

## Contents

**Preface** *xi*

**Acknowledgments** *xv*

### **Part I Classical and Advanced Control Theory:**

**Simulation and Examples** *1*

|          |  |          |
|----------|--|----------|
| <b>1</b> | <b>Field Elements of Classic Control Systems</b>                                   | <b>3</b> |
| 1.1      | The Principles of Control (Industry 5.0)   | 3        |
| 1.2      | Field Elements of Classic and Modern Control Systems                               | 6        |
| 1.2.1    | Advantages   | 7        |
| 1.2.2    | Disadvantages  | 7        |
| 1.2.3    | Why Control and Monitor?   | 7        |
| 1.3      | Process Modeling in Control Systems Design   | 11       |
| 1.4      | Ordinary Differential Equations and Laplace  | 13       |
| 1.5      | Linear Systems   | 18       |
| 1.6      | Nonlinear Dynamical Systems  | 20       |
| 1.7      | Stability Theory   | 21       |
| 1.8      | Systems' Identification  | 23       |
| 1.8.1    | Recursive Least Squares Method (Applied to Chapter 8)                              | 23       |
| 1.8.2    | Parameter Identification   | 25       |
| 1.8.3    | Ordinary Least Squares   | 25       |
| 1.8.4    | Recursive Least Squares (Applied to Chapter 6)                                     | 26       |
| 1.9      | General Methodology Based on Recursive Least Squares for Nonlinear Systems         | 28       |
| 1.10     | Optimal Controllers  | 33       |
| 1.10.1   | Linear Quadratic Regulator   | 33       |
| 1.10.2   | Optimal PI   | 36       |
| 1.10.3   | Pontryagin Maximum Principle   | 44       |
| 1.11     | Observer-based Controllers   | 45       |
| 1.12     | Examples of Modeling, Simulation, and Practical Platforms for Industrial Processes | 46       |

vi | Contents

|          |   |           |
|----------|---|-----------|
| 1.12.1   | LabVIEW   | 47        |
| 1.13     | Sensors   | 48        |
| 1.13.1   | ESP32   | 48        |
| 1.13.2   | Specifications  | 49        |
| 1.13.3   | Sensor Infrastructure   | 49        |
| 1.14     | Module MQ   | 50        |
| 1.15     | Sensor Operation  | 50        |
| 1.15.1   | Sensor Calibration  | 51        |
| 1.15.2   | Methane Sensor Programming Codes  | 52        |
| 1.15.3   | Carbon Dioxide Sensor Programming   | 54        |
| 1.15.4   | Carbon Dioxide Vernier Probe Programming                                  | 56        |
| 1.15.5   | MATLAB Function   | 56        |
|          | References  | 57        |
| <b>2</b> | <b>Advanced Control Theory Fundamentals</b>                               | <b>63</b> |
| 2.1      | Nonlinear Controllers and Advanced Control Theory                         | 63        |
| 2.2      | Nonlinear Control   | 67        |
| 2.3      | Accessibility Rank Condition  | 67        |
| 2.4      | Steady-output Controllability   | 69        |
| 2.5      | Controllable and Reachable Subspaces                                      | 70        |
| 2.6      | Controllable Matrix Test  | 70        |
| 2.7      | Eigenvector Test for Controllability                                      | 70        |
| 2.8      | Popov–Belevitch–Hautus  | 71        |
| 2.9      | Lyapunov Test for Controllability   | 71        |
| 2.10     | Sliding-mode Control Systems  | 71        |
| 2.10.1   | Sliding surface design  | 72        |
| 2.10.2   | Control Law First-order SMC   | 73        |
| 2.11     | Filippov’s  | 73        |
| 2.12     | Lyapunov Method   | 74        |
| 2.13     | Sontag Universal Formula  | 74        |
| 2.14     | Control of Industrial Time-delay Systems                                  | 77        |
| 2.14.1   | Delayed Systems   | 77        |
| 2.14.2   | Extension of LCF to Time-delay Systems                                    | 79        |
| 2.15     | Linear Time Systems with Delays and the Predictive Control Scheme         | 83        |
| 2.15.1   | LTI System with Input Delay   | 83        |
| 2.15.2   | Predictive Control for Systems with Input Delay                           | 83        |
| 2.15.3   | LTIS with State Delay   | 84        |
| 2.15.4   | LTIS with State Delay and Input Delay                                     | 87        |
| 2.15.5   | Prediction-based Control for LTIS with State Delay and Input Delay        | 87        |
| 2.15.6   | Dynamic Predictor-based Control for LTIS with State Delay and Input Delay | 88        |
| 2.15.7   | Linear Systems with State Delay and Two Input Delays                      | 89        |

- 2.15.8 Predictor-based Control for LTIS with State Delay and Two Input Delays 89
- 2.15.9 Dynamic Predictor-based Control for Linear Systems with Both State Delay and Two Input Delays 92
- References 93

**Part II Advanced Control Methods for Industrial Process 99**

**3 Design of a Nonlinear Controller to Regulate Hydrogen Production in a Microbial Electrolysis Cell 101**

- 3.1 Introduction 101
- 3.2 Mathematical Models 104
- 3.3 Bioprocess Modeling 105
  - 3.3.1 Unstructured Kinetic Models 105
- 3.4 MEC Modeling 106
- 3.5 Control Preliminaries 109
- 3.6 Methodology 111
- 3.7 Results and Discussion 111
- 3.8 System Model 114
- 3.9 Local Controllability Properties of the MEC Model 117
- 3.10 Measuring Hydrogen 121
- 3.11 Stability Test of the Proposed Controller 123
- 3.12 Conclusions 128
- References 128

