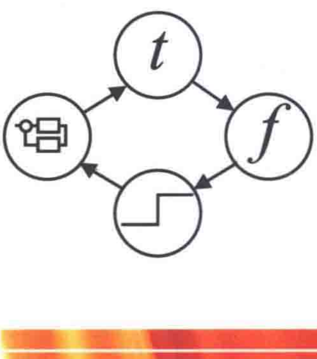
DAVID M. KOENIG



Practical Control Engineering

A Guide for Engineers, Managers, and Practitioners

MATLAB® examples

The McGraw·Hill Companies

Library of Congress Cataloging-in-Publication Data

Koenig, David M.
Practical control engineering : a guide for engineers, managers, and practitioners / David M. Koenig.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-07-160613-4 (alk. paper)
1. Automatic control. 2. Control theory. I. Title.
TJ213.K578 2009
629.8—dc22 2008037488

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. To contact a special sales representative, please visit the Contact Us page at www.mhprofessional.com.

Practical Control Engineering

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 1 4 3 2 1 0 9

ISBN 978-0-07-160613-4
MHID 0-07-160613-0

The pages within this book were printed on acid-free paper containing 15% post-consumer fiber.

Sponsoring Editor
Taisuke Soda

Acquisitions Coordinator
Michael Mulcahy

Editorial Supervisor
David E. Fogarty

Project Manager
Preeti Longia Sinha

Copy Editor
Ragini Pandy

Proofreader
Bhavna Gupta

Indexer
David M. Koenig

Production Supervisor
Richard C. Ruzycka

Composition
International Typesetting and Composition

Art Director, Cover
Jeff Weeks

Practical Control Engineering

About the Author

David M. Koenig had a 27 year career in process control and analysis for Corning, Inc., retiring as an Engineering Associate. His education started at the University of Chicago in chemistry, leading to a PhD in chemical engineering at The Ohio State University. He resides in upstate New York where his main job is providing day care for his six month old grandson.

To Joshua Lucas, Ryan, Jennifer, Denise,
Julie and Bertha and
in memory of Wilda and Rudy.

Preface

You may be an engineering student, a practicing engineer working with control engineers, or even a control engineer. But I am going to assume that you are a manager.

Managers of control engineers sometimes have a difficult challenge. Many companies promote top managerial prospects laterally into unfamiliar technical areas to broaden their outlook. A manager in this situation often will have several process control engineers reporting directly to her and she needs an appreciation for their craft. Alternatively, technical project managers frequently supervise the work of process control engineers on loan from a department specializing in the field. This book is designed to give these managers insight into the work of the process control engineers working for them. It can also give the student of control engineering an alternative and complementary perspective.

Consider the following scenario. A sharp control engineer, who either works for you or is working on a project that you are managing, has just started an oral presentation about his sophisticated approach to solving a knotty control problem. What do you do? If you are a successful manager, you have clearly convinced (perhaps without foundation) many people of your technical competence so you can probably ride through this presentation without jeopardizing your managerial prestige. However, you will likely want to actually critique his presentation carefully. This could be a problem since, being a successful manager, you are juggling several technically diverse balls in the air and haven't the time to research the technological underpinnings of each. Furthermore, your formal educational background may not be in control engineering. The above-mentioned control engineer, embarking on his presentation, is probably quite competent but perhaps he has been somewhat enthralled by the elegance of his approach and has missed the forest for the trees (it certainly happened to me many times over the years). You should be able to ask some penetrating questions or make some key suggestions that will get him on track and make him (and you) more successful. Hopefully, you will pick up a few hints on the kind of questions to ask while reading this book.

The Curse of Control Engineering

The fundamental stumbling block in understanding process control engineering is its language—applied mathematics. I could attempt to skirt the issue with a qualitative book on control engineering. Not only is this difficult to do but it would not really equip the manager to effectively interact with and supervise the process control engineer. To do this, the manager simply has to understand (and speak) the language.

