

# Contents

<b>1</b>	<b>Introduction to Adaptive Control</b>	<b>1</b>
1.1	Adaptive Control—Why?	1
1.2	Adaptive Control Versus Conventional Feedback Control	3
1.2.1	Fundamental Hypothesis in Adaptive Control	6
1.2.2	Adaptive Control Versus Robust Control	6
1.3	Basic Adaptive Control Schemes	9
1.3.1	Open-Loop Adaptive Control	10
1.3.2	Direct Adaptive Control	11
1.3.3	Indirect Adaptive Control	13
1.3.4	Direct and Indirect Adaptive Control. Some Connections	16
1.3.5	Iterative Identification in Closed Loop and Controller Redesign	18
1.3.6	Multiple Model Adaptive Control with Switching	19
1.3.7	Adaptive Regulation	19
1.3.8	Adaptive Feedforward Compensation of Disturbances	20
1.3.9	Parameter Adaptation Algorithm	20
1.4	Examples of Applications	22
1.4.1	Open-Loop Adaptive Control of Deposited Zinc in Hot-Dip Galvanizing	22
1.4.2	Direct Adaptive Control of a Phosphate Drying Furnace	24
1.4.3	Indirect and Multimodel Adaptive Control of a Flexible Transmission	25
1.4.4	Adaptive Regulation in an Active Vibration Control System	26
1.4.5	Adaptive Feedforward Disturbance Compensation in an Active Vibration Control System	27
1.5	A Brief Historical Note	30
1.6	Further Reading	32
1.7	Concluding Remarks	32

<b>2</b>	<b>Discrete-Time System Models for Control</b>	35
2.1	Deterministic Environment	35
2.1.1	Input-Output Difference Operator Models	35
2.1.2	Predictor Form (Prediction for Deterministic SISO Models)	40
2.2	Stochastic Environment	43
2.2.1	Input-Output Models	43
2.2.2	Predictors for ARMAX Input-Output Models	45
2.2.3	Predictors for Output Error Model Structure	49
2.3	Concluding Remarks	50
2.4	Problems	52
<b>3</b>	<b>Parameter Adaptation Algorithms—Deterministic Environment</b>	55
3.1	The Problem	55
3.2	Parameter Adaptation Algorithms (PAA)—Examples	57
3.2.1	Gradient Algorithm	57
3.2.2	Recursive Least Squares Algorithm	61
3.2.3	Choice of the Adaptation Gain	67
3.2.4	Recursive Least Squares and Kalman Filter	72
3.2.5	Some Remarks on the Parameter Adaptation Algorithms	75
3.3	Stability of Parameter Adaptation Algorithms	76
3.3.1	Equivalent Feedback Representation of the Parameter Adaptation Algorithms and the Stability Problem	76
3.3.2	Stability Approach for the Synthesis of PAA Using the Equivalent Feedback Representation	82
3.3.3	Positive Real PAA Structures	90
3.3.4	Parameter Adaptation Algorithms with Time-Varying Adaptation Gain	97
3.3.5	Removing the Positive Real Condition	107
3.4	Parametric Convergence	111
3.4.1	The Problem	111
3.4.2	Persistently Exciting Signals	115
3.4.3	Parametric Convergence Condition	116
3.5	Concluding Remarks	118
3.6	Problems	119
<b>4</b>	<b>Parameter Adaptation Algorithms—Stochastic Environment</b>	121
4.1	Effect of Stochastic Disturbances	121
4.2	The Averaging Method for the Analysis of Adaptation Algorithms in a Stochastic Environment	126
4.3	The Martingale Approach for the Analysis of PAA in a Stochastic Environment	134
4.4	The Frequency Domain Approach	146
4.5	Concluding Remarks	149
4.6	Problems	150

