1. Introduction

Process control is a traditional area in process systems engineering which is of great practical importance. Control usually involves other related fields, like dynamic modeling, identification, diagnosis, *etc*.

The majority of practical control applications are mainly based on PID loops; there are only a few advanced control systems, either for operating units (equipment) with complex or unstable dynamic behavior, or plantwide optimizing control.

> *It is widely known in process systems engineering that almost all process systems are nonlinear in nature.*

Therefore advanced process control should necessarily use nonlinear control techniques.

1.1 A Brief Overview of Nonlinear Process Control

Elementary or introductory control courses for both control (electrical) and process engineers are almost entirely based on *linear systems*; this is what we all start with. The reason for this is twofold. First of all, there are relatively simple closed analytical solutions to many control problems (including LQR and pole-placement controller design, Kalman-filtering, model parameter and structure estimation, *etc.*), so the linear theory is nice, transparent and feasible. On the other hand, practical applications are also based on linear or linearized models in most cases and handle nonlinearities only when it is absolutely unavoidable.

The common way of controlling process systems with strong nonlinear character is to apply model-based predictive controllers where a detailed dynamic process model is used in an optimization framework. The popularity of model-based predictive control is partially explained by the fact that it fits so well into the "culture" of process systems engineering: it uses traditional dynamic process models which are usually available for design and/or simulation purposes. At the same time, model-based predictive control is being criticized by control engineers because of its lack or weakness of theoretical background, having no guarantee of convergence, stability, robustness, *etc.* in the general case.

Modern heuristic black-box-type control approaches, such as neural nets and fuzzy controllers, have also appeared recently even in industrial practice. At the same time, the results and approaches of modern nonlinear control theory have not earned acceptance in the field of process control. There are two reasons. Firstly, these techniques require an advanced mathematical background and skills, which are rarely taught to process engineers. Secondly, modern nonlinear control methods are computationally hard, and are only feasible for small-scale systems in the general case.

These problems with nonlinear control techniques applied in the general case indicate that a solid knowledge of the special characteristics of the nonlinear system in question may significantly help in developing nonlinear controllers for process systems with reasonably realistic complexity. Therefore, any work in the area of nonlinear process control should be based on an interdisciplinary approach that integrates the results and techniques of process systems engineering with nonlinear systems and control theory. The interdisciplinary nature of this approach behooves us to present an overview of the existing literature in both fields from a special integrating viewpoint.

There are excellent and widely used textbooks where the *nonlinear analysis and control techniques* are presented, such as:

1. H. Nijmeijer and A.J. Van der Schaft (1990) *Nonlinear Dynamical Control Systems*, Springer.
2. A. Isidori (1995) *Nonlinear Control Systems I.-II. (Communication and Control Engineering Series)*, Springer.
3. A.J. van der Schaft (1999) *L2-Gain and Passivity Techniques in Nonlinear Control (Communication and Control Engineering Series)*, Springer.

The above textbooks intend to cover a range of nonlinear analysis and control techniques in an abstract mathematical way, concentrating on the aspects relevant for refining or developing further the techniques. Also, the intended readers are graduate and postgraduate students specializing in control engineering or in applied mathematics. Therefore these books do not meet the needs of process engineering students interested in the application of these methods for process systems.

There are also application oriented textbooks available on the market dealing with nonlinear control, such as [10], [66] and [60]. These books cover a wide range of application areas, therefore they cannot take the specialities of process systems into account and do not build on the engineering knowledge readily available in the field.

1.2 Aims and Objectives

This textbook has been written for graduate and postgraduate students with a process engineering background. It aims to bridge the gap between process systems engineering and advanced nonlinear control theory by:

- providing the necessary mathematical preliminaries for graduate and postgraduate students with a process engineering background,
- presenting the relevant and promising theory and methods for analyzing and controlling nonlinear process systems,
- emphasizing the importance and use of process knowledge, mainly process models developed from first engineering principles, for obtaining feasible and effective special cases of the general methods.

The textbook deals with the basic concepts and with the most promising tools and techniques in nonlinear process analysis and control illustrated by simple examples and tutorial material.

The notions and techniques are always introduced and illustrated in the standard finite dimensional linear time-invariant continuous case, which serves as a basis for an extension to the nonlinear case. This way, the necessary links are also established with more widely known material, which makes the understanding of the concepts and methods a lot easier.

The Level of the Text. The level corresponds to graduate or postgraduate courses in process systems engineering.

The interdisciplinary and rapidly developing nature of the topic as well as the broad and diverse background of the potential readers requires us to restrict the prerequisite knowledge to a necessary minimum. Only basic higher mathematics common in engineering courses, such as linear algebra and elementary calculus are assumed. A solid knowledge of process modeling and control are advisable.

The advanced mathematical tools and notions we build upon are summarized in **Appendix A** of the textbook.

Learning Aids. This book is primarily a textbook. Therefore we provide special learning tools in order to make its use more comfortable for both lecturers and students of a course in analysis and control of nonlinear process systems. These include:

- an **Index** containing the special terms, definitions, methods and other important knowledge elements in the book,
- a **List of Definitions**, which is a special index for the most important terms and notions in the book,
- simple worked in-text examples, which have the following format:

Example 1.2.1 (Example of examples)
A simple example

....

