# Advances in Delays and Dynamics

Volume 10

Delay systems are largely encountered in modeling propagation and transportation phenomena, population dynamics and representing interactions between interconnected dynamics through material, energy and communication flows. Thought as an open library on delays and dynamics, this series is devoted to publish basic and advanced textbooks, explorative research monographs as well as proceedings volumes focusing on delays from modeling to analysis, optimization, control with a particular emphasis on applications spanning biology, ecology, economy and engineering. Topics covering interactions between delays and modeling (from engineering to biology and economic sciences), control strategies (including also control structure and robustness issues), optimization and computation (including also numerical approaches and related algorithms) by creating links and bridges between fields and areas in a delay setting are particularly encouraged.

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# Delays and Interconnections: Methodology, Algorithms and Applications

Springer

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# Preface

The purpose of this volume in the established series Advances in Delays and Dynamics (ADD@S) is to provide a collection of recent results on the design and analysis of *Delays and Networked Control Systems*.

Many of current control systems operate in networks across several domains such as Energy Systems, Robotics, and Biology. The possibilities are many as resources can be shared, thanks to technological advances related to the use of communication protocols of the networks. In these systems, the individual elements such as sensor, actuators, and the computational elements might be spatially distributed, and an analysis of the individual components of the network may predict the behavior of the interconnections. Therefore, these emerging applications of controlled systems impose the study of interconnections and their effects on the system performance. The development of methods and algorithms for this class of systems is a challenge of nowadays' applications in which not only the system elements but also the interconnections are heterogeneous.

In this context, properties of the interconnections have to be assessed in terms of properties of individual systems and require specific tools whenever delays, a common phenomenon in communication networks, are introduced. Mathematical models presenting delays may arise from communication or matter transportation, from sampling phenomena or provide alternative representations of infinite-dimensional systems such as the wave equation.

For interconnected systems with delays, the uncertainties and disturbances can be related to the limitation of the communications and are induced by limited bandwidth and packet losses. It is therefore important to evaluate the impact of these disturbances in closed loop. A common strategy is to look at system properties such as the Input-to-State Stability of the system. Even for standard linear control strategies, it is important to evaluate the delays margins as a measure of the expected performance when a control loop is implemented in a network. Also, in some cases, the delays induced by the sampling or the communication can be beneficial for the system robustness. Other phenomena related to interconnected systems and communication protocols may lead to oscillations and strategies to understand and suppress undesired behavior required taking into account the nonlinear elements in the control loops.

This volume proposes different methods and algorithms for the analysis of interconnected systems, in particular systems presenting delays in interconnected systems. The majority of the methods employed to study these classes of systems are either Lyapunov methods, based on a time-domain representation of the system, or spectral methods, based on the representation of linear systems in the frequency domain. These are the main tools used by the contributions presented in the volume, which reflects the contents of the talks presented in the 4th DelSys Workshop that took place on November 25–27, 2015, in the Laboratoire des Signaux et Systèmes, Gif-sur-Yvette, France. The workshop was the last of a series of meetings of the International Scientific Coordination Network on Delay Systems—DelSys, supported by the French Center for Scientific Research (CNRS). The DelSys Network was established to promote research on delay systems and to enable scientific exchanges among experts during the period of 2012–2015.

The contents of the book are organized in three parts:

## Interconnected Systems Analysis

Part one of the volume exposes several methods and strategies to cope with the analysis, control of interconnected systems. The seven chapters in this part cover continuous-time dynamical systems characterized by linear and nonlinear dynamics subject to state input or neutral delays as well as systems governed by a coupling between ordinary and partial differential equations.

This part starts with a chapter "Singular Perturbation Approach for Linear Coupled ODE-PDE Systems" authored by *Ying Tang, Christophe Prieur and Antoine Girard* where the problem of the singular perturbation approach is employed for the stability analysis and robustness of linear systems described by the interconnection of ordinary and partial differential equations.

The second chapter "On Some Neutral Functional Differential Equations Occurring in Synchronization" in this part, authored by *Vladimir Răsvan, Daniela Danciu and Dan Popescu*, deals with the relevance of neutral functional differential equations in the synchronization problem. The problem presented here arisen from the original setting of Huygens oscillators, where it appears that the dynamics of the coupled systems can be interpreted as neutral type of dynamics.

The third chapter "Dynamic Dissipativity Theory for Stability of Time-Delay Systems" provided by *Vijaysekhar Chellaboina and Wassim M. Haddad* aims at studying the dynamic dissipation theory for the stability analysis of time-delay systems. The originality of this contribution is to provide a method for systems subject to feedback interconnection that include delays. The main problem here is to create and enhance the links between the Lyapunov theory, more particularly the Lyapunov-Krasovskii method, and the dissipativity theory.