- 5 Recursive Plant Model Identification in Open Loop . . . . . 153**
  - 5.1 Recursive Identification in the Context of System Identification . . . . . 153
  - 5.2 Structure of Recursive Parameter Estimation Algorithms . . . . . 155
  - 5.3 Recursive Identification Methods Based on the Whitening of the Prediction Error (Type I) . . . . . 162
    - 5.3.1 Recursive Least Squares (RLS) . . . . . 162
    - 5.3.2 Extended Least Squares (ELS) . . . . . 162
    - 5.3.3 Output Error with Extended Prediction Model (OEEPM) . . . . . 164
    - 5.3.4 Recursive Maximum Likelihood (RML) . . . . . 165
    - 5.3.5 Generalized Least Squares (GLS) . . . . . 166
  - 5.4 Validation of the Models Identified with Type I Methods . . . . . 168
    - 5.4.1 Whiteness Test . . . . . 169
  - 5.5 Identification Methods Based on the Decorrelation of the Observation Vector and the Prediction Error (Type II) . . . . . 171
    - 5.5.1 Output Error with Fixed Compensator . . . . . 171
    - 5.5.2 Output Error with Adjustable Compensator . . . . . 172
    - 5.5.3 Filtered Output Error . . . . . 173
    - 5.5.4 Instrumental Variable with Auxiliary Model . . . . . 175
  - 5.6 Validation of the Models Identified with Type II Methods . . . . . 176
    - 5.6.1 Uncorrelation Test . . . . . 177
  - 5.7 Selection of the Pseudo Random Binary Sequence . . . . . 178
    - 5.7.1 Pseudo Random Binary Sequences (PRBS) . . . . . 178
  - 5.8 Model Order Selection . . . . . 181
    - 5.8.1 A Practical Approach for Model Order Selection . . . . . 182
    - 5.8.2 Direct Order Estimation from Data . . . . . 185
  - 5.9 An Example: Identification of a Flexible Transmission . . . . . 187
  - 5.10 Concluding Remarks . . . . . 190
  - 5.11 Problems . . . . . 191
- 6 Adaptive Prediction . . . . . 193**
  - 6.1 The Problem . . . . . 193
  - 6.2 Adaptive Prediction—Deterministic Case . . . . . 194
    - 6.2.1 Direct Adaptive Prediction . . . . . 194
    - 6.2.2 Indirect Adaptive Prediction . . . . . 196
  - 6.3 Adaptive Prediction—Stochastic Case . . . . . 198
    - 6.3.1 Direct Adaptive Prediction . . . . . 198
    - 6.3.2 Indirect Adaptive Prediction—Stochastic Case . . . . . 201
  - 6.4 Concluding Remarks . . . . . 202
  - 6.5 Problems . . . . . 203
- 7 Digital Control Strategies . . . . . 205**
  - 7.1 Introduction . . . . . 205
  - 7.2 Canonical Form for Digital Controllers . . . . . 207
  - 7.3 Pole Placement . . . . . 210

