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Editors

Recent Results on Nonlinear Delay Control Systems

In honor of Miroslav Krstic

Springer

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We dedicate this book to Prof. Miroslav Krstic on his 50th birthday, to help honor him for his many important contributions to control theory and its applications.

The Editors

Foreword

The past 5 years have seen many significant advances in the area of control theory for time-delay systems, including constructive methods for transforming Lyapunov functions into the Lyapunov-Krasovskii functionals that are convenient for establishing stability of nonlinear time-delay systems, controllers for hybrid systems that involve continuous time subsystems and rules for switching between the subsystems, predictive results that can compensate arbitrarily long input delays, and much more. Much of this theory is now being applied in key engineering applications, including fluid dynamics, oil production, and rehabilitation methods for patients with mobility disorders. As the editor for the *Advances in Delays and Dynamics* series, it is a pleasure to present this new volume, which covers many of these advances. The volume includes papers by many leaders in the controls field, including two papers by Miroslav Krstic to whom this volume is dedicated. The collection was meticulously edited by four prominent specialists in the field of delay systems whose research is also included in this volume. I hope you enjoy reading this volume as much as I appreciate the opportunity to present this excellent volume to you.

Gif-sur-Yvette, France
June 2015

Silviu-Iulian Niculescu

Preface

Time-delay systems occur in many important engineering applications. When the delays are small, they can sometimes be safely ignored, which reduces control problems to more standard problems that can be covered by traditional frequency-domain or well-known Lyapunov function techniques for systems free of delays. However, many engineering systems contain large time delays. For instance, large input delays often arise from communication delays between sensors and actuators, or from time-consuming information gathering. Using standard controls on nonstandard systems such as delay systems can yield poor control performance, and uncompensated input delays can produce hazards when used in engineering applications. This puts time-delay systems outside of the scope of standard methods that are commonly used for systems that have no delays, and it necessitates developing more reliable methods that can avoid the pitfalls of using traditional controllers on more complicated time-delay systems.

This volume collects some recent advances in the area of time-delay systems, with special emphasis on constructive generalized Lyapunov approaches that can certify key stability properties such as uniform global asymptotic stability, and predictive methods that can compensate arbitrarily long input delays. In this preface, we summarize the main contributions of the chapters to put the contributions in context. In the first chapter, we present an overview of recent advances in delay compensation for nonlinear time-delay systems, with emphasis on Lyapunov-Krasovskii functionals, and on tests for robustness of nonlinear controllers with respect to delays in the input. The second chapter is by Ahmed-Ali, Karafyllis, Krstic, and Lamnabhi-Lagarrigue and covers robustness of time delays systems with respect to measurement and modeling uncertainties, including systems with outputs and zero-order hold.

Backstepping is an important technique for generating controllers for nonlinear systems by building up from controllers for their subsystems. In the third chapter, Bekiaris-Liberis, Jankovic, and Krstic present a generalization of backstepping for systems in strict feedback form, where the delays may be nonconstant. Although linear systems are generally much easier to control than nonlinear systems, there are still significant challenges for linear systems with time-varying coefficients. The fourth chapter by Bresch-Pietri and Petit addresses some of these remaining challenges for linear systems, using a predictive approach. The next chapter is by Cacace, Germani, and Manes and it deals with state estimation under measurement delay, through the use of a chain-type high gain observer. Then Califano and Moog provide a chapter on new results on normal forms for time-delay systems, including novel necessary and sufficient conditions for a time-delay system to be decomposable into observable and nonobservable subsystems. The next chapter is by Downey, Kamalapurkar, Fischer, and Dixon and is a change of pace, focusing on an application of predictor-based delay compensation to neuromuscular electrical stimulation, which is a developing technology that can help restore movement in certain patients with mobility disorders. Homogeneity is an important property of certain nonlinear systems that can significantly facilitate the design and analysis of controllers, and the chapter by Efimov, Perruquetti, and Richard in this volume proposes a novel extension of homogeneity methods to time-delay systems based on a Lyapunov-Razumikhin approach.