If terms like $\frac{dy}{dt}$ or $\int_0^a dt\, e^{st}$ strike fear in your heart then you should consider looking first at the appendices which are elementary but detailed reviews of the applied mathematics that I will refer to in the main part of the text and that control engineers use in their work. Otherwise, start at the beginning of the book. As you progress through it, I will often show only the results of applying math to the problem at hand. In each case you will be able to go to an appendix and find the pertinent math in much more detail but presented at an introductory level. The chapters are the forest; the appendices are the trees and the leaves.

You may wonder why much of the math is not inserted into the body of the text as each new topic is discussed—it's a valid concern because most books do this. I am assuming that you will read over parts of this book many times and will not need to wade through the math more than once, if that. After all, you are a manager, looking at a somewhat bigger picture than the control engineer.

Also, you may wonder why there are so many appendices, some of them quite long, and relatively few chapters. You might ask, "Are you writing an engineering book or an applied mathematics book?" To those who would ask such an "or" question I will simply pause for a moment and then quietly say, "yes."

Style

The book's style is conversational. I do not expect you to "study" this book. You simply do not have the time or energy to hunker down and wade through a technical tome, given all the other demands of your job. There are no exercises at the ends of the chapters. Rather, I foresee you delving into this book during your relaxation or down time; perhaps it will be a bedtime read...well, maybe a little tougher than that. Perhaps you could spend some time reading it while waiting in an airport. As we progress through the book I will pose occasional questions and sometimes present an answer immediately in small print. You will have the choice of thinking deeply about the question or just reading my response—or perhaps both!

On the other hand, if this book is used in a college level course, the students will likely have access to Matlab and the instructor can easily assign homework having the students reproduce or modify the figures containing simulation and control exercises. I will, upon request, supply you with a set of Matlab scripts or m-files that will generate all the mathematically based figures in the book. Send me an e-mail and convince me you are not a student in a class using this book.

References

There aren't any. That's a little blunt but I don't see you as a control theory scholar—for one thing, you don't have time. However, if you are a college-level engineering student then you already have an arsenal of supporting textbooks at your beck and call.

A Thumbnail Sketch of the Book

The first chapter presents a brief qualitative introduction to many aspects of control engineering and process analysis. The emphasis is on insight rather than specific quantitative techniques.

The second chapter continues the qualitative approach (but not for long). It will spend some serious time dealing with how the engineer should approach the control problem. It will suggest a lot of upfront time be spent on analyzing the process to be controlled. If the approaches advocated here are followed, your control engineer may be able to bypass up the development of a control algorithm altogether.

Since the second chapter emphasized process analysis, the third chapter picks up on this theme and delves into the subject in detail. This chapter will be the first to use mathematics extensively. My basic approach here and throughout the book will be to develop most of the concepts carefully and slowly for simple first-order systems (to be defined later) since the math is so much friendlier. Extensions to more complicated systems will sometimes be done either inductively without proof or by demonstration or with support in the appendices. I think it is sufficient to fully understand the concepts when applied to first-order situations and then to merely feel comfortable about those concepts in other more sophisticated environments.

The third chapter covers a wide range of subjects. It starts with an elementary but thorough mathematical time-domain description of the first-order process. This will require a little bit of calculus which is reviewed in Appendix A. The proportional and proportional-integral control algorithms will be applied to the first-order process and some simple mathematics will be used to study the system. We then will move directly to the s-domain via the Laplace transform (supported in Appendix F). This is an important subject for control engineers and can be a bit scary. It will be my challenge to present it logically, straightforwardly, and clearly.

Just when you might start to feel comfortable in this new domain we will leave Chapter Three and I will kick you into the frequency domain. Chapter Four also adds two more process models to the reader's toolkit—the pure dead-time process and the first-order with dead-time process.

Chapter Five expands the first-order process into a third-order process. This process will be studied in the time and frequency domains. A new mathematical tool, matrices, will be introduced to handle the higher dimensionality. Matrices will also provide a means of looking at processes from the state-space approach which will be applied to the third-order process.

