IEEE *Control Systems Magazine* welcomes suggestions for books to be reviewed in this column. Please contact either Michael Polis or Zongli Lin, associate editors for book reviews.

Delft Pneumatic Bipeds

by MARTIJN WISSE and RICHARD Q. VAN DER LINDE

Springer, 2007
ISBN 978-3-540-72807-8
US$109, 136 pages.

The field of bipedal robotics has grown to the point where one can identify several schools of thought on the subject. Most visible to the general public, and probably to most of the readers of this magazine, is the part of the field focused on building humanoids, robots that are inspired by human morphology. The best known of these robots is undoubtedly Honda's ASIMO. Other robots in this vein include HRP-2 (Kawada Industries, Japan) and Johnnie (Technical University of Munich, Germany). These machines are very complicated, high-degree-of-freedom prototypes built as part of an effort to develop robots that will be able to serve humans or even directly replace humans in the operation or service of other machines. These robots involve a broad-ranging development effort that includes machine vision, portable power sources, artificial intelligence, force sensing, durability, and packaging. As such, upright, stable bipedal locomotion is only one piece of the overall effort, and, largely for reasons of expediency, the designers of these robots have adopted one of the simpler notions of gait stability. For the robots mentioned above, the stabilization algorithm boils down to maintaining the center of pressure of the ground reaction forces of the stance foot strictly within the convex hull of the foot. The resulting walking motions are flat footed and distinctly not human like.

At the opposite end of the complexity spectrum in terms of technology are the "minimalist" bipeds, whose designers seek the minimal assembly of links, joints, sensors, and actuators that can accomplish a given locomotion task. This area of bipedal locomotion was inspired by the pathbreaking work of Tad McGeer, who, in the late 1980s and early 1990s, analyzed and built planar bipedal robots that can walk stably (in the sense of possessing an exponentially stable periodic orbit) down a slight incline with no sensing or actuation whatsoever. Such robots are termed "passive" because they employ no active power source other than the effort of the person who places them at the top of the incline. For these devices, walking is purely the outcome of the interplay between gravity and the geometric and inertia properties of the robot. The legs move freely as pendula under the influence of gravity, and, if their masses and lengths are tuned just right, they can produce stable periodic motions without any feedback control. Further impetus to this area was provided by Collins, Wisse, and Ruina with their three-dimensional (3D) (spatial) passive walker [1]. There is a general feeling in the robotics community that the walking gaits of passive robots seem natural.

Digital Object Identifier 10.1109/MCS.2008.925868

THE BOOK

Passive walking is the starting point for the book under review. In the context of their Ph.D. research, Wisse and van der Linde constructed at Delft, The Netherlands, a series of five bipeds, starting with a McGeer-like planar, torso-less, passive walker and finishing with Denise, a 3D-biped with torso and arms, which uses arguably the simplest possible sensing, actuation, and feedback control system capable of achieving stable walking on a flat surface. Throughout the series of robots, the objective with each increase in electromechanical complexity was to characterize the resulting contribution to bipedal walking, in terms of enhanced capability, such as flat ground versus inclines, or spatial versus planar walking, and enhanced stability, in terms of a larger basin of attraction and the ability to tolerate deviations in the walking surface without falling. The authors have an interesting and coherent story to tell. While the book is based on their dissertations, they have done extensive rewriting and editing to arrive at a very compact, informative, and enjoyable presentation of their work.

Chapter 1 provides some of the basic motivation for research on bipedal robots and gives a terse but adequate summary of the state of the art. Chapter 2 provides an excellent technical summary of the passive walking literature, with ample citations. The hybrid nature of bipedal walking models is explained, and the primary mathematical tool for evaluating the existence and stability of periodic orbits, namely the Poincaré map, is reviewed. The authors confirm their mastery of McGeer's work by successfully building their own version of his famous robot. The chapter concludes with a discussion of useful tips for passive robot construction.

Chapter 3 focuses on the practical design and dynamic characterization of pneumatic actuators, in the form of McKibben's muscles, for bipedal robots. The McKibben's muscles are arranged in antagonistic pairs and used to actuate the sagittal-plane hip motion of a 3D biped named Baps; two additional muscles provide leg extension at the "prismatic knees." Sensing consists of a single gyroscope. A stable rocking motion in the frontal plane was sought through a shaped foot as in [1]. This 3D powered robot achieves autonomous walking on flat ground but falls frequently, just like the purely passive walkers. The authors attribute this behavior to the sagittal plane (fore-aft) motion not being sufficiently synchronized with the frontal plane (side-to-side) motion.

This experience motivates a return to planar bipeds in Chapter 4, where Mike is designed with the aim of avoiding falls in the forward direction. The authors start by providing numerical estimates of the basin of attraction of walking motions for the simplest walking model and thereby identify possible failure modes of falling forward or backward. Inspired by stability studies of the rimless wheel, a swing-leg control strategy is considered. Its purpose is to diminish the possibility of falling forward by rapidly placing the swing leg at a proper angle in front of the stance leg; to avoid falling backward, though, the swing leg should not be placed too far in the front of the stance leg. Despite the fact that this strategy does not address the problem of falling backward, it dramatically enhances stability; in fact, without swing-leg control, the basin of attraction is 0.3% of the basin of attraction with swing-leg control. The authors successfully implement this control strategy on Mike by alternating the states of antagonistic pairs of McKibben's muscles located at the hip based on feedback from foot contact sensors responsible for detecting heel strike.

