

This month's book reviews include a critique of Isermann's *Mechatronic System Fundamentals*. This review begins with a brief overview of the history of mechatronics from the industrial revolution through the present day. We also bring you reviews of books on important topics in control, namely, *Fundamentals of Adaptive Filtering* by Sayed and *Constrained Estimation and Control* by Goodwin, Seron, and Dona. Finally, the feature article by Åström, Klein, and Lennartsson on bicycle dynamics and control is complemented by a review of *Bicycling Science* by Wilson and Papadopoulos.

As usual, I welcome your comments and suggestions for future books that we might consider for review. I can be reached at:

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Mechatronic Systems Fundamentals by Rolf Isermann, Springer, 2003, 624 pp., ISBN 1-85233-693-5, US\$124. Reviewed by Vikram Kapila.

Mechatronics as a Design Paradigm

Mechatronics is the synergistic integration of mechanical engineering, control theory, computer science, and electronics to manage complexity, uncertainty, and communication in engineered systems. Mechatronics is increasingly being recognized as a contemporary, integrative design methodology. The typical knowledge base for the optimal design and operation of mechatronic systems includes system modeling and analysis, decision and control theory, sensors and signal conditioning, actuators and power electronics, hardware interfacing, rapid control prototyping, and embedded computing. The technological application

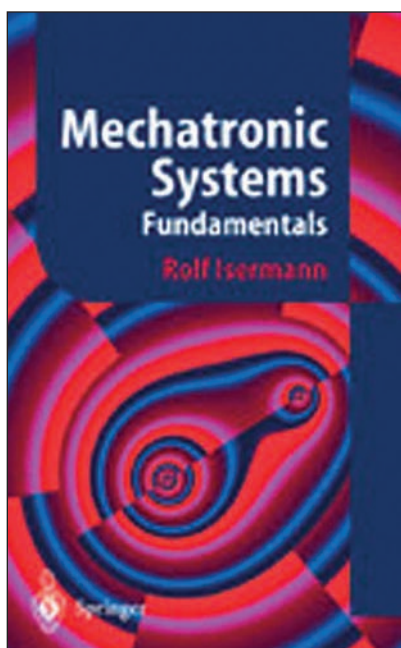
areas of mechatronics include medical, defense, manufacturing, robotics, automotive, and smart consumer products. Recently, *Technology Review: MIT's Magazine of Innovation* identified mechatronics as one of the ten emerging technologies that will change the world [1].

The evolution of mechatronics as a contemporary design paradigm can be viewed as a culmination of the industrial, semiconductor, and information revolutions that have led to major technological advancements in the design and operation of engineering products. Specifically, the industrial revolution enabled the design of products and processes that convert and transmit energy for industrial activities. Engineering designs of that era performed operations of motion transmission, sensing, actuation, and computation using mechanical components like cams, gears, levers, and linkages. Watt's flywheel governor typifies the engineering designs of this era. Unfortunately, purely mechanical systems suffer from limited power amplification and energy losses due to tolerances, inertia, and friction [2].

Semiconductors led to the development of integrated circuit technol-

ogy and constituted the next large impact on the design of engineering products. The development of cost-effective, miniaturized power electronics for efficient power amplification then followed. Semiconductor technology thus provided a practical means, through electrical supply, for delivering required levels of power to actuate mechanical devices. Similarly, on the sensing side, semiconductor technology afforded the ability to condition and encode physical measurements as analog/digital signals. Furthermore, hardwired, onboard, analog/digital electronics provided rudimentary computation. Rapid developments in electromechanical sensing and actuation hardware, which began in an earlier era, further fueled the adoption of semiconductor technology in the design and operation of mechanical devices. Now, the design of engineering products and processes had reached a phase where the mechanical device was energetically isolated [3] from the sensing, actuation, and computation operations.

Semiconductor and information technology industries experienced explosive growth in the closing decades of the 20th century. Computing hardware became ubiquitous and cheap, thus setting the stage for a momentous transformation in the design and operation of mechanical devices and systems. Information technology emerged as a technology enabler imparting intelligence to numerous consumer products, industrial processes, and machines. Microprocessors began replacing precision mechanical components. For example, precision-machined camshafts, which in many applications function as timing devices, were replaced by digital timers. In addition, the programmability of microprocessors provided a versatile and flexible alternative to hardwired analog/digital computation. With computation now being implemented as software, the mechanical device, sensors,



actuators, and processor had become energetically isolated from one another [3]. Integrated computer-electrical-mechanical devices were now capable of converting, transmitting, and processing both the physical energy and the virtual energy (information). Thus, recent years have seen a major and evolving trend toward the development of highly efficient products and processes by judicious exploitation of integrated computer-electrical-mechanical technology.

Mechatronics Texts

The development of significantly improved engineering products through the fusion of different engineering disciplines requires a systematic understanding of the underlying disciplines. This graduate-level book by Isermann focuses on the dynamic modeling and interactions of various components of mechatronic systems and the characterization of the behavior of integrated mechatronic systems. *Mechatronic Systems Fundamentals* is highly recommended as a modeling reference for graduate students, researchers, and practicing engineers working in the field of mechatronics.

