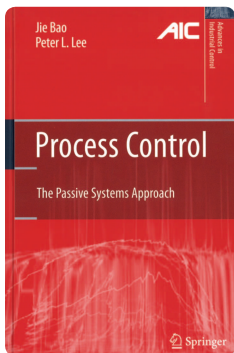


IEEE Control Systems Magazine welcomes suggestions for books to be reviewed in this column. Please contact either Michael Polis or Zongli Lin, associate editors for book reviews.



Process Control: The Passive Systems Approach

by JIE BAO and PETER L. LEE
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A passive system cannot deliver more energy than what is stored. Typically, a passive system delivers less than what is stored since useful energy is invariably and irreversibly lost through friction and other dissipative processes that convert useful work into heat. Such properties show that passivity is related to principles used to develop

mathematical models for all kinds of physical systems. Applications of passivity-based control methods are found in robotics [1]–[3], systems biology [4], large-scale systems analysis [5], [6], and chemical process control [7]. One of the more intriguing aspects of passivity is that it relates to thermodynamics [8], [9]. The latter property motivates the use of passivity-based methods for chemical process control since it suggests that it may be possible to derive process control systems directly from process physics.

To define the notion of passivity we consider a dynamical system with input u and output y . This system is *passive* if there exists a *storage function* $W(t) \geq 0$ such that, for all $t_0 < t_1$,

$$W(t_1) \leq W(t_0) + \int_{t_0}^{t_1} y(t)u(t)dt. \quad (1)$$

The product yu is the *supply rate*, and $W(t)$ can be thought of as the stored energy. The classical example of a passive system is an electrical circuit with resistors and capacitors [10]. In this case the input u corresponds to the current, the output y corresponds to the voltage, and the product uy represents electrical power. The relationship between passivity and conservation principles is now clear. Equality in (1) shows that all energy can be with-

drawn as electrical power. A strict inequality indicates that some electrical energy is dissipated as heat in the resistors. Inequality (1) furthermore shows that a system is passive if u and y have the same sign, a statement that has considerable intuitive content.

Passivity simplifies control design. To illustrate this property it suffices to set $u = -Ky$, where $K > 0$ is a gain. Inequality (1) then yields the estimate

$$K \int_{t_0}^{t_1} y^2(t)dt \leq S(0),$$

which implies that y is square integrable on the interval $[t_0, t_1]$. This property shows that we can control a passive system using proportional control—a remarkable fact that holds true independently of the complexity of the underlying system. The system can be described by nonlinear differential equations, it may be a hybrid system with discrete and continuous dynamics, or it may be described by partial differential equations. In fact, a state-space representation is not even required. These ideas extend to dynamic and nonlinear control systems. One version of the celebrated *passivity theorem*, which is particularly useful in this context [11, p. 247], states that a feedback connection between two passive systems is passive. This result and related results show that passivity can be used to separate the tasks of control design and system modeling. Passivity theory is useful in the analysis and design of interconnected systems since it focuses on input-output properties and how systems are connected, rather than their inner workings.

Murray Gell-Mann stated that, "...no gluing together of partial studies of a complex nonlinear system can give a good idea of the behavior of the whole" [12]. Furthermore, Norbert Wiener claimed that complex systems are better understood in terms of what they do than what they are made of [13]. These observations certainly apply to chemical process control. Passivity theory shows that all chemical processes can be controlled using PI control provided the control and measurement configurations are suitably chosen [14]. Such results are supported by industrial practice [15]. Given such close relationships between passivity and process control, it is surprising that it has taken until now for a book on the subject to appear.

THE CHAPTERS

The book begins with a comprehensive introduction to passivity theory. The major results are reviewed, and it is shown how systems that are not passive can be made to

look passive using a combination of feedback and feedforward control. This discussion paves the way for the definition of the *passivity index*, a concept that is used repeatedly throughout the text. The passivity index measures shortage or excess passivity. Nonpassive systems have a shortage of passivity that sometimes can be compensated for by using a combination of feedback and feedforward control. A strictly passive systems has excess passivity, which can be used to compensate for passivity shortage in other systems. These concepts are illustrated by a simple, yet practical and illuminating example.

In the next chapter the authors use the passivity index to develop a new approach for worst-case robust control that relies on phase margin rather than gain margin. The authors argue that this approach complements classical methods for H_∞ robust control and that the passivity design method can lead to less conservative results than methods based on small gain stability. An example illustrates the latter point. The authors present design algorithms that can be implemented using the robust control system and LMI toolboxes in Matlab.

The authors then proceed to apply passivity-based control to decentralized control design for chemical process systems. The book describes the concepts of decentralized and block-decentralized integral controllability (DIC/BDIC) for multivariable systems using passivity theory. The authors develop interaction measures that characterize the degree of coupling among variables in a multivariable system. The book also discusses a procedure for designing decentralized control systems using the passivity index. This chapter breaks new ground by providing the basis for further research on decentralized control of chemical process systems.

In Chapter 5 the authors address the problem of fault-tolerant control systems. The objective here is to design a control system that maintains stability even when one or more control loops fail. The approach relies on inherent passivity properties of the system and controller redundancy. The authors develop a method that ensures that the process remains passive (stable) even when some loops are out of commission. This problem is of practical interest since control-loop failures in chemical plants can lead to expensive and tragic accidents if system stability is not maintained. The motivation for the problem is briefly reviewed before the idea of decentralized unconditional stability (DUS) is developed. Again we find that the passivity index provides the critical tool for the analysis. If the system is unstable, it is necessary to include fault detection to switch to a backup controller. Several illustrative examples are provided.

