

Contents

Acknowledgements	iii
Abstract	v
PART I INTRODUCTION	
1 The Problem of Fault-Tolerant Task Assignment	3
1.1 Introduction to Fault-Tolerant Control of Networked Systems	3
1.1.1 General Idea	3
1.1.2 Illustrative Example	5
1.1.3 Cooperative Tasks versus Subtasks	6
1.1.4 Fault-Tolerant Systems	6
1.1.5 Network of Dynamical Systems	8
1.2 Aim of This Thesis	9
1.3 Classification of the Existing Literature	13
1.3.1 Networked Systems	14
1.3.2 Fault-Tolerant Control	16
1.3.3 Fault Diagnosis in Networked Systems	17
1.3.4 Reconfiguration in Networked Systems	18
1.3.5 Tracking Control	21
1.3.6 Task Assignment	25
1.3.7 Publications of the Author	26
1.4 Structure and Contributions of this Thesis	27
2 Preliminaries	33
2.1 Notation	33
2.2 Linear Time-Invariant Systems	35
2.2.1 Stability	36
2.2.2 Observability and Controllability	37
2.3 Networked Systems	38
2.4 Linear Algebra	39
2.4.1 Pseudoinverse	39
2.4.2 Linear Systems of Equations	40
2.4.3 Definite Matrices	41

Contents

PART II FAULT-TOLERANT CONTROL

3 Fault-Tolerant Task Assignment for Stuck-At Faults	45
3.1 Introduction	45
3.2 Fault-Tolerant Control Problem	48
3.2.1 Cooperative Task	48
3.2.2 Model of the Subsystems	50
3.2.3 Assignable Tasks	54
3.3 Nominal Task Assignment	56
3.3.1 Requirements	56
3.3.2 Illustration of the Nominal Task Assignment	56
3.3.3 Consistent References	58
3.3.4 Satisfiable References	60
3.3.5 Summary of Nominal Task Assignment	63
3.3.6 Spline Interpolation	65
3.4 Autonomy of the Subsystems	68
3.4.1 Active and Passive Subsystems	68
3.4.2 Switching States of Passive Subsystems	71
3.4.3 Ongoing Passivity	73
3.4.4 Summary	75
3.5 Redistribution of Tasks	76
3.5.1 Requirements	76
3.5.2 Naive Solution	78
3.5.3 Redistribution by Mapping	80
3.5.4 Redistribution by Redesign	83
3.5.5 Analysis of the Assignability in the Fault Case	89
3.6 Optimal Redistribution of Tasks	92
3.6.1 Aim	92
3.6.2 Review of Quadratic Programming	93
3.6.3 Reformulation of the Optimization Problem	93
3.6.4 Solving the Quadratic Problem	95
3.7 Numerical Example: Transportation System	97
3.7.1 Control Aim	97
3.7.2 Analysis of the Assignability in the Fault Case	99
3.7.3 Simulation Results	100
3.8 Summary of the Chapter	103
4 Fault Diagnosis in Networked Systems	105
4.1 Diagnostic Problem	105
4.2 Generation and Evaluation of Residuals	108
4.3 Observer-Based Residual Generation	109
4.4 Estimation of the Coupling Input	111