In contrast to Isermann's book, existing mechatronics texts such as [4]–[6], [8], and [9] treat primarily introductory, undergraduate-level material. For example, [4] and [6] cover analog circuits, instrumentation, sensors, measurement, actuators, digital electronics, and computer hardware and interfacing while [6] also covers control system fundamentals. Similarly, [9] covers dynamic system modeling, sensors, actuators, and computer hardware and interfacing as well as signals, systems, and control. Using a different approach, after introducing sensor/actuator modeling and computer interfacing, [8] focuses on topics such as mixed-signal modeling for integrated mechatronic systems, virtual prototyping, hardware-in-the-loop experimentation, virtual instrumentation, and rapid control prototyping using tools

such as LabVIEW, MATLAB, and dSPACE. Furthermore, [5] provides a typical treatment of the undergraduate-level dynamic-system modeling and feedback control material along with an introduction to sensors, actuators, and computer hardware and interfacing topics. Finally, while [10] focuses primarily on the application of mechatronics technology to computer-numerical-controlled machines, [7] presents a qualitative survey of mechatronics principles, components, and applications.

The Text

The 12 chapters of Isermann's book are divided in two parts. The first section, Chapters 1–8, focuses primarily on modeling, while Chapters 9–12 cover components, such as sensors, actuators, and microcomputers, and provide examples of integrated mechatronic systems.

Chapter 1 begins by reviewing the historical paradigm shift from purely mechanical systems to mechatronic systems in which mechanical systems, electronic systems, and information technology are integrated. A review of various mechanical systems, such as machine elements, machines, precision machinery, micromechanics, and process apparatus, follows. Next, an overview of various functions enabled by mechatronics is given, including design innovation, distribution of electromechanical functionality, allowance for wider operating ranges, and the addition of new functions such as parameter adaptation, fault tolerance, and intelligence. Two forms of integration that arise in mechatronic systems are considered. First, the integration of components that require systematic design and embedding of sensing, actuation, and information processing elements is briefly mentioned. Next, a detailed discussion on integration by information processing is given, where information processing involves hierarchical control, signal processing, parameter and state estimation, and intelligent computing.

There is a discussion of information and energy flow in mechatronics systems, as such systems evolve from purely mechanical systems. Finally, a detailed 11-step procedure for the design of mechatronic systems is given.

In Chapter 2, the notion of flows consisting of energy, matter, and information is introduced. Each flow is classified as either a main flow or a side flow, which correspond to dominant and weak flows, respectively. Process elements are categorized as sources, storages, transformers, converters, and sinks. A further distinction for process elements is active versus passive elements. Symbolic representation is provided for various active and passive elements. One- and two-port models of various process elements are described. Next, fundamental equations governing the behavior of process elements characterized by energy and mass flow are presented. Specifically, balance equations, constitutive equations, and phenomenological equations are derived. These models cover a range of elements (sources, storages, transformers, and converters) and processes (heat conduction, diffusion, chemical reaction, electricity, and fluid flow). Modeling of mechanical, thermo-fluid, gaseous, and electrical systems is treated in detail using energy balance equations. Node and mesh equations are employed to model interconnections of process elements. Analogies between mechanical and electrical systems are developed.

Chapter 3 treats dynamic modeling of mechanical systems undergoing translational and rotational motion. After presenting Newton's three laws of motion for a point mass, d'Alembert's method and Lagrange's method are developed for mechanical systems consisting of a system of particles. Chapter 4 develops mathematical models of commonly used mechanical elements such as bars, springs, dampers, and bearings. Detailed models are produced for single-degree-of-freedom translational

and rotational oscillators. These models are extended to two-degree-of-freedom systems. Significant effort is devoted to model such effects as force input, base excitation, rotational unbalance, gear trains, and belt-drives. Static and sliding friction, as well as backlash, are also covered. Throughout the chapter, various systems are modeled using differential equation, state-space, and transfer-function approaches. The underlying systems are systemically described using block diagrams, multiport diagrams, and basic equations. The interconnections between components are carefully considered.

Chapter 5 focuses on electrical drives such as electromagnets, dc motors, and ac motors. After presenting the governing equations of electromagnetism, the static and dynamic behavior of simple magnetic circuits and electromagnets is modeled. Particularly noteworthy elements of the derived models are inclusion of the influence of the magnetization curve on the static behavior of a simple magnetic circuit, characterization of the effect of air gap changes on the dynamic model of a simple magnetic circuit, and inclusion of nonlinearities arising due to nonideal electromagnets in the dynamic model of a simple electromagnet.

Next, after reviewing dc motor construction and various techniques for the excitation of dc motor field coils, a dynamic model is derived for a constant excitation dc motor. Both the armature electrical circuit and the mechanical subsystem dynamics are modeled. Cascade proportional (P) plus integral (I)-PI control is proposed for speed control of dc motors and a P-PI-PI control scheme is proposed for position control of these motors. The dc motor section concludes by developing a mathematical model for a brushless dc motor.

