
Contents

List of Principal Notationxxiii

1 Continuous Control Systems: A Review 1

 1.1 Continuous-time Models..... 1

 1.1.1 Time Domain..... 1

 1.1.2 Frequency Domain 2

 1.1.3 Stability 4

 1.1.4 Time Response 6

 1.1.5 Frequency Response..... 7

 1.1.6 Study of the Second-order System 10

 1.1.7 Systems with Time Delay..... 14

 1.1.8 Non-minimum Phase Systems..... 15

 1.2 Closed-loop Systems..... 16

 1.2.1 Cascaded Systems 16

 1.2.2 Transfer Function of Closed-loop Systems 17

 1.2.3 Steady-state Error 18

 1.2.4 Rejection of Disturbances..... 19

 1.2.5 Analysis of Closed-loop Systems in the Frequency Domain:
 Nyquist Plot and Stability Criterion 20

 1.3 PI and PID Controllers..... 22

 1.3.1 PI Controller 22

 1.3.2 PID Controller 23

 1.4 Concluding Remarks..... 24

 1.5 Notes and References..... 24

2 Computer Control Systems..... 25

 2.1 Introduction to Computer Control 25

 2.2 Discretization and Overview of Sampled-data Systems 28

 2.2.1 Discretization and Choice of Sampling Frequency 28

 2.2.2 Choice of the Sampling Frequency for Control Systems..... 31

 2.3 Discrete-time Models..... 34

 2.3.1 Time Domain..... 34

2.3.2	Frequency Domain	38
2.3.3	General Forms of Linear Discrete-time Models	42
2.3.4	Stability of Discrete-time Systems	44
2.3.5	Steady-state Gain.....	46
2.3.6	Models for Sampled-data Systems with Hold	47
2.3.7	Analysis of First-order Systems with Time Delay.....	49
2.3.8	Analysis of Second-order Systems	52
2.4	Closed Loop Discrete-time Systems	55
2.4.1	Closed Loop System Transfer Function	55
2.4.2	Steady-state Error	56
2.4.3	Rejection of Disturbances.....	57
2.5	Basic Principles of Modern Methods for Design of Digital Controllers	58
2.5.1	Structure of Digital Controllers	58
2.5.2	Digital Controller Canonical Structure	61
2.5.3	Control System with PI Digital Controller	64
2.6	Analysis of the Closed Loop Sampled-Data Systems in the Frequency Domain	66
2.6.1	Closed Loop Systems Stability	66
2.6.2	Closed Loop System Robustness.....	69
2.7	Concluding Remarks.....	81
2.8	Notes and References.....	84
3	Robust Digital Controller Design Methods	85
3.1	Introduction.....	85
3.2	Digital PID Controller	86
3.2.1	Structure of the Digital PID 1 Controller.....	87
3.2.2	Design of the Digital PID 1 Controller.....	90
3.2.3	Digital PID 1 Controller: Examples	95
3.2.4	Digital PID 2 Controller	99
3.2.5	Effect of Auxiliary Poles	102
3.2.6	Digital PID Controller: Conclusions	104
3.3	Pole Placement.....	105
3.3.1	Structure	105
3.3.2	Choice of the Closed Loop Poles ($P(q^{-1})$).....	107
3.3.3	Regulation (Computation of $R(q^{-1})$ and $S(q^{-1})$).....	108
3.3.4	Tracking (Computation of $T(q^{-1})$).....	113
3.3.5	Pole Placement: Examples.....	116
3.4	Tracking and Regulation with Independent Objectives	117
3.4.1	Structure	120
3.4.2	Regulation (Computation of $R(q^{-1})$ and $S(q^{-1})$).....	121
3.4.3	Tracking (Computation of $T(q^{-1})$).....	124
3.4.4	Tracking and Regulation with Independent Objectives: Examples	125
3.5	Internal Model Control (Tracking and Regulation)	129
3.5.1	Regulation	129
3.5.2	Tracking.....	131

