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Model-based control of particulate processes

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Abstract

In this work, we present an overview of recently developed methods for model-based control of particulate processes. We primarily discuss methods developed in the context of our previous research work and use examples of crystallization, aerosol and thermal spray processes to motivate the development of these methods and illustrate their application. Specifically, we initially discuss control methods for particulate processes which utilize suitable approximations of population balance models to design nonlinear, robust and predictive control systems and demonstrate their application to crystallization and aerosol processes. Finally, we discuss the issues of control problem formulation and controller design for high-velocity oxygen-fuel (HVOF) thermal spray processes and close with few thoughts on unresolved research challenges on control of particulate processes.

Keywords: Particulate processes; Order reduction; Model-based feedback control; Crystallization; Aerosol processes; Thermal spray processes

1. Introduction

Particulate processes (also known as dispersed-phase processes) are characterized by the co-presence of and strong interaction between a continuous (gas or liquid) phase and a particulate (dispersed) phase and are essential in making many high-value industrial products. Particulate processes play a prominent role in a number of process industries since about 60% of the products in the chemical industry are manufactured as particulates with an additional 20% using powders as ingredients. Representative examples of industrial particulate processes include the crystallization of proteins for pharmaceutical applications, the emulsion polymerization for the production of latex, the fluidized bed production of solar-grade silicon particles through thermal decomposition of silane gas, the aerosol synthesis of titania powder used in the production of white pigments, and the thermal spray processing of nanostructured thermal barrier and wear resistant coatings. The industrial importance of particulate processes and the realization that the physicochemical and mechanical properties of materials made with particulates depend heavily on the characteristics of the underlying particle-size distribution (PSD) have motivated significant research attention over the last 10 years on model-based control of particulate processes. These efforts have also been complemented by recent and on-going developments in measurement technology which allow the accurate and fast on-line measurement of key process variables including important characteristics of PSDs (e.g., Larsen et al., 2006; Rawlings et al., 1992, 1993). The recent efforts on model-based control of particulate processes have also been motivated by significant advances in the modeling of particulate processes. Specifically, population balances have provided a natural framework for the mathematical modeling of PSDs in broad classes of particulate processes (see, for example, the tutorial article (Hulburt and Katz, 1964) and the review article (Ramkrishna, 1985)), and have been successfully used to describe PSDs in emulsion polymerization reactors (e.g., Dimitratos et al., 1994; Doyle et al., 2002), crystallizers (e.g., Braatz and Hasebe, 2002; Rawlings et al., 1993), aerosol reactors (e.g., Friedlander,

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Modelbased Control Of Particulate Processes

Panagiotis D. Christofides

Modelbased Control Of Particulate Processes:

Model-Based Control of Particulate Processes Panagiotis D. Christofides,2013-04-17 Particulate processes are characterized by the co presence of a contin uous phase and a dispersed particulate phase and are widely used in industry for the manufacturing of many high value products Examples include the crystallization of proteins for pharmaceutical applications the emulsion polymerization reactors for the production of latex the aerosol synthesis of titania powder used in the production of white pig ments and the thermal spray processing of nanostructured coatings It is now well understood that the physico chemical and mechanical properties of materials made with particulates depend heavily on the characteristics of the corresponding particle size distribution This fact together with recent advances in dynamics of infinite dimensional sys tems and nonlinear control theory has motivated extensive research on model based control of particulate processes using population balances to achieve tight control of particle size distributions This book the first of its kind presents general methods for the synthesis of nonlinear robust and constrained feedback controllers for broad classes of particulate process models and illustrates their applica tions to industrially important crystallization aerosol and thermal spray processes The controllers use a finite number of measurement sensors and control actuators to achieve stabilization of the closed loop system output tracking attenuation of the effect of model uncertainty and han dling of actuator saturation