Next, modeling and control strategies are discussed for induction and synchronous motors that are driven by three-phase power supply sys-

tems. By transforming the three-phase stator and rotor winding systems into two-phase systems, a fourth-order coupled nonlinear differential equation model is developed for the electrical subsystem of an ac induction motor. A brief overview of single-phase motors, such as universal and squirrel-cage motors, is also included. Finally, the chapter reviews power electronics components such as the diode, BJT, MOSFET, IGBT, and thyristor, as well as power circuits consisting of a variety of converters.

Chapter 6 considers the coupling of power-generating machines, such as engines and motors, with power-consuming machines, such as pumps and machine tools. Specifically, machine characteristics are analyzed to determine whether a specific coupling of a power-generating machine with a power-consuming machine yields a favorable combination from the point of view of transient and disturbance response. Static and dynamic models are developed for power-generating machines coupled to power-consuming machines, often through a drive train. Dynamic modeling of machines and drive trains is illustrated by developing dynamic models for a combustion engine test stand, a machine-tool feed drive, a centrifugal pump driven by an ac motor, and an automobile drive train. Finally, issues such as model parameter identification, drive train flexibility, and system behavior dependence on the operating point, as well as various control designs, are addressed.

Frequently, the structure and parameters of models of many real-world dynamic systems are not well known. Chapter 7 treats system identification for such systems. Different identification techniques are first categorized. The method of least-squares estimation (LSE) for parameter identification of linear time-invariant discrete- and continuous-time systems is then developed. Parameter identification

for linear systems with time-varying parameters is handled through a recursive least-squares (RLS) estimator with forgetting memory. The use of LS and RLS estimators is suggested for parameter identification of nonlinear processes by developing a linear-in-parameter representation of a nonlinear process. This approach is illustrated for nondifferentiable or discontinuous processes such as friction and backlash. Finally, the chapter considers neural-network and fuzzy-logic-based system identification techniques for nonlinear systems where prior knowledge of system structure is unavailable.

Periodic oscillations often arise in mechatronic systems, sometimes by design and, at other times, unintentionally. Chapter 8 deals with modeling and identification of periodic oscillations. The chapter starts by introducing the following concepts for periodic oscillations: superposition, amplitude/frequency/phase modulation, beating phenomena, and nonlinear transformation. Following a brief review of Fourier analysis and Fourier transforms, identification of periodic oscillation characteristics using the discrete Fourier transform and the fast Fourier transform is discussed. Next, parametric models such as moving average, autoregressive, and autoregressive moving average filters are proposed for modeling periodic signals. Maximum entropy spectral estimation for parameter estimation is discussed. Finally, the utility of periodic oscillation modeling and identification approaches developed in the chapter is illustrated by performing fault diagnostics on a combustion engine.

Chapter 9 begins with a brief review of various classes of sensors, criteria for sensor evaluation, and types of signals produced by sensors. Next, a short overview of sensors that measure mechanical quantities (displacement, velocity, and force) and thermal quantities (temperature) is provided. The chapter concludes

with a discussion of potential opportunities for developing novel intelligent and integrated sensors through on-chip integration of sensor, signal processing, analog-to-digital conversion, and computing elements.

Chapter 10 presents a survey of actuators based on types of auxiliary energy and actuator operating characteristics. This survey encompasses a variety of electromechanical drives, including electric motors and electromagnets. Basic fluid dynamics principles are introduced and applied to develop dynamic models of commonly used hydraulic components such as valves, transmission lines, accumulators, cylinders, and rotary motors. Hydraulic actuator modeling is illustrated by developing a model for a hydraulic servo-axis. Next, in a similar manner, basic gas dynamics principles are introduced and applied to develop dynamic models of commonly used pneumatic components such as valves, accumulators, valve-accumulator interconnections, transmission lines, translatory motors, and pneumatic valves. Furthermore, a model-based framework for controlling a pneumatic servo-axis is described. The advantages, disadvantages, areas of application, and physical properties of a variety of unconventional actuators are discussed. Thermobimetals and shape memory alloys, electrorheological, magnetorheological, thermal expansion elements, electrochemical, piezoelectric, electrostrictive, magnetostrictive, and micro-actuators are all mentioned. By exploiting the transductive property of smart materials, these actuators facilitate conversion of a variety of stimuli to actuation energy. Although not discussed here, some of these smart materials often find applications as sensing elements in mechatronic devices. Next, electromagnetic, pneumatic, hydraulic, and piezoelectric actuators are compared. The systematic integration of actuators in mechatronic systems is also briefly discussed. The chapter ends with a

brief introduction to the concept of fault tolerance. The chapter presents strategies for handling nonlinear effects commonly encountered by actuation devices.

Chapter 11 begins with a history and discussion of trends in microcomputer technology development. An overview of microcomputer architectures is given for standard processors based on the von Neumann principle (the principle of the stored-program computer) such as the Princeton and Harvard structures. In addition, software for standard processors is described. Memory, peripherals (such as analog/digital/binary inputs and outputs) and analog-to-digital and digital-to-analog converters are covered. Next, the discussion focuses on microcontrollers, followed by digital signal processors and application-specific integrated circuits. Finally, several field bus systems are reviewed.

