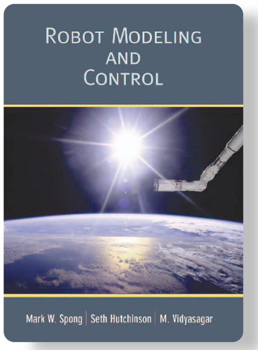

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Robot Modeling and Control

by MARK W. SPONG,
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The field of robotics began in the 1960s and 1970s with the design and control of general purpose robotic manipulators. During the 1980s the expense of integrating robotics into manufacturing lines and the difficulty of performing seemingly easy tasks, such as manipulating flexible objects or washing a window, led to disenchantment among many researchers and funding agencies. Since the 1990s the popularity of robotics has resurged with many new exciting areas of application particularly in the medical, defense, and service sectors. Robotics has grown from a field that is primarily concerned with problems such as the manipulation of rigid bodies in well-structured environments to a field that has tackled challenging problems such as extraterrestrial exploration and remote minimally invasive surgery. I began my involvement in the field of robotics as a graduate student studying control theory. My project was to design a control algorithm to induce stable walking in a biped robot. As with many control problems, before formulating a solution I had to determine a suitable model for the plant. Since I was an electrical engineering student with little background in the kinematics and dynamics of rigid-body mechanical systems, this task was daunting. With some guidance from a fellow student, I fumbled my way through Lagrange's method to derive the robot's equations of motion. I had little idea at the time why forming the Lagrangian and taking certain derivatives resulted in the right equations. For insight I was pointed to various texts on classical mechanics. While these texts provided the desired insight, I was still left with questions: Given an arbitrary system, how do I systematically construct the Lagrangian so that I can derive the system's equation of motion? What are the most effective techniques for robot control? What special aspects of the robot's dynamics should be considered in developing controllers?

Five years after my introduction to the field of robotics, I now know that research in the field goes well beyond the dynamics and control of traditional manipulators. The concepts required to analyze and control manipulators, however, are still needed in modern robotics research. These fundamental concepts, which are addressed by many introductory texts on robotics, are the following:

1) Forward kinematics: Given joint displacements, determine the position and orientation of the end-effector with respect to a specified reference frame.
2) Inverse kinematics: Given the position and orientation of the end-effector frame relative to a specified reference frame, determine the joint variables that give rise to this configuration.
3) Differential kinematics: Given the manipulator's joint rates, determine the linear and angular velocities of the end-effector frame relative to a fixed reference frame.
4) Statics: Given the forces and moments applied to the manipulator, determine the corresponding joint forces and torques required to maintain equilibrium in the presence of applied forces and moments.
5) Dynamics: Determine the equations of motion of the system. Specifically, determine the differential equations relating the applied forces and torques to the joint variables, joint rates, and joint accelerations.
6) Trajectory generation: Given initial and final configurations of the manipulator, find a trajectory of the joint variables connecting these two configurations.
7) Control: Given desired joint trajectories or forces between the end-effector and the environment determine joint torques and forces that effect these joint trajectories and forces.

THE BOOK

When it comes to choosing a book that addresses these fundamental questions in an introductory graduate course, *Robot Modeling and Control* is my book of choice. The text is a significantly updated and subtly renamed version of *Robot Dynamics and Control* by Spong and Vidyasagar [1]. The most significant changes are in the chapters on control and the addition of material on motion planning, computer vision, and visual servo control.

The text covers all of the essential areas of classical robotic manipulators. Chapter 1 gives a short overview of the field and introduces the essential terminology, notation, and typical kinematic arrangements. Chapter 2 introduces the mathematical machinery required to describe the relative position and orientation of rigid bodies. For pedagogical reasons, I like the identification of rigid-body rotations and homogeneous transformations as elements of the Lie groups SO(3) and SE(3), which is not done in [2] and [3], although the connections between the transformations' properties and the groups' structures are not as extensively developed as in [4].

In Chapter 3 the tools of Chapter 2 are used to derive the forward and inverse kinematics of manipulators. Forward kinematics are treated using the traditional Denavit-Hartenberg (DH) convention, as in [2] and [3]. Although the treatment of forward kinematics is simpler using twists and the product-of-exponentials formula [4], the DH approach requires tools that are less mathematically abstract. Consequently, the DH convention is usually preferred.

