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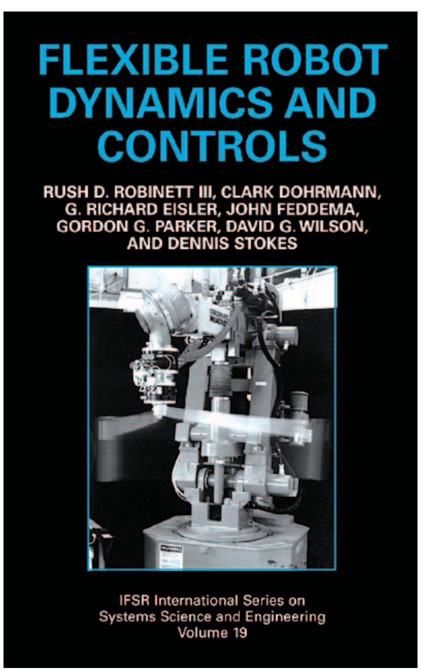
Flexible Robot Dynamics and Control by Rush D. Robinett, III, Clark R. Dohrmann, G. Richard Eisler, John T. Feddema, Gordon G. Parker, David G. Wilson, and Dennis Stokes, Kluwer Academic/Plenum Publishers, 2002, 339 pp., US$89.50, ISBN 0-306-46724-0. *Reviewed by Lyanne George.*

This book, one of the few works available on the subject, presents a thorough overview of flexible robots, including modeling, system identification, and control. The authors include many exercises and example problems, and an overhead gantry robot is used as a recurring example throughout the book to reinforce the concepts and techniques introduced. The real strength of this book is the implementation of the techniques introduced on robots at Sandia National Laboratory (SNL), however. According to the preface, this book is the culmination of more than ten years of research, and the authors' extensive expertise clearly shines through.



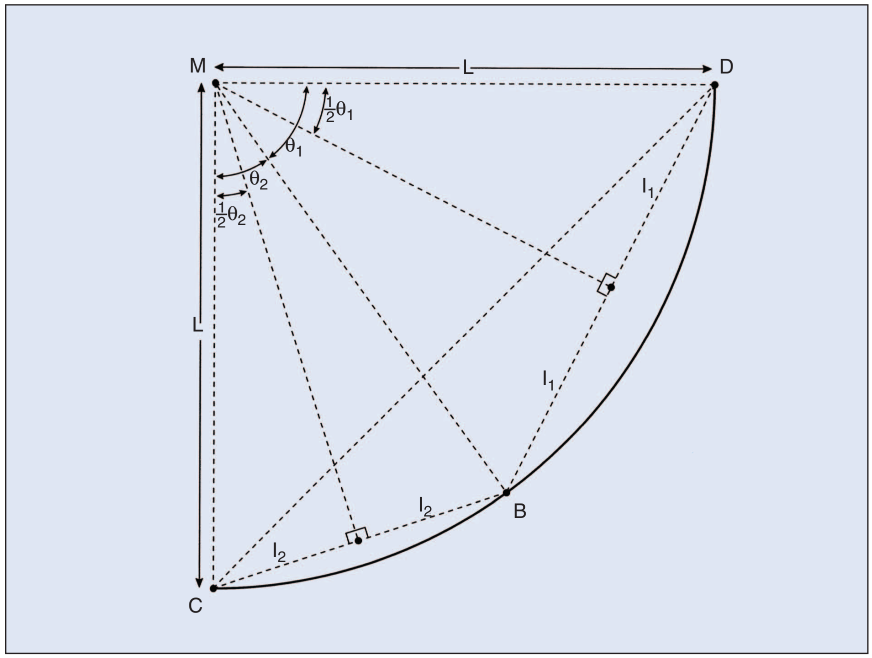
The first part of the book provides necessary background information along with a complete introduction to flexible robot modeling. Input shaping techniques can, theoretically, remove residual vibration in flexible systems if the system damping ratio and natural frequencies are known. Hence, system identification and modeling are critical to successful implementation of such systems, and an entire chapter is devoted to it. Linear and nonlinear least-squares techniques are discussed, and concepts are solidified using the overhead gantry robot. Of particular interest are discussions of some of the real-life problems inherent in modeling flexible systems. Alternative modeling methods, including homotopy methods and backward propagation techniques, are introduced as additional tools. A nonlinear least-squares method is used to calculate the period of oscillation of a gantry robot, and the result is used to design input-shaping techniques that produced swing-free motion on a gantrylike robot at SNL.