Chapter 12 presents several case studies involving mechatronic components and systems. These studies are used to illustrate the concepts and methods developed in the book. Specifically, a dc solenoid valve, an electrical throttle valve for spark ignition engines, an automotive suspension system, an electromagnetic disc break, and an industrial robotic manipulator are studied. These case studies address issues such as dynamic modeling, nonlinearity compensation, parameter identification, feedback control, and fault detection and diagnosis. This chapter also presents a qualitative introduction to modern controller design and implementation tools (such as control prototyping and hardware-in-the-loop simulation) through a diesel engine example.

Conclusions

This book is based on over a decade of significant research in real-world mechatronic projects conducted by the author and his collaborators. The text presents advanced graduate-

level material that can be used as an excellent technical reference for modeling mechatronic systems that involve interdisciplinary interaction among the underlying components. This focus on modeling sets this text apart from [4]–[10]. The book contains numerous informative and useful illustrations for various mechatronics components and systems; these illustrations encompass classifications, examples, analogies, schematics, characteristic behavior, and comparative analysis.

Since the book's focus is on modeling, it is understandable that many topics that dominate real-world mechatronic system designs (sensors, signal conditioning, power electronics, control/computer hardware interfacing, rapid control prototyping, and embedded computing) are not widely covered in the text. For additional coverage of these topics, the interested reader may consult [4], [6], [9] and [11]–[13] for sensors and signal conditioning; [4], [6] and [14] for power electronics; and [3], [4], [6], and [8] for hardware interfacing, rapid control prototyping, and embedded computing.

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Review of Fundamentals of Adaptive Filtering by Ali H. Sayed, Wiley, 2003, ISBN:0-471-46126-1, US\$132. Reviewed by Phillip A. Regalia.

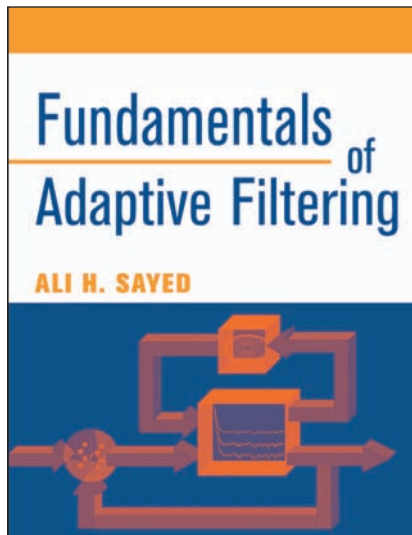
Adaptive Filters

Adaptive filters, which aim to transform information-bearing signals into “cleaned up” or “improved” versions, adjust their characteristics according to the signals encountered. They form the simplest examples of algorithms within the field of machine learning. Adaptive filters are often preferred over their fixed-characteristic counterparts, which are fundamentally unable to adjust to changing signal conditions. The convenient autonomous adaptability of adaptive filters explains their widespread application in signal restoration, interference cancellation,

system identification, and medical diagnostics, to name just a few areas.

Ubiquitous among the different adaptive filtering algorithms are the least-mean-square (LMS) and recursive least-squares (RLS) approaches. A considerable body of research on these approaches has been developed over the past four decades, enumerated in countless journal papers and textbooks. Indeed, given the nearly exhaustive character of such research into these algorithms, and the plethora of texts on adaptive filters that populate library shelves, academic offices, and research labs, one may legitimately ask: How much more could possibly be written on this subject? The answer is no less than 1,000 pages, according to Prof. Ali H. Sayed, in this remarkable book.

The competition in this arena is tough, leading one to ask what this text offers beyond the standard fare. The short answer is that this work is remarkably up to date, encyclopedic in its historic notes, respectful towards the earlier contributors to the field, and replete with detailed examples and guided homework problems, including an abundance of thoroughly designed computer assignments. The text is well written, detailed, and quite accessible to students and researchers alike.



Contents

The first few chapters present estimation theory as it relates to LS approximation, beginning with optimal estimation in Chapter 1, linear estimation in Chapter 2, and constrained linear estimation in Chapter 3. The opening chapters are quite pedagogical and display keen analytic skill, preparing the reader with the tools and insights necessary to analyze adaptive filtering algorithms and their corresponding signal environments in subsequent chapters.

Steepest descent procedures and the LMS algorithm are developed in Chapters 4 and 5, respectively. Although the material in these chapters may be considered standard, Sayed’s clarity and thoroughness avoid the “dull, overworked” qualifiers that could otherwise be attached to this material. Indeed, the sections on iteration-dependent optimal step sizes, and the illustration of performance in the context of channel estimation and equalization, lend a refreshing perspective since they reinforce the core material in ways not developed in other texts.

Detailed performance analyses account for Chapters 6–9, which address steady-state performance, tracking behavior, finite precision effects, and transient phases, respectively. Although this material has traditionally been handled with complicated analysis requiring dexterity and sophistication, Sayed’s treatment is surprisingly balanced and accessible. Key to this approach is the energy balance relation established for the basic parameter update equation underlying a broad class of algorithms; this relation has fueled much of the research emanating from Prof. Sayed’s laboratory in recent years. The use of energy balance and energy conservation approaches has a rich history in applied mathematics, especially in circuit theory, classical network synthesis, and more recently in \mathcal{H}_∞ control and model reduction. It is fitting,

therefore, to apply this approach to adaptive filter analysis. In particular, the energy balance perspective leads to a reasonably unified treatment for the many relations on step-size bounds, excess mean-square error, tracking lag and offsets, finite precision degradation, and initial weight-vector evolution.

