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

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REVIEWER INFORMATION

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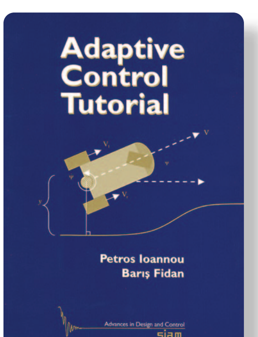

SIAM, 2006
ISBN 0898716152
US$99, 389 pages.

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

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

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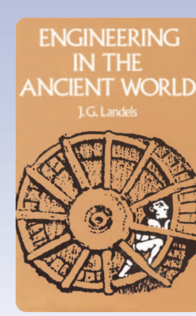
Clean Derivation

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*,
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