Chapter 5 presents Max, which is a planar biped similar to Mike, but this time a torso is included. The authors start by analyzing an extension of the simplest walking model that includes an inverted pendulum attached at the hip representing the torso. Through this analysis, it is deduced that, with the upper body slaved to be at the middle of the two legs by means of a suitable holonomic constraint, stable walking can be achieved. Surprisingly, the model reveals that walking with an upper body is almost twice as efficient as walking with no upper body, while changes in the mass and size of the upper body have little effect on stability. Consistent with the spirit of passive dynamic walkers, the authors use a passive, mechanical means, namely, a bisecting mechanism, to keep Max's torso upright. Actuation is included to inject the energy required to compensate for losses at heel strike and to enhance stability in the sagittal plane through rapid recirculation of the leg, just as was done in Mike. The control system requires feedback only from foot contact switches triggering the hip actuators and releasing the knee latches of the swing leg at the early stages of the protraction phase.

Chapter 6 concludes the story with the 3D biped Denise. Here, the focus is on extending passive walking in three dimensions and achieving stability in the frontal plane, that is, side-to-side stability. Contrary to most of the 3D walkers, stability is not sought by weakening the coupling among the fore-aft, sideways, and turning modes of the robot's motion. Instead, the central idea is to take advantage of such coupling by specifically designing the ankle joint of the robot so that leaning to one side results in turning in that direction, which provides a restoring moment. This approach is consistent with the "passive dynamics" point of view, which seeks solutions that bring the unactuated dynamics of the system into effective use. The authors, after performing a series of simulations to elucidate their concepts, implement their ideas on Denise. By combining the swing-leg control strategy employed in Mike and the hip-bisecting mechanism developed for Max with the new ankle joint design that couples leaning with steering, Denise successfully demonstrates autonomous stable 3D dynamic walking on level ground. Like its ancestors, Denise exhibits natural motions combined with improved energy efficiency. The book ends with Chapter 7, in which the authors discuss next steps in their research program.

COMMENTS

In control-theoretic terms, Wisse and Van der Linde are emphasizing the proper design of the "bipedal plant" to make the control problem (that is, achieving asymptotically stable, periodic, bipedal locomotion) as easy and natural as possible. Feedback control is being used. For instance, implementation of the leg recirculation strategy to enhance sagittal plane stability requires event-based triggering of the hip actuators. Furthermore, feedback control laws are embedded through mechanical design into the morphology of the robots; for example, the hip-bisecting mechanism imposes (mechanically) a holonomic constraint, which essentially reduces the stability problem to one that can be addressed by the leg recirculation controller. Such mechanical solutions combined with minimal feedback control laws are consistent with the scope of this book, whose emphasis is on achieving energy-efficient walking on flat ground through the effective use of the natural dynamics of highly underactuated machines. The flip side of the coin is that these mechanisms exhibit a limited notion of locomotion. The remarkable elegance and economy of these walkers comes at the cost of poor ability in achieving tasks other than walking at a fixed speed, such as climbing stairs, standing, turning, or running. On the other hand, the impressive versatility demonstrated by robots such as ASIMO comes at the cost of increased power consumption, heavy actuators, and expensive electronics.

It is therefore natural to ask how the efficiency and elegance of the minimalist walkers can be combined with the versatility of robots such as ASIMO. In addressing this question, two issues are of central importance [2]–[4]. First, it must be determined which aspects of the behavior need to be embedded in the robot's structure and morphology, and which need to be implemented through software control, thus allowing for diverse behavior patterns. Second, novel feedback laws must be developed that work in concert with—and not against—the natural dynamics of the system in achieving stability and robustness of the implemented behaviors.

As soon as enough actuation is included to allow both slow and fast walking, walking on flat ground, climbing and descending stairs, running, and transitioning among these modes, nonlinear feedback control can play a key role in achieving stable, elegant, energy-efficient gaits [3], [5]–[8].

—Reviewed by Jessy Grizzle and Ioannis Poulakakis

REFERENCES

[1] S. Collins, M. Wisse, and A. Ruina, "A three-dimensional passive-dynamic walking robot with two legs and knees," *I. Jo. Robotics Res.*, vol. 20, no. 7, pp. 607–615, July 2001.

[2] M. Raibert, *Legged Robots That Balance*. Cambridge, MA.: MIT Press, 1986.

[3] P. Holmes, R.J. Full, D. Koditschek, and J. Guckenheimer, "The dynamics of legged locomotion: Models, analyses, and challenges," *SIAM Rev.*, vol. 48, no. 2, pp. 207–304, 2006.

[4] A.D. Kuo, "Choosing your steps carefully," *IEEE Robot. Automat. Mag.*, vol. 14, no. 2, pp. 18–29, June 2007.

[5] Y. Hürmüzlü, F. Génot, and B. Brogliato, "Modeling, stability and control of biped robots—a general framework," *Automatica*, vol. 40, no. 10, pp. 1647–1664, 2004.

[6] M. Spong and F. Bullo, "Controlled symmetries and passive walking," *IEEE Trans. Automat. Contr.*, vol. 50, no. 7, pp. 1025–1031, July 2005.