Chapter 4 uses the manipulator Jacobian to develop the relation between joint velocities and the velocity of a frame rigidly attached to the manipulator. The use of the Jacobian to compute static force relations using D'Alembert's principle is saved until the chapter on dynamics, Chapter 7.

Chapter 5, which is the first chapter to consider the manipulator's operating environment, presents the essential techniques for path and trajectory planning. An introduction to potential fields and probabilistic methods is a pleasing addition to the chapter. As the authors point out, a more extensive treatment of these topics can be found in [5]. The treatment of trajectory planning is standard and sufficient.

Chapter 6 briefly discusses the dynamics of permanent-magnet dc motors and then, in detail, covers independent joint control, the most basic form of joint tracking control in which each joint is treated as a decoupled SISO system. After a brief discussion of joint flexibility, the chapter rounds out with a discussion of state space feedback control and observer design.

In a presentation that is accessible to control theorists, Chapter 7 covers all of the basics of deriving the equations of motion for open-chain n-link rigid-body robots. The most significant results of the chapter are two systematic techniques for deriving the equations of motion. The methods are systematic in the sense that the derivations are algorithmic. The focus of the development is on Lagrange's method, with a section devoted to highlighting the beautiful properties of the Lagrangian equations of motion. The chapter concludes with a presentation of the more intricate Newton-Euler formulation, which, unlike the Lagrangian formulation, is recursive and requires consideration of all forces and moments acting on the system including reaction forces that do no work. By explicitly including all of the forces and moments acting on the system, however, the Newton-Euler formulation is more readily amenable to the incorporation of applied forces such as friction.

With the necessary background in place, Chapter 8 presents multivariable tracking control. The presentation begins with discussions of multivariable PD control and how to include the effects of joint flexibility in the robot's equations of motion. The presentation continues with joint space and task space inverse dynamics control, which are special cases of feedback linearization from input to joint displacement and input to end-effector position and orientation, respectively. Two methods are then given for mitigating the effects of uncertainty, namely, robust and adaptive versions of inverse dynamics control. The chapter ends with a brief presentation of passivity-based control.

Continuing with the general topic of control, Chapter 9 covers two versions of force control, specifically, impedance control and hybrid impedance control. In impedance control, the most basic form of force control, the apparent inertia, apparent damping, and apparent stiffness of the robot are regulated, where "apparent" refers to the effective closed-loop properties. The less well-known method of hybrid impedance control allows regulation of both the impedance and the position and force.

In a step up in mathematical sophistication from the earlier chapters, Chapter 10 provides an introduction to geometric nonlinear control. The introduction is self-contained and sufficient to fully develop feedback linearization of n-link robots (introduced in Chapter 8) and to discuss the controllability of systems subject to nonholonomic constraints, such as a wheeled robot, using Chow's theorem on the controllability of drift-free control systems. For alternative treatments of nonholonomic systems, see chapters 7 and 8 of [4] as well as [6].

The final two chapters introduce the use of vision in robot control. Chapter 11 gives an introduction to the fundamentals of computer vision. This chapter covers camera calibration, segmentation, and estimation of the position and orientation of objects in the camera's image. For a more complete treatment, see [7]. Building on the developments of Chapter 11, Chapter 12 gives an introduction to vision-based control, which is complementary to the other chapters on control (chapters 6, 8, and 9). Since no other introductory texts on robotics include this material, this chapter helps the book stand out over other choices, such as [2]–[4].

The book also includes four appendices with introductions to topics relevant to the main body of the book. Appendix A is a two-page summary of useful facts on trigonometry. Appendix B is a primer on the basic linear algebra required to read the rest of the book. Appendix C is a four-page introduction to a few concepts in dynamical systems theory. Finally, Appendix D gives an overview of essential Lyapunov stability analysis for time-invariant nonlinear systems.

Overall, the number of examples given in the book is adequate, and the examples are clear and illustrative. In general, the division between purely academic examples and more realistic examples is balanced. The one exception is the chapter on dynamics (Chapter 7), which can benefit from at least one more example involving a high-degree-of-freedom manipulator. I find that students benefit from having more realistic examples that they can use to check their understanding.