Chapter Six is devoted to the next new process—the mass/spring/dashpot process that has underdamped behavior on its own. This process is studied in the time, Laplace, frequency and state-space domains. Proportional-integral control is shown to be lacking so an extra term containing the derivative is added to the controller. The chapter concludes with an alternative approach, using state feedback, which produces a modified process that does not have underdamped behavior and is easier to control.

Chapter Seven moves on to yet another new process—the distributed process, epitomized by a tubular heat exchanger. To study this process model, a new mathematical tool is introduced—partial differential equations. As before, this new process model will be studied in the time, Laplace, and frequency domains.

At this point we will have studied five different process models: first-order, third-order, pure dead-time, first-order with dead-time, underdamped, and distributed. This set of models covers quite a bit of territory and will be sufficient for our purposes.

We need control algorithms because processes and process signals are exposed to disturbances and noise. To properly analyze the process we must learn how to characterize disturbances and noise. So, Chapter Eight will open a whole new can of worms, stochastic processes, that often is bypassed in introductory control engineering texts but which, if ignored, can be your control engineer's downfall.

Chapters Eight and Nine deal with the discrete time domain, which also has its associated transform—the Z-transform, which is introduced in the latter chapter. As we move into these two new domains I will introduce alternative mathematical structures for our set of process models which usually require more sophisticated mathematics.

In Chapter Five, I started frequently referring to the state of the process or system. Chapter Ten comes to grips with the estimation of the state using the Kalman filter. A state-space based approach to process control using the Kalman filter is presented and applied to several example processes.

Although the simple proportional-integral-derivative control algorithm is used in the development of concepts in Chapters Three through Nine, the eleventh chapter revisits control algorithms using a slightly different approach. It starts with the simple integral-only algorithm and progresses to PI and the PID. The widely used concept of cascade control is presented with an example. Controlling processes subject to white noise has often been a controversial subject, especially when statisticians get involved. To stir the pot, I spend a section on this subject.

This completes the book but it certainly does not cover the complete field of process control. However, it should provide you with a starting point, a reference point and a tool for dealing with those who do process control engineering as a profession.

If you feel the urge, let me know your thoughts via

dmkoenig@alumni.uchicago.edu.

Good luck while you are sitting in the airports!

Practical
Control Engineering

Contents

Preface xvii

1 **Qualitative Concepts in Control Engineering and Process Analysis** **1**
1-1 What Is a Feedback Controller 1
1-2 What Is a Feedforward Controller 3
1-3 Process Disturbances 5
1-4 Comparing Feedforward and Feedback Controllers 7
1-5 Combining Feedforward and Feedback Controllers 8
1-6 Why Is Feedback Control Difficult to Carry Out 9
1-7 An Example of Controlling a Noisy Industrial Process 10
1-8 What Is a Control Engineer 15
1-9 Summary 16

2 **Introduction to Developing Control Algorithms** . **17**
2-1 Approaches to Developing Control Algorithms 17
2-1-1 Style, Massive Intelligence, Luck, and Heroism (SMILH) 17
2-1-2 A Priori First Principles 18
2-1-3 A Common Sense, Pedestrian Approach 19
2-2 Dealing with the Existing Process 19
2-2-1 What Is the Problem 20
2-2-2 The Diamond Road Map 20
2-3 Dealing with Control Algorithms Bundled with the Process 27
2-4 Some General Comments about Debugging Control Algorithms 29
2-6 Documentation and Indispensability 35
2-7 Summary 36

3 **Basic Concepts in Process Analysis** **37**
3-1 The First-Order Process—an Introduction . 37
3-2 Mathematical Descriptions of the First-Order Process 39

3-2-1 The Continuous Time Domain Model . 39
3-2-2 Solution of the Continuous Time Domain Model 42
3-2-3 The First-Order Model and Proportional Control 44
3-2-4 The First-Order Model and Proportional-Integral Control 48
3-3 The Laplace Transform 57
3-3-1 The Transfer Function and Block Diagram Algebra 59
3-3-2 Applying the New Tool to the First-Order Model 60
3-3-3 The Laplace Transform of Derivatives 61
3-3-4 Applying the Laplace Transform to the Case with Proportional plus Integral Control 62
3-3-5 More Block Diagram Algebra and Some Useful Transfer Functions 65
3-3-6 Zeros and Poles 67
3-4 Summary 73