[7] A. Ames and R. Gregg, "Stably extending two-dimensional bipedal walking to three," in *Proc. 2007 American Control Conf.*, New York, 2007, pp. 177–182.

[8] E. Westervelt, J. Grizzle, C. Chevallereau, J. Choi, and B. Morris, *Feedback Control of Dynamic Bipedal Robot Locomotion*, ser. Control and Automation. Boca Raton: CRC Press, June 2007.

REVIEWER INFORMATION

Jessy Grizzle is a professor in the Department of Electrical Engineering and Computer Science at the University of Michigan. His research interests include theoretical foundations of nonlinear control, hybrid electric vehicles, and feedback control of robotic bipedal locomotion. He can be reached at grizzle@umich.edu.

Ioannis Poulakakis is a Ph.D. candidate in the Department of Electrical Engineering and Computer Science at the University of Michigan. His research interests include the design of nonlinear feedback control algorithms for underactuated hybrid mechanical systems with applications to walking and running robots. He can be reached at poulakas@umich.edu.

Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples

by MARK B. TISCHLER and ROBERT K. REMPLE

AIAA Education
Series, 2006
ISBN 1563478374
US$119.95, 600 pages.

I have always been amazed at the volume of quality research devoted to the synthesis of feedback control systems. There are many elegant theories for control designers to choose from, and virtually all of these theories begin with a model of system dynamics. In control theory, the plant dynamics are simply a given, a starting point for the successful design of a control system. But in the world of aircraft flight dynamics and control, development of the dynamic model is not at all trivial. Aircraft dynamics are driven by complex aerodynamic forces, and accurate models based on fundamental physics are not easily derived. Experimental data from wind tunnel testing and other sources is a valuable tool in dynamic model development, but quality test data are typically expensive and almost always incomplete. Some might even say that knowledge of the aircraft dynamics is more than half the journey toward the design and implementation of a successful control system.

System identification is the process of deriving a dynamic model through experimentation. Known inputs provide excitation of the system, outputs of the system are measured, and a model is derived that best represents the experimental data. The methodology has been applied to many different engineering and nonengineering disciplines to model dynamic systems. System identification is now a vital aspect of aircraft flight control design and testing. In fact, identified models of aircraft have many applications beyond control design, including validation and refinement of flight simulation models, structural mode analysis, and flying qualities analysis. Several textbooks cover the most common algorithms used in system identification [1]–[4], which serve as both references for practicing engineers and as textbooks for graduate-level courses. However, none of these texts focus on the specific application of identification of aircraft dynamics. Additionally, there are unique challenges associated with the application of system identification to aircraft, not the least of which are related to the inherent cost and risk associated with flight testing. Intelligent and *efficient* application of system

Digital Object Identifier 10.1109/MCS.2008.925223

1066-033X/08/$25.00©2008IEEE

identification is absolutely critical for the method to be an integral part of aircraft design and development.

The American Institute of Aeronautics and Astronautics has recently published three textbooks dedicated to the topic of aircraft system identification. In addition to Tischler and Remple's book, they have published books by Klein and Morelli [5] and Jategaonkar [6]. The world of aircraft system identification is divided into two camps, namely, those who use time-domain methods and those who use frequency-domain methods. Jategaonkar's book is devoted to the time-domain method, and, while Klein and Morelli provide one chapter on frequency-domain methods, their text is also primarily focused on time domain. On the other hand, Tischler and Remple are firmly in the frequency-domain camp, and their entire book is dedicated to this approach to system identification.

A positive aspect of the book is that it presents numerous examples with real flight test data. The rotorcraft examples, which include the XV-15, UH-60, and AH-64, far outnumber the fixed-wing examples. This focus is not surprising considering Tischler's position with the U.S. Army Aeroflightdynamics Directorate, which has been involved in virtually every U.S. Army rotorcraft program over the last few decades as well as many U.S. Navy and civil rotorcraft programs. Since my experience is primarily with the rotorcraft industry, I know first hand that Tischler's frequency domain approach to system ID is prevalent throughout that industry. In particular, the software package Comprehensive Identification from Frequency Responses (CIFER), which was developed by Tischer's group, has seen wide usage throughout the rotorcraft industry.

It should be noted that the material in the book is inherently linked to the CIFER software. Several chapters have a direct correlation with specific components of the software, and virtually all of the example results are produced by CIFER. Although many of the methods presented in the text could be applied using other software tools, it would be difficult to reproduce the example results or do the end-of-chapter exercises without adopting the software along with the book. Fortunately, a student version of the software is provided free through AIAA. New users should be warned that there is a learning curve, but the user interface has improved significantly over the last few years and will hopefully continue to improve. Over the years I have reproduced some of the features of CIFER in Matlab code, but a complete reproduction requires a significant investment in time and access to the appropriate references cited in the book.

CONTENTS

Chapter 1 presents an overview of the aircraft system identification process, along with a review of basic concepts, a description of the frequency-domain method, and some history and background. Much of Chapter 1 is devoted to discussing the relative merits of frequency-domain versus time-domain methods for aircraft system identification. The authors make a strong case for the frequency-domain method, pointing out its ability to identify pure time delays, accommodate sensor biases and unstable systems, and efficiently estimate models for high-order systems. All of these features make the approach especially well suited for rotorcraft. The authors also indicate a few of the weaknesses of the frequency domain, including its inability to identify nonlinear models and the requirement for long flight test records. One issue not discussed is the fact that frequency-domain identification is essentially a batch process that is not well suited for online identification.