7.3.1	Regulation . . . . .	210
7.3.2	Tracking . . . . .	214
7.3.3	Some Properties of the Pole Placement . . . . .	216
7.3.4	Some Particular Pole Choices . . . . .	221
7.4	Tracking and Regulation with Independent Objectives . . . . .	223
7.4.1	Polynomial Design . . . . .	223
7.4.2	Time Domain Design . . . . .	227
7.5	Tracking and Regulation with Weighted Input . . . . .	229
7.6	Minimum Variance Tracking and Regulation . . . . .	232
7.6.1	Design of Minimum Variance Control . . . . .	233
7.6.2	Generalized Minimum Variance Tracking and Regulation . . . . .	236
7.7	Generalized Predictive Control . . . . .	237
7.7.1	Controller Equation . . . . .	243
7.7.2	Closed-Loop Poles . . . . .	244
7.7.3	Recursive Solutions of the Euclidian Divisions . . . . .	246
7.8	Linear Quadratic Control . . . . .	249
7.9	Concluding Remarks . . . . .	252
7.10	Problems . . . . .	254
<b>8</b>	<b>Robust Digital Control Design . . . . .</b>	<b>259</b>
8.1	The Robustness Problem . . . . .	259
8.2	The Sensitivity Functions . . . . .	261
8.3	Robust Stability . . . . .	262
8.3.1	Robustness Margins . . . . .	262
8.3.2	Model Uncertainties and Robust Stability . . . . .	267
8.3.3	Robustness Margins and Robust Stability . . . . .	271
8.4	Definition of “Templates” for the Sensitivity Functions . . . . .	272
8.5	Properties of the Sensitivity Functions . . . . .	275
8.5.1	Output Sensitivity Function . . . . .	275
8.5.2	Input Sensitivity Function . . . . .	283
8.5.3	Noise Sensitivity Function . . . . .	285
8.6	Shaping the Sensitivity Functions . . . . .	286
8.7	Other Design Methods . . . . .	287
8.8	A Design Example: Robust Digital Control of a Flexible Transmission . . . . .	287
8.9	Concluding Remarks . . . . .	288
8.10	Problems . . . . .	290
<b>9</b>	<b>Recursive Plant Model Identification in Closed Loop . . . . .</b>	<b>293</b>
9.1	The Problem . . . . .	293
9.1.1	The Basic Equations . . . . .	296
9.2	Closed-Loop Output Error Algorithms (CLOE) . . . . .	298
9.2.1	The Closed-Loop Output Error Algorithm (CLOE) . . . . .	298
9.2.2	Filtered Closed-Loop Output Error Algorithm (F-CLOE) . . . . .	299

- 9.2.3 Extended Closed-Loop Output Error Algorithm (X-CLOE) . . . . . 300
- 9.3 Filtered Open-Loop Recursive Identification Algorithms (FOL) . . . 303
  - 9.3.1 Filtered Recursive Least Squares . . . . . 303
  - 9.3.2 Filtered Output Error . . . . . 305
- 9.4 Frequency Distribution of the Asymptotic Bias in Closed-Loop Identification . . . . . 305
  - 9.4.1 Filtered Open-Loop Identification Algorithms . . . . . 307
  - 9.4.2 Closed-Loop Output Error Identification Algorithms . . . . 308
- 9.5 Validation of Models Identified in Closed-Loop . . . . . 309
  - 9.5.1 Statistical Validation . . . . . 310
  - 9.5.2 Pole Closeness Validation . . . . . 311
  - 9.5.3 Time Domain Validation . . . . . 312
- 9.6 Iterative Identification in Closed-Loop and Controller Redesign . . 312
- 9.7 Comparative Evaluation of the Various Algorithms . . . . . 314
  - 9.7.1 Simulation Results . . . . . 314
  - 9.7.2 Experimental Results: Identification of a Flexible Transmission in Closed-Loop . . . . . 318
- 9.8 Iterative Identification in Closed Loop and Controller Redesign Applied to the Flexible Transmission . . . . . 321
- 9.9 Concluding Remarks . . . . . 324
- 9.10 Problems . . . . . 325
- 10 Robust Parameter Estimation . . . . . 329**
  - 10.1 The Problem . . . . . 329
  - 10.2 Input/Output Data Filtering . . . . . 331
  - 10.3 Effect of Disturbances . . . . . 332
  - 10.4 PAA with Dead Zone . . . . . 338
  - 10.5 PAA with Projection . . . . . 340
  - 10.6 Data Normalization . . . . . 344
    - 10.6.1 The Effect of Data Filtering . . . . . 349
    - 10.6.2 Alternative Implementation of Data Normalization . . . . 352
    - 10.6.3 Combining Data Normalization with Dead Zone . . . . . 352
  - 10.7 A Robust Parameter Estimation Scheme . . . . . 355
  - 10.8 Concluding Remarks . . . . . 355
  - 10.9 Problems . . . . . 356
- 11 Direct Adaptive Control . . . . . 359**
  - 11.1 Introduction . . . . . 359
  - 11.2 Adaptive Tracking and Regulation with Independent Objectives . . 360
    - 11.2.1 Basic Design . . . . . 360
    - 11.2.2 Extensions of the Design . . . . . 368
  - 11.3 Adaptive Tracking and Regulation with Weighted Input . . . . . 372
  - 11.4 Adaptive Minimum Variance Tracking and Regulation . . . . . 374
    - 11.4.1 The Basic Algorithms . . . . . 375
    - 11.4.2 Asymptotic Convergence Analysis . . . . . 380

