Book Reviews

Switching in Systems and Control—Daniel Liberzon (Boston, MA: Birkhäuser, 2003) *Reviewed by Guisheng Zhai*

A *hybrid* system is a dynamical system whose evolution depends on a coupling between variables that take values in a continuum and variables that take values in a finite or countable set [8]. Therefore, two kinds of dynamics, namely continuous dynamics and discrete events, coexist and interact in such systems. Since there are many practical systems which should reasonably be described as hybrid systems, there has been increasing interest in the analysis and design for such systems in the last two decades. Due to its interdisciplinary nature, research attention in this relatively new but very active area has been growing among people with very diverse backgrounds including mathematicians, control engineers and computer scientists. As was also pointed out in [8], the current research on hybrid systems has been inspired by motivations in many areas. For example, computer scientists are interested in verification of correctness of programs interacting with continuous environments (embedded systems); control theorists are focused on hierarchical control, interaction of data streams and physical processes, stabilization of nonlinear systems by switching control; and mathematicians consider optimization and equilibrium problems with inequality constraints, differential equations with discontinuous right sides, etc. Among the literature on general hybrid systems, especially from the viewpoint of dynamical control systems, one may want to refer to [5], [6], and [8].

Related closely to the study of hybrid systems is the theory of *switched systems*, which are known to contain continuous-time systems with discrete switching events from a certain class. Usually, researchers with a background and interest in continuous-time systems and control theory are concerned primarily with continuous dynamics and, thus, the discrete behavior, on the other hand, is usually regarded as a tool serving to achieve desired properties of the continuous dynamics, such as Lyapunov stability. The excellent survey papers [2] and [4] have given precise introduction to the perspectives and results on stability analysis and controller design of switched systems. Some systematic study for stability and $\mathcal{L}_2$ gain properties of switched systems has been done in [3].

The book by Liberzon is not a book on general hybrid systems, but rather a book on switched systems written from a control-theoretic perspective. In particular, the reader will not find a formal definition of a hybrid system here, since the focus is on formulating and solving stability analysis and control design problems for switched systems and not on studying general models of hybrid systems. The main goal of the book is to bridge the gap between classical mathematical control theory and the interdisciplinary field of hybrid systems. More specifically, system-theoretic tools are used to analyze and synthesize systems that involve nontrivial switching behavior and thus fall outside the scope of traditional control theory.

Chapter 1 (Part I) provides an introduction to the book. It is asserted that the switching events in switched systems should be classified into

- *state-dependent* versus *time-dependent*;
- *sutonomous (uncontrolled)* versus *controlled*.

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Solutions of switched systems are discussed using locally Lipschitz condition, Zeno behavior, sliding modes, and hysteresis switching.

Chapters 2 and 3 make up Part II of the book, which is started by two examples showing the following.

- Unconstrained switching may destabilize a switched system even if all individual subsystems are stable.
- It may be possible to stabilize a switched system by appropriately designed switching even if all individual subsystems are unstable.

First, stability analysis under arbitrary switching is addressed in Chapter 2. Obviously, the necessary condition is that all individual subsystems should be stable, but additional requirements must be imposed so that arbitrary switching is admissible. The discussion is based on the result that if all individual subsystems have a radially undounded common Lyapunov function, then the switched system is globally asymptotically stable (GAS). It is shown that if all individual subsystems constitute a finite set of commuting $\mathcal{C}^1$ vector fields and the origin is a GAS equilibrium for all subsystems, then the switched system is GAS under arbitrary switching. Parallel results are obtained using Lie algebra conditions. For switched linear systems, it is usually natural to consider quadratic common Lyapunov functions (QCLFs). However, a counterexample in this chapter shows that even if the switched system is globally exponentially stable, it does not imply the existence of a QCLF. It is noted here that, supplementary to the discussion in this chapter using commutation or Lie algebra conditions, the possibility of arbitrary switching (or common Lyapunov function) has been discussed in [10] for switched symmetric systems concerning both stability and $\mathcal{L}_2$ gain properties.

Chapter 3 addresses stability of switched systems under constrained switching, using *multiple Lyapunov functions* (MLFs) and *state-dependent switching*. It is well known that Lyapunov function theory is the most general and useful approach for studying qualitative properties of various control systems. For switched systems, a natural extension is multiple Lyapunov functions, usually one or more for each of the individual subsystems being activated. This chapter first states and proves a result using a class of MLFs, under which a switched system is GAS. Using this result together with the proposed MLF, it is then shown how to formulate and justify the property that a switched system is stable if all individual subsystems are stable and the switching is (on the average) sufficiently slow in the sense of small *(average) dwell time*. In contrast to such time-dependent switching, another way of constrained switching is state-dependent switching, where a switching event occurs when the trajectory reaches a switching surface. Stabilization of switched systems composed of two unstable subsystems is then dealt with under the assumption that there is a stable convex combination of the subsystem matrices, and a hysteresis-based stabilizing switching strategy is constructed so as to avoid fast switching. It is noted here that the proposed switching method is similar to the conic switching law which was originally proposed for second-order switched systems by Xu and Antsaklis [9]. For more general issues concerning state-dependent switching, the reviewer recommends [7] as a good reference, where many analysis and design problems of switched systems are reduced to LMI feasibility problems.