Chapter 2 presents a more detailed overview of the frequency-domain method, defining fundamental concepts and presenting some introductory examples, including identification of the XV-15 tilt-rotor aircraft in both the hover and cruise flight conditions. Chapter 3 presents more detailed descriptions of the example cases used throughout the text, including the XV-15 cases and a simple pendulum example, while Chapter 4 gives an overview of the CIFER software. Although the authors claim this book is not intended to be a user's manual, Chapter 4 would certainly suffice as a quick reference guide for CIFER, since it includes screen shots, description of menu items, and even a summary of function keys. This chapter would be of no value to someone not using the software.

Chapters 5 and 6 focus on the details of collecting and validating flight test data. Chapter 5 may be most valuable to flight test engineers who support the system identification process. This chapter essentially provides guidelines for the flight testing procedure such as recommendations on instrumentation and techniques for producing desirable pilot-generated or automated inputs. These guidelines are the lessons learned over many years of flight testing experience and thus cannot be derived from theory or found in software manuals. Reading the chapter could help engineers get the most out of the precious flight time they are allotted for system identification. Chapter 6 discusses methods for checking data consistency and reconstructing data contaminated with measurement errors and thus is useful for the flight test engineer who finds large portions of data contaminated by dropouts and other errors.

Chapters 7–12 present the theory and implementation of the frequency-domain identification methods incorporated in the CIFER software, with most of the chapters having a direct correspondence to a specific component of the software. Chapter 7 covers methods for deriving frequency responses of single-input, single-output (SISO) systems using fast Fourier transform (FFT) and chirp-Z transforms. Chapter 8 discusses the implications of identifying frequency responses of closed-loop systems. The placement of the chapter seems odd, but much of the material is useful for illustrating the concept of input correlation, and thus is a good transition to the extensions to MIMO systems presented in Chapter 9. Chapter 10 discusses a composite windowing averaging method, which is useful for obtaining smooth and accurate frequency responses over a wide range of frequencies. Finally, chapters 11 and 12 deal with fitting dynamics models to represent the identified frequency responses using optimization, with Chapter 11 dealing with transfer function models of SISO systems and Chapter 12 dealing with state space models of multi-input, multi-output (MIMO) systems. Chapter 12 also presents Cramer-Rao bounds and alternative metrics for measuring accuracy of the identified models.

Chapter 13 continues the discussion of state-space models by showing how the model can be related to the physical properties of the aircraft. This chapter shows how to select the structure for the state-space model and how some known parameters can be fixed or constrained to make the identification process more efficient and accurate. The chapter discusses useful guidelines that will be helpful for engineers who are first attempting one of the most difficult tasks in the identification process. The state-space model tends to be overparameterized, and novices are prone to constructing models that have little correlation to the physical properties of the aircraft. Many of the potential pitfalls of system ID can be avoided by carefully studying this chapter.

The material in chapters 7–13 is not intended to constitute a rigorous theoretical formulation of the methods but instead provide reasonable background for engineers who want to apply the method. In other words, although readers should not expect to be able to produce their own code to perform frequency domain ID using only the equations presented in this book, the text cites references that can be used to find more theoretical detail on the algorithms. I found [7] to be particularly useful for reproducing some of the features of CIFER in the Matlab environment.

Chapter 14 discusses time-domain verification of the identified model by comparing the response of the linear model to that of flight test using standard inputs such as doublets. It is a relatively trivial step, but the chapter allows the authors to show how a model's fit to frequency-domain data can be independently tested using time-domain results. Chapter 15 discusses issues relating to the development of high-order dynamic models of rotorcraft, and, in particular, models that involve rotor-body coupling. This chapter is of great significance to engineers designing high-bandwidth flight control systems for rotorcraft, but much of it may be difficult to follow without some background in rotorcraft flight mechanics.

CONCLUSIONS

There is no question that *Aircraft and Rotorcraft System Identification* is an essential reference for those working in system identification of rotorcraft and obviously to anyone who is using CIFER. Frequency-domain identification is a powerful and simple concept in theory, but it is a multistep process with myriad details and potential pitfalls when put into practice. The book contains many of the helpful guidelines and rules of thumb that have been acquired from thousands of hours of experience with control design and flight test programs. These guidelines, along with the inclusion of real flight test examples, are the most powerful feature of the text. The main limitation of the book is its tie-in to a specific software package that has not been universally adopted across the aerospace community. In my opinion, a Matlab toolbox based on these methods would go a long way toward generalizing the audience for this book and the software.

The real question is: Will the text be useful to a more general audience? Will engineers who are working with fixed-wing aircraft and have no intention of using CIFER find the book useful? My feeling is that the book is definitely worth reading if an engineer is considering the use of frequency-domain methods for system identification. I expect it is increasingly common for those in the fixed-wing aircraft industry to have to deal with issues such as higher order dynamics associated with structural modes or inherently unstable airframes, and they may find the frequency-domain identification methods presented in this book to be useful. The book could also potentially serve as a textbook for a special topics course on frequency domain identification of aircraft or even as a supplemental text for a course on rotorcraft flight dynamics. However, instructors would need to integrate the student version of CIFER into their course and be prepared to deal with the overhead of teaching the software as part of the course.