Model-Based Control of Particulate Processes Panagiotis D. Christofides,2002-10-31 The interest in control of particulate processes has been triggered by the need to achieve tight distributed control of size distributions that greatly influence particulate product properties and quality Drawing from recent advances in dynamics of infinite dimensional systems and nonlinear control theory control of particulate processes using population balances has evolved into a very active research area within the field of process control This book the first of its kind presents general methods for the synthesis of nonlinear robust and constrained feedback controllers for broad classes of particulate process models and illustrates their applications to industrially important crystallization aerosol and thermal spray processes The controllers use a finite number of measurement sensors and control actuators to achieve stabilization of the closed loop system output tracking attenuation of the effect of model uncertainty and handling of actuator saturation Beginning with an introduction to control of particulate processes the book discusses nonlinear order reduction and nonlinear robust and constrained control of particulate spatially homogeneous processes and nonlinear control of spatially homogeneous particulate processes The synthesis of the controllers is performed by using geometric and Lyapunov based control techniques The book includes comparisons of the methods followed for controller synthesis with other approaches and discussions of practical implementation issues that can help researchers and engineers understand the development and application of the methods in greater depth The methods are applied to continuous and batch crystallization processes a titania aerosol reactor and a thermal spray process to regulate product size distribution The resulting benefits in closed loop performance robustness and

actuator saturation handling compared to other techniques for control of particulate processes are demonstrated through computer simulations The book assumes a basic knowledge about population balances and nonlinear control Researchers and graduate students in process control particle technology and control systems theory applied mathematicians and process control engineers will find this book a useful resource The Control Handbook William S. Levine,2018-10-08 At publication The Control Handbook immediately became the definitive resource that engineers working with modern control systems required Among its many accolades that first edition was cited by the AAP as the Best Engineering Handbook of 1996 Now 15 years later William Levine has once again compiled the most comprehensive and authoritative resource on control engineering He has fully reorganized the text to reflect the technical advances achieved since the last edition and has expanded its contents to include the multidisciplinary perspective that is making control engineering a critical component in so many fields Now expanded from one to three volumes The Control Handbook Second Edition organizes cutting edge contributions from more than 200 leading experts The second volume Control System Applications includes 35 entirely new applications organized by subject area Covering the design and use of control systems this volume includes applications for Automobiles including PEM fuel cells Aerospace Industrial control of machines and processes Biomedical uses including robotic surgery and drug discovery and development Electronics and communication networks Other applications are included in a section that reflects the multidisciplinary nature of control system work These include applications for the construction of financial portfolios earthquake response control for civil structures quantum estimation and control and the modeling and control of air conditioning and refrigeration systems As with the first edition the new edition not only stands as a record of accomplishment in control engineering but provides researchers with the means to make further advances Progressively organized the other two volumes in the set include Control System Fundamentals Control System Advanced Methods The Control Handbook (three volume set) William S. Levine,2018-10-08 At publication The Control Handbook immediately became the definitive resource that engineers working with modern control systems required Among its many accolades that first edition was cited by the AAP as the Best Engineering Handbook of 1996 Now 15 years later William Levine has once again compiled the most comprehensive and authoritative resource on control engineering He has fully reorganized the text to reflect the technical advances achieved since the last edition and has expanded its contents to include the multidisciplinary perspective that is making control engineering a critical component in so many fields Now expanded from one to three volumes The Control Handbook Second Edition brilliantly organizes cutting edge contributions from more than 200 leading experts representing every corner of the globe They cover everything from basic closed loop systems to multi agent adaptive systems and from the control of electric motors to the control of complex networks Progressively organized the three volume set includes Control System Fundamentals Control System Applications Control System Advanced Methods Any practicing engineer student or researcher working in fields as diverse as electronics aeronautics or

