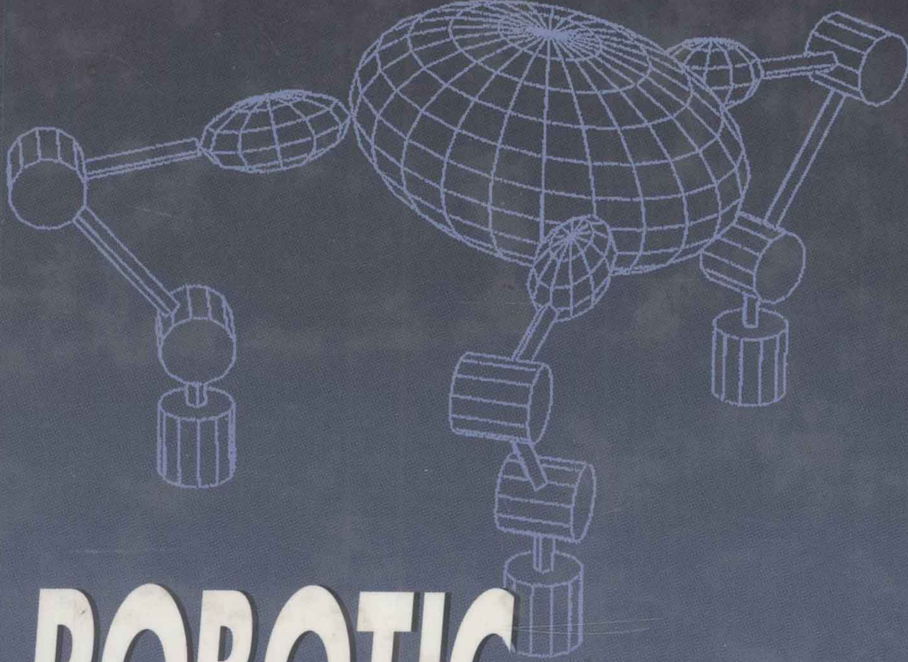
A Mathematical Introduction to



ROBOTIC MANIPULATION

Richard M. Murray
Zexiang Li
S. Shankar Sastry

A Mathematical Introduction to ROBOTIC MANIPULATION

Richard M. Murray
California Institute of Technology

Zexiang Li
Hong Kong University of Science and Technology

S. Shankar Sastry
University of California, Berkeley
and Harvard University

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A Mathematical Introduction to ROBOTIC MANIPULATION

To RuthAnne (RMM)

To Jianghua (ZXL)

In memory of my father (SSS)

Preface

In the last two decades, there has been a tremendous surge of activity in robotics, both in terms of research and in terms of capturing the imagination of the general public as to its seemingly endless and diverse possibilities. This period has been accompanied by a technological maturation of robots as well, from the simple pick and place and painting and welding robots, to more sophisticated assembly robots for inserting integrated circuit chips onto printed circuit boards, to mobile carts for parts handling and delivery. Several areas of robotic automation have now become "standard" on the factory floor and, as of the writing of this book, the field is on the verge of a new explosion to areas of growth involving hazardous environments, minimally invasive surgery, and micro electro-mechanical mechanisms.

Concurrent with the growth in robotics in the last two decades has been the development of courses at most major research universities on various aspects of robotics. These courses are taught at both the undergraduate and graduate levels in computer science, electrical and mechanical engineering, and mathematics departments, with different emphases depending on the background of the students. A number of excellent textbooks have grown out of these courses, covering various topics in kinematics, dynamics, control, sensing, and planning for robot manipulators.

Given the state of maturity of the subject and the vast diversity of students who study this material, we felt the need for a book which presents a slightly more abstract (mathematical) formulation of the kinematics, dynamics, and control of robot manipulators. The current book is an attempt to provide this formulation not just for a single robot but also for multifingered robot hands, involving multiple cooperating robots. It grew from our efforts to teach a course to a hybrid audience of electrical engineers who did not know much about mechanisms, computer scientists who did not know about control theory, mechanical engineers who were suspicious of involved explanations of the kinematics and dynamics of garden variety open kinematic chains, and mathematicians who were curious, but did not have the time to build up lengthy prerequisites before beginning a study of robotics.

