

Preface

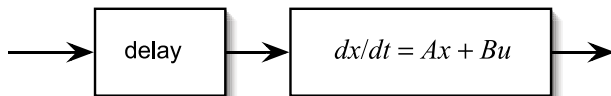
This year is the 50th anniversary of Otto J. Smith's 1959 publication of a control design idea commonly referred as the *Smith predictor* for the compensation of actuator delays. Actuator and sensor delays are among the most common dynamic phenomena that arise in engineering practice but fall outside the scope of the standard finite-dimensional systems.

Predictor-based feedbacks and other controllers for systems with input and output delays have been (and continue to be) an active area of research during the last five decades. Several books exist that focus on the mathematical and engineering problems in this area. The goals of this book are not to duplicate the material in those books nor to present a comprehensive account about control of systems with input and output delays. Instead, the book's goal is to shed light on new opportunities for predictor feedback, through extensions to nonlinear systems, delay-adaptive control, and actuator dynamics modeled by PDEs more complex than transport (pure delay) PDEs.

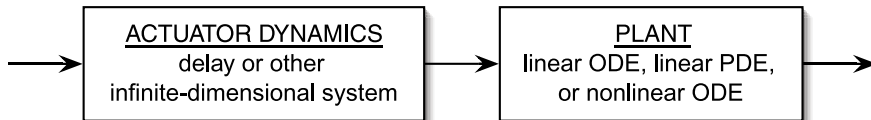
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What Does the Book Cover? This book is a research monograph that introduces the treatment of systems with input delays as PDE-ODE cascade systems with *boundary control*. The PDE-based approach yields Lyapunov–Krasovskii functionals that make the control design constructive and enables stability analysis with quantitative estimates, which leads to the resolution of several long-standing problems in predictor feedback for linear time-invariant (LTI) systems. More importantly, the PDE-based approach enables the extension of predictor feedback design to nonlinear systems and to adaptive control for systems with unknown delays.

However, the book's treatment of input and output delays as transport PDEs allows it to aim even further, in expanding the predictor feedback ideas to systems with other types of infinite-dimensional actuator dynamics and sensor dynamics. We develop methods for compensating heat PDE and wave PDE dynamics at the input of an arbitrary, possibly unstable, LTI-ODE plant. Similarly, we develop observers for LTI-ODE systems with similar types of sensor dynamics. Finally, we introduce problems for PDE-PDE cascades, such as, for example, the notoriously



The standard problem of linear ODE plant with input delay, leading to conventional predictor feedback control.



The problems considered in this book.

difficult problem of a wave PDE with input delay where, if the delay is left uncompensated, an arbitrarily short delay destroys the closed-loop stability (as shown by Datko in 1988).

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Who Is the Book For? The book should be of interest to all researchers working on control of delay systems—engineers, graduate students, and delay systems specialists in academia. The latter group will especially benefit from this book, as it opens several new paradigms for delay research. Many opportunities present themselves to extend the present results to systems that contain state delays (discrete and/or distributed) in addition to input delays.

Mathematicians with interest in the broad area of control of distributed parameter systems, and PDEs in particular, will find the book stimulating because it tackles nonlinear ODEs simultaneously with linear PDEs, as well as PDEs from different classes. These problems present many stimulating challenges for further research on the stabilization of ever-expanding classes of unstable infinite-dimensional systems.

Chemical engineers and process dynamics researchers, who have traditionally been users of the Smith predictor and related approaches, should find the various extensions of this methodology that the book presents (adaptive, nonlinear, other PDEs) to be useful and exciting. Engineers from other areas—electrical and computer engineering (telecommunication systems and networks), mechanical and aerospace engineering (combustion systems and machining), and civil/structural engineering—have no doubt faced problems with actuator delays and other distributed parameter input dynamics and will appreciate the advances introduced by this book.