- 11.4.3 Martingale Convergence Analysis . . . . . 383
- 11.5 Robust Direct Adaptive Control . . . . . 389
  - 11.5.1 The Problem . . . . . 389
  - 11.5.2 Direct Adaptive Control with Bounded Disturbances . . . . . 390
  - 11.5.3 Direct Adaptive Control with Unmodeled Dynamics . . . . . 393
- 11.6 An Example . . . . . 402
- 11.7 Concluding Remarks . . . . . 404
- 11.8 Problems . . . . . 405
- 12 Indirect Adaptive Control . . . . . 409**
  - 12.1 Introduction . . . . . 409
  - 12.2 Adaptive Pole Placement . . . . . 413
    - 12.2.1 The Basic Algorithm . . . . . 413
    - 12.2.2 Analysis of the Indirect Adaptive Pole Placement . . . . . 417
    - 12.2.3 The “Singularity” Problem . . . . . 424
    - 12.2.4 Adding External Excitation . . . . . 429
  - 12.3 Robust Indirect Adaptive Control . . . . . 430
    - 12.3.1 Standard Robust Adaptive Pole Placement . . . . . 431
    - 12.3.2 Modified Robust Adaptive Pole Placement . . . . . 434
    - 12.3.3 Robust Adaptive Pole Placement: An Example . . . . . 439
  - 12.4 Adaptive Generalized Predictive Control . . . . . 442
  - 12.5 Adaptive Linear Quadratic Control . . . . . 444
  - 12.6 Adaptive Tracking and Robust Regulation . . . . . 444
  - 12.7 Indirect Adaptive Control Applied to the Flexible Transmission . . . . . 445
    - 12.7.1 Adaptive Pole Placement . . . . . 445
    - 12.7.2 Adaptive PSMR Generalized Predictive Control . . . . . 450
  - 12.8 Concluding Remarks . . . . . 455
  - 12.9 Problems . . . . . 455
- 13 Multimodel Adaptive Control with Switching . . . . . 457**
  - 13.1 Introduction . . . . . 457
  - 13.2 Principles of Multimodel Adaptive Control with Switching . . . . . 458
    - 13.2.1 Plant with Uncertainty . . . . . 458
    - 13.2.2 Multi-Estimator . . . . . 459
    - 13.2.3 Multi-Controller . . . . . 459
    - 13.2.4 Supervisor . . . . . 460
  - 13.3 Stability Issues . . . . . 461
    - 13.3.1 Stability of Adaptive Control with Switching . . . . . 461
    - 13.3.2 Stability of the Injected System . . . . . 462
  - 13.4 Application to the Flexible Transmission System . . . . . 464
    - 13.4.1 Multi-Estimator . . . . . 464
    - 13.4.2 Multi-Controller . . . . . 464
    - 13.4.3 Experimental Results . . . . . 465
    - 13.4.4 Effects of Design Parameters . . . . . 470
  - 13.5 Concluding Remarks . . . . . 475
  - 13.6 Problems . . . . . 475