It is our premise that abstraction saves time in the long run, in return for an initial investment of effort and patience in learning some mathematics. The selection of topics—from kinematics and dynamics of single robots, to grasping and manipulation of objects by multifingered robot hands, to nonholonomic motion planning—represents an evolution from the more basic concepts to the frontiers of the research in the field. It represents what we have used in several versions of the course which have been taught between 1990 and 1993 at the University of California, Berkeley, the Courant Institute of Mathematical Sciences of New York University, the California Institute of Technology, and the Hong Kong University of Science and Technology (HKUST). We have also presented parts of this material in short courses at the Università di Roma, the Center for Artificial Intelligence and Robotics, Bangalore, India, and the National Taiwan University, Taipei, Taiwan.

The material collected here is suitable for advanced courses in robotics consisting of seniors or first- and second-year graduate students. At a senior level, we cover Chapters 1–4 in a twelve week period, augmenting the course with some discussion of technological and planning issues, as well as a laboratory. The laboratory consists of experiments involving on-line path planning and control of a few industrial robots, and the use of a simulation environment for off-line programming of robots. In courses stressing kinematic issues, we often replace material from Chapter 4 (Robot Dynamics) with selected topics from Chapter 5 (Multifingered Hand Kinematics). We have also covered Chapters 5–8 in a ten week period at the graduate level, in a course augmented with other advanced topics in manipulation or mobile robots.

The prerequisites that we assume are a good course in linear algebra at the undergraduate level and some familiarity with signals and systems. A course on control at the undergraduate level is helpful, but not strictly necessary for following the material. Some amount of mathematical maturity is also desirable, although the student who can master the concepts in Chapter 2 should have no difficulty with the remainder of the book.

We have provided a fair number of exercises after Chapters 2–8 to help students understand some new material and review their understanding of the chapter. A toolkit of programs written in Mathematica for solving the problems of Chapters 2 and 3 (and to some extent Chapter 5) have been developed and are described in Appendix B. We have studiously avoided numerical exercises in this book: when we have taught the course, we have adapted numerical exercises from measurements of robots or other "real" systems available in the laboratories. These vary from one time to the next and add an element of topicality to the course.

The one large topic in robotic manipulation that we have not covered in this book is the question of motion planning and collision avoidance for robots. In our classroom presentations we have always covered some aspects of motion planning for robots for the sake of completeness. For graduate classes, we can recommend the recent book of Latombe on motion planning as a supplement in this regard. Another omission from this book is sensing for robotics. In order to do justice to this material in our respective schools, we have always had computer vision, tactile sensing, and other related topics, such as signal processing, covered in separate courses.

The contents of our book have been chosen from the point of view that they will remain foundational over the next several years in the face of many new technological innovations and new vistas in robotics. We have tried to give a snapshot of some of these vistas in Chapter 9. In reading this book, we hope that the reader will feel the same excitement that we do about the technological and social prospects for the field of robotics and the elegance of the underlying theory.

Richard Murray
Zexiang Li
Shankar Sastry

Berkeley, August 1993

Acknowledgments

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The heart of the approach in Chapters 2 and 3 of this book is a derivation of robot kinematics using the product of exponentials formalism introduced by Roger Brockett of Harvard University. For this and manifold other contributions by him and his students to the topics in kinematics, rolling contact, and nonholonomic control, it is our pleasure to acknowledge his enthusiasm and encouragement by example. In a broader sense, the stamp of the approach that he has pioneered in nonlinear control theory is present throughout this book.

We fondly remember the seminar given at Berkeley in 1983 by P. S. Krishnaprasad of the University of Maryland, where he attempted to convince us of the beauty of the product of exponentials formula, and the numerous stimulating conversations with him, Jerry Marsden of Berkeley, and Tony Bloch of Ohio State University on the many beautiful connections between classical mechanics and modern mathematics and control theory. Another such seminar which stimulated our interest was one on multifingered robot hands and cooperating robots given at Berkeley in 1987 by Yoshi Nakamura, now of the University of Tokyo. We have also enjoyed discussing kinematics, optimal control, and redundant mechanisms with John Baillieul of Boston University; Jeff Kerr, now of Zebra Robotics; Mark Cutkosky of Stanford University and Robert Howe, now of Harvard University; Dan Koditscheck, now of the University of Michigan; Mark Spong of the University of Illinois at Urbana-Champaign; and Joel Burdick and Elon Rimon at the California Institute of Technology. Conversations with Hector Sussmann of Rutgers University and Gerardo Lafferiere of Portland State University on nonholonomic motion planning have been extremely stimulating as well.