In the following chapter, authors Han, Fridman, and Spurgeon present a sliding mode observer that is based on linear matrix inequalities and provides ultimate boundedness of the observation error. Neutral systems with delay play an important role in distributed networks, heat exchangers, and population models, and are characterized by having time delays entering the time derivatives of the states. In the following chapter, authors Mazenc and Ito present a novel Lyapunov-Krasovskii functional method for proving stability properties for large-scale neutral systems, where the delays occur in both the interconnection channels and the subsystems themselves. Small gain theory is another powerful method for establishing stability of large-scale systems, based on studying growth conditions on the compositions of the comparison functions in the stability estimates for the individual subsystems. In their chapter on input-to-state stability and switched systems, authors Jiang, Lin and Wang combine small gain arguments with Razumikhin function methods to establish conditions under which a switched system consisting of input-to-state stable subsystems is itself input-to-state stable.

Returning to the important themes of Lyapunov-Krasovskii methods and neutral systems, the next chapter by Karafyllis and Pepe presents converse Lyapunov functional methods for neutral systems that generalize existing results by allowing uncertainties, delays, and more general difference operators that were not already covered in the literature. Although converse Lyapunov theory is largely nonconstructive, it has had significant theoretical ramifications for systems free of delays, so time delay converse theory has the potential for wide use across control theory. The next chapter by Liu and Teel discusses several recent efforts to extend hybrid systems theory to time-delay systems with uncertainties, by covering foundational issues such as well-posedness of solutions.

The next chapter is by Novella-Rodriguez, Witrant, and Sename, and it extends some time-delay systems notions to hyperbolic systems of PDEs, by considering transport in fluid pipes. Returning to the predictor approach, the chapter by Oguchi provides an analog of finite spectrum assignment for time-delay systems, which leads to a predictive approach that does not require numerical integration. Input constraints are another key challenge for delay compensating controllers, because saturating the control values in a stabilizing controller can lead to a failure of the control to ensure the required stability properties. In their chapter, authors Seuret, Gouaisbaut, Tarbouriech, and Gomes da Silva address input saturation problems in the context of delayed sampled data systems, by studying a convex optimization problem. The following chapter by Verriest studies a state reconstruction problem, whose goal is to find values of the state using current or delayed values of an output, including cases where the delay is not required to be constant.

Continuing with the theme of nonconstant delays but returning to the theme of sliding mode controls, the next chapter by Yan, Spurgeon, and Orlov uses Lyapunov-Razumikhin methods to provide a sliding mode observer for nonlinear systems with time-varying delays, assuming a time invariant output matrix and general conditions on the nonlinear parts of the systems. Maintaining the theme of time-varying delays, the following chapter by Yoon, Anantachaisilp, and Lin uses linear matrix inequalities to stabilize linear systems under input saturations and time-varying delays, including an application to an experimental test rig for active magnetic bearings. In the final chapter, Zheng and Richard address the problem of identifying input delays, using the theory of noncommutative rings, and they apply their methods to establish causal and noncausal observability for nonlinear time-delay systems with unknown inputs.

We dedicate this volume to Prof. Miroslav Krstic, on the occasion of his 50th birthday. Through his many excellent presentations and publications including 10 books and his helpful discussions, Miroslav has inspired each of us to work on challenging control problems that can impact several parts of engineering. Infinite thanks go to Dr. Silviu-Iulian Niculescu, our longstanding mentor, for his continuous advice and precious guidance. This volume would not have been possible without the help of the external referees who reviewed each chapter, and the technical support we received from Thomas Ditzinger and his colleagues at Springer, so we thank the reviewers and everyone at Springer for their help and for the opportunity to publish this work. We hope you enjoy reading this volume as much as we appreciated the opportunity to edit it.

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