Preface to the Second Edition

The interconnection between two (or more) physical systems is always accompanied by *transfer* phenomena (material, energy, information) such as *transport* and *propagation*. Mathematically speaking, transport and propagation phenomena can be represented by *delay elements*. In this way the corresponding overall systems are governed by a special type of differential equations, namely *delay-differential equations*.

Delay-differential equations are also used in modeling various other phenomena coming from biosciences (heredity in population dynamics [202, 223]), chemistry (behaviors in chemical kinetics [367, 334]), physics (lasers [102]), acoustics (wind instruments [102]) or economy (dynamics of business cycles [368]). Further examples in engineering can be found in [359, 290, 130, 102].

As mentioned by El'sgol'ts and Norkin [97] and Răsvan [335], time-delay systems have a long history, and, to the best of our knowledge, the first delay-differential equations are encountered in the work of Bernoulli and Condorcet. However, the theory started to be developed in the second half on the 20th century with the work of the East European Mathematical school: Myshkis [286], Krasovskii [200], and Halanay [145] (to cite only a few), who devoted most of their attention to the extension of the Lyapunov theory to such classes of differential equations. In the 1960s, an increasing interest in the topic appeared also in North America as confirmed by the monographs of Pinney [326] and Bellman and Cooke [23], (the former almost forgotten), with a particular interest in complex-domain approach and related frequency-domain techniques and methods. Subsequently, the theory arrived at some maturity in the 1970s as proven by the publications and monographs devoted to the field during that period. Among them, we mention the pioneering work of Hale [148] (the second edition of the monograph published in 1971), which is one of the most cited reference in the field not only for the fundamental results and approaches, but also for the quality and the clarity of the presentation. For further references and a deeper historical perspective, we refer the reader to [290, 332, 304].

It is important to point out that various references devoted to time-delay systems in engineering existed even before the 1950s as, for example, the papers coauthored by Callender [61, 62] and the editorial of the journal *Engineer* [357], with some contradictory conclusions concerning the effects induced by the delay presence in dynamical systems: sometimes *destabilizing* (mainly by using "huge" gains), and sometimes *stabilizing* (mainly in controlling some oscillatory modes). The explanation of such "dichotomic" behaviors was done case by case, without any attempt at a comprehensive explanation of the situations where stabilizing/destabilizing effects may occur.

Although by now the fundamental results in the theory of functional differential equations are well known and well understood (see, for instance, [23, 148, 151], to cite only a few), the increasing number of applications involving large-scale systems with corresponding complex decision making strategies in which the *delay* (transport, propagation, communication, decision) becomes a "critical" parameter made necessary the development of efficient numerical algorithms and methods for evaluating critical delays and related stability/instability properties. This monograph presents some approaches and techniques in this sense.

Recent approaches in *robust control* opened interesting perspectives and issues in dealing with delays in dynamical systems, where delays are eventually treated as *uncertainty* [130, 290, 32]. Some of them (frequency-sweeping tests, matrix pencil approaches) will be largely discussed in this monograph. Such interpretations of delays as uncertainty were at the origin of an abundant literature in the control area by the end of the 20th century. The corresponding results are expressed in terms of solutions of appropriate Riccati equations [225], and in terms of linear matrix inequalities [32] in connection (or not) with the μ-formalism [318]. An exhaustive overview concerning these approaches in the context of stability analysis can be found in [290].

At the same time, the increasing number of efficient algorithms for dealing with *nonlinear eigenvalue problems* [27, 237, 179] represented another important issue in treating delay systems. As in the finite-dimensional case, the essential properties of time-delay systems (asymptotic behavior, stability, instability, oscillations) are connected with the spectrum location of the corresponding linearized systems. As we shall explain in the following chapters, time-delay systems are infinite-dimensional systems, but with particular spectral properties. Such properties will be explicitly exploited in deriving the main (stability and stabilization) results and related algorithms. Crucial in recent algorithms is the exploitation of some duality in the frequency domain, in the sense that characteristic roots appear as solutions of a finite-dimensional nonlinear eigenvalue problem as well as an infinite-dimensional linear eigenvalue problem. Particular attention will be paid to the distinction between *retarded* and *neutral* systems because, although both belong to the class of time-delay systems, the spectral properties are considerably distinct.

It is important to point out that, excepting the functional differential equations–based representation, there are several ways to *represent* time-delay systems: as evolution equations over infinite-dimensional spaces [25, 84] (infinite-dimensional setting), 2-D (or n-D) systems [215], systems over rings of operators [184], and behavioral-based representations [120]. Throughout the volume, we adopt the functional differential equation based representation, although the connection with ODEs over a function space plays a major role in developing numerical methods. We further assume that the nominal models are completely known. In other words, we do not focus on delay modeling, identification, or identifiability.