The real meat of the text begins with the fifth chapter, which starts with a description of the technique of input shaping and the constrained optimization problem for designing optimal trajectories. The methods of recursive quadratic programming and homotopy are introduced to approximate minimum-time and tracking-error tip trajectories. Since input-shaping problems can often be expressed as optimal control problems, an alternative method based on dynamic programming is introduced. The implementation of optimal trajectories on the Sandia two-link flexible manipulator is presented. as well as an experiment demonstrating open-loop input shaping on a slewing, flexible rod.

The last few chapters of the text delve into closed-loop control system design tools. Basic application of potential difference (PD), lag stabilization, proportional-integral differential (PID), and linear-quadratic-Gaussian (LQG) control techniques are described. Flexibility in the links is especially challenging when the sensors and tip point are not colocated. A combination of feedforward and LQG techniques is used to develop an optimal controller, and the results are applied to a two-link flexible robot at SNL. The final chapters introduce more complex control methods, including nonadaptive and adaptive sliding mode control, both of which are applied to a slewing beam at SNL.

When Least Is Best: How Mathematicians Discovered Many Clever Ways to Make Things as Small (or as Large) as Possible by Paul Nahin, Princeton University Press, 2004, 370 pp., US$29.95, ISBN 0-691-07078-4. *Reviewed by Dennis S. Bernstein.*

The development of control theory is often described in terms of a classical frequency-domain phase followed by a modern time-domain phase. However, this order of events tends to obscure the fact that the underlying mathematics for modern control predates the classical control era. When Kalman and others developed the modern theory of linear-quadratic control in the late 1950s and early 1960s, they drew on a rich collection of ideas such as the calculus of variations developed in the 18th century, Lyapunov methods developed in the late 19th century, and matrix methods developed since the mid-19th century. Thus, existing mathematics supported the development of control theory in directions that were distinct from the frequency domain methods of Nyquist and Bode.



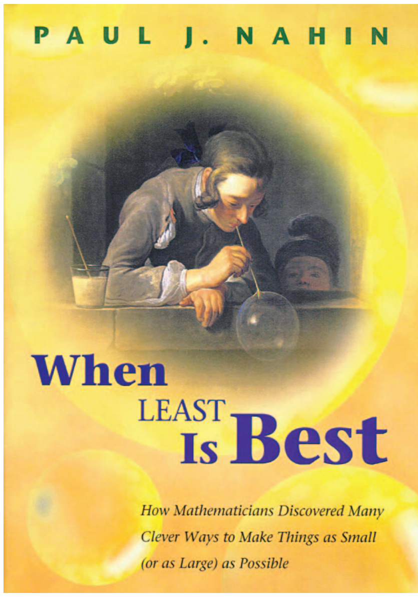
Galileo's analysis of the descent time along a circular arc. Galileo used a piecewise linear approximation to show that the descent time is independent of the starting point along the arc. Nahin shows that the descent time along a circular arc is about 1.5% slower than along the optimal brachistochrone curve. (Figure reprinted with permission of Princeton University Press.)

The convoluted history of control theory can be mind bending for a student trying to fit the intellectual pieces together. I learned linear systems theory in 1976 from Wolovich's book, taught by his post-doc Panos Antsaklis at Brown University, only to enroll the following year in a course at the University of Michigan given by Lamberto Cesari on the calculus of variations and optimal control. Prof. Cesari gave wonderful insights into the relationship between the calculus of variations and optimal control theory, showing how the maximum principle was the culmination of 250 years of research in the calculus of variations. As an undergraduate, I had seen Bode plots used in a circuits course to analyze the stability of feedback amplifiers, but the intellectual distance from Bode plots to companion forms to Hamiltonians was far beyond my comprehension. I was clueless about their connections. As many years passed, I discovered and read Lee and Markus, Bryson and Ho, Chen, and Kwakernaak and Sivan, which eventually—but sometimes painfully—helped fill in and connect the pieces of the puzzle.

Today, our pedagogy has become much better. We're careful to help students bridge the gap between Nyquist and Bode on the one hand and the linear quadratic regulator on the other. But it is still not easy. Root locus is about output feedback, as is Nyquist. But the linear-quadratic regulator (LQR), presented as a more advanced topic, is downright primitive in requiring full-state information. The output feedback linear quadratic Gaussian (LQG) controller is often downplayed because of its reliance on stochastic (or, in more modern presentations, function-theoretic) foundations. Along the way, students might face the complexities of time-varying systems, which are certainly beautiful and important, but present a technical stumbling block and are orthogonal to classical analysis. So the student faces a long road in reaching the point at which modern methods can address the problems to which root locus and Nyquist apply.

