Contents

1 Introduction to plug-and-play control **1**

1.1 Plug-and-play control 1

1.2 Motivation and application scenarios 2

1.2.1 Motivation example: Power networks 2

1.2.2 Application scenarios used in this thesis 4

1.2.3 Further application scenarios 5

1.3 Problem formulation and fundamental questions 6

1.3.1 The plug-and-play control problem 6

1.3.2 Approaches and fundamental questions 8

1.4 Literature on plug-and-play control 10

1.4.1 Controller design with limited model information 10

1.4.2 Plug-and-play in networked control systems 14

1.4.3 Plug-and-play in manufacturing systems 15

1.4.4 Implementation of plug-and-play control 16

1.4.5 Classification of this thesis 16

1.5 Contributions of this thesis 17

1.6 Structure of this thesis 19

2 Preliminaries **23**

2.1 Notation and definitions 23

2.1.1 General notation 23

2.1.2 Definitions on stability 25

2.1.3 Convex sets 26

2.1.4 Linear matrix inequalities 29

2.1.5 Set invariance in control 30

2.1.6 Graph theory 31

2.2 Models 31

2.2.1 Interconnected system 31

2.2.2 Controlled interconnected system 34

2.2.3 Communication network 34

2.3 Robust control techniques . . . 34
2.3.1 Systems with unknown-but-bounded model uncertainty . . . 35
2.3.2 Basics on H_∞-norm . . . 37
2.4 Fault-tolerant control methods . . . 39
2.4.1 Model of the faulty subsystem . . . 39
2.4.2 Controller reconfiguration by a virtual actuator . . . 40
2.4.3 Model-based fault diagnosis . . . 41
2.5 Demonstration examples . . . 44
2.5.1 Interconnected thermofluid process . . . 45
2.5.2 Multizone furnace . . . 47

3 Handling of model information 49
3.1 Connection of models . . . 49
3.2 Models of plug-and-play control . . . 53
3.2.1 Global view and local view . . . 53
3.2.2 Models from the local view . . . 54
3.3 Design agents . . . 58
3.4 Interconnection graph and communication graph . . . 59
3.4.1 Interconnection graph . . . 59
3.4.2 Communication graph . . . 60

4 Plug-and-play control using the model of the physical interaction 63
4.1 Problem formulation . . . 63
4.2 A distributed algorithm to model the physical interaction . . . 65
4.3 Analysis of the modelling algorithm . . . 69
4.4 Application scenario: Fault-tolerant control . . . 74
4.4.1 Local reconfiguration with a virtual actuator using the model of the physical interaction . . . 74
4.4.2 Plug-and-play reconfiguration algorithm . . . 76
4.4.3 Example: Interconnected tank system . . . 77

5 Plug-and-play control using the local model based on restricted operating sets 81
5.1 Problem formulation . . . 81
5.2 Conditions to enable the design with the local model . . . 83
5.3 Local design conditions . . . 87
5.3.1 Boundedness conditions . . . 87
5.3.2 Performance conditions . . . 88

5.4 Controller design based on robustly positively invariant operating sets 90
5.4.1 LMI-based design of a static state-feedback 90
5.4.2 Design of a tube-based model predictive controller 93
5.5 Application scenario: Fault-tolerant control 102
5.5.1 Plug-and-play reconfiguration algorithm 103
5.5.2 Experiment: Interconnected thermofluid process 104
5.5.3 Further application scenarios 111

6 Plug-and-play control using the local model based on limited amplifications 113
6.1 Problem formulation 113
6.2 Conditions to enable the design with the local model 115
6.3 Local design conditions 119
6.3.1 I/O stability conditions 119
6.3.2 I/O performance conditions 124
6.4 H_∞-controller design 127
6.5 Application scenario: Integration of new subsystems 133
6.5.1 Plug-and-play integration algorithm 133
6.5.2 Experiment: Interconnected thermofluid process 136
6.5.3 Further application scenarios 142

7 Plug-and-play control using an approximate model of the physical interaction 143
7.1 Problem formulation 143
7.2 A local algorithm to approximate the dynamics of the physical interaction . . . 146
7.2.1 Separation of relevant and irrelevant dynamics 146
7.2.2 A measure of the coupling strength 149
7.2.3 A local condition to adjust the accuracy of the interaction model 151
7.2.4 Model procurement algorithm 158
7.3 Cooperative design conditions 160
7.3.1 Conditions to enable the design with an approximate model of the physical interaction 160
7.3.2 I/O stability conditions 164
7.3.3 I/O performance conditions 168
7.3.4 H_∞-controller design 170

7.4 Application scenario: Fault-tolerant control . . . 171
7.4.1 Local reconfiguration with a virtual actuator using an approximate model of the physical interaction . . . 172
7.4.2 Plug-and-play reconfiguration algorithm . . . 174
7.4.3 Example: Multizone furnace . . . 174
7.4.4 Further application scenarios . . . 179

8 Plug-and-play diagnosis using an approximate model of the physical interaction 181
8.1 Problem formulation . . . 181
8.2 Models of plug-and-play diagnosis . . . 184
8.2.1 Approximate model for the design of the diagnosis system . . . 184
8.2.2 Structure of the local diagnosis system . . . 187
8.3 Design of the residual evaluation . . . 188
8.3.1 Design issues . . . 188
8.3.2 Tolerance bands of the residuals . . . 189
8.3.3 Robust fault detectability and robust fault isolability . . . 192
8.3.4 Thresholds for fault detection and fault isolation . . . 194
8.4 Design of the residual generation . . . 196
8.4.1 Design issues . . . 196
8.4.2 A robust residual generator . . . 196
8.5 Plug-and-play diagnosis algorithm . . . 203
8.6 Example: Multizone furnace . . . 206

9 Conclusion 211
9.1 Summary . . . 211
9.2 Outlook . . . 213

Bibliography 215

Appendices 231

A Models of the demonstration processes 233
A.1 Interconnected thermofluid process model . . . 233
A.1.1 Nonlinear model . . . 233
A.1.2 Linearised model . . . 235
A.2 Multizone furnace . . . 237

B Proofs **239**
B.1 Proof of Theorem 4.1 . . . 239
B.2 Proof of Corollary 4.1 . . . 240
B.3 Proof of Theorem 5.1 . . . 241
B.4 Proof of Corollary 5.1 . . . 242
B.5 Proof of Corollary 5.2 . . . 242
B.6 Proof of Lemma 6.1 . . . 243
B.7 Proof of Theorem 6.3 . . . 244
B.8 Proof of Lemma 7.1 . . . 246
B.9 Proof of Theorem 7.2 . . . 247
B.10 Proof of Lemma 7.2 . . . 248
B.11 Proof of Theorem 7.3 . . . 249
B.12 Proof of Proposition 7.2 . . . 251
B.13 Proof of Corollary 7.5 . . . 252

C Construction rules of transfer functions **255**
C.1 Physical interaction, relevant part and irrelevant part . . . 255
C.2 Cooperatively controlled subsystem . . . 257

D List of symbols **259**