Part III of the book is composed of Chapters 4–6, devoted to *switching control*. The motivation is summarized by listing the categories of control problems for which one needs to consider switching, instead of a continuous feedback law.

1) Due to the nature of the problem itself, continuous control is not suitable.
2) Due to sensor and/or actuator limitations, continuous control can not be implemented.
3) The model of the system is highly uncertain, and a single continuous law can not be found.

These categories are discussed, respectively, in Chapters 4–6.

It is pointed out in Chapter 4 that there are several different situations fitting into the first category. For example, unpredictable environmental influences or component failures, significantly different system trajectories desired on different intervals, obstacles in the state–space of the process, requirement of different controllers at different stages, etc. Another obstruction to continuous stabilization may come from the mathematics of the system itself. The present chapter deals with a well-known class of such systems, namely nonholonomic control systems, and proposes several switching control techniques for some systems in this class. As a demonstrative example, a benchmark problem of stabilizing an inverted pendulum on a cart in the upright position is discussed, and a stabilizing switching control is proposed using "energy injection."

Chapter 5 is focused on systems with sensor and/or actuator constraints. The simplest example of an actuator constraint is when the control input is bounded, e.g., due to saturation. It is well known that the optimal control of such systems involves switching (bang–bang) control, and the first section shows how this works for linear time-invariant systems. Then, by the example of static output feedback, it is shown that switching control is a useful tool for stabilization of general linear systems via output feedback. The main body of this chapter is devoted to hybrid control of systems with quantization, which includes the author's most recent research results. In the classical feedback control setting, the output of the process is assumed to be passed directly to the controller, which generates the control input and in turn passes it directly back to the process. That is, all signals will not be "twisted" on the transmission routes among the system components. However, this is not the case when the interface between the controller and the process involves some additional information-processing devices. Such considerations arise in almost any computer-aided control systems and networked control systems [1]. One important aspect in such considerations is *signal quantization*. The present chapter gives precise results and proofs for general linear and nonlinear systems with general types of *quantizers* affecting the state of the system, the measured output, or the control input. An important feature is that all the control laws are constructed explicitly, and asymptotical stability is achieved.

Chapter 6 considers control problems for uncertain systems with large modeling uncertainty. Since the uncertainty set is large, robust control design tools are not applicable and thus an adaptive control approach is required. However, the traditional approach to adaptive control, where controller selection is achieved by means of continuous tuning, has some siginficant inherent limitations. For example, if unknown parameters enter the process model in complicated ways, it may be very difficult to construct a continuously parametrized family of candidate controllers. As an alternative to traditional adaptive control, the approach of *supervisory control* is proposed here so as to overcome some of the difficulties while retaining the fundamental ideas on which adaptive control is based. The main feature that distinguishes it from conventional adaptive control is that the controller selection procedure is carried out by means of logic-based switching rather than continuous tuning. Switching among candidate controllers is orchestrated by a high-level decision maker called a *supervisor*. By supervisory control, one can handle process models that are nonlinearly parametrized over nonconvex sets and to avoid loss of stabilizability of the estimated model. Further, one may gain greater flexibility in applications and more tractability in stability analysis of the resulting system. This chapter describes precisely the basic building blocks of a supervisory control system, the basic requirements that need to be imposed on the different parts, which include the multiestimator, the candidate controllers and the switching logics. Both linear and nonlinear supervisory control are discussed, and an example dealing with a nonholonomic system with uncertainty is demonstrated.

Part IV of the book provides some supplementary materials. Appendix A reviews some basic facts from Lyapunov's stability theory, including stability definitions, Lyapunov's direct (second) method, LaSalle's invariance principle, etc. Appendix B gives an overview of basic properties of Lie Algebra.

At the end of the book, there is a section entitled "Notes and References." It complements the main text by providing many additional comments and pointers to a large list of literature, from research articles to a variety of related topics not covered in the book.

The book is written in depth, and all the topics are closely related to the basic problems in analysis and control of switched systems. Furthermore, all the main results presented here are contributed originally by the author and his collaborators. These results, along with the author's recent work on nonlinear control, play a pioneering role in the area of switched systems and switching control. Therefore, the reviewer recommends this book to all researchers who are interested in studying switched/hybrid systems and their applications. Control theorists and mathematicians will find that this book is a very comprehensive reference source.

Although many results are the latest ones and the proofs may not be easy to understand, the author has made great efforts in the arrangement of the book so that the content is easier to follow. There are many insightful examples, figures and illustrations, and the author has provided many other resource related to the book in the main text and the "Notes and References" section. Another feature is that many exercises are scattered throughout the book. The reviewer has many reasons to recommend this book to graduate students and beginners who want to start research in switched systems and switching control.

In addition to the distinguished theoretical developments, the reviewer believes that the book is equally valuable to practicing engineers. Most of the results included in the book are applicable to general systems, and many problems originate from practical settings. For example, switching control for systems with sensor or actuator constraints (Chapter 5) is very realistic and beneficial in networked control systems [1], and the dynamic quantization method proposed there is easy to implement for real control systems.

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