The next chapter "Stability of Interconnected Uncertain Delay Systems: A Converse Lyapunov Approach" in part one was contributed by *Ihab Haidar, Paolo Mason and Mario Sigalotti*. The objective of this chapter is to study the stability of interconnected uncertain systems subject to time delays. The originality of the present chapter relies on the characterization of a converse Lyapunov theorem for this class of systems.

A chapter "ISS-Stabilization of Delayed Neural Fields by Small-Gain Arguments" prepared by *Antoine Chaillet, Georgios Is. Detorakis, Stéphane Palfi and Suhan Senova* deals with the characterization of ISS stabilization for delayed neural fields by small-gain arguments. The main motivations of this chapter are related to the fact that integrodifferential equations describing the spatiotemporal activity of cerebral structures include delayed interconnection. The theoretical contributions therein are then to provide ISS properties of stabilization for this class of systems.

The following chapter "Robustness of Delayed Multistable Systems" copes with the robustness of delayed multistable systems and has been authored by *Denis Efimov, Johannes Schiffer and Romeo Ortega*. Sufficient conditions for input-to-state stability of delayed systems are provided based on the application of the Lyapunov-Razumikhin theorem. It is notably shown therein that ISS multistable systems are robust with respect to delays in the feedback path.

Part one ends with a chapter "A Small-Gain Method for the Design of Decentralized Stabilizing Controllers for Interconnected Systems with Delays" on the application of the small-gain theorem for the design of decentralized controllers for interconnected systems with delays, whose authors are *Pierdomenico Pepe, Hiroshi Ito and Zhong-Ping Jiang*. More particularly, a decentralized and practical input-to-state stabilization method is provided for a class of interconnected systems, affected by time delays in both the internal variables and in the communication channels, is considered.

## Delay Systems: Modeling and Analysis

Part two of the volume exposes new trends in numeric as well as symbolic developments in the qualitative analysis of infinite-dimensional dynamical systems. As a matter of fact, both time-delay dynamical systems (continuous-time and discrete-time) and wave propagation equations are considered. The latter is a typical example of partial differential equations reducible to time-delay systems of neutral type. This part contains seven chapters covering theoretical contributions as well as applications in the control of infinite-dimensional systems.

This part opens with a chapter "Stability Analysis of Uniformly Distributed Delay Systems: A Frequency-Sweeping Approach" authored by *Xu-Guang Li, Silviu-Iulian Niculescu, Arben Çela and Lu Zhang* in which the stability of a class of systems including uniformly distributed delays is addressed, and a frequency-sweeping curve framework is proposed.

The second chapter "Asymptotic Analysis of Multiple Characteristics Roots for Quasi-polynomials of Retarded-Type" of this part is authored by

*A. Martínez-González, S.-I. Niculescu, J. Chen, C.F. Méndez-Barrios, J.G. Romero and G. Mejía-Rodríguez* where the asymptotic behavior of multiple critical roots of quasi-polynomials is addressed. The proposed analysis is based on the construction Weierstrass polynomial.

The third chapter "Scanning the Space of Parameters for Stability Regions of a Class of Time-Delay Systems; A Lyapunov Matrix Approach" authored by *Carlos Cuvas, Adrián Ramírez, Luis Juárez and Sabine Mondié* proposes a numerical stability test based on delay Lyapunov matrices allowing to detect stability regions in the space of parameters.

The fourth chapter "A Symbolic Computation Approach Towards the Asymptotic Stability Analysis of Differential Systems with Commensurate Delays" of the third part authored by *Yacine Bouzidi, Adrien Poteaux and Alban Quadrat* addresses the problem of delay perturbation effect on the stability of dynamical systems. It proposes certified symbolic-numerical algorithms for computing the set of critical pairs of a given quasipolynomial and for computing a Newton-Puiseux series at a critical pair.

The fifth chapter "Delay-Dependent Reciprocally Convex Combination Lemma for the Stability Analysis of Systems with a Fast-Varying Delay" is authored by *Alexandre Seuret and Frédéric Gouaisbaut*. It deals with the stability analysis of linear systems subject to fast-varying delays. The authors propose an improved version of the reciprocally convex lemma and use the Wirtinger-based integral inequality allowing to new stability conditions.

The sixth chapter "Wave Equation Modelling and Freeness Properties for Wind Power Systems" of this part is authored by *Hugues Mounier and Luca Greco*; it deals with some structural properties of partial differential equations. In particular, it considers two-wave equation model for strings of generators connected to a wind farm and investigates the differential flatness of the system.

This part closes by a chapter "A Delayed Mass-Action Model for the Transcriptional Control of Hmp, an NO Detoxifying Enzyme, by the Iron-Sulfur Protein FNR" on delayed mass-action model describing a biochemical reaction authored by *Marc R. Roussel*. It consists of a qualitative/quantitative study of the transcriptional control of an enzyme known to be a key contributor to the detoxification of nitric oxide.

