

Contents

1	Introduction	1
1.1	Overview.....	1
1.2	Notation and Nomenclature.....	1
1.2.1	Scalars, Vectors and Matrices.....	1
1.2.2	Subscripts and Superscripts.....	2
1.2.3	Constants and Variables	2
1.2.4	Nomenclature and Standard Symbols	3
1.2.5	Variables and Their Laplace Transforms	4
1.3	Review of Traditional PID Controllers and Their Variants.....	4
1.3.1	Traditional Error-Actuated Controllers.....	4
1.3.2	Zero-Less Versions of the Traditional Controllers.....	19
1.3.3	Traditional Controller Selection Guidelines	22
1.3.4	Measurement Noise Filtering for Derivative Term	25
1.3.5	Anti-windup Loop for Integral Term	32
1.4	Dominance in the Pole–Zero Distribution	43
1.4.1	Background.....	43
1.4.2	Modes of Linear Systems	43
1.4.3	Dominance in Pole Distributions	49
1.4.4	Dominance in Systems with Zeros	53
1.5	The Steps of Control System Design	69
1.6	The Flexibility of Digital Implementation	71
	Reference	71
2	Plant Modelling	73
2.1	Introduction.....	73
2.1.1	Overview	73
2.1.2	Dynamical and Non-Dynamical Systems	73
2.1.3	Linearity and Nonlinearity	76
2.1.4	Modelling Categories and Basic Forms of Model	80

2.2	Physical Modelling	81
2.2.1	Introduction.....	81
2.2.2	Mechanical Modeling Principles	81
2.2.3	Two Basic Mechanical Components	92
2.2.4	Modelling for Vehicle Attitude and Position Control	97
2.2.5	Electric Motors	104
2.2.6	Vector-Controlled AC Motors as Control Actuators...	109
2.2.7	Fluid and Thermal Subsystems	117
2.3	Identification of LTI Plants from Measurements	121
2.3.1	Overview	121
2.3.2	Plant Model Determination from Step Response	122
2.3.3	Plant Model Determination from Frequency Response.....	127
2.3.4	Recursive Parameter Estimation: An Introduction....	151
	References.....	167
3	Plant Model Manipulation and Analysis	169
3.1	Introduction.....	169
3.2	The State Space Model.....	170
3.2.1	Introduction.....	170
3.2.2	Forming a State-Space Model	171
3.2.3	The General State-Space Model	172
3.2.4	The General LTI State-Space Model	173
3.2.5	Some Preliminary Control Theory	175
3.2.6	Controllability Analysis of Continuous LTI Plant Models.....	179
3.2.7	Observability Analysis of Continuous LTI Plant Models.....	183
3.2.8	The State-Variable Block Diagram	187
3.2.9	Transfer Function from Continuous LTI State Space Model.....	190
3.2.10	Relative Degree.....	192
3.3	State Representation.....	194
3.3.1	Introduction.....	194
3.3.2	LTI SISO State-Space Models from Transfer Functions	200
3.3.3	Transformation Matrices Connecting Linear Models	211
3.3.4	Modal Forms for Multivariable LTI Plants: Transformations	217
3.3.5	SISO Controller and Observer Canonical Forms	237
3.3.6	Multivariable Controller and Observer Canonical Forms	245

3.4	Discrete LTI Plant Models	255
3.4.1	Formation of the Discrete State Space Model	255
3.4.2	State Space Model Derivation from Modal Basis Functions.....	259
3.4.3	Plant z -Transfer Function Model	274
3.4.4	Change of Sampling Period for z -Transfer Function Models	282
3.4.5	Controllability Analysis of Discrete LTI Plant Models.....	287
3.4.6	Analysis of Discrete LTI Plant Models.....	290
	References.....	293
4	Traditional Controllers: Model Based Design	295
4.1	Approach	295
4.2	Pole Assignment	297
4.3	Definition of Settling Time	299
4.4	PID Controllers and Their Variants.....	300
4.4.1	First Order Systems	300
4.4.2	Second Order Systems	307
4.4.3	Cascade Control Structure	319
4.5	Systems of Third and Higher Order	325
4.5.1	Attainable Closed Loop Dynamics	325
4.5.2	The Laplace to Time Domain Inverse Scaling Law ...	327
4.5.3	Step Responses with Coincident Closed Loop Poles.....	329
4.5.4	Derivation of the Settling Time Formulae	331
4.5.5	Settling Time Formula Error Determination and Correction	333
4.5.6	Closed Loop Poles for Given Overshoot and Settling Time.....	335
4.6	Performance Specifications in the Frequency Domain	337
4.6.1	Background.....	337
4.6.2	Closed Loop System Bandwidth	337
4.6.3	Sensitivity and Robustness.....	339
4.6.4	Stability Analysis in the Frequency Domain.....	347
	References.....	354
5	Linear Controllers for LTI SISO Plants of Arbitrary Order: Model-Based Design	355
5.1	Overview.....	355
5.2	Linear Continuous State Feedback Control	356
5.2.1	Introduction.....	356
5.2.2	Linear State Feedback Control Law	357
5.2.3	Matrix–Vector Formulation	358
5.2.4	Closed-Loop Transfer Function	360