—Reviewed by Joseph F. Horn

REFERENCES

[1] L. Ljung, *System Identification: Theory for the User*, 2nd ed. Upper-Saddle River, NJ: Prentice-Hall, 1999.

[2] R. Pitleon, *System Identification: A Frequency Domain Approach*. New York: Wiley-IEEE Press, 2001.

[3] T. Soderstrom and P. Stoica, *System Identification*, Prentice-Hall, Upper-Saddle River, NJ, 1989.

[4] J. Juang, *Applied System Identification*, . Upper-Saddle River, NJ: Prentice-Hall, 1993.

[5] V. Klein and E.A. Morelli, *Aircraft System Identification: Theory and Practice*. Reston, VA: AIAA Education Series, 2006.

[6] R. Jategaonkar, *Flight Vehicle System Identification: A Time Domain Methodology*. Reston, VA: AIAA Education Series, 2006.

[7] R.K. Otnes and L. Enochson, *Applied Time Series Analysis*. New York: Wiley, 1976.

REVIEWER INFORMATION

Joseph F. Horn is an associate professor with the Department of Aerospace Engineering at Pennsylvania State University. He received his B.S. and M.S. in mechanical and aerospace engineering from the University of Virginia in 1990 and 1992, respectively, and his Ph.D. in aerospace engineering from The Georgia Institute of Technology in 1999. Formerly, he worked as an engineer in the helicopter industry for Sikorsky Aircraft Corporation and Piasecki Aircraft Corporation. He joined the Penn State faculty in 2000, where his research interests are in rotorcraft flight dynamics and control. He is currently an associate director of the Penn State Vertical Lift Research Center of Excellence.

Elsevier, 2006
ISBN: 978-0-12-088400-1
USD$75.95.

Visualizing Quaternions

by ANDREW J. HANSON

Visualizing Quaternions presents the properties of quaternions and their applications. The pedagogy employed is a marriage of three-dimensional visualization with tractable mathematics. The text is arranged into three parts. Part I, which consists of 14 chapters, reviews the fundamental properties of quaternions; Part II, which also consists of 14 chapters, presents methodologies for utilizing quaternions in an efficient and effective manner; and Part III uses three chapters to challenge the reader to generalize the properties of quaternions to higher dimensional spaces.

For several years the computer graphics, kinematics, and geometry communities have lacked a comprehensive text that presents quaternions in an accessible and focused manner. *Visualizing Quaternions* satisfies that need. Quaternions have become an indispensible tool for representing the orientation of bodies, realizing rotational motion, and interpolating rotations. By presenting a sound exposition of quaternions in conjunction with the visualization of their inherent three (and even *four!*) dimensionality, *Visualizing Quaternions* is a success.

Visualizing Quaternions is unique in its presentation of quaternions with respect to the related texts [1]–[4]. Kuiper's text [1] elegantly presents quaternions and rotation operators from a mathematics perspective but lacks the visualization and software implementation that is included in *Visualizing Quaternions*. Although [2] and [3] present sound discussions of quaternions, these works are general kinematics texts that have broader scopes. Nevertheless, the interested reader of *Visualizing Quaternions* would be well served to review these alternative presentations. Whereas [4] presents a complete and formal presentation of the subject of spatial rotations, *Visualizing Quaternions*, by virtue of focusing on quaternions, is able to present the material in a modern and accessible fashion that is very appealing. Additional historical accounts of the development of quaternions are found in [5] and [6]. Other related works include [7], which presents an algebraic approach to the study of quaternions with applications to physics, and [8], which lucidly presents the geometry of quaternion and octonion algebras.

Digital Object Identifier 10.1109/MCS.2008.925869

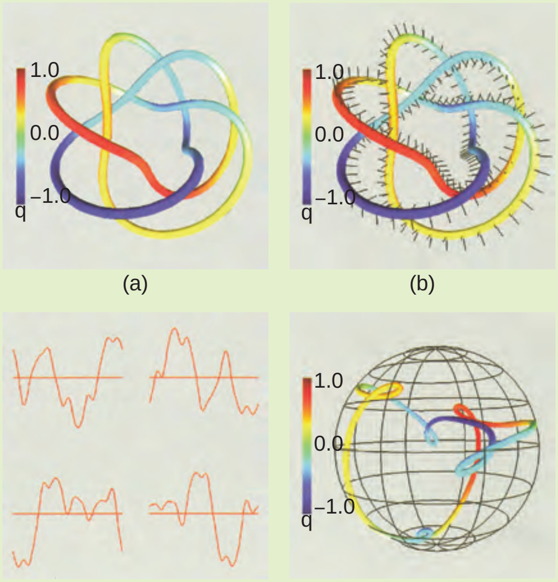
CONTENTS

Part I begins with two of the strengths of this book, the motivational and historical chapters. To the uninitiated, quaternions are often a mysterious and abstract mathematical entity, having Chapter 2 dedicated to motivating the study of quaternions with sound physical and computer graphics examples brings the subject to life. Moreover, the author's recounting of the history of Sir W.R. Hamilton's obsession to generalize complex numbers to three-dimensional space that eventually led to his discovery of quaternions in Chapter 1 is entertaining and places the development of quaternions within the modern history of mathematics.