4 A New Domain and More Process Models 75
4-1 Onward to the Frequency Domain 75
4-1-1 Sinusoidally Disturbing the First-Order Process 75
4-1-2 A Little Mathematical Support in the Time Domain 79
4-1-3 A Little Mathematical Support in the Laplace Transform Domain 81
4-1-4 A Little Graphical Support 82
4-1-5 A Graphing Trick 85
4-2 How Can Sinusoids Help Us with Understanding Feedback Control? 87
4-3 The First-Order Process with Feedback Control in the Frequency Domain 91
4-3-1 What's This about the Integral? 94
4-3-2 What about Adding P to the I? 95
4-3-3 Partial Summary and a Rule of Thumb Using Phase Margin and Gain Margin 98
4-4 A Pure Dead-Time Process 99
4-4-1 Proportional-Only Control of a Pure Dead-Time Process 102
4-4-2 Integral-Only Control of a Pure Dead-Time Process 103

4-5 A First-Order with Dead-Time (FOWDT) Process . . . 107
4-5-1 The Concept of Minimum Phase . . . 109
4-5-2 Proportional-Only Control . . . 109
4-5-3 Proportional-Integral Control of the FOWDT Process . . . 111
4-6 A Few Comments about Simulating Processes with Variable Dead Times . . . 114
4-7 Partial Summary and a Slight Modification of the Rule of Thumb . . . 116
4-8 Summary . . . 118

5 Matrices and Higher-Order Process Models . . . 121
5-1 Third-Order Process without Backflow . . . 121
5-2 Third-Order Process with Backflow . . . 129
5-3 Control of Three-Tank System with No Backflow . . . 133
5-4 Critical Values and Finding the Poles . . . 139
5-5 Multitank Processes . . . 140
5-6 Summary . . . 143

6 An Underdamped Process . . . 145
6-1 The Dynamics of the Mass/Spring/Dashpot Process . . . 145
6-2 Solutions in Four Domains . . . 149
6-2-1 Time Domain . . . 149
6-2-2 Laplace Domain Solution . . . 149
6-2-3 Frequency Domain . . . 150
6-2-4 State-Space Representation . . . 151
6-2-5 Scaling and Round-Off Error . . . 152
6-3 PI Control of the Mass/Spring/Dashpot Process . . . 153
6-4 Derivative Control (PID) . . . 156
6-4-1 Complete Cancellation . . . 161
6-4-2 Adding Sensor Noise . . . 161
6-4-3 Filtering the Derivative . . . 163
6-5 Compensation before Control—The Transfer Function Approach . . . 165
6-6 Compensation before Control—The State-Space Approach . . . 171
6-7 An Electrical Analog to the Mass/Dashpot/Spring Process . . . 174
6-8 Summary . . . 176

7 Distributed Processes **177**
- 7-1 The Tubular Energy Exchanger—Steady State 177
- 7-2 The Tubular Energy Exchanger—Transient Behavior 180
  - 7-2-1 Transfer by Diffusion 182
- 7-3 Solution of the Tubular Heat Exchanger Equation 183
  - 7-3-1 Inlet Temperature Transfer Function 184
  - 7-3-2 Steam Jacket Temperature Transfer Function 184
- 7-4 Response of Tubular Heat Exchanger to Step in Jacket Temperature 185
  - 7-4-1 The Large-Diameter Case 185
  - 7-4-2 The Small-Diameter Case 186
- 7-5 Studying the Tubular Energy Exchanger in the Frequency Domain 188
- 7-6 Control of the Tubular Energy Exchanger .. 192
- 7-7 Lumping the Tubular Energy Exchanger .. 194
  - 7-7-1 Modeling an Individual Lump 194
  - 7-7-2 Steady-State Solution 196
  - 7-7-3 Discretizing the Partial Differential Equation 197
- 7-8 Lumping and Axial Transport 200
- 7-9 State-Space Version of the Lumped Tubular Exchanger 202
- 7-10 Summary 204