5.2.5	Pole Assignment Using the Matrix–Vector Formulation.....	361
5.2.6	Pole Assignment Using Mason’s Formula.....	364
5.2.7	Pole Assignment for Plants with Significant Zeros....	368
5.2.8	State Feedback Controllers with Additional Integral Terms	387
5.3	Polynomial Control	398
5.3.1	Introduction.....	398
5.3.2	Formulation of Polynomial Controller Structure	399
5.3.3	Constraints on Controller Polynomial Degrees	401
5.3.4	Determination of the Controller Parameters	403
5.3.5	The Polynomial Integral Controller	407
	References.....	414
6	Discrete Control of LTI SISO Plants	415
6.1	Introduction.....	415
6.2	Real-Time Operation of Digital Controllers	416
6.3	Dynamics of Discrete Linear Systems	417
6.3.1	Stability Analysis in the z -Plane.....	417
6.3.2	Connection Between Dynamic Behaviour and the z -Plane Pole Locations	425
6.3.3	The Effects of Zeros in the z -Plane.....	432
6.4	Criterion for Applicability of Continuous LTI System Theory	435
6.5	Discrete Control for Small Iteration Intervals	439
6.5.1	Introduction.....	439
6.5.2	Discrete Equations of the Basic Elements	439
6.5.3	Discrete Controller Block Diagrams for Simulation	443
6.5.4	Control Algorithms and Flow Charts.....	447
6.6	Discrete Control with Unlimited Iteration Intervals	452
6.6.1	Pole Placement Design with the Settling Time Formulae	452
6.6.2	Pole Placement for Negligible Digital Processing Time	456
6.6.3	Computational Delay Allowance	464
6.6.4	Discrete Integral Polynomial Control	472
6.6.5	Control of Plants Containing Pure Time Delays	476
	References.....	480
7	Model Based Control of Nonlinear and Linear Plants	481
7.1	Introduction.....	481
7.2	Linearisation About an Operating Point.....	482
7.2.1	Basic Principle	482
7.2.2	Linear State-Space Model	484
7.2.3	Limitation.....	491

7.3	Feedback Linearising and Forced Dynamic Control	491
7.3.1	Preliminaries.....	491
7.3.2	Feedback Linearising Control of Plants with Full Relative Degree.....	495
7.3.3	Feedback Linearising Control of Plants Less Than Full Relative Degree	509
7.3.4	Forced Dynamic Control of Continuous LTI Plants ...	522
7.3.5	FDC and FLC Using Discrete Plant Models	543
7.3.6	Near-Time-Optimal Position Control Through FDC.....	550
	References	560
8	State Estimation	561
8.1	Introduction.....	561
8.2	The Full State Continuous Observer for LTI SISO Plants.....	562
8.2.1	Introduction.....	562
8.2.2	The Separation Principle and the Transparency Property	565
8.2.3	Design of the Real-Time Model Correction Loop	567
8.2.4	Estimation of Disturbances	575
8.3	The Full State Discrete Observer for LTI SISO Plants	587
8.3.1	Introduction.....	587
8.3.2	Observer Algorithm and Design Procedure	587
8.4	The Full State Observer for Multivariable Plants	592
8.4.1	Introduction.....	592
8.4.2	Matrix–Vector Design Method for SISO LTI Plants	592
8.4.3	Matrix–Vector Design Method for Multivariable LTI Plants	594
8.5	The Noise Filtering Property of the Observer.....	596
8.5.1	Background.....	596
8.5.2	Lumped Plant Noise and Measurement Noise Sources	597
8.5.3	State Estimation Error Variation with Observer Gains	598
8.5.4	State Estimation Error Transfer Function Relationship	599
8.5.5	Considering Noise Levels in Observer Design	602
8.6	The Kalman Filter	613
8.6.1	Introduction.....	613
8.6.2	The Discrete Observer	614
8.6.3	The Kalman Filter: State Difference and Error Equations	615
8.6.4	Derivation of the Discrete Kalman Gain Algorithm ...	617

8.6.5	The Steady-State Kalman Filter	621
8.6.6	The Kalman–Bucy Filter	622
	References	624
9	Switched and Saturating Control Techniques	625
9.1	Introduction	625
9.1.1	Switched Control	625
9.1.2	Saturating Control	627
9.2	Pulse Modulation for Use with Continuous Controllers	628
9.2.1	Basic Concept	628
9.2.2	Implementation	629
9.3	Switched State Feedback Control: Basic Concepts	638
9.4	Switching Function Sign Convention	641
9.5	Boundary Layer for Saturating Control Systems	642
9.6	Supporting Theory	644
9.6.1	Background	644
9.6.2	Optimal Control Through Pontryagin’s Maximum Principle	644
9.7	Feedback Control of First-Order Plants	651
9.7.1	Time-Optimal Feedback Control: Analytical Method	651
9.7.2	Time-Optimal Feedback Control: Graphical Approach	654
9.7.3	Limit Cycling and Its Control	655
9.7.4	Control with Time-Varying Reference Inputs	658
9.7.5	Continuous Control with Saturation	662
9.8	Feedback Control of Second-Order Plants	666
9.8.1	Introduction	666
9.8.2	State Trajectories and State Portraits	666
9.8.3	Time-Optimal Feedback Control of the Double Integrator Plant	669
9.8.4	Time-Optimal Control Law Synthesis Using State Portraits	672
9.8.5	Continuous Control with Saturation	676
9.8.6	Limit Cycling Control	687
9.9	Feedback Control of Third and Higher-Order Plants	687
9.9.1	Overview	687
9.9.2	Time-Optimal Control of the Triple Integrator Plant	687
9.9.3	Posicast Control of Fourth-Order Plants with Oscillatory Modes	696
	References	704