Contents

4.5	Local Residual Evaluation	112
4.5.1	Evaluation Unit	112
4.5.2	Choice of the Threshold	113
4.6	Summary of the Solution	115
PART III TRACKING CONTROL		
5	Tracking Control of Linear Systems	119
5.1	Tracking Problem	119
5.2	Flatness-Based Feedforward Control	121
5.3	Flat Linear Systems	124
5.3.1	Control Canonical Form for Multiple Input Systems	125
5.3.2	Flat Parametrization	127
5.4	Conversion of the Desired Output into a Desired Flat Output	130
5.4.1	Relationship between the Plant's Output and the Flat Output . . .	130
5.4.2	Solving Differential-Algebraic Equations	132
5.4.3	Control-Related Properties of the Plant	134
5.5	Output Tracking	137
5.5.1	Application of the Feedforward Signal	137
5.5.2	Consistent Initial States	139
5.6	Analysis of the Input and Output Signals	144
5.6.1	Consistent Outputs	144
5.6.2	Differentiability of the Reference Trajectory	145
5.6.3	Unbounded Control Signals	146
5.7	Extension to Two-Degrees-of-Freedom Control	146
5.8	Summary	148
6	Tracking Control in Networked Systems	149
6.1	Tracking Problem	149
6.2	Preliminaries	151
6.2.1	Design Challenges	151
6.2.2	Separation of the Subsystems in Local Part and Network Part . .	152
6.3	Approach 1: Attenuation of the Coupling Input	155
6.3.1	Description of the Idea	155
6.3.2	Unknown Coupling Input	156
6.3.3	Implementation in a Digital Communication Network	159
6.4	Approach 2: Utilizing the Physical Network	159
6.4.1	Description of the Idea	159
6.4.2	Unknown Coupling Input	161
6.4.3	Implementation in a Digital Communication Network	165

Contents

6.5	Analysis of the Digital Communication Network	165
6.5.1	Design Phase Versus Working Phase	165
6.5.2	Information Structure Versus Communication Structure	167
6.5.3	Transmission of Trajectories	169
6.6	Extension to Two-Degrees-of-Freedom Control	170
6.7	Summary	173
PART IV EXPERIMENTS		
7	COCO: Description of the Testbed	177
7.1	Introduction	177
7.1.1	Testbed	177
7.1.2	Theoretical Control Structure	180
7.1.3	Practical Control Structure	182
7.2	Specific Aim of this Chapter	183
7.2.1	Inner loop	184
7.2.2	Outer loop	185
7.3	Hardware and Software	186
7.3.1	Mechanical Setup	186
7.3.2	Electrical Components	186
7.3.3	Software Architecture	188
7.4	Inner Loop: Controlling the Linear Actuators	189
7.4.1	Modeling the Linear Actuators	189
7.4.2	Parameter Identification	190
7.4.3	Control Signals of the Actuators	193
7.4.4	Stability Analysis of the Inner Loop	197
7.5	Testing the Inner Loop with a Traveling Wave	201
7.5.1	Desired Shape of the Surface	201
7.5.2	Experimental Results: Output Signals	201
7.5.3	Experimental Results: Control Signals	203
7.6	Outer-Loop: Stabilization of the Ball Position	204
7.6.1	Control Problem	204
7.6.2	State-Feedback Control for Vanishing Inner Loop	207
7.6.3	Simplified Model for the Inner Loop	209
7.6.4	Extend Controller by Integral Part	212
7.6.5	Position Control in Combination with Feedforward Control	214
7.7	Summary	215
8	Cooperative Fault-Tolerant Transportation Process	217
8.1	Aim of the Experiments	217
8.1.1	Introduction	217

Contents

8.1.2	Desired Performance Output	219
8.1.3	Switching Time and Switching State	219
8.2	Transportation Under Nominal Conditions	221
8.2.1	Cooperative Behavior	221
8.2.2	Subtasks	222
8.2.3	Autonomy and Active Subsystems	226
8.2.4	Switching State and Switching Time	226
8.3	Transportation in Case of Stuck-at Linear Actuators	227
8.3.1	Necessity of Redistribution	227
8.3.2	Fault Diagnosis	230
8.3.3	Cooperative Behavior	231
8.3.4	Subtasks	234
8.3.5	Active Subsystems	237
8.3.6	Switching State and Switching Time	237
8.3.7	Computational Aspects	238
8.4	Summary	240
9	Conclusions	241
9.1	Summary	241
9.2	Open Problems	243
	Bibliography	245
	APPENDIX	
	A Collection of Mathematical Lemmas	261
	B List of Symbols	267
	Acronyms	281