Once sufficient modern control theory is developed to address single-input, single-output (SISO) linear time-invariant systems (assuming the student does not get discouraged and move on to other pursuits), the fun begins in connecting the modern with the classical. What Nyquist strategy does LQG use to stabilize a system? Does LQG try to mimic root locus? Does LQG have guaranteed gain and phase margins? How can LQG be robustified? How can linear-quadratic methods be used to place poles? The serendipitous connections between the modern and the classical are fascinating, but the methods seem worlds apart.

Let's face it, despite our best efforts, most education, on first sight, is like setting up a few trees and hoping a forest appears. Like watching a movie for the first time, students have virtually no perspective on the subject matter. Concepts, definitions, and techniques must be mastered as they fly by, and there is limited context for the ideas. How can I teach in such a way that the student sees the big picture? How can I explain to students that LQR and LQG are really modern manifestations of the mathematics of the calculus of variations, the same subject that governs Lagrangian dynamics, the same subject that Lamberto Cesari traced out in class from Euler to Pontryagin, and that Lee and Markus and Kwakernaak and Sivan carried yet further to the engineering borders of Nyquist and Bode? I see students struggle to tie these ideas together from course to course, and I see their frustration. How many students today, who benefit from the streamlined teaching of classical and modern control, glimpse the connections between Lagrange and LQG? More to the point: Is the calculus of variations a mere footnote to our subject, or does it play a central role that has been overshadowed



by the need to solve matrix Riccati equations and compute Lie brackets?

Much of the tension I've alluded to is simply related to the issue of optimality versus no optimality. It is not uncommon to hear practicing engineers question the value of "optimality." Does it matter whether the system is optimal so long as it meets specifications? What good is an optimal control that is not robust or does not address a constraint on (fill in the blank)? What good is an optimal control that takes too much effort to develop when the optimal solution is only a few percent better than a nonoptimal control? All of these are valid questions, and each has its place in certain contexts. But the short answer is this: The notion of optimality is of immense power, and it is effective in many practical situations. This is where Nahin's book comes in.

Nahin's book is a tour de force about the deep intellectual threads that surround the notion of optimality. In physics, engineering, and mathematics, while touching on a wide range of applications, Nahin asks over and over again: What is the optimal solution, and why does it matter? Since I've spent most of my professional career thinking about optimality in one form or another, I was skeptical about whether or not I would find anything new in this book. But I was astounded to find something new and interesting on virtually every page. Some examples:

- Preface: Torricelli's funnel, which has finite volume and can be filled, but has infinite surface area and cannot be painted; and a slick proof that an irrational number raised to an irrational power can be rational.
- Chapter 1: An optimization problem that is not amenable to calculus, but whose solution can be discerned by some clever insight; an optimization problem that *is* amenable to calculus, but whose solution can be arrived at by algebra; and the use of the arithmetic mean-geometric mean inequality in optimization a recurring tool in the book.
- Chapter 2: The ancient isoperimetric problem of Dido on maximal area, how it remained unsolved until modern times; the fact that there exists a figure in the plane whose area is equal to the area of the period at the end of this sentence and which contains a line segment 1 million light years in length that can be rotated 360° within the figure (the shape of the figure is a little hard to picture); and the fact that there are two consecutive prime numbers the gap between which is greater than a googolplex (don't ask what they are).
- Chapter 3: Optimization problems involving the viewing of a painting, the rings of Saturn, folding envelopes, carrying a pipe around a corner in a hallway, the maximum height of mud ejected from a wheel, and other daily concerns.
- Chapter 4: Snell's law, the path of light, and the feud between Descartes and Fermat.
- Chapter 5: The power of the calculus, the aiming of basketballs and cannon, Kepler's wine barrel, L'Hospital's pulley problem, United Parcel Service package size constraints, and the geometry of rainbows.
- Chapter 6: Galileo's piecewise linear analysis of the descent of a particle sliding along the arc of a circle; the discovery of the minimum-time brachistochrone curve by Jacob Bernoulli, arrived at by an argument based on the minimum-time path of light in a variable-density medium, his bias against Newton, and Newton's anonymously published solution to the problem; the isochronous property of both the circle and brachistochrone, which states that the descent time is independent of the starting location along the curve (a sufficiently fascinating fact that it appears in chapter 96 of *Moby Dick* and which left me wondering which paths are isochronous since a straight line is clearly not); the fact that Bernoulli's brachistochrone is about 1.5% faster than Galileo's circular arc and that a brachistochrone tunnel dug from New York to Los Angeles would entail a travel time of a mere 28 minutes, assuming frictionless sliding and requiring no propulsion; the fact that a launch angle of 45° maximizes the range of a golf ball, whereas 56.466° maximizes the arc length; the Euler-Lagrange equation of the calculus of variations and its proof formulated by Lagrange at age 19; the hyperbolic cosine shape of the catenary loaded by its own weight as compared to the parabolic shape of a string under uniform loading; the rigorous solution of the isoperimetric problem of Dido by Weierstrass; the theory of