8 Stochastic Process Disturbances and the Discrete Time Domain **205**
- 8-1 The Discrete Time Domain 205
- 8-2 White Noise and Sample Estimates of Population Measures 206
  - 8-2-1 The Sample Average 207
  - 8-2-2 The Sample Variance 207
  - 8-2-3 The Histogram 208
  - 8-2-4 The Sample Autocorrelation 209
  - 8-2-5 The Line Spectrum 212
  - 8-2-6 The Cumulative Line Spectrum 212
- 8-3 Non–White Stochastic Sequences 215
  - 8-3-1 Positively Autoregressive Sequences 215
  - 8-3-2 Negatively Autoregressive Sequences 218

8-3-3 Moving Average Stochastic Sequences 220
8-3-4 Unstable Nonstationary Stochastic Sequences 223
8-3-5 Multidimensional Stochastic Processes and the Covariance 225
8-4 Populations, Realizations, Samples, Estimates, and Expected Values 226
8-4-1 Realizations 226
8-4-2 Expected Value 227
8-4-3 Ergodicity and Stationarity 228
8-4-4 Applying the Expectation Operator 228
8-5 Comments on Stochastic Disturbances and Difficulty of Control 230
8-5-1 White Noise 230
8-5-2 Colored Noise 231
8-6 Summary 234

9 The Discrete Time Domain and the Z-Transform 235
9-1 Discretizing the First-Order Model 236
9-2 Moving to the Z-Domain via the Backshift Operator 238
9-3 Sampling and Zero-Holding 239
9-4 Recognizing the First-Order Model as a Discrete Time Filter 243
9-5 Descretizing the FOWDT Model 244
9-6 The Proportional-Integral Control Equation in the Discrete Time Domain 244
9-7 Converting the Proportional-Integral Control Algorithm to Z-Transforms 246
9-8 The PIfD Control Equation in the Discrete Time Domain 247
9-9 Using the Laplace Transform to Design Control Algorithms—the Q Method 249
9-9-1 Developing the Proportional-Integral Control Algorithm 249
9-9-2 Developing a PID-Like Control Algorithm 252
9-10 Using the Z-Transform to Design Control Algorithms 253
9-11 Designing a Control Algorithm for a Dead-Time Process 256
9-12 Moving to the Frequency Domain 259

9-12-1 The First-Order Process Model 260
9-12-2 The Ripple 261
9-12-3 Sampling and Replication 262
9-13 Filters 263
9-13-1 Autogressive Filters 263
9-13-2 Moving Average Filters 265
9-13-3 A Double-Pass Filter 267
9-13-4 High-Pass Filters 269
9-14 Frequency Domain Filtering 271
9-15 The Discrete Time State-Space Equation ... 273
9-16 Determining Model Parameters from Experimental Data 274
9-16-1 First-Order Models 274
9-16-2 Third-Order Models 276
9-16-3 A Practical Method 278
9-17 Process Identification with White Noise Inputs 279
9-18 Summary 283

10 Estimating the State and Using It for Control 285

10-1 An Elementary Presentation of the Kalman Filter 286
10-1-1 The Process Model 286
10-1-2 The Premeasurement and Postmeasurement Equations 287
10-1-3 The Scalar Case 288
10-1-4 A Two-Dimensional Example 288
10-1-5 The Propagation of the Covariances ... 289
10-1-6 The Kalman Filter Gain 290
10-2 Estimating the Underdamped Process State 291
10-3 The Dynamics of the Kalman Filter and an Alternative Way to Find the Gain 296
10-3-1 The Dynamics of a Predictor Estimator 298
10-4 Using the Kalman Filter for Control 299
10-4-1 A Little Detour to Find the Integral Gain 300
10-5 Feeding Back the State for Control 301
10-5-1 Integral Control 302
10-5-2 Duals 302
10-6 Integral and Multidimensional Control 303
10-6-1 Setting Up the Example Process and Posing the Control Problem 303
10-6-2 Developing the Discrete Time Version 304