Still, one could argue that the analysis as presented assumes an idealized signal model: the minimized modeling error is white and independent of the input regressors, which themselves are assumed to be mutually independent. This long-standing criticism has been levied against many analysis attempts, and considerable debate has ensued over the years concerning the relative merits and drawbacks of alternative approaches, such as averaging theory or stochastic differential equations. Sayed takes a pragmatic road, noting that, for “sufficiently slow” adaptation, the different analysis methods agree more than differ and that experimental results are in good agreement with behavior predicted from the so-called independence assumption. In the spirit of the encyclopedic coverage that characterizes this work, due recognition is given to alternative approaches, including averaging theory, the ordinary differential equation approach, and even the notion of almost sure convergence.

Chapter 10 covers block adaptive filters, which are of interest when seeking efficient implementation of filters with long impulse responses. The text then delves into a comprehensive treatment of LS algorithms. Chapters 11 and 12 develop in detail the LS and RLS formulations, respectively, setting the stage for Chapter 13, which covers array-based implementations. The array forms have been known for many years, usually associated with square-root algorithms that have recognized numerical advantages, but often seem to be relegated to an appendix in other texts. Sayed breaks from tradition by finally putting such array forms in the

forefront. This approach is refreshing, not only due to its implementation advantages, but also since many important algebraic relations can be more expediently derived in this framework, as subsequent chapters amply demonstrate.

Fast LS algorithms form the basis of the next three chapters, starting with transversal filters in Chapter 14, and moving to lattice and Laguerre filters in Chapters 15 and 16. “Fast” in this context refers to the computational complexity of this algorithm class, which is linear in the number of adjustable filter parameters, as opposed to conventional LS algorithms whose complexity is quadratic in the number of parameters. The subject has a rich history dating back nearly 30 years, beginning with so-called transversal-based filters, which directly adjust the impulse response terms of a tapped delay line filter structure. Sayed’s treatment of fast transversal-based filters is fairly clear and coherent, which is no small feat given the notational nightmares that this subject often conjures even for experienced DSP engineers.

Throughout their history, fast algorithms have been tainted by numerical instability problems that were observed early on; these problems initially put such algorithms into ill repute. Sayed’s treatment certainly notes these difficulties, but rather than offering heuristic or “hand-waving” partial remedies that have permeated the technical folklore over the decades, he instead brings forward works that demystify the true origins of this problem. This, in turn, lends a much-improved understanding to some partial successes in stabilizing this algorithm class. In short, instability is not inherent to fast LS algorithms but regrettably afflicts fast transversal-based algorithms due to unstable “parasitic” dynamics that are excited only in finite precision arithmetic.

Alternative classes of fast algorithms are not afflicted by these unstable dynamics; most notable are

lattice algorithms, which are covered in Chapter 15. Here Sayed displays his pedagogical skill by reducing a set of complicated relations to a sequence of well-reasoned manipulations using the array algorithm framework developed earlier in the text. An added bonus is that, unlike most treatments of the subject, this development is not limited to regressor vectors displaying the so-called shift structure. This generalization sets the stage for Laguerre-based adaptive filtering algorithms, which extend some of the power of orthonormal basis functions to linear adaptive filtering. These three chapters on fast LS algorithms constitute one of the more complete catalogues of available algorithms, which clearly situates this work as a valuable reference text.

The closing chapter of the book reexamines robustness issues in adaptive filtering algorithms. This consideration is important when confronted with unknown signals and disturbances. The favored development measures the extent to which estimation errors are influenced by the presence of disturbances in the signal and seeks to minimize this measure. Readers familiar with robust control will recognize the \mathcal{H}_∞ flavor of this setting. Interestingly, many of the algorithms in the previous chapters can be shown to be \mathcal{H}_∞ -optimal solutions once the appropriate weighting matrix is identified. This final chapter distinguishes this book from others in adaptive signal processing and adaptive control.

Conclusions

Inevitably, one can find specific faults within this work. Although Sayed’s attention to detail is commendable, this attention results in perhaps too many footnotes for specific points that, on occasion, could have been merged into the main text for improved continuity. On a lesser level, the size of this book (1,125 pages) may prove daunting to

prospective instructors considering it as a course text, not to mention students who may fear having to lug this volume around. The book does include, however, detailed guidelines on how the various chapters can be structured into a one-semester or two-semester course, with provisions for adapting the material according to the audience's level. In this sense, the size of the volume may be considered a testament to the versatility and adaptability of its contents.

In summary, Ali Sayed's book is a remarkably clear, accessible, and up-to-date text. It is highly recommended for students at the graduate level, and it is an invaluable and comprehensive reference text in the field of adaptive filtering for researchers at all levels.

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Constrained Control and Estimation: An Optimization Approach by Graham C. Goodwin, María M. Seron, and José A. DeDoná, Springer, 2005,

ISBN: 1-8523-3548-3, US\$109. Reviewed by Vincent J. Winstead and Ilya V. Kolmanovskiy.