- 14 Adaptive Regulation—Rejection of Unknown Disturbances . . . . . 477**
  - 14.1 Introduction . . . . . 477
  - 14.2 Plant Representation and Controller Design . . . . . 481
  - 14.3 Robustness Considerations . . . . . 484
  - 14.4 Direct Adaptive Regulation . . . . . 484
  - 14.5 Stability Analysis . . . . . 487
  - 14.6 Indirect Adaptive Regulation . . . . . 489
  - 14.7 Adaptive Rejection of Multiple Narrow Band Disturbances  
on an Active Vibration Control System . . . . . 491
    - 14.7.1 The Active Vibration Control System . . . . . 491
    - 14.7.2 Experimental Results . . . . . 491
  - 14.8 Concluding Remarks . . . . . 496
  - 14.9 Problems . . . . . 497
  
- 15 Adaptive Feedforward Compensation of Disturbances . . . . . 499**
  - 15.1 Introduction . . . . . 499
  - 15.2 Basic Equations and Notations . . . . . 503
  - 15.3 Development of the Algorithms . . . . . 505
  - 15.4 Analysis of the Algorithms . . . . . 509
    - 15.4.1 The Deterministic Case—Perfect Matching . . . . . 509
    - 15.4.2 The Stochastic Case—Perfect Matching . . . . . 511
    - 15.4.3 The Case of Non-Perfect Matching . . . . . 512
    - 15.4.4 Relaxing the Positive Real Condition . . . . . 513
  - 15.5 Adaptive Attenuation of Broad Band Disturbances on an Active  
Vibration Control System . . . . . 514
    - 15.5.1 System Identification . . . . . 515
    - 15.5.2 Experimental Results . . . . . 516
  - 15.6 Concluding Remarks . . . . . 519
  - 15.7 Problems . . . . . 520
  
- 16 Practical Aspects . . . . . 523**
  - 16.1 Introduction . . . . . 523
  - 16.2 The Digital Control System . . . . . 524
    - 16.2.1 Selection of the Sampling Frequency . . . . . 524
    - 16.2.2 Anti-Aliasing Filters . . . . . 525
    - 16.2.3 Digital Controller . . . . . 525
    - 16.2.4 Effects of the Digital to Analog Converter . . . . . 526
    - 16.2.5 Handling Actuator Saturations (Anti-Windup) . . . . . 527
    - 16.2.6 Manual to Automatic Bumpless Transfer . . . . . 528
    - 16.2.7 Effect of the Computational Delay . . . . . 529
    - 16.2.8 Choice of the Desired Performance . . . . . 529
  - 16.3 The Parameter Adaptation Algorithm . . . . . 531
    - 16.3.1 Scheduling Variable  $\alpha_1(t)$  . . . . . 533
    - 16.3.2 Implementation of the Adaptation Gain Updating—  
The U-D Factorization . . . . . 535
  - 16.4 Adaptive Control Algorithms . . . . . 536

- 16.4.1 Control Strategies . . . . . 536
- 16.4.2 Adaptive Control Algorithms . . . . . 537
- 16.5 Initialization of Adaptive Control Schemes . . . . . 538
- 16.6 Monitoring of Adaptive Control Systems . . . . . 539
- 16.7 Concluding Remarks . . . . . 540
- Appendix A Stochastic Processes . . . . . 541**
- Appendix B Stability . . . . . 545**
- Appendix C Passive (Hyperstable) Systems . . . . . 549**
  - C.1 Passive (Hyperstable) Systems . . . . . 549
  - C.2 Passivity—Some Definitions . . . . . 550
  - C.3 Discrete Linear Time-Invariant Passive Systems . . . . . 552
  - C.4 Discrete Linear Time-Varying Passive Systems . . . . . 557
  - C.5 Stability of Feedback Interconnected Systems . . . . . 559
  - C.6 Hyperstability and Small Gain . . . . . 561
- Appendix D Martingales . . . . . 565**
- References . . . . . 573**
- Index . . . . . 585**





<http://www.springer.com/978-0-85729-663-4>

Adaptive Control

Algorithms, Analysis and Applications

Landau, I.D.; Lozano, R.; M'Saad, M.; Karimi, A.

2011, XXII, 590 p. With online files/update., Hardcover

ISBN: 978-0-85729-663-4