Dynamics and Nonlinear Control of Integrated Process Systems

Presenting a systematic model reduction and hierarchical controller design framework for broad classes of integrated process systems encountered in practice, this book first studies process systems with large material recycle and/or with small purge streams, followed by systems with energy integration. Step-by-step model reduction procedures are developed to derive nonlinear reduced models of the dynamics in each time scale. Hierarchical control architectures, consisting of coordinated levels of control action in different time scales, are proposed for each class of process systems considered in order to enforce stability, tracking performance, and disturbance rejection. Numerous process applications are discussed in detail to illustrate the application of the methods and their potential to improve process operations. Matlab codes are also presented to guide further application of the methods developed and facilitate practical implementations.

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To our families

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Preface

The chemical process industry is an intensely competitive environment, where cost reduction represents a critical factor towards increasing profit margins. Over the last few decades, an ever growing need to lower utility costs and energy consumption, and to improve raw material use, has spurred the development and implementation of increasingly integrated process designs that make extensive use of material recycling and energy recovery.

The significant reduction in capital and operating costs associated with process integration does, however, come at the price of additional operational and control challenges. Research on the control of interconnected process systems and entire chemical plants has been driven both by developments in control and optimization theory, and by shifts in market demands and industry needs. Initial efforts focused on decentralized multi-loop control structures and on including plant-wide considerations in the tuning of PID controllers. The associated benefits dwindled, however, with the rise of modern, tightly integrated processes with strong dynamic coupling between the different process units. More recently, control systems developed within the linear model predictive control (MPC) paradigm have allowed centralized decision making and accounting for economic optimality under operating constraints. In the (petro)chemical industry, MPC remains the established means for regulatory control and plant operation around a given steady state.

The current economic environment is, however, highly dynamic. Economically optimal plant operations thus entail frequent switching among different operating conditions (i.e., different steady states), having different product grades and production rates. Adopting or adapting the existing fully centralized or completely decentralized control designs for enforcing such transitions is neither practical nor effective in the context of integrated processes, where the interactions between the process units become significant and unique dynamic features emerge.

Developed around an extensive body of recent research by the authors, this book provides a new paradigm for the effective control of tightly integrated process systems, by

- documenting rigorously the dynamic behavior that emerges at the plant level when tight integration through material recycling and energy recovery is employed
- presenting the means for deriving explicit and physically meaningful low-dimensional models of the dominant plant dynamics
- describing a hierarchical controller design framework that discerns and coordinates between regulatory control at the unit level and supervisory, plant-wide control, and enables the design of nonlinear controllers for enforcing plant-wide transitions
- illustrating the application of the theoretical concepts to several integrated processes found in the chemical and energy industries

The chapters strive to balance rigor and practicality. The systematic analysis of generic, prototypical processes that exemplify the process integration structures encountered in practice is emphasized together with the unique dynamic features and control challenges that they present. Illustrative examples and extensive case studies on specific problems support the theoretical developments and provide a practical vista. The text adopts a unique and quintessentially chemical engineering perspective by introducing the concept of a process-level dimensionless number to characterize process integration from both a process *design* and a process *control* point of view. We are hopeful that our approach will allow readers to rapidly master the underlying theory and develop extensions to other classes of problems. Implementation details (sample computer codes) are provided in order to further encourage the rapid deployment of practical applications.

The book targets graduate students and researchers interested in dynamics and control, as well as practitioners involved in advanced control in industry. It can serve as a reference text in an advanced process systems engineering or process control course and as a valuable resource for the researcher or practitioner. Written at a basic mathematical level (and largely self-contained from a mathematical point of view), the material assumes some familiarity with process modeling and an elementary background in nonlinear dynamical systems and control.

We are grateful to our colleagues at the Department of Chemical Engineering and Materials Science at Minnesota for maintaining an environment of scientific excellence and collegiality over the years. M.B. is also grateful to the fellow researchers at the Praxair Technology Center in Tonawanda, NY for creating an intellectually stimulating atmosphere. We owe special thanks to Ed Cussler for his advice and encouragement in the initial stages of the writing of this book, the staff at Cambridge University Press for their support and advice, and the National Science Foundation for the support it provided for the research that formed the basis for this book. We also owe a special note of appreciation to Aditya Kumar for his instrumental role in the initial phase of research on this subject, and to Sujit Jogwar, whose recent work further solidified the basic thesis and direction of the book.

This book is dedicated to my parents, with gratitude for their unconditional love and support, and to the memory of my grandparents, who fondly followed my childhood scientific pursuits.

M.B.

I dedicate this book to my wife Aphrodite for her uncompromising pursuit of beauty in all aspects of our life, and to my children Stylianos and Euphrosyne for the immeasurable joy and inspiration they bring.

P.D.