soap bubble shapes by Plateau, who was blinded by an optics experiments he performed during his Ph.D. research; and a brief illustration of optimal control theory.

- Chapter 7: Hofmann's solution of Steiner's problem on minimum distance to the sides of a triangle and its use by Delta Airlines to save money on its phone bill; the traveling salesman problem, linear programming, and a tutorial on dynamic programming along with a brief biography of IEEE Medal of Honor recipient Richard Bellman with emphasis on the fact that IEEE is an engineering society rather than a mathematical society.

For a control audience, the connections between control and optimization consist of the lengthy discussion on the calculus of variations and the tutorial on dynamic programming. My only (minor) disappointment was the lack of more discussion about the nature of optimality in mechanics; that is, the least action principle, which is the specialization of Hamilton's principle to conservative systems. This underlying principle of mechanics is not, in fact, a statement of optimality but rather one of *stationarity*. While Nahin was careful to point out the absence of optimality, I wish he had further clarified and explored this point, which is rarely discussed in the literature.

When Least Is Best is clearly the result of immense effort. The author's notes suggest that most of the book was written in a single year, which is amazing. Not only are many topics covered, but mathematical details abound. The author, who is known for popular treatments of technical subjects (*An Imaginary Tale: The Story of i*, *Dueling Idiots and Other Probability Puzzlers*, *The Science of Radio*, *Oliver Heaviside: Sage in Solitude*, *Time Travel*), just seems to get better and better.

The book was produced with painstaking care. While there surely are errors somewhere, this eagle-eyed editor-in-chief spotted none. I would guess that the book has roughly half as many figures as pages, all drawn with great accuracy. To say the price of the book is reasonable would be an understatement.

Who might find this book of interest? The book is really a popular book of mathematics that touches on a broad range of problems associated with optimization. Some mathematical sophistication, as well as calculus, is needed to follow the details. But much in this book could be digested by high school students, even without calculus. The flavor and richness of the subject matter cannot help but whet the curiosity of neophytes. Undergraduate and graduate engineering students of all disciplines will find something that relates to their coursework. Finally, for those of us who work and teach in the control area, this book provides a valuable service in reminding us of the intellectual roots of our subject, thereby helping us understand from where our field has evolved and, indirectly, where its future lies.

Linear Time-Invariant Systems by Martin Schetzen, IEEE Press, Wiley Inter-Science, 2003. *Reviewed by Jessy W. Grizzle.*

This interesting book covers the usual topics that one would expect to find in an engineering textbook on continuous-time signals, systems, and transforms. What sets it apart are the author's attempt to be more mathematically careful than the typical engineering undergraduate textbook and his appeal to philosophy when discussing the ramifications of systems theory and systems concepts. The level of the presentation is definitely advanced undergraduate, so if you are looking for an introductory textbook, this is probably not a good choice. On the other hand, if you wish to direct a good student to a more advanced textbook, read on!

Personally, at the University of Michigan, when teaching our continuous-time signals and systems course to sophomores and juniors, I am obliged to trade off mathematical rigor for computational examples and motivational discussions on how I use systems concepts in my professional life as a control engineer. So, while most of my students can determine if a signal is Fourier transformable or not, almost all of them believe that every linear time-invariant (LTI) system has a convolution representation, even though this is false. In fact, essentially all introductory signals and systems textbooks present a proof that requires continuity of the system as a mapping from input signals to output signals, but not all systems are continuous in the required sense.

Is this misconception a horrible miscarriage of academic responsibility? Probably not. I am sure that we mislead the typical undergraduate by leaving out certain hypotheses in almost every subject we teach them at Michigan, and yet we still seem to turn out highly sought-after engineers. Nevertheless, each semester, I invariably have a few students who are sufficiently mathe-