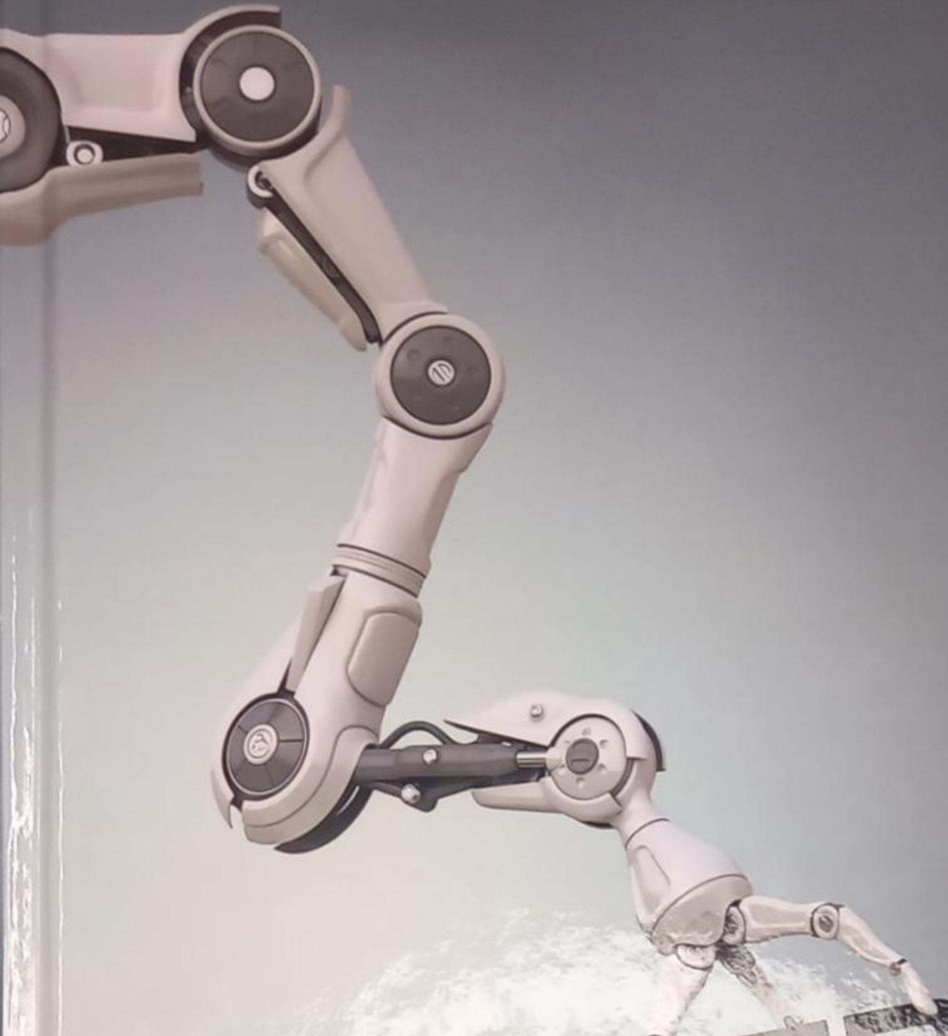

MODERN ROBOTICS

MECHANICS, PLANNING, AND CONTROL

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Modern Robotics: Mechanics, Planning, and Control

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Preface

It was at the IEEE International Conference on Robotics and Automation in Pasadena in 2008 when, over a beer, we decided to write an undergraduate textbook on robotics. Since 1996, Frank had been teaching robot kinematics to Seoul National University undergraduates using his own lecture notes; by 2008 these notes had evolved to the kernel around which this book was written. Kevin had been teaching his introductory robotics class at Northwestern University from his own set of notes, with content drawn from an eclectic collection of papers and books.

We believe that there is a distinct and unifying perspective to the mechanics, planning, and control for robots that is lost if these subjects are studied independently or as part of other more traditional subjects. At the 2008 meeting, we noted the lack of a textbook that (a) treated these topics in a unified way, with plenty of exercises and figures, and (b), most importantly, was written at a level appropriate for a first robotics course for undergraduates with only freshman-level physics, ordinary differential equations, linear algebra, and a little bit of computing background. We decided that the only sensible recourse was to write such a book ourselves. (We didn't know then that it would take us more than eight years to finish the project!)

A second motivation for this book, and one that we believe sets it apart from other introductory treatments on robotics, is its emphasis on modern geometric techniques. Often the most salient physical features of a robot are best captured by a geometric description. The advantages of the geometric approach have been recognized for quite some time by practitioners of classical screw theory. What has made these tools largely inaccessible to undergraduates – the primary target audience for this book – is that they require an entirely new language of concepts and constructs (screws, twists, wrenches, reciprocity, transversality, conjugacy, etc.), and their often obscure rules for manipulation and transformation. However, the mostly algebraic alternatives to screw theory often mean that students end up buried in the details of calculation, losing the simple and elegant geometric interpretation that lies at the heart of what they are calculating.

The breakthrough that made the techniques of classical screw theory accessible to a more general audience arrived in the early 1980s, when Roger Brockett showed how to describe kinematic chains mathematically in terms of the Lie group structure of rigid-body motions (Brockett, 1983b). This discovery allowed one, among other things, to re-invent screw theory simply by appealing to basic linear algebra and linear differential equations. With this "modern screw theory" the powerful tools of modern differential geometry can be brought to bear on a wide-ranging collection of robotics problems, some of which we explore here, and others of which are covered in the excellent but more advanced graduate textbook by Murray et al. (1994).