This book is not meant to be a standalone textbook for any individual graduate course. However, its parts can be used as supplemental material in lectures or projects in many graduate courses:

- general distributed parameter systems (Chapters 2, 3, 6, 14–20),
- linear delay systems (Chapters 2, 3, 6, 18, and 19),
- partial differential equations (Chapters 14–20),
- nonlinear control (Chapters 10–13),

- state estimators/observers (Chapters 3 and 17),
- adaptive control (Chapters 7–9), and
- robust control (Chapters 4 and 5),
- linear time-varying (LTV) systems (Chapter 6).

The background required to read this book includes little beyond the basics of function spaces and Lyapunov theory for ODEs. However, the basics of the Poincaré and Agmon inequalities, Lyapunov and input-to-state stability, parameter projection for adaptive control, and Bessel functions are summarized in appendices for the reader's convenience.

I hope that the reader will not view the book as a collection of problems that have been solved, but will focus on it as a collection of tools and techniques that are applicable in open problems, many more of which exist than have been solved in this book, particularly in the areas of interconnected systems of ODEs and PDEs, systems with simultaneous input and state delays, nonlinear delay systems, and systems with unknown delays.

In no book are all chapters equal in value for the reader. My personal recommendations to a reader on a time budget are Chapters 7, 10, 16, and 18 if the reader is interested mainly in feedback design problems and tools. A reader primarily interested in analysis and robustness problems for delay systems might also enjoy Chapter 5.

Acknowledgments. I would like to thank Delphine Bresch-Pietri, Andrey Smyshlyaev, and Rafael Vazquez for their contributions in Chapters 8, 9, 11, 14, and elsewhere.

I am also grateful to Mrdjan Jankovic for exchanges of ideas and his guidance through the area of control of delay systems. If it were not for Mrdjan's superb and innovative papers on control of nonlinear delay systems, I would never have been enticed to start to work on these problems. I am also pleased to express special gratitude to Iasson Karafyllis for some helpful and inspiring discussions.

Many thanks to Manfred Morari, Silviu Niculescu, Galip Ulsoy, and Qing-Chang Zhong for discussions on delay systems and on the Smith predictor. I would also like to thank Anu Annaswamy for getting me intrigued with her papers on adaptive control of delay systems.

Finally, Petar Kokotovic's encouragement and interest in new research results are priceless—often a key difference between deciding whether or not to spend time on writing a new book.

Over the course of writing this book, I had the pleasure to meet Otto J. M. Smith on the occasion of my visit to the University of California at Berkeley in October 2008. "Predictably," I chose the results on predictor feedback as the topic of my Nokia Distinguished Lecture. Otto Smith was a professor at Berkeley from 1947 until his retirement in 1988. I have never met a 91-year-old person with as sharp a mind as Otto Smith's. Truth be told, I have met few 30-year-olds who would be worth a comparison. Even at this age, Otto Smith was every bit the inventor and creative engineer as his list of patents indicates. I had the pleasure of hearing about his favorite designs, from the HP function generator to his current interest in solar

energy turbine power plants with controlled focusing via heliostats. We never got to discuss the “Smith predictor”—there was so much else worth hearing about from Otto Smith’s bank of engineering knowledge. I am grateful to Alex Bayen and Dean Shankar Sastry for arranging for Otto Smith to come to campus that day. I also thank Masayoshi Tomizuka for sharing many thoughts on Otto Smith during my Springer Professor sabbatical stay at Berkeley in the fall of 2007.

Sadly, Otto Smith passed away on May 10, 2009 as a result of a fall at his home. In the five decades since the publication of his influential paper on compensation of dead time, he had seen his idea become one of the most commonly used tools in control practice.

I am grateful to Cymer (Bob Akins, Danny Brown, and other friends) and General Atomics (Mike Reed, Sam Gurol, Bogdan Borowy, Dick Thome, Linden Blue, and other friends) for their support through the *Cymer Center for Control Systems and Dynamics* at UC San Diego. I also very much appreciate the support by Bosch (Nalin Chaturvedi and Aleksandar Kojic) and the National Science Foundation (Kishan Baheti and Suhada Jayasuriya).

Finally, for all the hundreds of evening and weekend hours that were spent on this book and not with my family, for all the mathematics homework that I was excused from helping with, my gratitude and love go to Alexandra, Victoria, and Angela.

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