Part II, "Advanced Quaternion Concepts," makes up the bulk of the text. The level of mathematics utilized is a step above that in Part I, yet the author succeeds in maintaining the level of accessibility of the material. These 14 chapters present the properties of quaternions and algorithms for their use. While some are well known in the research community, many of these algorithms and properties will be new to even the accomplished practitioner. Included are classical Frenet-Serret frames, quaternion frames, quaternion volumes, quaternion interpolation, a review of rotation groups, spherical Riemannian geometry, and induced metrics on spheres.

In the 38 pages that make up Part III, titled "Beyond Quaternions," the book generalizes the properties of quaternions to higher dimensional spaces, for example, Clifford algebras and octonions. This part of the text is accessible to advanced graduate students and well-versed practitioners.

The numerous color illustrations provided in the book and the demonstration software codes and other materials



(a) (b)
(c) (d)

FIGURE 1. Figure 20.14 from *Visualizing Quaternions*. Reprinted with permission from the publisher.

1066-033X/08/$25.00©2008IEEE

available at the author's companion Web site (www.visualizingquaternions.com) are effective supplements to the printed text. For example, in Figure 1, *Visualizing Quaternions* presents the visualization of the Frenet frames assigned to a three-dimensional (3,5) torus knot. The frames are assigned by using the algorithm included in Section 20.7.1. Image (d) of the figure shows the projection of the quaternion frame components onto the 3-sphere.

The organization of the material into small concise chapters, where the average length of the 32 chapters is 12 pages, facilitates the use of *Visualizing Quaternions* as a reference. However, with some effort on the part of the instructor, the text could be used to support a course. Part I is suitable for a junior/senior level course, while parts I and II combined would be suitable for a first-year graduate-level course. Such courses would be appropriate electives for students studying computer sciences, physics, geometry, aerospace control, and robotics. Two challenges to the instructor in using the text in a course would be the lack of problems and the mixture of software languages included in the examples and companion website, for example, C and Mathematica.

A useful inclusion in *Visualizing Quaternions* is an extensive appendix, 51 pages long, that consists of the equations and algorithms presented in the text as well as some useful related material. The appendix presents these materials in a layout that facilitates the writing of software to implement the algorithms found in the text.

Visualizing Quaternions concludes with Chapter 32, which in two pages eloquently restates the simplicity, beauty, and utility of the quaternion. For those already familiar with quaternions, I suggest reading this chapter first. From it you will quickly garner an appreciation of the author's passion for the subject and his collegial writing style.

CONCLUSIONS

Though targeted at the computer graphics community, kinematicians, geometers, aerospace flight dynamics and controls engineers, astrophysicists, and the like would benefit from adding *Visualizing Quaternions* to their working library.

—Reviewed by Pierre Larochelle

REFERENCES

[1] J.B. Kuipers, *Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace, and Virtual Reality*. Princeton, NJ: Princeton Univ. Press, 1999.

[2] J.M. McCarthy, *Introduction to Theoretical Kinematics*. Cambridge, MA: MIT Press, 1990.

[3] O. Bottema and B. Roth, *Theoretical Kinematics*. New York: Dover, 1990 (reprint).

[4] S. Altmann, *Rotations, Quaternions, and Double Groups*. New York: Dover, 2005 (reprint).

[5] S. Altmann, "Hamilton, rodrigues, and the quaternion scandal," *Math. Mag.*, vol. 62, no. 5, pp. 291–308, 1989.

[6] J. Dai, "An historical review of the theoretical development of rigid body displacements from Rodrigues parameters to the finite twist," *Mechanism Mach. Theory*, vol. 41, pp. 41–52, 2006.

[7] P.R. Girard, *Quaternions, Clifford Algebras, and Relativistic Physics*. Basel: Birkhauser, 2007.

[8] J.A. Conway and D. Smith, *On Quaternions and Octonions*. AK Peters, 2003.

REVIEWER INFORMATION

Pierre Larochelle is a professor in the Department of Mechanical and Aerospace Engineering at the Florida Institute of Technology with expertise in robotic mechanical system design. At Florida Tech he is the founder and director of the Robotics and Spatial Systems Laboratory (RASSL). He received the Ph.D. in 1994 from the Mechanical & Aerospace Engineering Department at the University of California-Irvine. He is an associate editor for the *ASME Journal of Mechanical Design* as well as the journal *Mechanics Based Design of Structures amd Machines*. He is a member of Tau Beta Pi, Pi Tau Sigma, ASME, ASEE, and IEEE. He can be reached at pierrel@fit.edu.

SIAM, 2006
ISBN 0898716152
US$99, 389 pages.

Adaptive Control Tutorial

by PETROS IOANNOU and BARIS FIDAN

Adaptive control is a branch of modern control methodologies, with a mature theoretical foundation. Like other control methodologies, adaptive control relies on feedback of system signals. The unique feature of adaptive control is its capacity for adaptation to handle system uncertainties. An adaptive controller can guarantee the desired system stability and tracking performance in the presence of large-system parameter uncertainties, which is desirable for many performance-critical applications. Adaptive control has experienced advances and successes in both theory and applications and is developing rapidly with the emergence of new problems and solutions. Despite the vast amount of literature on both theory and applications, there is still a high demand for a comprehensive and pragmatic understanding and presentation of adaptive control theory, technical issues, and design techniques.