3.5.3	An Interpretation of the Internal Model Control.....	132
3.5.4	The Sensitivity Functions	133
3.5.5	Partial Internal Model Control (Tracking and Regulation).....	134
3.5.6	Internal Model Control for Plant Models with Stable Zeros	135
3.5.7	Example: Control of Systems with Time Delay	136
3.6	Pole Placement with Sensitivity Function Shaping	141
3.6.1	Properties of the Output Sensitivity Function.....	142
3.6.2	Properties of the Input Sensitivity Function	152
3.6.3	Definition of the “Templates” for the Sensitivity Functions	155
3.6.4	Shaping of the Sensitivity Functions	157
3.6.5	Shaping of the Sensitivity Functions: Example 1	160
3.6.6	Shaping of the Sensitivity Functions: Example 2	161
3.7	Concluding Remarks.....	165
3.8	Notes and References.....	166
4	Design of Digital Controllers in the Presence of Random Disturbances.....	169
4.1	Models for Random Disturbances	169
4.1.1	Description of the Disturbances.....	169
4.1.2	Models of Random Disturbances.....	174
4.1.3	The ARMAX Model (Plant + Disturbance)	178
4.1.4	Optimal Prediction.....	179
4.2	Minimum Variance Tracking and Regulation.....	181
4.2.1	An Example	183
4.2.2	General Case.....	186
4.2.3	Minimum Variance Tracking and Regulation: Example	191
4.3	The Case of Unstable Zeros: Approximation of the Minimum Variance Tracking and Regulation by Means of Pole Placement	192
4.3.1	Controller Design	192
4.3.2	An Example	194
4.4	Generalized Minimum Variance Tracking and Regulation	195
4.4.1	Controller Design	196
4.5	Concluding Remarks.....	197
4.6	Notes and References.....	199
5	System Identification: The Bases.....	201
5.1	System Model Identification Principles.....	201
5.2	Algorithms for Parameter Estimation	207
5.2.1	Introduction	207
5.2.2	Gradient Algorithm	209
5.2.3	Least Squares Algorithm	215
5.2.4	Choice of the Adaptation Gain	221
5.3	Choice of the Input Sequence for System Identification.....	226
5.3.1	The Problem	226
5.3.2	Pseudo-Random Binary Sequences (PRBS).....	230
5.4	Effects of Random Disturbances upon Parameter Estimation	233
5.5	Structure of Recursive Identification Methods	236

5.6	Concluding Remarks.....	240
5.7	Notes and References.....	245
6	System Identification Methods	247
6.1	Identification Methods Based on the Whitening of the Prediction Error (Type I).....	247
6.1.1	Recursive Least Squares (RLS).....	247
6.1.2	Extended Least Squares (ELS).....	248
6.1.3	Recursive Maximum Likelihood (RML).....	251
6.1.4	Output Error with Extended Prediction Model (OEEPM).....	252
6.1.5	Generalized Least Squares (GLS).....	254
6.2	Validation of the Models Identified with Type I Methods.....	256
6.3	Identification Methods Based on the Uncorrelation of the Observation Vector and the Prediction Error (Type II).....	258
6.3.1	Instrumental Variable with Auxiliary Model.....	259
6.3.2	Output Error with Fixed Compensator	261
6.3.3	Output Error with (Adaptive) Filtered Observations	263
6.4	Validation of the Models Identified with Type II Methods	265
6.5	Estimation of the Model Complexity.....	267
6.5.1	An Example.....	267
6.5.2	The Ideal Case (No Noise).....	269
6.5.3	The Noisy Case.....	270
6.5.4	Criterion for Complexity Estimation	273
6.6	Concluding Remarks.....	274
6.7	Notes and References.....	276
7	Practical Aspects of System Identification.....	279
7.1	Input/Output Data Acquisition.....	279
7.1.1	Acquisition Protocol.....	279
7.1.2	Anti-Aliasing Filtering	282
7.1.3	Over Sampling.....	282
7.2	Signal Conditioning.....	284
7.2.1	Elimination of the DC Component.....	284
7.2.2	Identification of a Plant Containing a Pure Integrator	284
7.2.3	Identification of a Plant Containing a Pure Differentiator.....	285
7.2.4	Scaling of the Inputs and Outputs.....	285
7.3	Selection (Estimation) of the Model Complexity	285
7.4	Identification of Simulated Models: Examples.....	290
7.5	Plant Identification Examples.....	296
7.5.1	Air Heater.....	296
7.5.2	Distillation Column	300
7.5.3	DC Motor	305
7.5.4	Flexible Transmission.....	309
7.6	Concluding Remarks.....	314
7.7	Notes and references.....	315

