venice's San Marcos clock tower that hit the clock on the hour and figurines that tell a story in the fifteenth-century Astronomical Clock on the side of the Old Town Hall Tower in Prague (Figure 1.1). Toys, from simple types to sophisticated machines with repeating movements, are other examples. In Hollywood, movies have even portrayed robots and humanoids as superior to humans.

Although in principle humanoids are robots and are designed and governed by the same basics, in this book, we will primarily study industrial manipulator type robots. This book covers some basic introductory material that familiarizes you with the subject; it presents an analysis of the mechanics of robots including kinematics, dynamics, and trajectory planning; and it discusses the elements used in robots and in robotics, such as actuators, sensors, vision systems, and so on. Robot rovers are no different, although they usually have fewer degrees of freedom and generally move in a plane. Exoskeletal and humanoid robots, walking machines, and robots that mimic animals and insects have many degrees of freedom (DOF) and may possess unique capabilities. However, the same principles we learn about manipulators apply to robot rovers too, whether kinematics, differential motions, dynamics, or control.

Robots are very powerful elements of today's industry. They are capable of performing many different tasks and operations, are accurate, and do not require common safety and comfort elements humans need. However, it takes much effort and many resources to make a robot function properly. Most companies of the mid-1980s that made robots are gone, and with few exceptions, only companies that make real industrial robots have remained in the market (such as Adept, Staubli, Fanuc, Kuka, Epson, Motoman, Denso, Fuji, and IS Robotics as well as specialty robotic companies such as Mako Surgical Corp. and Intuitive Surgical). Early industrialist predictions about the possible number of robots

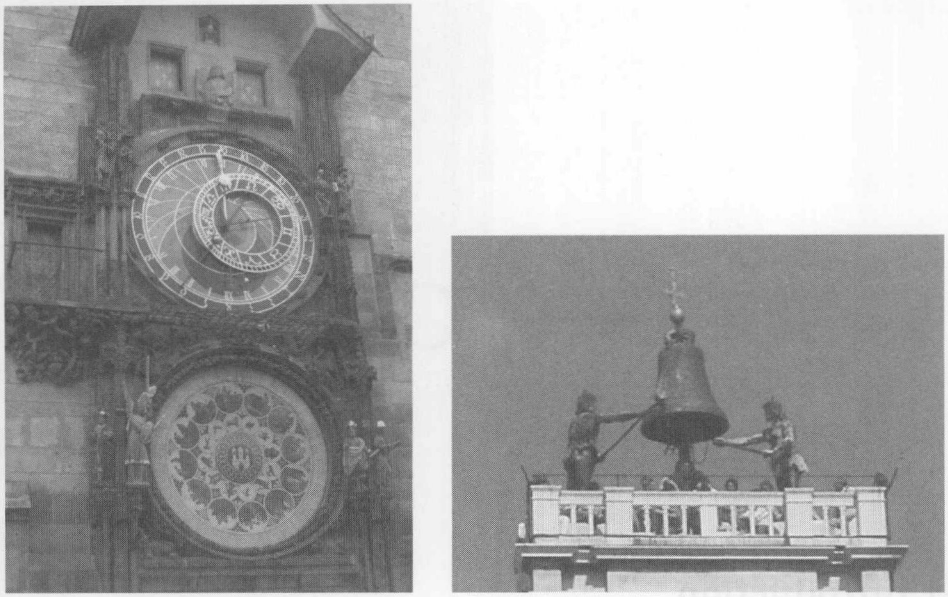

Figure 1.1 Centuries-old figurines and statues that mimic human motions.

in industry never materialized because high expectations could not be satisfied with the present robots. As a result, although there are many thousands of robots in industry working tirelessly and satisfactorily for the intended jobs, robots have not overwhelmingly replaced workers. They are used where they are useful. Like humans, robots can do certain things, but not others. As long as they are designed properly for the intended purposes, they are very useful and continue to be used.

