

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

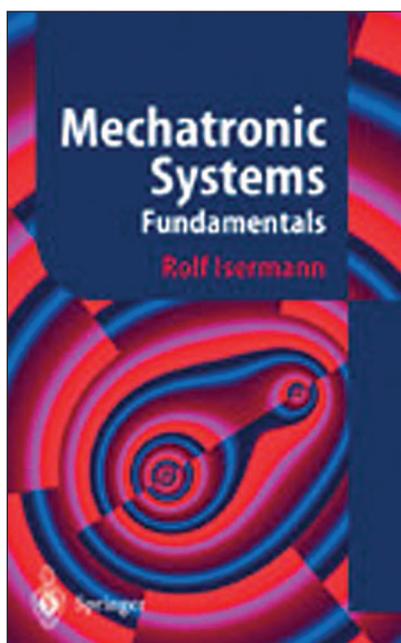
areas of mechatronics include medical, defense, manufacturing, robotics, automotive, and smart consumer products. Recently, *Technology Review: MIT's Magazine of Innovation* identified mechatronics as one of the ten emerging technologies that will change the world [1].

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.

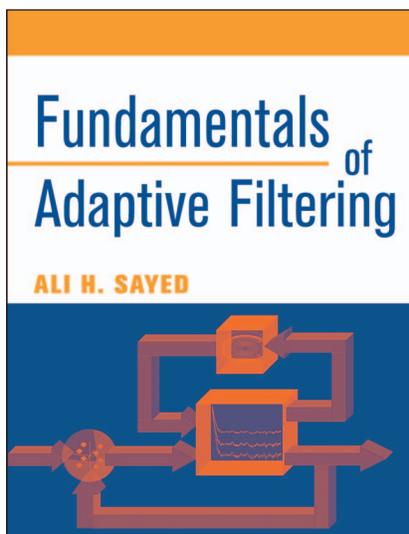
Adaptive Filters

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,