## Delay Systems: Stabilization and Control Strategies

Part three of the volume focuses on various strategies used to stabilize and control systems with delays. The five chapters in this part cover linear and nonlinear dynamics, continuous- and discrete-time systems, as well as single-input single-output (SISO) and multi-input multi-output (MIMO) systems.

This part opens with a chapter "A Comparison of Shaper-Based and Shaper-Free Architectures for Feedforward Compensation of Flexible Modes" authored by *Dan Pilbauer, Wim Michiels and Tomáš Vyhlídal* where the authors present a detailed study to compare the influence of shaper-based and shaper-free architectures for feedforward compensation of flexible modes. One highlight of the chapter is that shaper-free control design can be effective to achieve proper filtering; however, certain limitations in such controllers further motivate the use of shaper-based compensation schemes, which are designed using time delays.

The second chapter "Proportional-Retarded (PR) Protocol for a Large Scale Multi-agent Network with Noisy Measurements; Stability and Performance" in this part is authored by *Adrián Ramírez and Rifat Sipahi* on the stability analysis and performance assessment of proportional-retarded (PR) controllers in a multi-agent system. The authors identify the stable operating regions of the PR parameters with respect to the eigenvalues of the graph Laplacian of the multi-agent system, and present case studies on how PR controllers can help achieve fast consensus while satisfactorily rejecting noise in measurements.

The third chapter "Inversion of Separable Kernel Operator and Its Application in Control Synthesis", authored by *Guoying Miao, Matthew M. Peet and Keqin Gu*, demonstrates an operator-theoretic framework by which control synthesis problem can be posed in a convex optimization form. The proposed framework makes use of parameterization into finite-dimensional vectors, positive matrices, and certain inversion using algebraic manipulation, to reach a control synthesis approach amenable for computation of state-feedback controllers for differential-difference equations, which include the class of delay differential equations with discrete delays.

The next chapter "Delay Margin for Robust Stabilization of LTI Delay Systems" in part three is authored by *Tian Qi, Jing Zhu and Jie Chen*, on the investigation of delay margin for robust stabilization of LTI SISO closed-loop systems affected by a delay. Here, the authors focus on open-loop plants with unstable poles and non-minimum zeros, to first show a practical approach to obtain a lower bound on the largest delay margin achievable in the closed-loop, and next show how the results extend in the case of time-varying delays.

Part three closes with a chapter "Nonlinear Sampled-Data Stabilization with Delays" on nonlinear sampled-data stabilization with delays, authored by *Salvatore Monaco, Dorothée Normand-Cyrot and Mattia Mattioni*. In this chapter, the authors demonstrate how the effects of sampling stabilize nonlinear dynamics with delays. In particular, the authors demonstrate how to design sampled-data controllers and how sampling could actually help in the stabilization effort. The presentation includes comparisons of several pertaining approaches on this topic, and results are illustrated over academic examples.

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# Contents

# Acronyms

| | |
|---|---|
| AC | Alternating Current |
| AG | Asymptotic Gain |
| CD | Critical delay |
| CIR | Critical imaginary root |
| CLF | Control Lyapunov Function |
| CLKF | Control Lyapunov-Krasovskii Functional |
| CLRF | Control Lyapunov-Razumikhin Function |
| CRS | Completely Regular Splitting |
| CTCR | Cluster Treatment of Characteristic Roots |
| DDE | Delay Differential Equations |
| DG | Distributed Generation |
| FSC | Frequency-Sweeping Curve |
| GAS | Globally Asymptotically Stable |
| GPe | External globus pallidus |
| HANSO | Hybrid Algorithm for Non-Smooth Optimization |
| I&I | Immersion and Invariance |
| ILM | Input-Lyapunov Matching |
| IR | Integral-Retarded |
| ISS | Input-to-State Stability |
| LHP | Left-Half Plane |
| LIM | Limit Property |
| LMI | Linear Matrix Inequality |
| LQR | Linear Quadratic Regulator |
| LR | Lyapunov-Razumikhin |
| LTI | Linear-Time-Invariant |
| MIMO | Multi-Input Multi-Output |
| mRNA | Messenger RNA |
| NO | Nitric Oxide |
| ODE | Ordinary Differential Equation |
| pAG | Practical Asymptotic Gain |

| | |
|---|---|
| PDE | Partial Differential Equation |
| pGS | Practical global stability |
| PID | Proportional Integral Derivative |
| PIR | Proportional-Integral-Retarded |
| PR | Proportional-Retarded |
| RFDE | Retarded Functional Differential Equation |
| RHP | Right-Half Plane |
| RNAP | RNA Polymerase |
| RS | Regular Splitting |
| RUR | Rational Univariate Representation |
| S-GAS | Sampled-data Globally Asymptotically Stable |
| SISO | Single-Input Single-Output |
| SOS | Sum-Of-Squares |
| STN | Subthalamic Nucleus |
| TDS | Time-Delay Systems |
| UDDS | Uniformly Distributed Delay System |