Background

Once considered only an implementation issue, the subject of control with input and state constraints has recently emerged as an active research area with numerous approaches and directions. Powerful techniques based on receding horizon optimization and model predictive control have been developed for controlling constrained systems. In its basic form, receding horizon optimization applied to a discrete-time system involves computing a control sequence that minimizes a cost function over a finite horizon, where the current state of the system serves as the initial state. The first element of the optimal control sequence is then applied to the system, and the same procedure is repeated at each subsequent time instant.

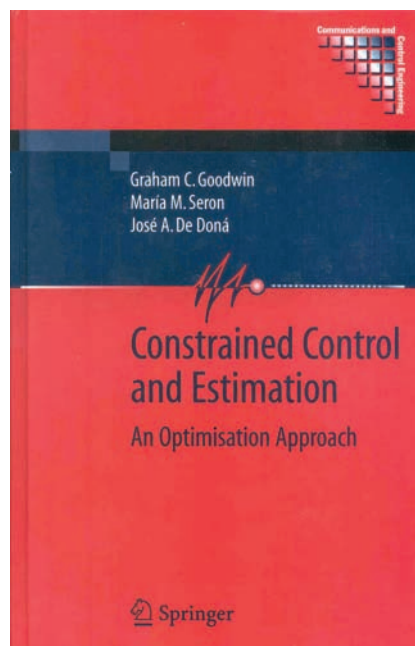
While the basic ideas have existed for more than 30 years (according to [1]), an understanding of stability and robustness properties as well as computational aspects has evolved significantly in recent years (see [1]–[4] and references therein). Related developments have taken place in the area

of receding horizon estimation and fault monitoring (see, for example, [5]). The opportunities for systematic treatment of constrained hybrid systems have greatly contributed to the appeal of receding horizon control methodology [6].

On the application side, receding horizon control techniques have been quite successful in the chemical process industry [7]. In fact, the basic tools have not only been applied but, in part, developed and optimized by the practitioners. In more recent years, the range of feasible applications has expanded to include automotive systems characterized by fast dynamics and limited computational resources. Toward this end, [8], which addresses idle speed control of internal combustion engines with constraints, appears to be one of the first reported automotive applications; several others have been reported in more recent years. Procedures that precompute the receding horizon control law as a function of the system state and store the control for online implementation have been developed to accommodate computational demands (see [3] and references therein). The stored control law is referred to as the explicit form of the receding horizon control law. These procedures are advantageous compared to online optimization for systems with low state dimension.

Contents of the Book

This text covers established previous work as well as recent extensions to the field of constrained optimal control for discrete-time systems. The text is organized in a natural progression from introductory remarks and intuitive observations on control of systems with constraints, to the development of concrete tools for treating constrained optimal control problems for discrete-time systems. It covers fixed horizon and receding horizon problems and develops a framework for solving these and related problems in estimation and output



feedback control. The text concludes with an extensive example section including multiple chapters, each of which is dedicated to a practical control problem.

The authors introduce the class of problems in Chapter 1 using simple feedback system constructions to illustrate the nature of constrained systems as well as the effects of constraints on the system dynamics. Instead of running full speed into heavy theoretical and complex mathematical descriptions, the text eases into the topic so that readers with minimal background in control can understand the key issues.

Chapter 2, which is based on the material in [9], provides a good overview of key concepts in optimization theory. In this and other chapters, the authors frequently rely on convexity properties. While the details of convexity are not at the level of depth found in [10], the authors cover various convexity notions important for the treatment of optimization problems. Chapter 3 uses the constrained function minimization ideas reviewed in Chapter 2 to derive the necessary conditions for optimality in fixed-horizon discrete-time optimal control problems. Dynamic programming is briefly touched upon, as is the interpretation of adjoint variables in terms of the cost-to-go sensitivity.

Chapter 4 considers receding horizon optimal control problems. The treatment is developed in the context of nonlinear systems having nonlinear cost functionals. The necessary stability definitions, stability criteria, and required assumptions are carefully introduced. Furthermore, conditions that guarantee closed-loop stability using the terminal set and terminal penalty approach are derived based on an elegant and comprehensive treatment in [1].

Chapter 5 considers the constrained linear-quadratic optimal control problem and demonstrates how this problem can be reduced to a qua-

dratic programming problem. Several enhancements of the basic problem formulation are also covered, including the output measurement case and the inclusion of time delays. The content through Chapter 5 consists primarily of well-known results, and this material provides the foundation needed for subsequent chapters. Chapter 6 continues the theme of constrained linear-quadratic optimal control and develops an explicit form of the receding horizon control law. More specifically, Chapter 6 provides a geometric characterization of this control law as a partition of the state space into polyhedral regions where, within each region, the control is an affine function of the state. Chapter 7 provides techniques for regional optimal control, under saturation constraints, that exploit the links between the finite horizon and the infinite horizon cases. Chapter 8 provides the reader with insights into computational techniques that can be used for solving the underlying quadratic programming problems. Specifically, active set methods and interior point methods are covered. The computational complexity issues relevant for the explicit form of the receding horizon control law are briefly reviewed.