As the title indicates, this book covers what we feel to be the fundamentals of robot mechanics, together with the basics of planning and control. A thorough treatment of all the chapters would likely take two semesters, particularly when coupled with programming assignments or experiments with robots. The contents of Chapters 2–6 constitute the minimum essentials, and these topics should probably be covered in sequence.

The instructor can then selectively choose content from the remaining chapters. At Seoul National University, the undergraduate course M2794.0027 Introduction to Robotics covers, in one semester, Chapters 2–7 and parts of Chapters 10–12. At Northwestern, ME 449 Robotic Manipulation covers, in an 11-week quarter, Chapters 2–6 and 8, and then touches on different topics in Chapters 9–13 depending on the interests of the students and instructor. A course focusing on the kinematics of robot arms and wheeled vehicles could cover Chapters 2–7 and 13, while one on kinematics and motion planning could additionally include Chapters 9 and 10. A course on the mechanics of manipulation would cover Chapters 2–6, 8, and 12, while another on robot control would cover Chapters 2–6, 8, 9, and 11. If the instructor prefers to avoid dynamics (Chapter 8), the basics of robot control (Chapters 11 and 13) can be covered by assuming that the velocity at each actuator is controlled, not the forces and torques. A course focusing only on motion planning could cover Chapters 2 and 3, Chapter 10 in depth (possibly supplemented by research papers or other references cited in that chapter), and Chapter 13.

To help the instructor choose which topics to teach and to help the student keep track of what she has learned, we have included summaries at the ends of chapters and a summary of important notation and formulas used throughout the book in Appendix A. For those whose primary interest in this text is as an introductory reference, we have attempted to provide a reasonably comprehensive, though by no means exhaustive, set of references and bibliographic notes at the end of each chapter. Some of the exercises provided at the end of each chapter extend the basic results covered in the book and, for those who wish to probe further, these should be of interest in their own right. Some of the more advanced material in the book can be used to support independent study projects.

Another important component of the book is the software, which is written to reinforce the concepts in the book and to make the formulas operational. The software was developed primarily by Kevin's ME 449 students at Northwestern and is freely downloadable from `http://modernrobotics.org`. Video lectures that accompany the textbook are also available at the website. The intention of the video content is to help the instructor to "flip" the classroom: students watch brief lectures on their own time, rewinding as needed, and class time is focused more on the collaborative problem-solving that has traditionally occurred between classes. This way, the professor is present when the students are applying the material and discovering the gaps in their understanding; this creates the opportunity for interactive mini-lectures addressing the concepts that need most reinforcing. We believe that the added value of the professor is greatest in this interactive role, not in delivering a lecture in the same way that it was delivered the previous year. This approach has worked well for Kevin's introduction to mechatronics course, `http://nu32.org`.

The video content is generated using the Lightboard, `http://lightboard.info`, created by Michael Peshkin at Northwestern University. We thank him for sharing this convenient and effective tool for creating instructional videos.

We have also found the V-REP robot simulation software to be a valuable supplement to the book and its software. This simulation software allows students to explore interactively the kinematics of robot arms and mobile manipulators and to animate trajectories that are the result of exercises on kinematics, dynamics, and control.

While this book presents our own perspective on how to introduce the fundamental topics in first courses on robot mechanics, planning, and control, we acknowledge the excellent textbooks that already exist and that have served our field well. Among these, we would like to mention as particularly influential the books by Murray et al. (1994), Craig (2004), Spong et al. (2005), Siciliano et al. (2009), Mason (2001), and Corke (2017), and the motion planning books by Latombe (1991), LaValle (2006), and Choset et al. (2005). In addition, the *Handbook of Robotics* (Siciliano and Khatib, 2016), with a multimedia extension edited by Kröger (`http://handbookofrobotics.org`), is a landmark in our field, collecting the perspectives of hundreds of leading researchers on a huge variety of topics relevant to modern robotics.

It is our pleasure to acknowledge the many people who have been the sources of help and inspiration in writing this book. In particular, we would like to thank our Ph.D. advisors, Roger Brockett and Matt Mason. Brockett laid down much of the foundation for the geometric approach to robotics employed in this book. Mason's pioneering contributions to analysis and planning for manipulation form a cornerstone of modern robotics. We also thank the many students who provided feedback on various versions of this material, in M2794.0027 at Seoul National University and in ME 449 at Northwestern University. In particular, Frank would like to thank Seunghyeon Kim, Keunjun Choi, Jisoo Hong, Jinkyu Kim, Youngsuk Hong, Wooyoung Kim, Cheongjae Jang, Taeyoon Lee, Soocheol Noh, Kyumin Park, Seongjae Jeong, Sukho Yoon, Jaewoon Kwen, Jinhyuk Park, and Jihoon Song, as well as Jim Bobrow and Scott Ploen from his time at UC Irvine. Kevin would like to thank Matt Elwin, Sherif Mostafa, Nelson Rosa, Jarvis Schultz, Jian Shi, Mikhail Todes, Huan Weng, and Zack Woodruff.

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Publication note.
The authors consider themselves to be equal contributors to this book. The author order is alphabetical.

Notes on the second printing.
Readers are encouraged to consult the companion website

`http://modernrobotics.org`

for more information on the Modern Robotics software library, videos, online courses, robot simulations, practice problems with solutions, errata, a linear algebra refresher chapter, and more.

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