biomedicine will find this handbook to be a time saving resource filled with invaluable formulas models methods and innovative thinking In fact any physicist biologist mathematician or researcher in any number of fields developing or improving products and systems will find the answers and ideas they need As with the first edition the new edition not only stands as a record of accomplishment in control engineering but provides researchers with the means to make further advances Feedback Control of MEMS to Atoms Jason J. Gorman,Benjamin Shapiro,2011-12-16 Control from MEMS to Atoms illustrates the use of control and control systems as an essential part of functioning integrated systems The book is organized according to the dimensional scale of the problem starting with micro scale systems and ending with atomic scale systems Similar to macro scale machines and processes control systems can play a major role in improving the performance of micro and nano scale systems and in enabling new capabilities that would otherwise not be possible However the majority of problems at these scales present many new challenges that go beyond the current state of the art in control engineering This is a result of the multidisciplinary nature of micro nanotechnology which requires the merging of control engineering with physics biology and chemistry **Model-Based Control:** Paul M.J. van den Hof,Carsten Scherer,Peter S.C. Heuberger,2009-08-05 Model Based Control will be a collection of state of the art contributions in the field of modelling identification robust control and optimization of dynamical systems with particular attention to the application domains of motion control systems high accuracy positioning systems and large scale industrial process control systems The book will be directed to academic and industrial people involved in research in systems and control industrial process control and mechatronics *Modeling and Control of Batch Processes* Prashant Mhaskar,Abhinav Garg,Brandon Corbett,2018-11-28 Modeling and Control of Batch Processes presents state of the art techniques ranging from mechanistic to data driven models These methods are specifically tailored to handle issues pertinent to batch processes such as nonlinear dynamics and lack of online quality measurements In particular the book proposes a novel batch control design with well characterized feasibility properties a modeling approach that unites multi model and partial least squares techniques a generalization of the subspace identification approach for batch processes and applications to several detailed case studies ranging from a complex simulation test bed to industrial data The book s proposed methodology employs statistical tools such as partial least squares and subspace identification and couples them with notions from state space based models to provide solutions to the quality control problem for batch processes Practical implementation issues are discussed to help readers understand the application of the methods in greater depth The book includes numerous comments and remarks providing insight and fundamental understanding into the modeling and control of batch processes Modeling and Control of Batch Processes includes many detailed examples of industrial relevance that can be tailored by process control engineers or researchers to a specific application The book is also of interest to graduate students studying control systems as it contains new research topics and references to significant recent work Advances in Industrial Control reports and encourages the transfer of

technology in control engineering The rapid development of control technology has an impact on all areas of the control discipline The series offers an opportunity for researchers to present an extended exposition of new work in all aspects of industrial control **Nonlinear Model-based Control of Particulate Processes** Timothy Yeechung Chiu,2000

Handbook of Continuous Crystallization Nima Yazdanpanah,Zoltan K Nagy,2020-02-04 Continuous crystallization is an area of intense research with particular respect to the pharmaceutical industry and fine chemicals Improvements in continuous crystallization technologies offer chemical industries significant financial gains through reduced expenditure and operational costs and consistent product quality Written by well known leaders in the field The Handbook of Continuous Crystallization presents fundamental and applied knowledge with attention paid to application and scaling up and the burgeoning area of process intensification Beginning with concepts around crystallization techniques and control strategies the reader will learn about experimental methods and computational tools Case studies spanning fine and bulk chemicals the pharmaceutical industry and employing new mathematical tools put theory into context *Fault-Tolerant Process Control* Prashant Mhaskar,Jinfeng Liu,Panagiotis D. Christofides,2012-11-27 Fault Tolerant Process Control focuses on the development of general yet practical methods for the design of advanced fault tolerant control systems these ensure an efficient fault detection and a timely response to enhance fault recovery prevent faults from propagating or developing into total failures and reduce the risk of safety hazards To this end methods are presented for the design of advanced fault tolerant control systems for chemical processes which explicitly deal with actuator controller failures and sensor faults and data losses Specifically the book puts forward A framework for detection isolation and diagnosis of actuator and sensor faults for nonlinear systems Controller reconfiguration and safe parking based fault handling methodologies Integrated data and model based fault detection and isolation and fault tolerant control methods Methods for handling sensor faults and data losses and Methods for monitoring the performance of low level PID loops The methodologies proposed employ nonlinear systems analysis Lyapunov techniques optimization statistical methods and hybrid systems theory and are predicated upon the idea of integrating fault detection local feedback control and supervisory control The applicability and performance of the methods are demonstrated through a number of chemical process examples Fault Tolerant Process Control is a valuable resource for academic researchers industrial practitioners as well as graduate students pursuing research in this area

