# Contents

**Abstract** i

**1 Introduction to networked discrete-event systems** 1

1.1 Networked discrete-event systems . . . . . 1
1.2 Literature overview . . . . . 7
1.2.1 Literature on networked discrete-event systems . . . . . 7
1.2.2 Literature on controller design . . . . . 11
1.2.3 Literature on abstraction methods . . . . . 12
1.2.4 Literature on networked fault-tolerant control . . . . . 14
1.3 Main contributions of the thesis . . . . . 15
1.4 Structure of the thesis . . . . . 17

**2 Autonomous and cooperative control problems** 19

2.1 Preliminaries . . . . . 19
2.1.1 Notation . . . . . 19
2.1.2 I/O automata and I/O maps . . . . . 19
2.1.3 Network of I/O automata and I/O maps . . . . . 23
2.1.4 Equivalence relation . . . . . 32
2.2 Autonomous and cooperative tasks . . . . . 33
2.2.1 Structure of the networked discrete-event system . . . . . 33
2.2.2 Local tasks . . . . . 36
2.2.3 Cooperative tasks . . . . . 37
2.2.4 Control problem . . . . . 42
2.3 Cooperative behaviour . . . . . 48

**3 Autonomous control and synchronisation of networked discrete-event systems** 51

3.1 Target-state control of deterministic I/O automata . . . . . 51
3.1.1 Control structure . . . . . 51
3.1.2 Controllability . . . . . 53
3.1.3 Trajectory matrix . . . . . 53
3.1.4 Feedforward control . . . . . 57

3.1.5 State-feedback control . . . . . 60
3.2 Target-state control of extended deterministic I/O automata . . . . . 63
3.2.1 State-feedback target-state controller . . . . . 63
3.2.2 Behaviour of the closed-loop system . . . . . 65
3.3 Synchronisation of networked discrete-event systems . . . . . 67
3.3.1 Execution of synchronous state transitions . . . . . 67
3.3.2 Synchronisation unit . . . . . 70
3.3.3 Synchronisation of multi-agent systems . . . . . 71
3.3.4 Synchronisation of physically coupled systems . . . . . 78
3.3.5 Compatible target states . . . . . 84

**4 Cooperative control of networked discrete-event systems 87**
4.1 Cooperative target-state control . . . . . 87
4.2 Compositional model abstraction . . . . . 90
4.2.1 Quotient model of multi-agent systems . . . . . 90
4.2.2 Properties of the abstracted multi-agent system . . . . . 96
4.2.3 Quotient model of physically coupled systems . . . . . 101
4.2.4 Properties of the abstracted physically coupled system . . . . . 104
4.3 Determination of compatible state trajectories . . . . . 108
4.3.1 Cooperative target-state controller . . . . . 108
4.3.2 Decision unit . . . . . 111
4.4 Behaviour of networked discrete-event systems . . . . . 113
4.4.1 Behaviour of multi-agent systems . . . . . 113
4.4.2 Behaviour of physically coupled systems . . . . . 120

**5 Task-dependent and fault-tolerant cooperative control 123**
5.1 Task-dependent model abstraction . . . . . 123
5.1.1 Involved subsystems . . . . . 123
5.1.2 Task-dependent quotient model of multi-agent systems . . . . . 124
5.1.3 Task-dependent quotient model of physically coupled systems . . . . . 126
5.2 Task-dependent cooperative target-state control . . . . . 128
5.2.1 Task-dependent cooperative controller . . . . . 128
5.2.2 Task-dependent decision unit . . . . . 129
5.2.3 Task-dependent cooperative control of multi-agent systems . . . . . 133
5.2.4 Task-dependent cooperative control of physically coupled systems . . . 136
5.3 Online cooperative control . . . . . 137
5.3.1 Online model composition . . . . . 137

5.3.2 Local model communication and composition . . . 138
5.3.3 Online model composition with the $A^*$-algorithm . . . 140
5.3.4 Properties of the online model composition algorithm . . . 144
5.3.5 Online cooperative control . . . 151
5.4 Fault-tolerant control of networked discrete-event systems . . . 152
5.4.1 Fault-tolerant cooperative control problem . . . 152
5.4.2 Fault modelling . . . 154
5.4.3 Fault-tolerant cooperative control . . . 157
5.4.4 Decentralised control reconfiguration . . . 158

**6 Experimental evaluation 163**
6.1 Handling system HANS . . . 163
6.1.1 Hardware architecture . . . 163
6.1.2 Models of the subsystems . . . 165
6.2 Cooperative controller . . . 173
6.2.1 Compositional model abstraction . . . 173
6.2.2 Modelling of autonomous and cooperative tasks . . . 176
6.2.3 Design of the network units . . . 178
6.2.4 Control architecture . . . 179
6.3 Experimental results . . . 180
6.3.1 Distance measure and experimental data . . . 180
6.3.2 Evaluation of the autonomous tasks . . . 180
6.3.3 Evaluation of the cooperative tasks . . . 181
6.3.4 Communication structure and cooperative behaviour . . . 187

**7 Conclusion 189**
7.1 Summary . . . 189
7.2 Outlook . . . 191

**Bibliography 193**

**List of symbols 205**