Our colleagues have provided both emotional and technical support to us at various levels of development of this material: John Canny, Charles Desoer, David Dornfeld, Ronald Fearing, Roberto Horowitz, Jitendra Malik, and "Tomi" Tomizuka at Berkeley; Jaiwei Hong, Bud Mishra, Jack Schwartz, James Demmel, and Paul Wright at New York University; Joel Burdick and Pietro Perona at Caltech; Peter Cheung, Ruey-Wen Liu, and Matthew Yuen at HKUST; Robyn Owens at the University of West Australia; Georges Giralt at LAAS in Toulouse, France; Dorotheè Normand Cyrot at the LSS in Paris, France; Alberto Isidori, Marica Di Benedetto, Alessandro De Luca, and 'Nando' Nicoló at the Università di Roma; Sanjoy Mitter and Anita Flynn at MIT; Antonio Bicchi at the Università di Pisa; M. Vidyasagar at the Center for Artificial Intelligence and Robotics in Bangalore, India; Li-Chen Fu of the National Taiwan University, Taipei, Taiwan; and T.-J. Tarn of Washington University. Finally, we are greatful to Mark Spong, Kevin Dowling, and Dalila Argez for their help with the photographs.

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The manuscript was classroom tested in various versions by James Clark at Harvard, John Canny, Curtis Deno and Matthew Berkemeier at Berkeley, and Joel Burdick at Caltech, in addition to the three of us. Their comments have been invaluable to us in revising the early drafts. We appreciate the detailed and thoughtful reviews by Greg Chirikjian of Johns Hopkins, and Michael McCarthy and Frank Park of the University of California, Irvine.

In addition, many students suffering early versions of this course have contributed to debugging the text. They include L. Bushnell, N. Getz, J.-P. Tennant, D. Tilbury, G. Walsh, and J. Wendlandt at Berkeley; R. Behnken, S. Kelly, A. Lewis, S. Sur, and M. van Nieuwstadt at Caltech; and A. Lee and J. Au of the Hong Kong University of Science and Technology. Sudipto Sur at Caltech helped develop a Mathematica package for screw calculus which forms the heart of the software described in Appendix B. We are ultimately indebted to these and the unnamed others for the inspiration to write this book.

Finally, on a personal note, we would like to thank our families for their support and encouragement during this endeavor.

Contents

Chapter 1

Introduction

In the last twenty years, our conception and use of robots has evolved from the stuff of science fiction films to the reality of computer-controlled electromechanical devices integrated into a wide variety of industrial environments. It is routine to see robot manipulators being used for welding and painting car bodies on assembly lines, stuffing printed circuit boards with IC components, inspecting and repairing structures in nuclear, undersea, and underground environments, and even picking oranges and harvesting grapes in agriculture. Although few of these manipulators are anthropomorphic, our fascination with humanoid machines has not dulled, and people still envision robots as evolving into electromechanical replicas of ourselves. While we are not likely to see this type of robot in the near future, it is fair to say that we have made a great deal of progress in introducing simple robots with crude end-effectors into a wide variety of circumstances. Further, it is important to recognize that our impatience with the pace of robotics research and our expectations of what robots can and cannot do is in large part due to our lack of appreciation of the incredible power and subtlety of our own biological motor control systems.

1 Brief History

The word *robot* was introduced in 1921 by the Czech playwright Karel Capek in his satirical play *R. U. R.* (Rossum's Universal Robots), where he depicted robots as machines which resembled people but worked tirelessly. In the play, the robots eventually turn against their creators and annihilate the human race. This play spawned a great deal of further science fiction literature and film which have contributed to our perceptions of robots as being human-like, endowed with intelligence and even personality. Thus, it is no surprise that present-day robots appear primitive