**4 Comparison of Linear and Nonlinear State Observer Design Algorithms for Monitoring Energy Production in a Microbial Fuel Digester 135**

- 4.1 Introduction 135
  - 4.1.1 Anaerobic Biodigester 138
  - 4.1.2 Key Biodigester Parameters 138
- 4.2 Biodigester Operation 141
  - 4.2.1 Wet Biodigester 141
  - 4.2.2 Dry Biodigester 142
  - 4.2.3 Continuous Biodigester 142
  - 4.2.4 Semicontinuous Biodigester 143
  - 4.2.5 Anaerobic Digestion Model No. 1 143
- 4.3 State Estimation 147
- 4.4 Luenberger Observer 148
- 4.5 Sliding-mode Estimator 149
- 4.6 Proposed Nonlinear Estimator 152
- 4.7 Estimator Performance Index 155
- 4.8 Mathematical Modeling and Steady States 155
  - 4.8.1 Proposed Biodigester Model 156
  - 4.8.2 Stationary States 160

viii | Contents

|          |   |            |
|----------|---|------------|
| 4.8.3    | Local Observability Analysis  | 161        |
| 4.8.4    | Simulation and Comparison of Estimators   | 165        |
| 4.8.5    | Simulation of Disturbance with Sensor Noise   | 168        |
| 4.8.6    | Sensor Proposal   | 171        |
| 4.9      | Conclusions   | 175        |
|          | References  | 175        |
| <b>5</b> | <b>Optimal Control Approach Applied to a Fed-batch Reactor for Wastewater Treatment Plants</b>      | <b>183</b> |
| 5.1      | Introduction  | 183        |
| 5.2      | Metal and Contaminants’ Removal   | 184        |
| 5.3      | Operation Bioreactor  | 185        |
| 5.4      | Dynamic Model   | 186        |
| 5.5      | Proposed Model  | 187        |
| 5.5.1    | Sulfate-reduction Processes   | 187        |
| 5.6      | Isolation and Propagation of a Sulfate-reducing Bacteria Consortium                                 | 188        |
| 5.7      | Analytic Methods  | 189        |
| 5.8      | Results and Discussion  | 189        |
| 5.8.1    | Sulfate-reduction Processes   | 189        |
| 5.8.2    | Sensitivity Analysis  | 194        |
| 5.8.3    | Optimal Nonlinear Control of Finite Horizon   | 200        |
| 5.8.4    | Optimal Control of Finite Horizon for the Bioreactor  | 201        |
| 5.8.5    | Experimental System   | 203        |
| 5.9      | Conclusion  | 206        |
|          | References  | 207        |
| <b>6</b> | <b>Experimental Implementation of the Dynamic Predictive-based Control to a Coupled Tank System</b> | <b>213</b> |
| 6.1      | Introduction  | 213        |
| 6.2      | Coupled Tank System Description   | 214        |
| 6.2.1    | Mathematical Nonlinear Model  | 214        |
| 6.2.2    | Model Linearization   | 217        |
| 6.2.3    | Parameter Identification of the Coupled Tank System   | 219        |
| 6.2.4    | Implementation of the Recursive Least Square on LabVIEW   | 221        |
| 6.2.5    | Discretization of the Dynamic Predictors  | 224        |
| 6.2.6    | Gain Tuning and Poles   | 225        |
| 6.2.7    | Implementation of the Dynamic Predictive Control on LabVIEW   | 226        |
| 6.3      | Experimental Results  | 228        |
| 6.4      | Conclusion  | 229        |
|          | References  | 229        |

|          |  |            |
|----------|--|------------|
| <b>7</b> | <b>Temperature Robust Control Applied to a Tomato Dehydrator with the CLKF Approach</b>              | <b>233</b> |
| 7.1      | Introduction   | 233        |
| 7.2      | Dehydrator: Modeling and Description   | 234        |
| 7.2.1    | Description  | 235        |
| 7.2.2    | Mathematical Model   | 236        |
| 7.3      | Control Synthesis  | 241        |
| 7.4      | System Parameters  | 244        |
| 7.5      | Experimental Results   | 246        |
| 7.6      | Wi-Fi Monitoring System  | 250        |
| 7.7      | Conclusions  | 256        |
|          | References   | 256        |
| <br>     |  |            |
| <b>8</b> | <b>Design of an Adaptive Robust Controller: Temperature Regulation of a Heat Exchanger Prototype</b> | <b>261</b> |
| 8.1      | Introduction   | 261        |
| 8.2      | Methodology  | 263        |
| 8.3      | Robust and Adaptive Control Design   | 263        |
| 8.4      | Representation of the Control System   | 264        |
| 8.5      | Robust P and PI Control Law Design   | 265        |
| 8.6      | Adaptative P and PI Control Law Design   | 269        |
| 8.7      | Experimental Results   | 276        |
| 8.8      | MATLAB Code  | 276        |
| 8.9      | Experimental Platform and Identification   | 278        |
| 8.10     | Identification by Least Squares  | 282        |
| 8.11     | Additional Tools   | 284        |
| 8.12     | Robust P and PI Control  | 285        |
| 8.13     | Adaptative Robust P and PI Control   | 287        |
| 8.14     | Conclusions  | 290        |
|          | References   | 291        |
|          | <b>Credits</b>   | <b>293</b> |
|          | <b>Acronyms</b>  | <b>295</b> |
|          | <b>Index</b>   | <b>299</b> |