The subject of robotics covers many different areas. Robots alone are hardly ever useful. They are used together with other devices, peripherals, and other manufacturing machines. They are generally integrated into a system, which as a whole, is designed to perform a task or do an operation. In this book, we will refer to some of these other devices and systems used with robots.

1.2 What Is a Robot?

If you compare a conventional robot manipulator with a crane attached to, say, a utility or towing vehicle, you will notice that the robot manipulator is very similar to the crane. Both possess a number of links attached serially to each other with joints, where each joint can be moved by some type of actuator. In both systems, the "hand" of the manipulator can be moved in space and placed in any desired location within the workspace of the system. Each one can carry a certain load and is controlled by a central controller that controls the actuators. However, one is called a robot and one is called a manipulator (or, in this case, a crane). Similarly, material handling manipulators that move heavy objects in manufacturing plants look just like robots, but they are not robots. The fundamental difference between the two is that the crane and the manipulator are controlled by a human who operates and controls the actuators, whereas the robot manipulator is controlled by a computer that runs

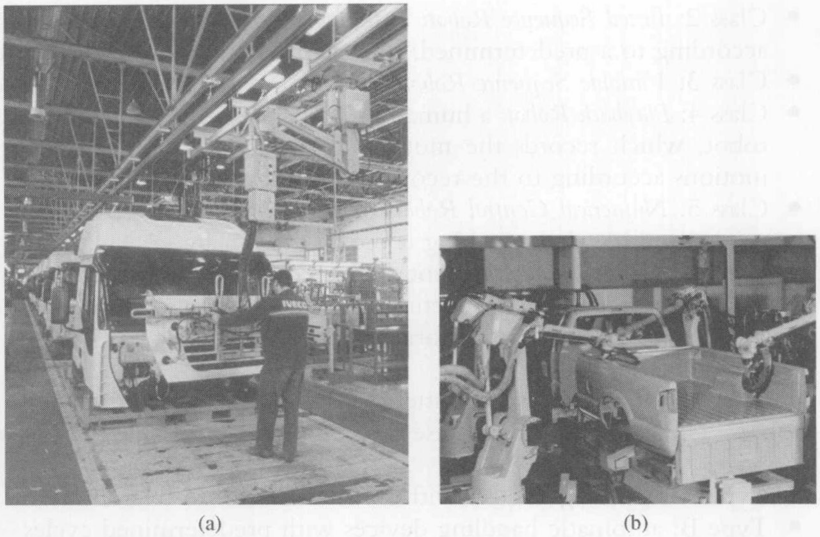

Figure 1.2 (a) Dalmec PM human-operated manipulator. (Printed with permission from Dalmec S.p.A.) (b) Fanuc S-500 robots performing seam-sealing on a truck. (Reprinted with permission from Fanuc Robotics, North America, Inc.) Both have similar construction and elements, but only the robot is controlled by a computer whereas the manipulator is controlled by an operator.

a program (Figure 1.2). This difference between the two determines whether a device is a simple manipulator or a robot. In general, robots are designed and meant to be controlled by a computer or similar device. The motions of the robot are controlled through a controller under the supervision of the computer, which is running some type of a program. Therefore, if the program is changed, the actions of the robot will change accordingly. The intention is to have a device that can perform many different tasks; consequently, it is very flexible in what it can do without having to be redesigned. Therefore, the robot is designed to be able to perform many tasks based on the running program(s) simply by changing the program. The simple manipulator (or the crane) cannot do this without an operator running it all the time.

Different countries have different standards for what they consider a robot. In American standards, a device must be easily reprogrammable to be considered a robot. Therefore, manual handling devices (devices that have multiple degrees of freedom and are actuated by an operator) or fixed sequence robots (devices controlled by hard stops to control actuator motions on a fixed sequence that are difficult to change) are not considered robots.

1.3 Classification of Robots

The following is the classification of robots according to the Japanese Industrial Robot Association (JIRA):

- Class 1: *Manual Handling Device*: a device with multiple degrees of freedom, actuated by an operator