- a **List of Examples** of the above which is another special index,
- learning aid sections, such as **Summary**, **Questions and Application Exercises** at the end of each chapter,
- an additional learning aid section **Further Reading** at the end of each non-introductory chapter (Chapters 5–12),
- a simple typographical scheme to distinguish important terms, definitions and statements in the text in the form:

This is an important knowledge item.

1.3 The Road Map of the Book

The material is divided into three logical parts:

- *Control-oriented modeling of concentrated parameter nonlinear systems* (Chapters 1-5).
  The basic notions of systems and signals are presented first in Chapter 2. Thereafter linear and nonlinear state-space models are discussed (Chapter 3). The construction and the special structure of dynamic process models is described in Chapter 4. Chapter 5 is devoted to input–output models important for some of the analysis and control techniques later on,
- *Nonlinear system analysis methods and tools* (Chapters 6–8).
  The most important nonlinear analysis methods for controllability, observability and stability are described first (Chapters 6 and 7). Chapter 8 is devoted to passivity analysis and the Hamiltonian description, which are powerful concepts with an important physical basis in the case of process systems,
- *Nonlinear feedback control* (Chapters 9–12).
  An introductory chapter (Chapter 9) deals with the basic notions and techniques for state feedback control, in particular pole-placement and LQR control of linear time-invariant systems. Thereafter separate chapters deal with the most important special techniques for nonlinear process control: feedback and input–output linearization, passivation and stabilization and loop-shaping based on the Hamiltonian view.

Finally, the necessary mathematical preliminaries not contained in a standard process engineering curriculum, namely coordinate transformations, norms, Lie-derivatives and -products, distributions as well as co-distributions are summarized in **Appendix A**.

The road map of the book, which shows using arrows the dependence of the material presented in the chapters, is depicted in Figure 1.1. Directed paths show how to proceed when taking a tour through the material: either by giving/taking a course or by self-learning.

The dashed arrows connecting Chapter 4 “Dynamic process models” to the other chapters indicate that each non-introductory chapter contains at least one section where process system case studies are described.

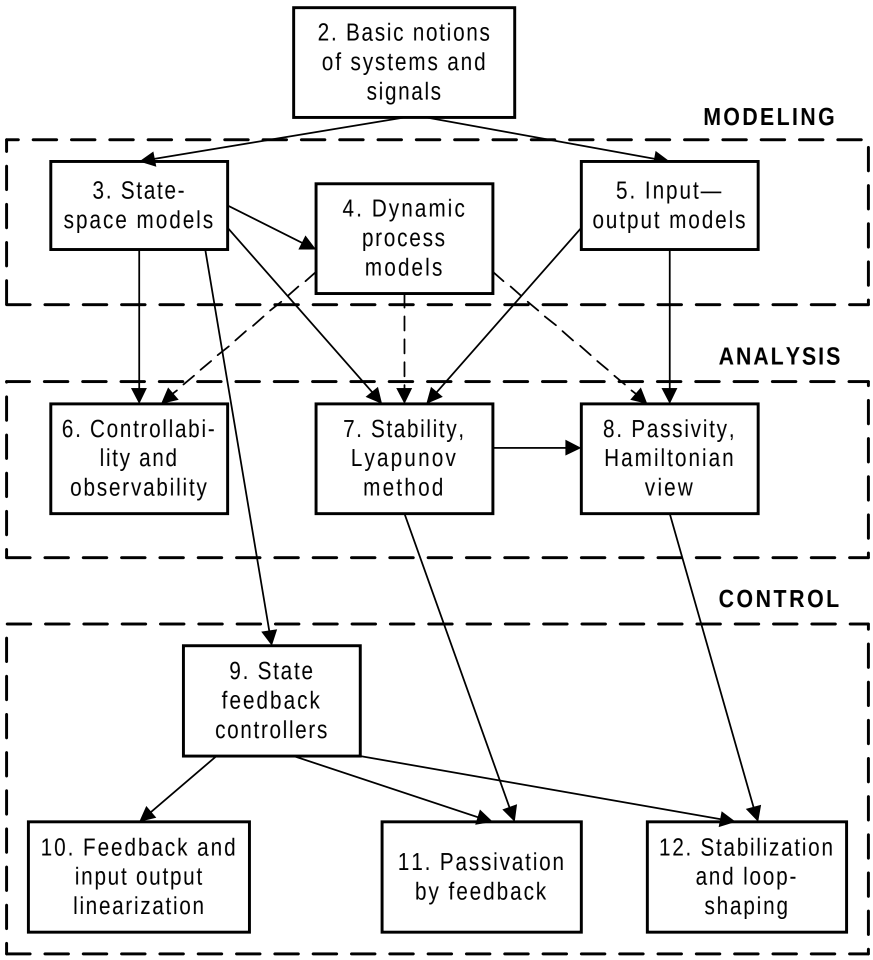

Figure 1.1. The road map of the book

The first draft version of this material was used for an intensive four-week postgraduate course taught for process engineers in the CAPEC Center, Department of Chemical Engineering, Technical University of Denmark (Lyngby, Denmark) in 2000.

Part of the material has been used for an elective course entitled “Modern control methods” taught for information engineers at the University of Veszprém, Hungary since 2003.