

Contents

Preface	ix
1 Introduction	1
1.1 Delay Systems	1
1.2 Control via Delay Compensation	2
1.3 Varying vs. Constant Delays	3
1.4 Future Paths	4
1.5 Organization of the Book	6
1.6 Spaces and Solutions	7
I Constant Delays	9
2 Linear Systems with Input and State Delays	11
2.1 Predictor Feedback Design for Systems with Input Delay	12
2.2 Strict-Feedback Systems with Delayed Integrators	19
2.3 Adaptive Control of Feedforward Systems with Unknown Delays	35
2.4 Notes and References	47
3 Linear Systems with Distributed Delays	51
3.1 Systems with Known Plant Parameters	51
3.2 Adaptive Control for Systems with Uncertain Plant Parameters	70
3.3 Notes and References	82
4 Application: Automotive Catalysts	87
4.1 Model Development	88
4.2 Analysis of the Model under a Square Wave Air-to-Fuel Ratio Input	92
4.3 Observer-Based Output Feedback	96
4.4 Notes and References	102
5 Nonlinear Systems with Input Delay	105
5.1 Nonlinear Predictor Feedback Design for Constant Delay	105
5.2 Nonlinear Infinite-Dimensional Backstepping Transformation	106
5.3 Lyapunov-Based Stability Analysis	108
5.4 Notes and References	113

II	Time-Varying Delays	115
6	Linear Systems with Time-Varying Input Delay	117
6.1	Predictor Feedback Design for Time-Varying Input Delay	117
6.2	Stability Analysis for Time-Varying Delays	120
6.3	Notes and References	128
7	Robustness of Linear Constant-Delay Predictors to Time-Varying Delay Perturbations	129
7.1	Robustness to Time-Varying Perturbation for Linear Systems	129
7.2	A Teleoperation-Like Example	137
7.3	Notes and References	139
8	Nonlinear Systems with Time-Varying Input Delay	141
8.1	Nonlinear Predictor Feedback Design for Time-Varying Delay	141
8.2	Stability Analysis	144
8.3	Stabilization of the Nonholonomic Unicycle with Time-Varying Delay	151
8.4	Notes and References	152
9	Nonlinear Systems with Simultaneous Time-Varying Delays on the Input and the State	155
9.1	Predictor Feedback Design for Systems with Both Input and State Delays	155
9.2	Stability Analysis	157
9.3	Simulations	168
9.4	Notes and References	169
III	State-Dependent Delays	171
10	Predictor Feedback Design When the Delay Is a Function of the State	173
10.1	Nonlinear Predictor Feedback Design for State-Dependent Delay	173
10.2	Notes and References	176
11	Stability Analysis for Forward-Complete Systems with Input Delay	179
11.1	Stability Analysis for Forward-Complete Nonlinear Systems	179
11.2	Example: Nonholonomic Unicycle Subject to Distance-Dependent Input Delay	190
11.3	Global Stabilization	192
11.4	Notes and References	193
12	Stability Analysis for Locally Stabilizable Systems with Input Delay	195
12.1	Stability Analysis for Locally Stabilizable Nonlinear Systems	195
12.2	Notes and References	204
13	Nonlinear Systems with State Delay	207
13.1	Problem Formulation and Controller Design	207
13.2	Stability Analysis for Forward-Complete Systems	208
13.3	Examples	216
13.4	Notes and References	219

14 Robustness of Nonlinear Constant-Delay Predictors to Time- and State-Dependent Delay Perturbations	221
14.1 Robustness to Time- and State-Dependent Delay Perturbations for Nonlinear Systems	221
14.2 Example: Control of a DC Motor over a Network	230
14.3 Proofs	231
14.4 Notes and References	241
15 State-Dependent Delays That Depend on Delayed States	243
15.1 Predictor Feedback under Input Delays	243
15.2 Stability Analysis under Input Delays	246
15.3 Example	252
15.4 Stabilization under State Delays	253
15.5 Notes and References	264
A Basic Inequalities	265
B Input-to-Output Stability	267
C Lyapunov Stability, Forward-Completeness, and Input-to-State Stability	273
C.1 Lyapunov Stability and \mathcal{K}_∞ Functions	273
C.2 Forward-Completeness	277
C.3 Input-to-State Stability	277
D Parameter Projection	283
Bibliography	287
Index	299