Coleman Brosilow/Babu Joseph

Techniques of Model-Based Control

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To

My wife Rosalie,
My children Rachelle and Benjamin, and
My grandchildren Adam, Maya, Tomer and Elah.
My parents Ethel and Samuel, may his memory be for a blessing.
Coleman Brosilow

My wife Philomina and
My children Mili, Neeraj, and Sonia
Babu Joseph

Preface

The design and tuning of any control system is always based on a model of the process to be controlled. For example, when an engineer tunes a PID control system online the controller gain and the integral and derivative time constants obtained from the tuning depend on the local behavior of the process, and this local behavior could, if desired, be well approximated by a mathematical model. It turns out, however, that even in the prosaic task of tuning a PID controller, much better control system behavior can be obtained if the local mathematical model of the process is actually obtained, and the PID tuning is based on that model (see Chapter 6 on PID tuning). The foregoing not withstanding, in this text the term model-based controller is used primarily to mean control systems that explicitly embed a process model in the control algorithm. In particular, we consider control algorithms such as internal model control (IMC), inferential control (IC) and model-predictive control (such as dynamic matrix control or DMC), which have found applications in the process industry over the last few decades.

The book focuses on techniques. By this we mean how the algorithms are designed and applied. There is less emphasis on the underlying theory. We have also used simple examples to illustrate the concepts. More complex and realistic examples are provided in the text as case study projects.

We have written the text with two types of audience in mind. One is the typical industrial practitioner engaged in the practice of process control and interested in learning the basics behind various controller tuning methods as well as advanced control strategies beyond traditional PID feedback control. Our aim is to provide sufficient understanding of the methodologies of model-based control to enable the engineer to determine where and when such control strategies can offer substantial improvement in control as well as how to implement and maintain such strategies. The second audience that we have in mind is students in senior or graduate level advanced process control courses. For such students, we have tried to provide homework exercises and suggested projects to enhance the learning process. It is assumed throughout that the student has convenient access to modern computing systems along with the necessary software. Most of the problems and examples cannot be carried out without the use of such tools. We have organized the book as shown in the following figure.

BASIC CONCEPTS

1 Introduction
2 Continuous-Time Models
3 One-Degree of Freedom Internal Model Control

CONTINUOUS-TIME MODEL-BASED CONTROL

4 Two-Degree of Freedom Internal Model Control
5 Model State Feedback Implementations of IMC
6 PI and PID Parameters From IMC Designs
7 Tuning and Synthesis of 1DF IMC for Uncertain Processes
8 Tuning and Synthesis of 2DF IMC for Uncertain Processes
9 Feedforward Control
10 Cascade Control
11 Output Constraint Control (Override Control)
12 Single Variable Inferential Control
13 Inferential Estimation Using Multiple Measurements

DISCRETE TIME MODEL-BASED CONTROL

14 Discrete-Time Models
15 Identification: Basic Concepts
16 Identification: Advanced Concepts
17 Basic Model Predictive Control
18 Advanced Model Predictive Control
19 Inferential MPC

SUPPORTING APPENDIX MATERIAL

A Review of Basic Concepts
B Frequency Response Analysis
C Review of Linear Least-Squares Regression
D Random Variables and Random Processes
E MATLAB and Control Toolbox Tutorial
F SIMULINK Tutorial
G Tutorial on IMCTUNE Software
H Identification Software
I SIMULINK Models For Case Studies

SUPPORTING SOFTWARE

IMCTUNE, MODELBUILDER, POLYID, AND PIDTUNER

Overview of Material in Text

Chapter 1 gives an overview of the hierarchical approach to process control. Chapter 2 reviews the various types of models used in process control with emphasis on continuous time models. Chapter 3 gives the development of the basic model-based control structure (IMC). The latter two chapters form the basis of the further developments in both continuous and discrete time implementations.

From this point on the reader can take two possible paths: the first path focuses on the development of theory and structures for continuous-time implementation using the IMC structure. The second path focuses on discrete-time (computer-based) implementation of model-based control.

Chapters 4 through 13 cover the first path. Chapter 4 focuses on simultaneous setpoint and disturbance rejection using a two-degree of freedom control structure. Chapter 5 shows how to handle control effort constraints using model state feedback. Chapter 6 shows the relationship between classical PID controllers and the internal model control structure. Chapter 7 shows how to design one-degree of freedom controllers in the presence of model uncertainty. Chapter 8 shows how to tune two-degree of freedom controllers. Chapters 9 through 11 focus on multiloop control structures such as feedforward, cascade, and constraint control. Chapter 12 discusses control using secondary measurements (called inferential control). Chapter 13 extends the concepts of Chapter 12 to inferential control using multiple secondary measurements using disturbance estimation methods.

Chapters 14 through 19 cover the second path dealing with discrete-time computer implementation of model-based controllers. Chapter 14 introduces the models used in discrete-time representation and Chapters 15 and 16 discuss algorithms used to identify such models from plant test data. Chapters 17 and 18 discuss the computer implementation of model-based control using the model-predictive control framework. Chapter 19 extends this to inferential control using secondary measurements.