10	Sliding Mode Control and Its Relatives	705
10.1	Introduction	705
10.1.1	Purpose and Origin	705
10.1.2	Basic Principle	705
10.1.3	Implementation for Robustness	707
10.2	Control of SISO Second-Order Plants of Full Relative Degree	713
10.2.1	The Plant Model	713
10.2.2	Phase Portraits	714
10.2.3	Sliding Motion	716
10.2.4	The Equivalent Control	718
10.2.5	Control Chatter	718
10.2.6	Conditions for the Existence of Sliding Motion	719
10.2.7	Reaching the Sliding Condition	720
10.2.8	Closed-Loop Dynamics in the Sliding Mode	723
10.2.9	Control with Time-Varying Disturbances and Reference Inputs	723
10.2.10	Rate-Limiting Switching Boundary for Zero Overshoot	725
10.2.11	Sub-Time-Optimal Control	726
10.3	Control of SISO Plants of Arbitrary Order	730
10.3.1	Control of Plants Having Full Relative Degree	730
10.3.2	Control of Plants Less Than Full Relative Degree	738
10.4	Methods for Elimination of Control Chatter	742
10.4.1	The Boundary Layer Method	742
10.4.2	The Control Smoothing Integrator Method	746
10.4.3	Higher-Order Sliding Mode Control	756
10.5	Controllers with Robust Pole Placement	766
10.5.1	Introduction	766
10.5.2	Output Derivative State Feedback Controller	767
10.5.3	Dynamic Controllers with Robust Pole Placement	770
10.6	Multivariable Sliding Mode Control: An Introduction	773
10.6.1	Overview	773
10.6.2	Simple Approach with Minimum Plant Information	774
10.6.3	Discrete Sliding Mode Control	778
	References	792
11	Motion Control	793
11.1	Introduction	793
11.2	Controlled Mechanisms	793
11.2.1	The General-Purpose Jointed-Arm Robot	793
11.2.2	General Model	794

11.2.3	Feedback Linearising Control Law	798
11.2.4	Simplified Model for Mechanisms with Geared Actuators	799
11.3	Dynamic Lag Pre-compensation	805
11.3.1	Definition of Dynamic Lag	805
11.3.2	Derivative Feedforward Pre-compensation	806
11.3.3	Implementation with Feedback Linearising Control	822
11.4	Optimal Control for Minimising Frictional Energy Loss	826
11.4.1	Motivation	826
11.4.2	Formulation of Optimal Control	827
11.4.3	Minimum Frictional Energy State Feedback Control Law	830
11.4.4	Higher-Order Mechanisms	832
11.4.5	Near-Optimal Control Using a Reference Input Generator	832
	References	846
Tables	847
	Laplace Transforms and z-Transfer Functions	847
	Characteristic Polynomial Coefficients of the Settling Time Formulae	850
Appendices	853
A2	Appendix to Chap. 2	853
A2.1	Kinematics of Vehicle Attitude Control	853
A2.2	Plant Model Determination from Frequency Response	867
A2.3	A Case Study of Plant Modelling Undertaken in Industry: Modelling for a Throttle Valve Servomechanism	881
	References	899
A4	Appendix to Chap. 4	900
A4.1	Application of Mason's Formula Using Block Diagrams	900
A4.2	Traditional Controller Zero Cancellation by Pole Assignment	908
A4.3	Partial Pole Assignment for Traditional Controllers... Reference	915 919
A5	Appendix to Chap. 5	920
A5.1	Computer Aided Pole Assignment	920
A5.2	Linear Characteristic Polynomial Interpolation	927
A5.3	Routh Stability Criterion	936

A8	Appendix to Chap. 8	940
	A8.1 An Approach for State Estimation for Nonlinear Plants	940
	A8.1.2 Observer Based on Linearised Plant Model.....	941
	A8.1.3 Output Derivative Based State Estimator	941
A9	Appendix to Chap. 9	954
	A9.1 Limit Cycling Control for Second Order Plants	954
	References	970
A10	Appendix to Chap. 10	971
	A10.1 Observer Based Robust Control	971
	References	984
A11	Appendix to Chap. 11	985
	A11.1 Path Planning and Reference Input Trajectory Generation	985
	Reference	1002
Index		1003

Feedback Control

Linear, Nonlinear and Robust Techniques and Design
with Industrial Applications

Dodds, S.J.

2015, XXV, 1012 p. 674 illus., 3 illus. in color. With
online files/update., Softcover

ISBN: 978-1-4471-6674-0