8 Practical Aspects of Digital Control.....	317
8.1 Implementation of Digital Controllers.....	317
8.1.1 Choice of the Desired Performances	317
8.1.2 Effect of the Computational Time Delay.....	319
8.1.3 Effect of the Digital-to-analog Conversion	320
8.1.4 Effect of the Saturation: Anti Windup Device.....	321
8.1.5 Bumpless Transfer from Open Loop to Closed Loop Operation	326
8.1.6 Digital Cascade Control.....	326
8.1.7 Hardware for Controller Implementation	328
8.1.8 Measuring the Quality of a Control Loop.....	328
8.1.9 Adaptive Control	331
8.2 Digital Control of an Air Heater	333
8.3 DC Motor Speed Control.....	341
8.4 Cascade Position Control of a DC Motor Axis.....	344
8.5 Position Control by Means of a Flexible Transmission	352
8.6 Control of a 360° Flexible Robot Arm	358
8.7 Control of Deposited Zinc in Hot Dip Galvanizing (Sollac-Florange) ..	364
8.7.1 Description of the Process	364
8.7.2 Process Model	365
8.7.3 Model Identification	367
8.7.4 Controller Design	368
8.7.5 Open Loop Adaptation	369
8.7.6 Results	371
8.8 Concluding Remarks.....	372
8.9 Notes and References.....	373
9 Identification in Closed Loop.....	375
9.1 Introduction.....	375
9.2 Closed Loop Output Error Identification Methods	377
9.2.1 The Principle	377
9.2.2 The CLOE, F-CLOE and AF-CLOE Methods	378
9.2.3 Extended Closed Loop Output Error (X-CLOE).....	382
9.2.4 Identification in Closed Loop of Systems Containing an Integrator	383
9.2.5 Model Validation in Closed Loop	384
9.3 Other Methods for Identification in Closed Loop.....	387
9.4 Identification in Closed Loop: A Simulated Example	388
9.5 Identification in Closed Loop and Controller Re-Design (the Flexible Transmission)	391
9.6 Concluding Remarks.....	396
9.7 Notes and References.....	397
10.Reduction of Controller Complexity	399
10.1 Introduction.....	399
10.2 Estimation of Reduced Order Controllers by Identification in Closed Loop.....	404
10.2.1 Closed Loop Input Matching (CLIM)	404

10.2.2 Closed Loop Output Matching (CLOM)	407
10.2.3 Taking into Account the Fixed Parts of the Nominal Controller	407
10.2.4 Re-Design of Polynomial $T(q^{-1})$	408
10.3 Validation of Reduced Order Controllers	408
10.3.1 The Case of Simulated Data	409
10.3.2 The Case of Real Data	409
10.4 Practical Aspects.....	410
10.5 Control of a Flexible Transmission – Reduction of Controller Complexity	410
10.6 Concluding Remarks.....	415
10.7 Notes and References.....	415
A A Brief Review of Some Results from Theory of Signals and Probability	417
A.1 Some Fundamental Signals.....	417
A.2 The z - transform.....	419
A.3 The Gauss Bell.....	419
B Design of RST Digital Controllers in the Time Domain	423
B.1 Introduction.....	423
B.2 Predictors for Discrete Time Systems.....	424
B.3 One Step Ahead Model Predictive Control.....	429
B.4 An Interpretation of the Control of Systems with Delay	431
B.5 Long Range Model Predictive Control	434
B.6 Notes and References.....	440
C State-Space Approach for the Design of RST Controllers	441
C.1. State-Space Design	441
C.2. Linear Quadratic Control	449
C.3. Notes and References.....	450
D Generalized Stability Margin and Normalized Distance Between Two Transfer Functions	451
D.1 Generalized Stability Margin.....	451
D.2 Normalized Distance Between Two Transfer Functions	453
D.3 Robust Stability Condition.....	454
D.4 Notes and References.....	455
E The Youla–Kučera Controller Parametrization	457
E.1 Controller Parametrization.....	457
E.2 Notes and References.....	460
F The Adaptation Gain Updating – The U-D Factorization	461
F.1 The U–D Factorization.....	461
F.2 Notes and References.....	462

G Laboratory Sessions	463
G.1 Sampled-data Systems	463
G.2 Digital PID Controller	464
G.3 System Identification	465
G.4 Digital Control (Distillation Column Control Design)	467
G.5 Closed Loop Identification	468
G.6 Controller Reduction.....	469
H List of Functions (MATLAB[®], Scilab and C⁺⁺)	471
References	473
Index	479

Digital Control Systems

Design, Identification and Implementation

Landau, I.D.; Zito, G.

2006, XXIV, 484 p. 238 illus. With online files/update.,

Hardcover

ISBN: 978-1-84628-055-9