Book outline and content

The book is organized in three parts:

(a) Stability analysis of linear time-delay systems.

(b) Stabilization and robust fixed-order control.

(c) Applications.

With Part (a) and Part (b) our intention is to present an analysis of stability, robust stability, and the synthesis of controllers using a *unitary* methodology—the *eigenvalue-based approach*. Without any loss of generality, we mainly concentrate on the following aspects that, to our best knowledge, have not received a full treatment in the literature:

- Sensitivity analysis with respect to delays and to other systems' parameters (continuity of the spectrum with respect to the parameters based on Rouché type theorems and variants, pseudospectra, and related properties);

- Analytical, as well as numerical analysis tools (algorithms for computing characteristic roots, $\mathscr{H}_2$ and $\mathscr{H}_\infty$ norms).

- Design of fixed-order or fixed-structure stabilizing and robust controllers. These approaches, which are recent, even in the context of finite-dimensional systems, are grounded in numerical linear algebra and optimization.

A lot of examples complete the presentation and illustrate the main results proposed in the monograph. Most of the major ideas are explained by using (several) extremely simple, "easy-to-follow" (low-order) examples. Finally, Part (c) of the monograph is devoted to several applications spanning various fields from engineering to biology. All the applications considered start from some generic remarks on the way in which the models are derived, but without any deep discussions on the model derivation and its limitations. The choice of the applications was mainly motivated not only by their impact in engineering, biosciences, and related fields, but also by our own interest in the corresponding topics.

We have made the parts independent of each other as much as possible. However, a number of fundamental results are needed for the whole theoretical development and are presented in Chapter 1.

What's new in the second edition?

The first edition of the book was mainly targeted towards the mathematical control community. The focus was almost exclusively on the stability analysis and stabilization, which encompass only the first step in a control design. With this new edition of the book, first we make the leap from stabilization to the design of robust and optimal controllers, thus enlarging the scope of the book within the control area. Second, by including a lot of new material on numerical methods, we aim at reaching other research communities, in particular the numerical linear algebra and the numerical optimization community. Finally we have extended the number of applications that we address. More specifically, the changes can be summarized as follows:

- In addition to the existing material on the stability analysis and stabilization, we have included several new chapters and sections related to the design of robust controllers, with the emphasis on optimal $\mathscr{H}_2$ and $\mathscr{H}_\infty$ controllers.

- In contrast to the first edition, this new edition contains a *significant part on numerical methods*: (large-scale) eigenvalue computations, level set methods, and structured eigenvalue problems (related to the $\mathscr{H}_\infty$ norm computation), solving generalizations of Lyapunov equations (related to the $\mathscr{H}_2$ norm computation). Throughout the book, an overview of numerical methods for control is proposed, where the details are worked out for the class of time-delay systems. The controller synthesis approaches in the new chapters rely on a direct optimization approach (fixed-order control based on eigenvalue optimization). Eigenvalue optimization and its applications is a relatively young research domain which lies at the intersection of numerical optimization, linear algebra, and control. Appendix A.5 contains, among others, a description of software corresponding to algorithms presented in the book. This software is publicly available.

- While in the first edition most of the material was devoted to delay systems described by retarded functional differential equations, the new edition addresses a larger class of systems represented by delay-differential algebraic equations, covering both retarded and neutral differential equations–based representations. Insights on the existing links between such systems and control feedback problems will be particularly emphasized. We further note that differential algebraic equations represent the standard way to perform modeling in large-scale interconnected systems, such as electronic circuits. In Part I and Part II of this new edition, Section 1.3, Chapter 2, Section 3.5, Chapter 4, Section 5.5, Section 7.4, Section 8.4, and Chapter 9 are completely new.

- New applications have been added to Part III of the book and some of the existing ones have been appropriately updated with new material. To be more precise, some of the first-edition chapters have disappeared, while others have been restructured by including new sections devoted to new topics, and some new chapters have appeared. In particular, the two first edition chapters devoted to output feedback stabilization have been merged into one chapter including the multiple delays case as a section. Furthermore, a new section including some insights on delay effects in networked control systems has been added. The chapter on congestion control algorithms has been completed by a section devoted to Smith predictor–type schemes and related robustness issues (computing the maximal allowable delay uncertainty by using a geometric approach). Next, a new chapter is included on synchronization of delay-coupled nonlinear oscillators including the stability analysis of synchronized equilibria as well as an application to Lorenz oscillators. Finally, the chapter discussing delay models in biosciences now includes an extra section devoted to the stability of biochemical networks. Furthermore, the section dealing with immune dynamics models in leukemia now contains updated material as well as a more elaborated model. Finally, we tried to give a unitary presentation of the delay models in biosciences by using an appropriate multicompartment modeling angle for genetic regulatory networks or a simplified human respiration system model, or for describing immune dynamics in chronic myelogenous leukemia.

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