

Contents

1	Introduction to Adaptive Control	1
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

- 2 Discrete-Time System Models for Control 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

- 3 Parameter Adaptation Algorithms—Deterministic Environment 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

- 4 Parameter Adaptation Algorithms—Stochastic Environment 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
8	Robust Digital Control Design	259
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
9	Recursive Plant Model Identification in Closed Loop	293
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