Adaptive Control Tutorial by Petros Ioannou and Baris Fidan is an excellent manuscript for meeting such a demand. The purpose of this book is to present the fundamental techniques and algorithms of adaptive control in a tutorial manner, with the aim of serving a wide audience, including engineers, students, and researchers who are interested in adaptive control for applications, learning, and advanced research. With eight

Digital Object Identifier 10.1109/MCS.2008.925222

1066-033X/08/$25.00©2008IEEE

chapters plus an appendix of mathematical and systems theory background, the book is a self-contained, rich, and valuable addition to the adaptive control literature. It is complementary to other adaptive control textbooks in the sense that, as a tutorial, it covers a wide spectrum of adaptive systems and control theory, including parameter estimation, model reference adaptive control, adaptive pole placement control in both continuous time and discrete time, adaptive backstepping control, and adaptive neurocontrol, along with illustrative examples. The book gives a comprehensive presentation of many concepts, algorithms, and theorems of adaptive control. Moreover, it provides a useful internet-accessible Web page http://www.siam.org/books/dc11/, which contains additional examples, illustrations, and stability proofs.

CONTENTS

Chapter 1 gives an informative overview of the basic design methods, technical issues, motivation, and history of adaptive control. The chapter explains how adaptive control is effective in handling large parameter uncertainties in both the controlled system and its external disturbances.

Chapter 2 presents two common parametric models of dynamic systems, namely, input-output models and state-space models, with various illustrative examples. Adaptive control deals with uncertain dynamic systems, for which system parameterization is crucial. A typical parametric model separates uncertain parameters from known signals in an inherent structure determined by the controlled system.

Chapter 3 addresses the adaptive parameter identification (estimation) problem for continuous-time systems. The basic procedure is to employ a parametric system model $y(t) = \theta^{*T}\omega(t)$, where $y(t)$ and $\omega(t)$ are measured vectors and θ^* is an unknown parameter vector, to generate an estimation error $\varepsilon(t) = \theta^T\omega(t) - y(t)$ using an estimate θ of θ^*. Such an estimation error is linear in the parameter error $\theta - \theta^*$, that is, $\varepsilon(t) = (\theta - \theta^*)^T\omega(t)$. Zero parameter error $\theta - \theta^* = 0$ implies zero estimation error $\varepsilon(t)$. However, because $\theta - \theta^*$ is a vector, zero estimation error $\varepsilon(t)$ does not imply zero parameter error. In general, an adaptive algorithm for updating the parameter estimate can ensure only that the estimation error converges to zero. The parameter error can converge to zero with additional conditions on the system input and structure. In this chapter, the parameter estimation problem is introduced by illustrative examples. Popular gradient and least-squares algorithms for adaptive parameter updating are presented and clarified for various parametric models. The concepts of persistent excitation and dominant richness are introduced for the study of parameter convergence, while parameter projection is studied with several commonly used algorithms. Parameter projection is a technique used to ensure that the parameter estimates stay within a prespecified convex region, which is useful for applications where some parameters have physical meaning or should be chosen to avoid control singularity, for example, a control signal escaping to infinity within a finite time. The topic of robust parameter estimation in the presence of system modeling errors and disturbances is rigorously addressed with several robust adaptive laws, such as sigma-modification, parameter projection, and deadzone modification.

Chapter 4 addresses the adaptive parameter identification (estimation) problem for discrete-time systems, a theory crucial for digital control and signal processing. The chapter presents the essentials of adaptive parameter estimation theory for dynamic systems. Compared with their continuous-time counterparts, the concepts, algorithms, stability, and robustness of discrete-time theory have several new features. The projection, gradient, and least-squares algorithms for parameter estimation, the associated conditions for parameter convergence, and the adaptive control law modifications for robustness are nicely derived and analyzed. In particular, a discretization analysis of a continuous-time adaptive algorithm is given in detail, showing connections between continuous-time and discrete-time designs.

Chapter 5 develops a comprehensive theory of model reference adaptive control (MRAC) for continuous-time systems. MRAC systems have been studied for several decades, and MRAC theory has evolved into a mature control theory with systematic design and analysis tools, as well as practical control algorithms that guarantee closed-loop system stability and tracking performance analytically. In this chapter, the basic MRAC ideas, design, and analysis techniques are given in a well-organized and rigorous presentation, using numerous illustrative examples and systematic theoretical developments with clear and simplified stability proofs. MRAC can be designed as either a direct scheme or an indirect scheme. For direct MRAC, the unknown system parameters are mapped to nominal controller parameters that are directly estimated by adaptive laws, while, for indirect MRAC, the unknown system parameters are estimated from input-output measurements, and the controller parameters are then calculated indirectly from the system parameter estimates. Both direct and indirect MRAC schemes are rigorously analyzed. An important issue in adaptive control is the robustness of stability and tracking performance with respect to system modeling errors, including unmodeled dynamics and external disturbances. A nice robustness analysis is given to show the basic technical issues and key theoretical results. This chapter is an excellent introduction to adaptive control, with plentiful examples and exercise problems.