As an aid to the various possible readers, we have provided an extensive set of appendices that contain the background material necessary for the material in the main body of the text. We have indicated at the beginning of each chapter the prerequisite material, and we suggest that the appropriate appendices be reviewed prior to reading the chapter. The following material is reviewed:

- Laplace transforms and block diagrams.
- Frequency response methods.
- Linear least square regression.
- Probability theory and random variables.
- MATLAB® and SIMULINK® software[1].

We have used the MATLAB/SIMULINK software system as the platform upon which to develop software that provides added functionality and a convenient interface for solving otherwise complex problems. Among the reasons for this choice is that the MATLAB platform provides the tools required to implement and test various control concepts with relatively little effort required to learn how to use the software. However, there is

[1] MATLAB and SIMULINK are trademarks of MathWorks, Inc.

other software that provides similar functionality, and the reader is encouraged to use whichever tools are most comfortable.

The website[2] associated with this text contains the following material:

- **IMCTUNE:** A user-friendly interface to a set of MATLAB m-files that enables the reader to design and tune both IMC and PID controllers for single loop, feedforward and cascade control systems. In addition to MATLAB and SIMULINK, IMCTUNE requires the Control System and Optimization toolboxes in addition to MATLAB 5.3.1 or later versions.

- **MODELBUILDER:** A set of MATLAB m-files to generate both discrete time and continuous time process models from input/output data. Requires the Identification Toolbox.

- **PIDTUNER:** A set of MATLAB m-files that implement and test classical PID tuning. Requires the Control System Toolbox.

- **SIMULINK case study models**: MATLAB/SIMULINK models of a number of process systems including the Shell fractionation column, a Naphtha cracker simulator and the Tennessee Eastman problem. These models can be used in course projects.

- **Microsoft PowerPoint slides** containing the text material.

- **MATLAB m-files, mat-files and data files, SIMULINK mdl-files** and Microsoft Word files related to the examples and exercises in the text. These files are identified by chapter and example number. The *.mat files for the examples in Chapters 3 through 11 are associated with IMCTUNE.

- **Syllabi** used by the authors in their respective undergraduate and graduate courses.

The reader is strongly encouraged to download the software listed above and to use it to reproduce results of examples in the text, and to solve the problems at the end of the chapters. Our experience with teaching using this text material indicates that hands-on exercises using simulated processes is important to get a good understanding of the concepts. Hence the reader is strongly urged to experiment with the software. We have provided a number of exercises that require computer implementation and testing of the concepts.

While the normal reader will have had an introductory course in process control, it is possible to use at least parts of this text in an introductory course. For example, Coleman Brosilow has used Chapters 3, 5, 6, 7, and parts of 9 and 10 in a first undergraduate course

[2] The website address is *http://www.phptr.com/brosilow/*

in process control for more than ten years. Babu Joseph has been using the Appendix material in the laboratory sessions associated with the undergraduate course. The entire material in this book can be included in a graduate course on process control. However, the book should be supplemented with some additional material on multivariable control.

The SIMULINK case studies provide comprehensive test beds for implementing and testing the various concepts and algorithms presented in the text. The visual feedback provided by the simulation case studies is valuable in understanding the performance and limitations of the control algorithms. Experience with the simulated examples can smooth the transition to real-world applications.

Acknowledgements

We want to thank the pioneers in the field of model-based control, who are listed in the references, and from whom we have borrowed extensively. We also want to thank the numerous anonymous reviewers who read this manuscript and gave very valuable suggestions. Also not to be overlooked are our many students who also made suggestions for improving the readability and clarity of the text. In particular we would like to thank our former graduate students Drs. Jiawen Dong, Frieda Wang-Hanratty, Peter Hanratty, Shi-Shang Jang, Tannakorn Kumsaen, Mario Laiseca, Srinivas Palavajjhala, Sairam Potaraju, Deepak Srinivasagupta, Karel Stryczek, Matthew Thomas, Srikanth Voorakaranam, and Chao-Ming Ying, who helped us develop the material in the book and the software at the website.

The IMCTUNE software development was started by Mario Laiseca, and continued, with many substantial changes and improvements, by Karel Stryczek, Jiawen Dong, and Tannakorn Kumsaen. It is not an exaggeration to say that without their work Coleman Brosilow's contribution to this text would not have been possible.

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We acknowledge Drs. Downs and Vogel for permission to include a SIMULINK model of the Tennessee Eastman (TE) process on our website. Dr. Palavajjhala graciously agreed to provide a copy of a chapter from his thesis dealing with this problem on the website. He also prepared the MATLAB m-files that simulate the TE process. Undergraduate students Andrew Tillinghast and Nick Graham developed the SIMULINK files for this process.

Thanks are also due to Dr. Ying, who developed the core programs used in the identification software provided with this text.

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TABLE OF CONTENTS