

# Contents

<b>Chapter 0</b>	
<b>Mathematical Preliminaries</b>	<b>1</b>
0.1 Notation	1
0.2 Linear Spaces	1
0.3 Subspaces	3
0.4 Maps and Matrices	6
0.5 Factor Spaces	9
0.6 Commutative Diagrams	11
0.7 Invariant Subspaces. Induced Maps	12
0.8 Characteristic Polynomial. Spectrum	13
0.9 Polynomial Rings	14
0.10 Rational Canonical Structure	15
0.11 Jordan Decomposition	18
0.12 Dual Spaces	21
0.13 Tensor Product. The Sylvester Map	23
0.14 Inner Product Spaces	25
0.15 Hermitian and Symmetric Maps	26
0.16 Well-Posedness and Genericity	28
0.17 Linear Systems	30
0.18 Transfer Matrices. Signal Flow Graphs	31
0.19 Rouché's Theorem	32
0.20 Exercises	33
0.21 Notes and References	35
<b>Chapter 1</b>	
<b>Introduction to Controllability</b>	<b>36</b>
1.1 Reachability	36
1.2 Controllability	38

1.3	Single-Input Systems	40
1.4	Multi-Input Systems	41
1.5	Controllability is Generic	44
1.6	Exercises	45
1.7	Notes and References	47
Chapter 2		
Controllability, Feedback and Pole Assignment		48
2.1	Controllability and Feedback	48
2.2	Pole Assignment	50
2.3	Incomplete Controllability and Pole Shifting	51
2.4	Stabilizability	54
2.5	Exercises	54
2.6	Notes and References	55
Chapter 3		
Observability and Dynamic Observers		57
3.1	Observability	57
3.2	Unobservable Subspace	59
3.3	Full Order Dynamic Observer	60
3.4	Minimal Order Dynamic Observer	61
3.5	Observers and Pole Shifting	64
3.6	Detectability	66
3.7	Detectors and Pole Shifting	68
3.8	Pole Shifting by Dynamic Compensation	72
3.9	Observer for a Single Linear Functional	77
3.10	Preservation of Observability and Detectability	79
3.11	Exercises	80
3.12	Notes and References	84
Chapter 4		
Disturbance Decoupling and Output Stabilization		86
4.1	Disturbance Decoupling Problem (DDP)	86
4.2	$(A, B)$ -Invariant Subspaces	87
4.3	Solution of DDP	90
4.4	Output Stabilization Problem (OSP)	92
4.5	Exercises	97
4.6	Notes and References	101
Chapter 5		
Controllability Subspaces		102
5.1	Controllability Subspaces	103
5.2	Spectral Assignability	105

5.3	Controllability Subspace Algorithm	106
5.4	Supremal Controllability Subspace	108
5.5	Transmission Zeros	112
5.6	Disturbance Decoupling with Stability	113
5.7	Controllability Indices	116
5.8	Exercises	122
5.9	Notes and References	128
Chapter 6		
<b>Tracking and Regulation I: Output Regulation</b>		<b>129</b>
6.1	Restricted Regulator Problem (RRP)	131
6.2	Solvability of RRP	133
6.3	Extended Regulator Problem (ERP)	138
6.4	Example	142
6.5	Concluding Remarks	144
6.6	Exercises	145
6.7	Notes and References	145
Chapter 7		
<b>Tracking and Regulation II: Output Regulation with Internal Stability</b>		<b>146</b>
7.1	Solvability of RPIS: General Considerations	148
7.2	Constructive Solution of RPIS: $\mathcal{N} = 0$	151
7.3	Constructive Solution of RPIS: $\mathcal{N}$ Arbitrary	157
7.4	Application: Regulation Against Step Disturbances	161
7.5	Application: Static Decoupling	162
7.6	Example 1: RPIS Unsolvable	163
7.7	Example 2: Servo-Regulator	165
7.8	Exercises	169
7.9	Notes and References	177
Chapter 8		
<b>Tracking and Regulation III: Structurally Stable Synthesis</b>		<b>178</b>
8.1	Preliminaries	178
8.2	Example 1: Structural Stability	180
8.3	Well-Posedness and Genericity	182
8.4	Well-Posedness and Transmission Zeros	185
8.5	Example 2: RPIS Solvable but Ill-Posed	190
8.6	Structurally Stable Synthesis	192
8.7	Example 3: Well-Posed RPIS: Strong Synthesis	201
8.8	The Internal Model Principle	203
8.9	Exercises	210
8.10	Notes and References	213

Chapter 9	
Noninteracting Control I: Basic Principles	215
9.1 Decoupling: Systems Formulation	216
9.2 Restricted Decoupling Problem (RDP)	217
9.3 Solution of RDP: Outputs Complete	219
9.4 Extended Decoupling Problem (EDP)	220
9.5 Solution of EDP	222
9.6 Naive Extension	226
9.7 Example	228
9.8 Partial Decoupling	229
9.9 Exercises	230
9.10 Notes and References	233
Chapter 10	
Noninteracting Control II: Efficient Compensation	234
10.1 The Radical	234
10.2 Efficient Extension	238
10.3 Efficient Decoupling	242
10.4 Minimal Order Compensation: $d(\mathcal{B}) = 2$	246
10.5 Minimal Order Compensation: $d(\mathcal{B}) = k$	251
10.6 Exercises	254
10.7 Notes and References	256
Chapter 11	
Noninteracting Control III: Generic Solvability	257
11.1 Generic Solvability of EDP	257
11.2 State Space Extension Bounds	264
11.3 Significance of Generic Solvability	268
11.4 Exercises	269
11.5 Notes and References	269
Chapter 12	
Quadratic Optimization I: Existence and Uniqueness	270
12.1 Quadratic Optimization	270
12.2 Dynamic Programming: Heuristics	271
12.3 Dynamic Programming: Rigor	273
12.4 Matrix Quadratic Equation	277
12.5 Exercises	280
12.6 Notes and References	282

<b>Chapter 13</b>	
<b>Quadratic Optimization II: Dynamic Response</b>	<b>284</b>
13.1 Dynamic Response: Generalities	284
13.2 Example 1: First-Order System	285
13.3 Example 2: Second-Order System	285
13.4 Hamiltonian Matrix	287
13.5 Asymptotic Root Locus: Single Input System	288
13.6 Asymptotic Root Locus: Multivariable System	292
13.7 Upper and Lower Bounds on $P^0$	296
13.8 Stability Margin. Gain Margin	297
13.9 Return Difference Relations	298
13.10 Applicability of Quadratic Optimization	301
13.11 Exercises	301
13.12 Notes and References	303
<b>References</b>	<b>305</b>
<b>Index</b>	
<b>Relational and Operational Symbols</b>	<b>317</b>
Letter Symbols	319
Synthesis Problems	321
Subject Index	322