Chapter 6 shows how to design indirect adaptive pole placement control (APPC) schemes. A key design condition for MRAC is that the controlled system needs to be minimum phase, that is, all of its zeros must be stable, to design a feedback control input to force the system output to track an arbitrary reference output, by cancelling the system zeros stably. An APPC scheme does not need such a minimum-phase condition, and thus it can be used for applications with nonminimum phase zeros. This chapter presents detailed design and analysis procedures for indirect APPC schemes using polynomial and state-space approaches and addresses the related robustness issue. The chapter gives an informative overview of the stabilizability issue, which is crucial for APPC, along with some solution techniques. In addition, an adaptive linear-quadratic control scheme, which also does not require the minimum-phase condition, is introduced and illustrated by examples.

Chapter 7 presents discrete-time versions of MRAC and APPC schemes derived in chapters 5 and 6. Like their continuous-time counterparts, discrete-time MRAC schemes can be designed using either direct adaptation of controller parameters or indirect calculation of controller parameters from system parameter estimates. Furthermore, discrete-time MRAC can be designed using a structure that is simpler than the continuous-time structure, such as an adaptive one-step-ahead controller whose poles are assigned at the origin of the complex plane for faster system response. An APPC scheme is commonly designed using an indirect approach involving system parameter estimation before controller parameter calculation. In addition, discrete-time adaptive controllers are suitable for digital control implementation.

Chapter 8 provides an introduction to adaptive control of nonlinear dynamic systems, a growing area of research. The chapter provides nice coverage of the basics of feedback linearization, backstepping, and neural network approximation, which are popular and powerful design methods for adaptive control of nonlinear systems. In particular, a detailed stability characterization is derived for an adaptive neural-network-based control system. Control design and analysis for nonlinear systems often appear to be complicated, but step-by-step procedures are available, as illustrated by examples and exercise materials.

Finally the book has a well-prepared appendix that covers a broad list of topics and results on systems theory, especially stability theory, in both continuous time and discrete time. Adaptive control systems are nonlinear and time varying in nature even when the controlled system is linear and time invariant. There is a solid mathematical foundation for adaptive control theory, which is based on further developments of the stability theory commonly seen in textbooks on linear systems and nonlinear systems. This appendix provides a fine and extensive summary of such stability theory.

CONCLUSIONS

Adaptive Control Tutorial is comprehensive, rigorous, well written, and easy to read. I strongly recommend this book as an excellent resource on fundamental adaptive control theory for engineers, students, and researchers as either an introductory textbook or a technical reference. The book provides essential knowledge on adaptive systems and control for further study of advanced topics [1]–[8].

—Reviewed by Gang Tao

REFERENCES

[1] K.J. Astrom and B. Wittenmark, *Adaptive Control*, 2nd ed. Reading, MA: Addison Wesley, 1995.

[2] G.C. Goodwin and K.S. Sin, *Adaptive Filtering Prediction and Control*. Englewood Cliffs, NJ: Prentice Hall, 1984.

[3] P.A. Ioannou and J. Sun, *Robust Adaptive Control*. Upper Saddle River, NJ: Prentice Hall, 1996.

[4] M. Krstic, I. Kanellakopoulos, and P.V. Kokotovic, *Nonlinear and Adaptive Control Design*. New York: Wiley, 1995.

[5] Y.D. Landau, R. Lozano and M. M'Saad, *Adaptive Control.* London: Springer, 1998.

[6] K.S. Narendra, and A.M. Annaswamy, *Stable Adaptive Systems*. Englewood Cliffs, NJ: Prentice Hall, 1989.

[7] S. Sastry and M. Bodson, *Adaptive Control: Stability, Convergence, and Robustness*. Englewood Cliffs, NJ: Prentice Hall, 1989.

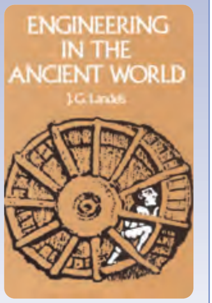
[8] G. Tao, *Adaptive Control Design and Analysis*. New York: Wiley, 2003.

REVIEWER INFORMATION

Gang Tao received the B.S. from the University of Science and Technology of China in 1982 and the Ph.D. from the University of Southern California in 1989. He has worked in the area of adaptive control for 25 years, and has authored, coauthored, or coedited five books on adaptive control. He is an associate editor for *Automatica* and a subject editor for the *International Journal of Adaptive Control and Signal Processing*. He is a Fellow of the IEEE.

Clean Derivation

In addition to these theoretical principles, we know from other sources that Archimedes devised a practical method of using them to assess the proportions of gold and silver in a crown made for the king of Syracuse. To do so, it was necessary to measure the exact volume of the crown, and his discovery of a method for doing this must surely be the most famous story in the history of science. On stepping into an over-filled bath-tub, he saw that the water which overflowed, if caught and measured, would give the exact volume of an irregularly shaped body—namely, his own. In his haste to get home from the public baths and try this out on the crown, he made his well-known "nude dash" through the streets of Syracuse, with shouts of "Heureka, Heureka" ("I have found it"). This must have mystified the onlookers, who probably were thinking that exactly the opposite had occurred.



—J.G. Landels, *Engineering in the Ancient World*,
Barnes and Noble Books, 1978, pp. 190, 191.