Some chemical processes are easy to control, whereas others are more difficult. Chemical plants have been built at great cost only to discover that they are inoperable because actuators and sensors are in the wrong places or the equipment has complex and uncontrollable dynamics.

Such systems have to be redesigned to make them controllable. This observation motivates the development of methods for assessing whether or not a chemical process system is controllable at the conceptual design stage. In Chapter 7 the authors develop a theory that can be used to address this problem. The current status of the field of interaction between design and control is reviewed. One approach is based on linearization of nonlinear process models around a given operating point followed by a steady-state operability analysis. Another approach analyzes dynamic operability using Hammerstein models.

The last chapter, authored by K.M. Hangos and G. Szederkeni, describes an emerging theory for process control based on thermodynamics. This chapter serves as a good point of departure for connecting thermodynamic stability theory with mathematical systems theory. The basic idea is to use the second law of thermodynamics to derive the storage function

$$W = Z^T w^* - S, \quad (2)$$

where Z is the vector of primary variables (internal energy, volume, and mol numbers of chemical constituents), $w^* = \partial S / \partial Z |_{Z=Z^*}$ is the vector of secondary variables (temperature, pressure, and chemical potential) evaluated at the reference state Z^* , and S is the entropy. The second law shows that the entropy is a degree-1-homogeneous and concave function of Z . It follows from definition (2) that $W \geq 0$ and that W can be used as a storage function for passivity design in inequality (1). The function W was first introduced by J.W. Gibbs [16] to study the stability of fluid phase equilibria.

Difficulties in developing passivity theory from thermodynamics to its fullest extent are twofold. First, the entropy function is not strictly concave due to degeneracy related to the number of phases and reactions present in the system. Second, it is necessary to apply the theory of nonequilibrium thermodynamics (NET) since we are interested in open systems. Although the formalism can appear intimidating, several excellent books provide overviews of the theory. For example, the classical book [17] provides foundations. The more recent book [18] provides a nice introduction to the subject of NET, whereas [19] provides links between thermodynamics and dynamical systems theory.

One strength of *Process Control: The Passive Systems Approach* is that the authors provide a brief and very readable account of NET. A heat-exchanger example illustrates the main points of the modeling framework. The authors proceed to describe how NET and passivity are linked using the storage function (2). These developments show how control systems can be derived from thermodynamics. They also show that thermodynamics can benefit from the formalism of mathematical systems theory as discussed in [19]. The last topic of the book is devoted to linking chemical process control and the Hamiltonian formulation favored in the

description of mechanical systems [2], [3]. Two case studies, a heat-exchanger and a chemical reactor, illustrate how these methods can be applied to chemical processes.

DISCUSSION

Process Control: The Passive Systems Approach provides material that is potentially valuable to students and researchers interested in learning the fundamentals of passivity-based methods and their application to chemical process control and thermodynamics. Passivity theory and its applications are covered from many angles. The focus on analysis is refreshing, especially in the wake of the successful development of model predictive control (MPC), a development so successful that one might wonder whether there will ever be a need for anything else. However, we might equally well ask the questions: Why is MPC so successful? Can the application of MPC be simplified, for example, how can MPC be interfaced with low-level decentralized control systems and programmable logic controllers? How are such controllers designed in the first place?

Although the book does not provide direct answers to all of these questions, a convincing case is made that passivity-based control can provide a formalism within which these questions can be addressed. This case is made especially clear in the last chapter, where the foundations for a more physical basis for passivity are derived from the theory of nonequilibrium thermodynamics.

The introduction to passivity theory in Chapter 2 is deeper than what is required, and it might scare some readers who are not familiar with nonlinear control theory. This situation would be most unfortunate. Most of the book (chapters 3–6) relies on linear theory, and, although Lie derivatives are introduced, they are not used later. Where nonlinear theory comes into play, it is in a simpler form than what is reviewed in Chapter 2. The systems described in Chapter 7 are nonlinear; however, the particular choice of storage function does not require the more sophisticated forms of nonlinear passivation reviewed in the beginning of the book.

The main strength of the book is that it shows that passivity can provide a formalism for studying process control. Relevant results are reviewed, and interesting research questions are posed. However, some important issues are not addressed. For example, it would be interesting to see how passivity methods can be modified to include input and output constraints. It would also be interesting to see a link between the robust and decentralized control theory developed in the earlier chapters with the physically based control theory described in the last chapter. Overall, the book is useful as a reference and as a source of new research ideas.

REVIEWER INFORMATION

B. Erik Ydstie has been a professor of chemical engineering at Carnegie-Mellon University since 1992 and professor II of electrical engineering at Norwegian University of Science and Technology (NTNU) since 2007. He earned the B.S. degree in chemistry at NTNU and the Ph.D. in chemical engineering at Imperial College, London. From 1982 to 1992 he was a professor of chemical engineering at the University of Massachusetts. In 1999–2000 he was director of research and development in ELKEM ASA. Since 2005 he has been chief technology officer of iLS, Inc. He has held visiting positions at Imperial College, L'Ecole des Mines de Paris, and the University of New South Wales in Australia. He has authored over 100 articles on process control, optimization, and modeling of chemical processes. In 2007 he was awarded the CAST award of AIChE for contributions related to process control. He has served on the advisory board of the American Chemical Society's Petroleum Research Fund since 2004.

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