Dynamic Process Modeling ,2013-10-02 Inspired by the leading authority in the field the Centre for Process Systems Engineering at Imperial College London this book includes theoretical developments algorithms methodologies and tools in process systems engineering and applications from the chemical energy molecular biomedical and other areas It spans a whole range of length scales seen in manufacturing industries from molecular and nanoscale phenomena to enterprise wide optimization and control As such this will appeal to a broad readership since the topic applies not only to all technical processes but also due to the interdisciplinary expertise required to solve the challenge The ultimate reference work for

years to come **Process Systems Engineering 2003** Bingzhen Chen,Art Westerberg,2003-06-06 Contains proceedings from the 8th International Symposium on Process Systems Engineering PSE which brought together the global community of process systems engineering researchers and practitioners involved in the creation and application of computing based methodologies for planning design operation control and maintenance of chemical processes Contains proceeding from the 8th International Symposium on Process Systems EngineeringConference theme for PSE 2003 is supporting business decision making *34th European Symposium on Computer Aided Process Engineering /15th International Symposium on Process Systems Engineering* Flavio Manenti,G.V. Rex Reklaitis,2024-06-27 The 34th European Symposium on Computer Aided Process Engineering 15th International Symposium on Process Systems Engineering contains the papers presented at the 34th European Symposium on Computer Aided Process Engineering 15th International Symposium on Process Systems Engineering joint event It is a valuable resource for chemical engineers chemical process engineers researchers in industry and academia students and consultants for chemical industries Presents findings and discussions from the 34th European Symposium on Computer Aided Process Engineering 15th International Symposium on Process Systems Engineering joint event **Dynamics and Control of Process Systems 2004** Sirish Shah,John F. MacGregor,2005-06-10 Monitoring Polymerization Reactions Wayne F. Reed,Alina M. Alb,2014-01-21 Offers new strategies to optimize polymer reactions With contributions from leading macromolecular scientists and engineers this book provides a practical guide to polymerization monitoring It enables laboratory researchers to optimize polymer reactions by providing them with a better understanding of the underlying reaction kinetics and mechanisms Moreover it opens the door to improved industrial scale reactions including enhanced product quality and reduced harmful emissions Monitoring Polymerization Reactions begins with a review of the basic elements of polymer reactions and their kinetics including an overview of stimuli responsive polymers Next it explains why certain polymer and reaction characteristics need to be monitored The book then explores a variety of practical topics including Principles and applications of important polymer characterization tools such as light scattering gel permeation chromatography calorimetry rheology and spectroscopy Automatic continuous online monitoring of polymerization ACOMP reactions a flexible platform that enables characterization tools to be employed simultaneously during reactions in order to obtain a complete record of multiple reaction features Modeling of polymerization reactions and numerical approaches Applications that optimize the manufacture of industrially important polymers Throughout the book the authors provide step by step strategies for implementation In addition ample use of case studies helps readers understand the benefits of various monitoring strategies and approaches enabling them to choose the best one to match their needs As new stimuli responsive and intelligent polymers continue to be developed the ability to monitor reactions will become increasingly important With this book as their guide polymer scientists and engineers can take full advantage of the latest monitoring strategies to optimize reactions in both the lab and the manufacturing plant Dynamic Flowsheet Simulation of Solids Processes Stefan