Concerning the end-of-chapter problems, seven of the twelve chapters have an adequate number that are of good pedagogical quality. Although the quality of the problems in the remaining chapters, chapters 7–9, 11, and 12, is good, the number of problems could be increased. A lack of quality problems appears to be a shortcoming in the more advanced chapters of most robotics texts. This shortcoming, however, is understandable. Creating a variety of problems that are of appropriate difficulty for a student is challenging for the simple reason that the equations associated with any manipulator other than those with the simplest configurations are unwieldy.

CONCLUSIONS

In summary, *Robot Modeling and Control* is my favorite text on classical robotic manipulators. All of the tools needed to gain entry into the field of robotics are thoroughly covered. Especially well treated is the topic of robot control. With authoritative introductions to joint trajectory tracking, force control, geometric nonlinear control, and vision-based control, this book also serves as an appropriate addition to the recommended reading list for a course on applied control theory. Although the text does not address or emphasize the current state of research in the field of robotics, which includes topics such as mobile robots, localization and mapping, and planning, these topics are covered in a suitable manner elsewhere.

For teaching purposes, I find the text preferable to [2]–[4] in its combination of mathematical rigor and accessible style. The book's level of sophistication is appropriate, neither too high nor too low, for an introductory course at the advanced undergraduate or first-year graduate student level in electrical or mechanical engineering. Having twice taught an introductory graduate course on the modeling and control of robotic manipulators from drafts of the book, I happily plan to continue using it.

Reviewed by E.R. Westervelt

REVIEWER INFORMATION

E.R. Westervelt received the B.S. degree in computer and systems engineering from Rensselaer Polytechnic Institute, Troy, NY, and the Ph.D. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1997 and 2003, respectively. Since August 2003 he has been an assistant professor with the Department of Mechanical Engineering at the Ohio State University. His research interests include the theory and practice of control as applied to mechanical systems. His current areas of application are the control of legged robots, human gait analysis and prosthetics, and the control of hybrid electric vehicle drivelines.

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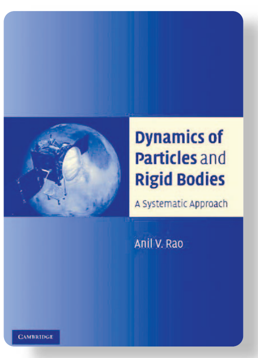

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Dynamics of Particles and Rigid Bodies

by ANIL V. RAO

I began teaching introductory dynamics to sophomores four years ago. At the time, I was stunned by the large number of textbooks available, which fill a couple of shelves in my office. It was clear that our students, and faculty, were dissatisfied with the previous text; I opted for a different text that worked no better. I switched texts again the next time I taught the course, and after two semesters with it there is still much frustration. It has become apparent to me that choosing a dynamics textbook is an intensely personal activity, and there seem to be as many opinions as there are variations on the theme. This situation makes writing a review somewhat difficult since there are sure to be many who disagree and just as many reasons for the disagreement.

The first question one asks, or is asked by the prospective publisher, is the obvious one: with so many choices, is there really room for another undergraduate dynamics textbook? In my opinion, yes, since I still have yet to find a text that mixes rigor with approachability to my satisfaction. Some of the most popular texts [1]–[5] sacrifice rigor and careful notation in an effort to simplify and make the material more approachable, resulting in a lack of clarity and confusion. Other texts [7], [8] take a more applied approach, focusing on engineering applications, and lose sight of the fundamental physics and main concepts. The text [6] does an excellent job of rethinking the presentation of concepts and takes a step forward in notation, along with a readable style. In more advanced topics such as multibody systems and three-dimensional rigid bodies, however, the rigor is lost to conciseness, and I found that students become confused. More advanced texts [9] tend to be too concise on Newton's method and are more appropriate for graduate courses. Many of us wish for a text with the notation and pedagogy of [10] and [11] but without the added complexity of Kane's method and with the slow buildup and approachable style desired by undergraduates.

Dynamics of Particles and Rigid Bodies does an admirable job of partially achieving this goal. This book is the best example I have seen of an undergraduate text that uses