Chapters 9 and 10 consider the problem of constrained estimation in stochastic systems. Truncated Gaussian distributions are employed to represent output and process noise. Bayes' rule and Markovian properties are utilized to demonstrate that the problem of deriving the best state estimate reduces to minimizing an objective function that depends on the output and process noise time history. This objective function is similar to the objective function for the dual optimal control problem. Duality between constrained estimation and control is explored in more detail in Chapter 10. Although most of the developments concern linear systems, estimation problems for nonlinear systems are also considered.

Chapter 11 is contributed by O. Rojas, who provides insight into the singular value structure of the quadratic programming (QP) problem and associated algorithmic opportunities. Chapter 12 is contributed by T. Perez and H. Haimovich, who provide extensions to the output feedback case.

The remaining chapters present applications of the techniques developed earlier in the text. These applications include finite alphabet controllers and estimators, rudder roll ship stabilization, cross-directional control of an industrial web-forming process, and control over communication networks.

Assessment

While *Constrained Control and Estimation* provides a timely and welcome addition to the literature on receding horizon control, the book also has certain limitations. The developments are geared toward disturbance-free linear systems with quadratic cost functionals. Two exceptions are Chapter 4 on stability of receding horizon optimal control for general nonlinear systems and Chapter 9 on nonlinear estimation. The importance of treating nonlinear systems stems from the fact that constraint violation may cause the system to diverge away from local regions of stability. This divergence can be especially problematic during large signal system behavior where the effect of nonlinearities, either modeled or unmodeled, or disturbances can impact the evolution of the system dynamics.

In Chapter 8, which considers computational aspects, the text covers only the basic ideas and approaches and falls short of a more complete and in-depth account of a range of special techniques. For example, methods based on large sparse matrix techniques [11] can be leveraged to enhance processing capability for high-dimensional problems. The authors could have included some additional description concerning practical real-time

application of the computational algorithms. Such author insight would have been extremely valuable. From the standpoint of extending the applicability of the receding horizon optimal control to faster processes, computational complexity represents an especially critical area.

In the text, input constraints are generally emphasized more than state constraints. However, other techniques, such as antiwindup compensation and gain scheduling, exist for dealing with pure input constraints. A discussion of the relative benefits of the techniques described in the text over those prevalent in the literature would have been beneficial.

Overall, a deeper look at links or extensions to nonlinear systems with general state and input constraints as well as at the associated computational issues would have been valuable. To be fair, the book does provide pointers to the literature should the reader desire a thorough look at these and other topics.

In summary, the book provides a self-contained, well-thought out, and accessible introduction to a wide range of topics and fundamental principles underlying receding horizon constrained control and estimation. The developments are presented at a sufficient level of detail and mathematical rigor to accomplish this objective. The book can be used as a textbook for a graduate-level course, for independent reading, or as a reference. Several other books have recently appeared on the subject of receding horizon optimal control for constrained systems, including [2] and [3]. While the present book has some overlap with these two texts in terms of its coverage (namely the consideration of discrete linear systems having input constraints), *Constrained Control and Estimation* stands on its own as a complete work and a rigorous yet accessible introductory text with unique perspectives on the application of convex optimization tools to systems having input constraints.

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Bicycling Science, 3rd ed., by David G. Wilson with J. Papadopoulos, MIT Press, 2004, 477 pp., ISBN 0-262-23237-5, US\$22.95. *Reviewed by Dennis S. Bernstein.*

There's something that's simultaneously primitive and high tech about bicycles. For retro folks like myself, the lack of any electrons running around circuits (perish the thought of a handlebar-mounted computer) gives my bike a kind of antique charm. On the other hand, the shiny, precision gears and composite suspension are pretty advanced. In short, my bicycle represents the best of all worlds.

In this age of gas-guzzling SUVs (which are great for transporting bikes around!) and dwindling petroleum reserves, bicycle lovers will not be surprised to learn that the bicycle is an amazingly efficient vehicle. Besides the healthful exercise and fresh air that the rider gets for free, the equivalent energy consumption of the bicycle is 1,350 miles/gallon at a speed of 20 miles/hour.

I never thought much about how a bicycle actually works until I read the Åström, Klein, and Lennartsson article [1]. Their delightful article shows us that a bicycle without control principles is like a transfer function without poles. Or maybe I should say zeros, since, as usual, zeros rule and poles drool.

Although I haven't read the earlier editions, the third edition of *Bicycling Science* is apparently a greatly updated version of a book well

known to bicycle enthusiasts. A large fraction of these enthusiasts are interested in speed, perhaps for racing or to develop innovative designs for breaking records. For these folks, *Bicycling Science* provides a semi-technical (“semi” for its sparse use of math and equations) compendium of a huge body of research on bicycle design and construction as well as the performance characteristics of the humans who ride them.

The Bike Bible

Bicycling Science begins with a brief but fascinating account of the history of the bicycle. A key point of this history is that it took humanity a long time to harness human leg power. The reasons are far from obvious, since the design of the modern bicycle is so simple that one would expect such a design to have arisen immediately. In fact, the earliest “bicycles” had no foot-driven mechanism (except of the Fred Flintstone sort) and no steering. Later, the lack of gearing led to the classic huge front wheel and tiny trailing wheel. For a much more detailed history, see the elegant [2].