Heinrich,2020-06-20 This book presents the latest advances in flowsheet simulation of solids processes focusing on the dynamic behaviour of systems with interconnected solids processing units but also covering stationary simulation The book includes the modelling of solids processing units for example for comminution sifting and particle formulation and also for reaction systems Furthermore it examines new approaches for the description of solids and their property distributions and for the mathematical treatment of flowsheets with multivariate population balances *Intelligent Control in Drying* Alex Martynenko,Andreas Bück,2018-09-03 Despite the available general literature in intelligent control there is a definite lack of knowledge and know how in practical applications of intelligent control in drying This book fills that gap Intelligent Control in Drying serves as an innovative and practical guide for researchers and professionals in the field of drying technologies providing an overview of control principles and systems used in drying operations from classical to model based to adaptive and optimal control At the same time it lays out approaches to synthesis of control systems based on the objectives and control strategies reflecting complexity of drying process and material under drying This essential reference covers both fundamental and practical aspects of intelligent control sensor fusion and dynamic optimization with respect to drying

Controlled Particle, Droplet and Bubble Formation D J Wedlock,2012-12-02 The ability to control particle size distributions and to characterize them once formed is an increasingly important topic in the processing industry Many standard processing techniques are looked at in this book but from new and innovative perspectives Well established techniques such as crystallization and precipitation are covered alongside newer technologies such as sol gel processing Formation of products using emulsions aerosols and polymers covered in this book are used across a wide variety of processing industries and all those involved in the processing of chemicals food minerals bioproducts and many other products will find this book an informative reference source **Spatio-Temporal Modeling of Nonlinear Distributed Parameter Systems** Han-Xiong Li,Chenkun Qi,2011-02-24 The purpose of this volume is to provide a brief review of the previous work on model reduction and identifi cation of distributed parameter systems DPS and develop new spatio temporal models and their relevant identifi cation approaches In this book a systematic overview and classifi cation on the modeling of DPS is presented fi rst which includes model reduction parameter estimation and system identifi cation Next a class of block oriented nonlinear systems in traditional lumped parameter systems LPS is extended to DPS which results in the spatio temporal Wiener and Hammerstein systems and their identifi cation methods Then the traditional Volterra model is extended to DPS which results in the spatio temporal Volterra model and its identification algorithm All these methods are based on linear time space separation Sometimes the nonlinear time space separation can play a better role in modeling of very complex processes Thus a nonlinear time space separation based neural modeling is also presented for a class of DPS with more complicated dynamics Finally all these modeling approaches are successfully applied to industrial thermal processes including a catalytic rod a packed bed reactor and a snap curing oven The work is presented giving a unifi ed view from time

space separation The book also illustrates applications to thermal processes in the electronics packaging and chemical industry This volume assumes a basic knowledge about distributed parameter systems system modeling and identifi cation It is intended for researchers graduate students and engineers interested in distributed parameter systems nonlinear systems and process modeling and control **12th International Symposium on Process Systems Engineering and 25th European Symposium on Computer Aided Process Engineering** ,2015-07-14 25th European Symposium on Computer Aided Process Engineering contains the papers presented at the 12th Process Systems Engineering PSE and 25th European Society of Computer Aided Process Engineering ESCAPE Joint Event held in Copenhagen Denmark 31 May 4 June 2015 The purpose of these series is to bring together the international community of researchers and engineers who are interested in computing based methods in process engineering This conference highlights the contributions of the PSE CAPE community towards the sustainability of modern society Contributors from academia and industry establish the core products of PSE CAPE define the new and changing scope of our results and future challenges Plenary and keynote lectures discuss real world challenges globalization energy environment and health and contribute to discussions on the widening scope of PSE CAPE versus the consolidation of the core topics of PSE CAPE Highlights how the Process Systems Engineering Computer Aided Process Engineering community contributes to the sustainability of modern society Presents findings and discussions from both the 12th Process Systems Engineering PSE and 25th European Society of Computer Aided Process Engineering ESCAPE Events Establishes the core products of Process Systems Engineering Computer Aided Process Engineering Defines the future challenges of the Process Systems Engineering Computer Aided Process Engineering community

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