The text devotes the next chapter to a detailed review of the performance characteristics of humans. This

material is of great value to engineers working on human-powered vehicles of all kinds, including aircraft and watercraft. What I found interesting about this chapter is not the fact that a particular human managed 2,378 W of power for three seconds but rather the challenge of making accurate and meaningful measurements in tricky situations. Machines can be designed (with great care) to measure human performance characteristics in the lab, but these devices must be supplemented by more challenging road measurements, where the cooling effect of the relative wind can have a significant impact on performance. Thermal effects are considered in the next chapter, followed by a physics-oriented chapter on power and speed.

After chapters on aerodynamic effects (how to reduce drag, explained nicely), tires and bearings (bad friction), and brakes (good friction), we finally reach the “controls” chapter: steering and balancing. This chapter begins with a warning and a teaser:

Unfortunately, the mathematics purporting to describe bicycle motion and self-stability are difficult and have not been validated experimentally, so design guidance remains highly empirical. The most significant design detail is a geometric quantity called “mechanical trail.” (p. 263)

The statement about mathematics is unique since, up to this point, there have been no “show stoppers” ascribed to difficult mathematics. Nevertheless, the chapter wastes no time grappling with control issues. One key point made almost immediately is that the rider’s mass is a large fraction of the mass of the system; thus, the rider is able to use body motion in complex ways to control the vehicle. Next, the basic ideas are explained in words rather than equations, as in:

Balancing a broomstick, or a bicycle, consists in making the small support motions necessary to counter each fall as

soon as it starts, by accelerating the base horizontally in the direction in which it is leaning, enough so that the acceleration reaction (the tendency of the center of mass to get left behind) overcomes the tipping effect of unbalance.

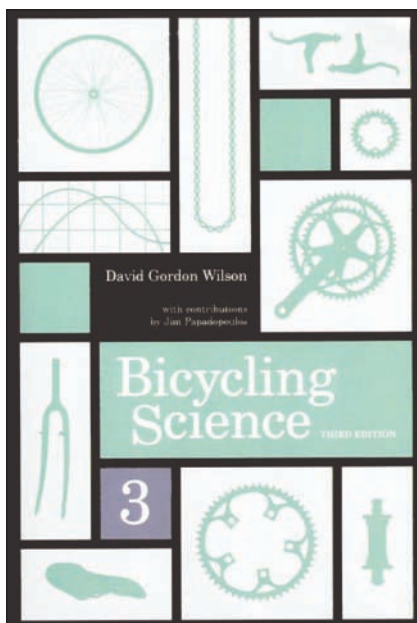
This style of exposition and thought process is rare in the control classroom. Our usual approach would be to derive equations of motion and then demonstrate through formulas the actions needed for balancing to occur. But for those who are not experts in control, words have to suffice, and I believe the authors have done a good job.

In [1], the authors focus on countersteering, that is, the need to steer left to turn right, and vice versa. This effect is analyzed in terms of right-half-plane zeros arising from open-loop unstable poles. In *Bicycling Science*, there is no mention of zeros, but the physical effect is explained graphically in multiple ways. First

To see [countersteering] most clearly, one can ride a bicycle along a painted line on the right edge of a road and watch the front wheel position while making a quick maneuver to change lanes rightward. One will notice a brief leftward deviation of the front wheel’s path, caused by briefly steering leftward before settling into a sustained rightward steer angle. (p. 270)

And again:

That everyone who knows how to ride a bicycle already unconsciously understands [countersteering] becomes clear when we are riding close to the edge of a curb or a slight drop-off. Riding closer than about 125 mm makes us feel nervous and “trapped”: we know that it will be necessary to turn *toward* the danger in order to steer *away* from it. If there’s no room, we sense that trying to escape will take us over the edge. (p. 271)



Some icing on the cake is the additional explanation that runners lean forward to accelerate and lean back to slow down. If the goal is to get somewhere fast, why not put a foot forward first? Of course, all of these phenomena can be traced to nonminimum phase zeros that arise from feedback stabilization.

The book continues with chapters on power transmission and materials. The penultimate chapter is a fascinating overview of unusual human-powered machines, such as aircraft, watercraft, and lawncraft (lawn mowers), all of which are pedaled. The final chapter focuses on trends that look toward the future. The authors' point seems to be that if engineers invested as much effort in designing human-powered tools and vehicles as they do designing gasoline-powered machines, then the world would be a better place. Amen.

Who Should Buy This Book?

This book is a necessity for anyone involved in a project involving human power. For all other engineers who like bikes (and who doesn't?), this book makes for semitechnical

reading with real-world relevance. Even if your goal isn't to optimize the drive train of your bicycle, *Bicycling Science* has a wealth of material for those bored with the usual "isn't the Internet amazing" chatter. The book would also make a great gift for the scientifically inclined younger set who just might catch the engineering bug. Of course, the text will appeal to anyone with an interest in science and technology. Finally, this book is "better together" with not only [2] but also the fascinating [3], which offers many beautiful illustrations and a wealth of mechanical engineering details and ingenious designs.

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